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Contents

Abstract

Using measurements taken from a circuit repeatedly driving a magnetic core enclosing current carrying wires into magnetic saturation we are able to estimate the net current going through the wires. The saturation circuit consist of two coils oppositely wrapped around a magnetic core which take turn saturating the core with opposite polarities. The work in this thesis examines currents entering and leaving an electric vehicle charging system and assume that any non-zero net current is a ground fault current.

From the saturation circuitry, we take three different measurements and show that all three produce valid estimates for any sinusoidal ground fault current with a constant offset. The performance of each of the estimates are comparable and the main separator is the attributed cost of implementation. Additional testing should be done to test reliability and how accuracy changes with ground fault current magnitude.

The developed system for ground fault current estimation will return an estimate for both the DC and AC component every 20ms as the system is designed to work with 50Hz AC power. If we wanted the system to work with 60Hz power we need only change one parameter in software. Changes can be done to get a faster refresh rate of ground fault current estimate, but this is left for future work. Future work can also encompass more sophisticated post-estimation data processing such as filtering or statistical analysis.

Nomenclature

A comprehensive list of abbreviations and electrical symbols being used in this thesis.

Abbreviations

AC	Alternating Current
CCD	Coil Current Draw
CVD	Coil Voltage Differential
DC	Direct Current
GFC	Ground Fault Current
GPIO	General-Purpose Input/Output
MC	Magnetic Core
RCD	Residual Current Device
TD	Timing Difference

Electrical symbols

C	Capacitor
J	Connector Jack/Test Point
L	Inductor
Pxy	Signal to GPIO module x, pin y
Q	Transistor

NOMENCLATURE

R	Resistor
U	Integrated Circuit

Chapter 1

Introduction

The modern world is electric. We are constantly surrounded by electrical devices that makes our lives better, but direct contact with electricity can be lethal. Because of this reason, electrical engineers have designed most devices to not require the user to directly anything conducting harmful levels of electricity, but this does not mean that accidents will not happen.

A ground fault is when an electric path is created from an electrical system to the ground system. This may only harm the electrical system itself, but if a human is in the path to ground, they may suffer great harm or potentially death. To reduce the risk of electrocutions, engineers developed the residual current device (RCD). This device will disconnect any power the moment a ground fault is detected.

As mentioned in [1] the earliest RCDs could reliably cut power when a ground fault of 500 millampere was detected and later developments brought this threshold down to 25 to 30 milliamperes. Charles F. Dalziel was able to increase sensitivity of the RCDs to about 5 milliamperes in [2].

What all these systems had in common was the use of a highly permeable metal core where the power lines acted as primary windings and a secondary winding would sense any magnetic field present in the core. The thought is that the magnetic fields from the current carrying wires would cancel each other when there was an equal amount of current going into the system as there is current exiting the system. In the event of a ground fault, there is an unequal amount of current going through each power line which would therefore induce a voltage in the secondary winding and trigger the RCD.

As a digression, the specific mention of Charles F. Dalziel was not coincidental. His work on electric safety started in the 1940s most notably by his experiments on what he called "let-go currents". These experiments tested the ability of willing men and women, himself included, to let go of a live conductor. He experimented with the intensity [3], frequency [4] and waveform [5] of the current delivered by the conductor and logged the responses from the people receiving the shock. By recording every participants maximal let-go current he determined the maximally allowable current to pass through a human should not exceed 5 milliamperes as he estimated 99.5% of men, women and children should be able to let go any conductor delivering this amount of current. His work has been instrumental in saving countless lives from electrocution and should not be understated.

1.1 Problem formulation

We wish to create a quantitative estimate of any ground fault currents in an electric vehicle charging system. To do this we will analyse three measurements taken from a circuit which magnetically saturate a magnetic core enclosing the wires going to the vehicle. We wish to find a relationship between these measurements and the magnitude of the ground fault current such that we can estimate the ground fault current based purely off a new measurement and historical data.

The goal is to use this estimate to determine if the power going to the electric vehicle should be turned off; this is to protect the user of the charger from potentially lethal electric shock. This thesis was written in collaboration with Easee to develop this system for their new charger. They wanted the flexibility and diagnostics that a microcontroller platform could provide since traditional residual current devices may only inform whether it was an alternating current or direct current that triggered the device.

1.2 About Easee

Easee specialises in creating smart chargers for electrical vehicles. The focus of this thesis has been to develop a RCD for their newest charger. Because the charger already houses a microcontroller, creating a microcontroller-based system for estimating the ground fault currents could be added without a large increase in cost.

Easee had already begun development of the electronics for this system when approached with this thesis proposal. They provided the principles of measurements and prototype circuit board with a physical realisation of these measurements. Easee also provided an office space with the equipment required to develop the contents of this thesis.

1.3 Outline of this thesis

This thesis is broken down into seven chapters.

- The first two chapters serve as an introduction to the problem and relevant background knowledge.
- By chapter three we get into specifics by introducing the three types of measurements used by the system to estimate the ground fault current.
- In chapter four we talk about how the hardware and software is set up to capture and process these measurements.
- Chapter five gives details of how the system is set up and how the measurements are recorded.
- Chapter six contain all the results from running the system and recording its responses. It gives details of how the system respond to different ground fault currents, creates models to estimate the ground fault currents from the data, and analyses the performance of each model.
- The final chapter wraps up the work done in this thesis. We give a final evaluation of the measurements, ask what could have been done differently, and what should get prioritised for future work.

Chapter 2

Background and theory

2.1 Electromagnetism

To understand how a ground fault detection circuit works, we need to discuss a simple inductor. It is created by coiling an insulated wire around a magnetic core and when current passes through the coil, a magnetic field will permeate through the magnetic core. If you increase the current, the magnitude of the magnetisation will also increase until you reach magnetic saturation. This is when the material in the magnetic core cannot increase the strength of the magnetic field even though you increase the current through the coil.

Magnetic fields cannot be created nor destroyed instantaneously. This is because electromagnetic fields carry energy which need time to change forms. Because the current in coils interact with magnetic fields, the electric current through coils are also resistant to instantaneous changes. This makes coils into temporary energy stores as their magnetic fields will induce the necessary voltage needed to keep the current continuous.

2.2 Concept behind the residual current device

In the introduction we briefly mentioned how the most common residual current device (RCD) use a coil wrapped around a magnetic core (MC) to sense imbalances in the current entering and exiting a system. A more novel approach piqued the interest of some engineers at Easee when they took apart a benvac RCD from VACUUMSCHMELZE [6]. The device would alternate bringing an MC into magnetic saturation using two oppositely wound coils. The specific details of how it worked was obfuscated by a proprietary microcontroller circuit which provided the motivation to explore how to build a similar, but potentially more sophisticated and verbose system.

The MC has two coils which will induce magnetic fields with opposing directions or polarities when a positive voltage is applied. Both coils have an equal number of turns and will therefore provide the same amount of magnetic flux per unit of current passing through the coil. The charging wires, or the wires being monitored, are fed through the hole in the toroidal MC and can be viewed as a single turn coil. Figure 2.1 will provide a sketch of the MC with its coils.

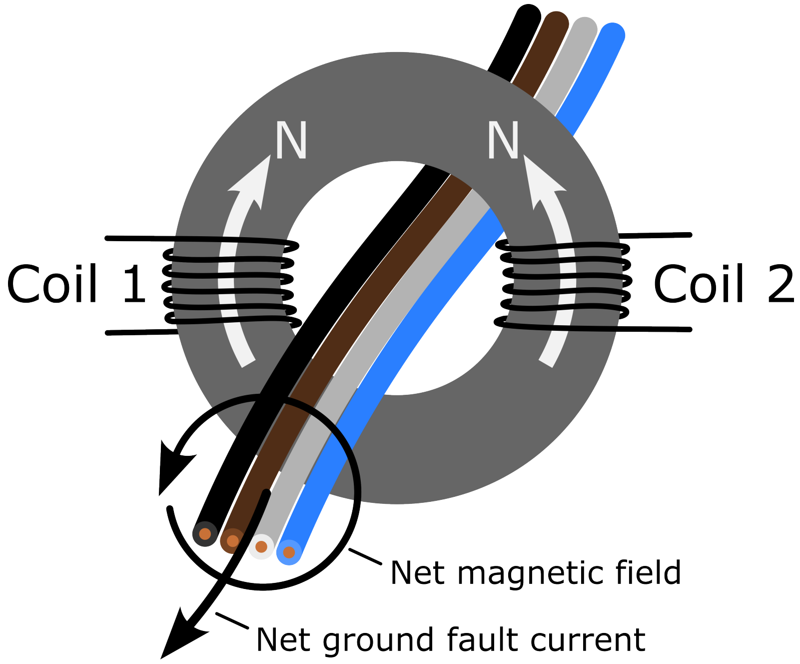


Figure 2.1: Diagram of magnetic core with charger wires and coils

The system will begin magnetising the core by applying voltage to the first coil. When the MC is saturated, the first coil will be turned off and the second coil will turn on. This will magnetise the MC in the opposite polarity until the point of saturation is reached and the system will switch off the second coil and turn on the first coil. This process will continue for as long as the RCD has power.

If the net magnetic field around the wires going to the vehicle is zero, the operation of driving the MC to magnetic saturation will be symmetrical in both directions. If the net magnetic field around the wires is non-zero, the net magnetic field will assist in saturating the MC in one direction and hinder in the other. This means that it would require a different amount of energy from the coils to magnetically saturate the MC in one way compared to the other.

For the net magnetic field to be non-zero, the net current in the wires need to be non-zero. Because of this, analysis of the saturation process can be related to current imbalances in the wires going through the MC. In this thesis we will analyse 3 different aspects of the saturation circuitry to see which measurement provide the most accurate and stable estimate of the ground fault current.

Chapter 3

Estimation methods

The goal with the proposed design is to estimate the net current going through the wires to the charger by measurements done on the saturation of the magnetic core (MC). The point of using such indirect measurements as opposed to measuring the charging current directly is to interfere as little as possible with the vehicle charging circuit. However this also means that all measurements need some processing to produce valid estimates of the current. Our efforts should therefore be in determining which measurements can be used to estimate the ground fault current (GFC) in the most reliable and accurate manner.

To talk about the specific points of measurements, the simplified circuit in figure 3.1 will be of help. When either Q1 or Q2 is active, the current through the corresponding coil will increase until the current through the bottom resistor is above a given threshold. When this happens, the active transistor is turned off and the other transistor will be turned on. The first measurement is to simply measure the time it takes to saturate the core. The second measurement will be the voltage difference between the two coils. The third measurement will be of the current drawn by the coils.

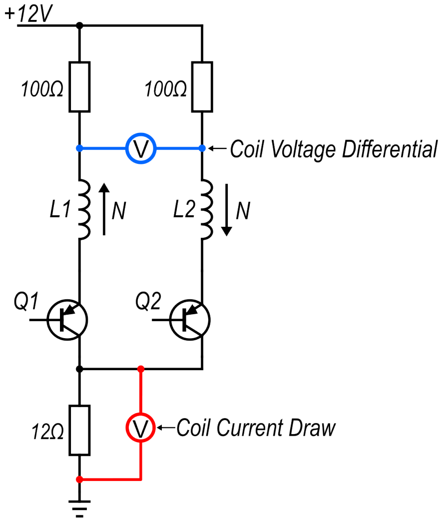


Figure 3.1: Simplified magnetic saturation circuit

3.1 Measurement one: Timing Difference

Since the microcontroller is controlling Q1 and Q2, it is not difficult to log the time between each switching. To do this, we keep a timer running which will count how much time has passed since the last reset and when saturation is reached, the timer records the time passed and is thereafter reset. Since the power source is a constant 12V, any asymmetry in the energy required to saturate the core will lead to a difference in time required to saturate the core. Given enough resolution in time, this timing difference (TD) should increase as the magnitude of the GFC increases. This measurement method is very simplistic, requiring no additional components to the system, which is good since it lowers implementation complexity.

3.2 Measurement two: Coil voltage differential

The coil voltage differential (CVD) is the voltage between the two coils of the saturation circuit. In figure 3.1 this is shown as the blue voltmeter. If there is any GFC of the system, the net magnetic field will induce a voltage in one coil and an equal, but opposite, voltage in the other coil since the coils are wound in opposing directions. Because of this, the CVD will be offset by a constant voltage which will increase as the magnitude of the GFC increases.

3.3 Measurement three: Coil current draw

The coil current draw (CCD) is the electrical current flowing through the active coil. In figure 3.1 this is represented as red voltmeter measuring the voltage over a resistor connected to ground. To get the current, we need only divide the voltage by 12Ω. If the system is experiencing a GFC, the induced voltage will increase or decrease the CCD depending on if the active coil saturates the MC in the same or opposite direction of the magnetic field from the GFC. This means that the CCD will alternate between being shifted up and down as the two coils are activated then deactivated; the amound of shifting will be related to the magnitude of the GFC.

Chapter 4

Design and construction of hardware and software

To create the residual current device (RCD) we need both hardware that can get the measurements we are after and software that is able to analyse the measurements and estimate the ground fault current (GFC). For this purpose we need to understand how the signals of the measurements act in the physical world and how they are represented in software.

4.1 Hardware

The hardware used for the RCD had already been designed and produced by Easee at the start of this thesis. The hardware consists of a microcontroller development board and a circuit board designed to mount on top of the development board and interface through its general-purpose input/output-pins (GPIO). The microcontroller is of the type STM32G4 and is mounted on the development NUCLEO-G474RE whose user manual can be found in appendix C.2. The additional circuit board has two functions: It houses and controls the saturation circuit given commands from the microcontroller and it converts the measurements of interest into appropriate ranges for the analogue to digital converters (ADCs) of the microcontroller. A complete schematic and printed circuit board-layout is provided in the appendices A.1 and A.2.

4.1.1 Measurement 1: Timing Difference

The timing difference (TD) measurement is a measurement of the time required to saturate the magnetic core (MC). When the MC is saturated, the coils will assume a steady state where they have low ohmic resistance. Because of this, current through the coils will increase as the MC get closer to saturation.

At the end of the saturation process, the current will spike as the voltage over the coils dissapears. The way we detect this is by measuring the voltage over a 12 Ω resistor in series after the coils. When the voltage reaches a threshold voltage, in our case 0.81 V or around 67.5 mA, we define this as the MC reaching saturation. This voltage is measured on pin PA1 which is internally connected to an analogue comparator on the microcontroller.

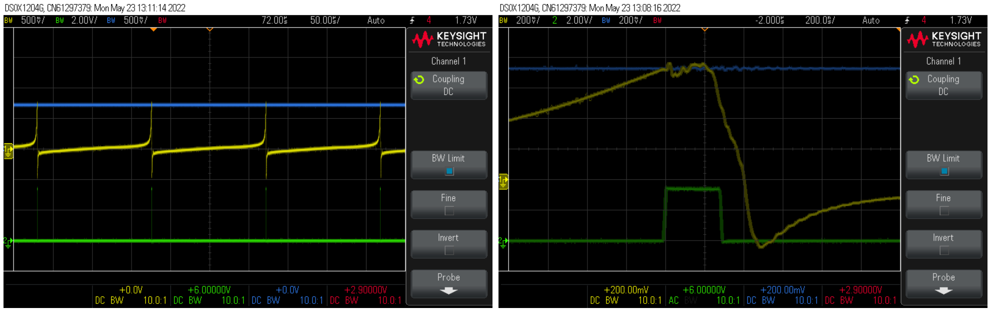
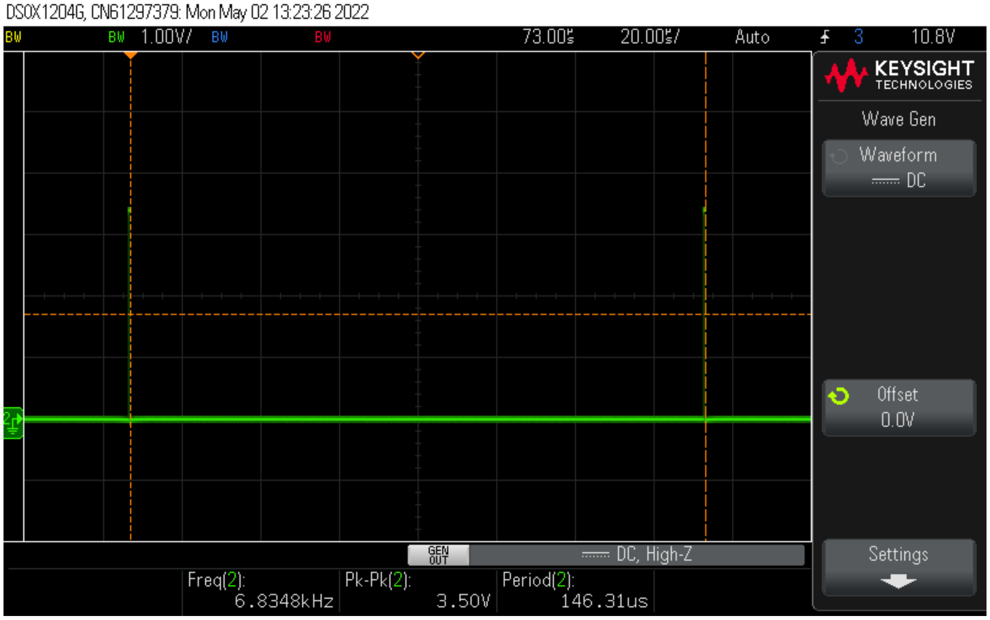


Figure 4.1: Voltage over the resistor as MC reaches saturation

When the voltage over the resistor (yellow channel in figure 4.1) reaches the 0.81 V (blue channel), the comparator output goes high (green channel) which triggers the timers to capture and save their counting registers and reset. The timers are also responsible for controlling the transistors which turn on and off the two coils. When the timer is asked to reset, it turns off the currently active coil, restarts the counting and after a small blanking delay it turns on the previously inactive coil. The timer then awaits the next saturation event from the comparator.

Figure 4.2 shows when the comparator output goes high depending on the GFC direction and magnitude. The oscilloscope is synchronised with one of the coils and shows that the saturation time increase or decrease depending on the direction of GFC.


DSOX1204G, CN61297379: Mon May 02 13:23:26 2022

Offset 0.0V

Waveform DC

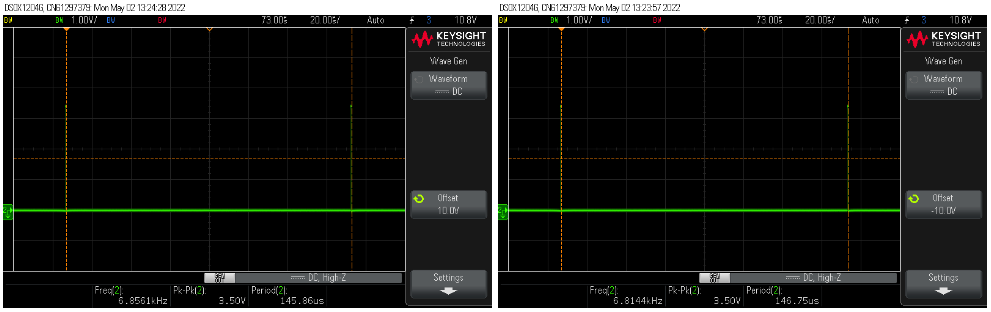
DC, High-Z

Freq(2): 6.8348kHz

Pk-Pk(2): 3.50V

Period(2): 146.31us

(a) No GFC


DSOX1204G, CN61297379: Mon May 02 13:24:28 2022

Offset 10.0V

Freq(2): 6.8561kHz

Pk-Pk(2): 3.50V

Period(2): 145.86us

DSOX1204G, CN61297379: Mon May 02 13:23:57 2022

Offset -10.0V

Freq(2): 6.8144kHz

Pk-Pk(2): 3.50V

Period(2): 146.75us

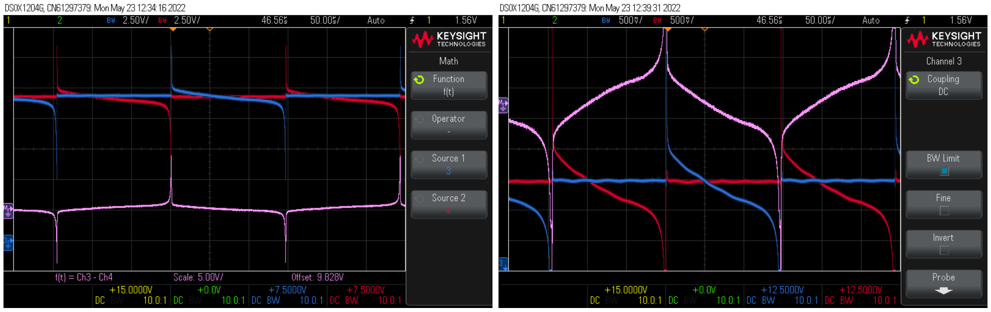
(b) Large positive GFC

(c) Large negative GFC

Figure 4.2: Time response from comparator output given varying GFC

4.1.2 Measurement 2: Coil voltage differential

Since the supply voltage to the coils is 12V, the coil voltages will naturally oscillate around this voltage. As shown in figure 4.3a, the coil voltages in red and blue varies around $5V \to 16V$. The coil voltage differential (CVD) in pink will oscillate between $\pm 9V$ when the MC reaches peak saturation. We are however more interested in the CVD during the saturation of the MC; figure 4.3b shows how relatively small this CVD is.

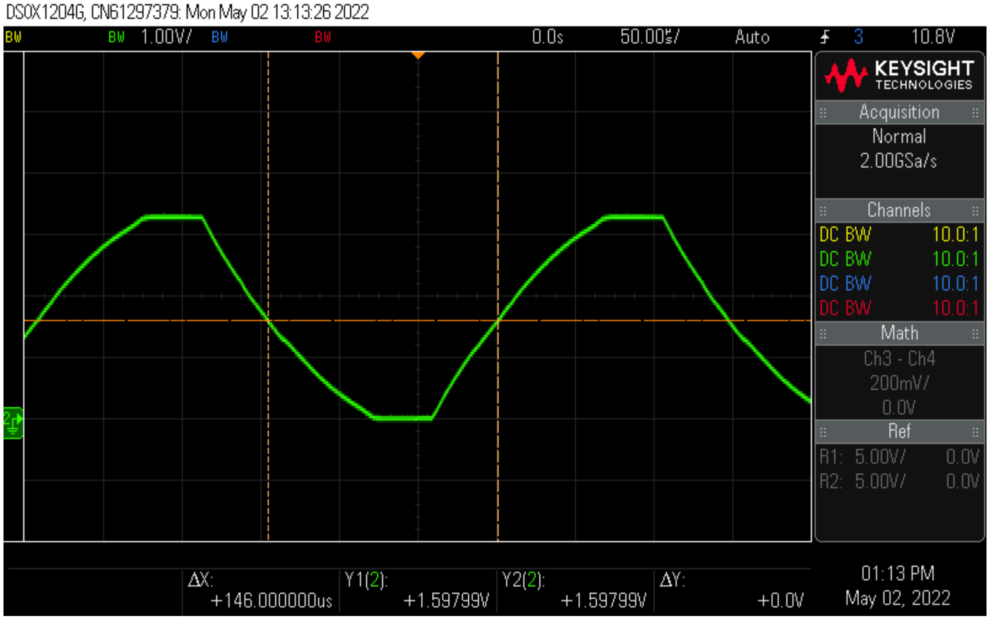


(a) Full coil voltage differential

(b) Focused on saturation stage

Figure 4.3: Voltage differential over time

The raw CVD is fed into an instrumentation amplifier with a gain of 29 and an offset of $12V$. This causes the signal to oscillate between $0V \rightarrow 24V$ (ground and supply voltage of the amplifier), and with an amplification of 29, any coil voltage difference above $\pm 0.4V$ will saturate the amplifier. This $\pm 0.4V$ voltage range is near the end of the saturation process where the coil voltage differential start to spike either up or down.



DSOX1204G, CN61297379: Mon May 02 13:13:26 2022

BW BW 1.00V/ BW BW 0.0s 50.00µs/ Auto 3 10.8V

Acquisition
Normal
2.00GSa/s

Channels
DC BW 10.0:1
DC BW 10.0:1
DC BW 10.0:1
DC BW 10.0:1

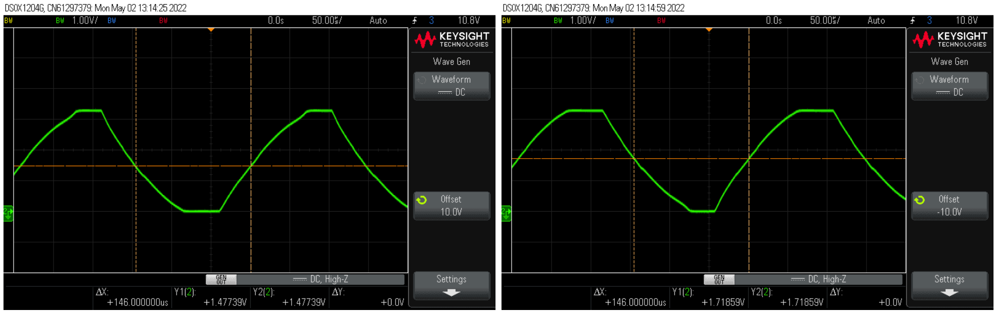
Math
Ch3 - Ch4
200mV/
0.0V

Ref
R1: 5.00V/ 0.0V
R2: 5.00V/ 0.0V

ΔX: +146.000000us
Y1(2): +1.59799V
Y2(2): +1.59799V
ΔY: +0.0V

01:13 PM
May 02, 2022

(a) No GFC



DSOX1204G, CN61297379: Mon May 02 13:14:25 2022

BW BW 1.00V/ BW BW 0.0s 50.00µs/ Auto 3 10.8V

Wave Gen
Waveform DC
Offset 10.0V
GEN OUT DC, High-Z

ΔX: +146.000000us
Y1(2): +1.47739V
Y2(2): +1.47739V
ΔY: +0.0V

DSOX1204G, CN61297379: Mon May 02 13:14:59 2022

BW BW 1.00V/ BW BW 0.0s 50.00µs/ Auto 3 10.8V

Wave Gen
Waveform DC
Offset -10.0V
GEN OUT DC, High-Z

ΔX: +146.000000us
Y1(2): +1.71859V
Y2(2): +1.71859V
ΔY: +0.0V

(b) Large positive GFC **(c)** Large negative GFC

Figure 4.4: Voltage differential over time at ADC input

We make a note to see that the GFC either raises or lower the CVD by the same amount in the active period of both the coils. This makes sense since any voltage the GFC will induce in one coil, the other coil will have an equal, but opposite voltage induced. When we then take the difference between these coil voltages, the induced voltage from the GFC will act as a constant offset assuming the GFC is constant. We nevertheless need to treat these measurements different to measurements 1 and 3 since the information about the GFC does not appear as a difference between the half periods.

4.1.3 Measurement 3: Coil current draw

The coil current draw (CCD) is estimated using the same resistor that the comparator triggering the timer is using. The current will be largest in amplitude before and immediately after the saturation threshold is passed; this was seen in figure 4.1. Like the CVD, we are interested in the measurements in the middle of the saturation process. The voltage over the resistor is sent to an inverting operational amplifier with a gain of $G = -\frac{R_{feedback}}{R_{input}} = -220$ and a supply voltage of $3.3V$.

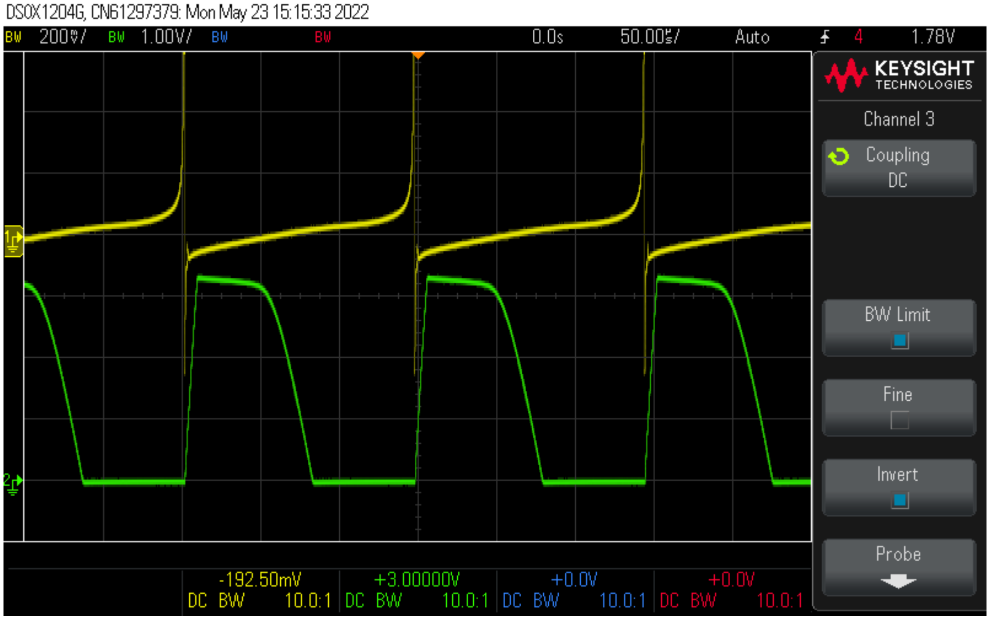
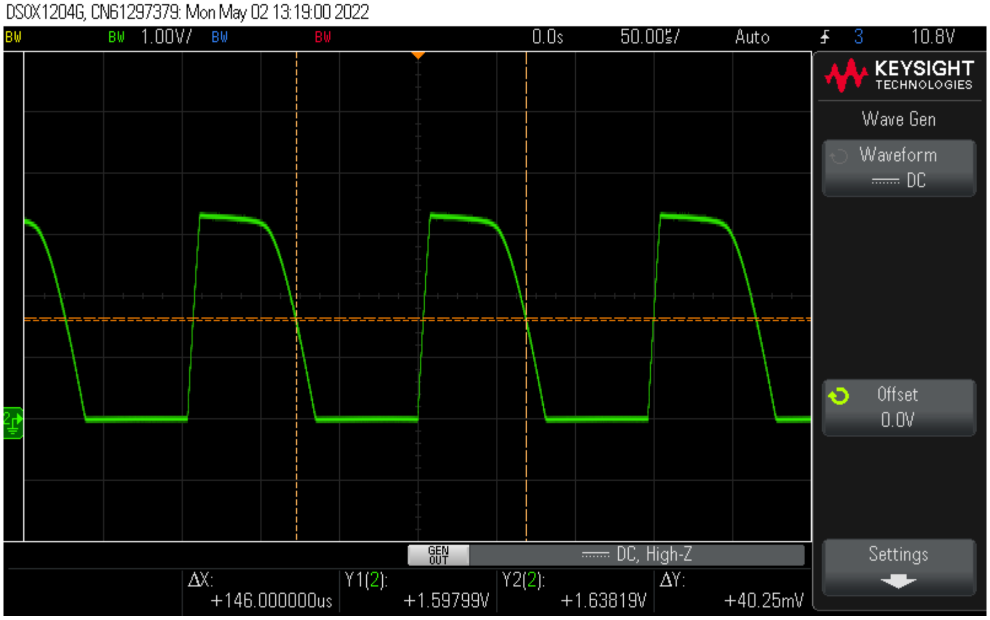


Figure 4.5: Coil current in yellow and amplified output in green

Since the supply voltage to the operational amplifier is only $3.3V$, the amplifier can only send voltages between $0V \rightarrow 3.3V$ which is the standard voltage range of most microcontroller ADCs. Since the gain is so large, the only range in currents that do not saturate the amplifier is between $0.2mA \rightarrow 2.3mA$ $(2.5mV \rightarrow 27.5mV)$.



DSOX1204G, CN61297379: Mon May 02 13:19:00 2022

1.00V/ 0.0s 50.00us/ Auto 3 10.8V

Wave Gen

Waveform DC

Offset 0.0V

DC, High-Z

ΔX: +146.000000us

Y1(2): +1.59799V

Y2(2): +1.63819V

ΔY: +40.25mV

(a) No GFC

DSOX1204G, CN61297379: Mon May 02 13:20:05 2022

Offset 10.0V

ΔX: +146.000000us

Y1(2): +1.03518V

Y2(2): +2.04020V

ΔY: +1.00500V

DSOX1204G, CN61297379: Mon May 02 13:19:32 2022

Offset -10.0V

ΔX: +146.000000us

Y1(2): +2.04020V

Y2(2): +1.11558V

ΔY: -924.50mV

(b) Large positive GFC **(c)** Large negative GFC

Figure 4.6: Coil current draw over time given at ADC input

A positive GFC effectively shifts the first half period of the CCD forwards in time and the second half period backwards in time. A negative GFC will likewise shift the first half period backwards and the second half period forwards in time. This means that depending on the magnitude and sign of the difference between the first and second half period, we can estimate the magnitude and direction of the GFC.

4.2 Software

Now that we are more familiar with the physical signals in our system, we can begin development of the software. The development of the GFC-estimation algorithm will not happen directly on the microcontroller, but rather using the higher level scripting language MATLAB [7] to process data taken from the microcontroller. This is to aid development and visualise data such that the result can be applied to the microcontroller to get a functioning prototype.

4.2.1 Firmware

The firmware is the software running on the microcontroller; this includes controlling the internal and external modules listed below.

- General-purpose input/output (GPIO)
- Analogue to digital converter (ADC)
- Digital to analogue converter (DAC)
- Comparator (COMP)
- (High resolution) Timer (HRTIM)
- (Low power) Universal asynchronous receiver-transmitter (LPUART)

This is in addition to all the system level modules such as the reset and clock control (RCC), nested vectored interrupt controller (NVIC) and direct memory access (DMA). The LPUART is used to interface with a laptop running a terminal emulator such as PuTTY which read serial data from a virtual COM-port.

Most of this firmware is automatically generated by STM32CubeIDE [8] which can generate code given specific parameters defined by the user in a graphical user interface. This means that after setting up the different modules as desired, the generated code will automatically take care of all the lower level details required to initialise the system. The code generation also creates functions such that higher level concepts can be executed by calling simple functions instead of having to control registers and set appropriate flags.

4.2.2 GFC estimation algorithm

The estimates are based off of two statistical properties of received data: The mean of the data and a measure of the variance around the mean. The mean will naturally reflect any DC GFC, but for the AC components we choose to look at the root mean square (RMS) of the variation around the mean. The RMS in this context is equivalent to the standard deviation, but scaled by a factor of $\sqrt{\frac{N-1}{N}}$ where N is the number of points of data. This means we expect the ground fault current to be in the form:

$$i_{GF}(t) = DC + \sqrt{2}AC \cdot \sin(2\pi f t) + \eta(t); \quad f \in \{50Hz,\ 60Hz\}$$

Here, DC is the constant DC offset the current varies around and AC is the RMS-value of the 50Hz or 60Hz sine wave. The $\eta(t)$ parameter represent other higher frequency components not of interest like noise and high-frequency, upper harmonics. Given a set of discrete points of data $d(n)$, the following estimates for DC and AC can be formulated:

$$DC = a_{DC}\frac{1}{N}\sum_{n=0}^{N-1} d(n) + b_{DC}$$

$$AC = a_{AC}\sqrt{\frac{1}{N}\sum_{n=0}^{N-1}\big(d(n)-\mu\big)^2} + b_{AC}; \quad \mu = \frac{1}{N}\sum_{n=0}^{N-1} d(n)$$

With this, we try to find a linear approximation between the mean and RMS of $d(n)$ and the mean and RMS of the ground fault current. The data, $d(n)$, is a placeholder for TD, CVD and CCD. Finding the a- and b-coefficients is the more difficult part; how does the internal data reflect the physical system.

Chapter 5

Test setup

To provide enough current and stable voltages to the circuit board, external power was provided through the DC power supply TENMA 72-2645. To visualise the different signals, the oscilloscope KEYSIGHT DSOX1204G has been used. The oscilloscope has a built-in signal generator which we will use to simulate different ground fault currents (GFC) to measure the response of the system. To measure DC and RMS of these currents, the FLUKE 289 multimeter has been used.

Figure 5.1 shows how the microcontroller and circuit board has been set up with the power supply and oscilloscope in the background. Net ground fault currents were simulated using a single wire that the current will pass through. In the bottom left we can see the alligator clips from the signal generator and that the positive direction of current was arbitrarily set to point downwards.

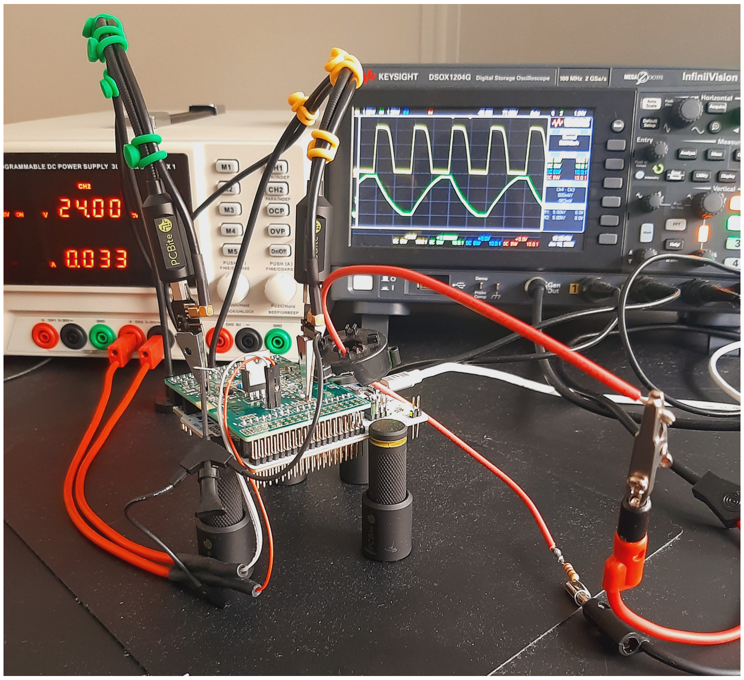
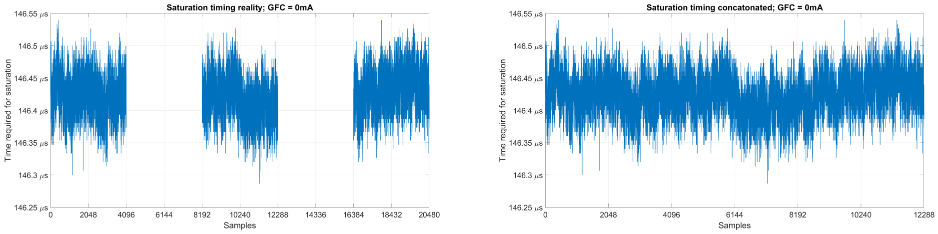


Figure 5.1: The prototype of the RCD used in this thesis

The microcontroller communicates with a laptop through a USB/UART-interface. The USB/UART-driver is unable to communicate at the speeds required to transfer data in real time. We sample at a speed of approximately 6.8 kHz and the data is represented as 16 bits which would require a transfer speed of 108.8 kbps. Any additional start or stop bits required for serial communication would require well over the 115.2 kBd speed that the Windows driver can communicate with. We choose to instead send 4096 samples at a speed which Windows is capable of digesting while discarding the next 4096 samples. This means that the microcontroller will start the transfer as it starts discarding samples and will finally end the transmission halfway through recording the next samples to send.



(a) How the data is actually sent

(b) Concatenated data for easier readability

Figure 5.2: Graph showing how chunks are spaced apart in time vs. how we will represent the different signals

Chapter 6

Results

As mentioned in section 4.2.2, we try to examine the linear relationship between the mean and root mean square (RMS) of the data with the mean and RMS of the ground fault current (GFC). The primary objective is to find fitting coefficients for the three principles of measurement and analyse how accurate and resistant to noise these measurements are. If the relationship between the data and GFC is highly non-linear, we expect to see a drastic drop in accuracy as we move towards any extremes of the data.

6.1 Data analysis

The saturation circuit gets interruptions every time magnetic saturation of the magnetic core (MC) is reached, but it is agnostic to the direction of magnetisation. However, since we know that every other interrupt correspond to the same polarity of magnetisation, we can infer that every other sample of the data vector is also corresponding to the same magnetisation. Since we are interested in looking at the differences or similarities in each polarities of saturation, it is therefore equivalent to look at the differences or similarities in the odd versus the even samples in the data vector. Since the microcontroller has predetermined initial conditions, we could determine which direction of the magnetic flux correspond to odd or even samples, but knowing that odd samples and even samples always will correspond to the same direction of flux is sufficient.

As mentioned in chapter 4, the GFC have different effects on the three measurements. For both the timing difference (TD) and coil current draw (CCD), the GFC will increase the differences between odd and even samples. The coil voltage differential (CVD) will raise or lower both the odd and even samples depending on the magnitude and direction fo the GFC. Because of this, each point of data relating to TD or CCD will be a difference between odd and even samples while the CVD points of data will be the sum of odd and even samples.

6.1.1 Measurement 1: Timing difference

The timing data is the time it takes for the saturation circuit to go from magnetic saturation in one polarity to saturation in the other polarity. Given ideal circumstances and no GFC, this process should take the same amount of time in both directions. We expect that any GFC will cause every odd sample to be either raised or lowered by an amount depending on the strength and magnitude of the GFC and every even sample will be raised or lowered by the same but opposite amount.

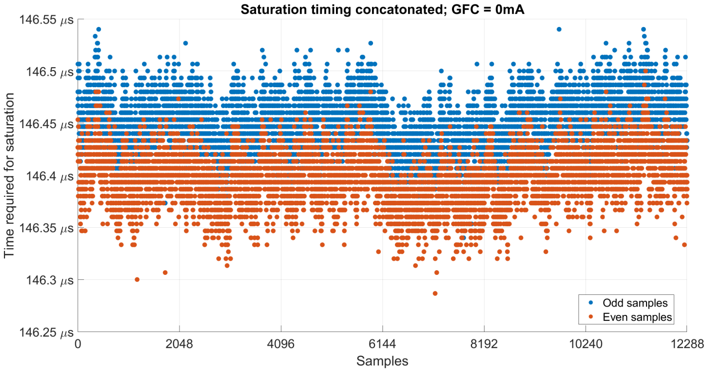


Figure 6.1: Saturation time for odd and even samples when there is no GFC

As we can note in this figure, even with no GFC, there looks to be a constant difference between odd and even samples. There are many reasons why this might be, such as a permanent residual magnetisation in the MC, differences in the resistances in each of the coil paths, et cetera. The reason(s) for this is not important, but when we develop a linear model, we need to remember that its y-intercept is non-zero. Also, this data has been scaled into the time-domain as the data read from the timer is represented as the amount of ticks from the clock has passed since the start of counting.

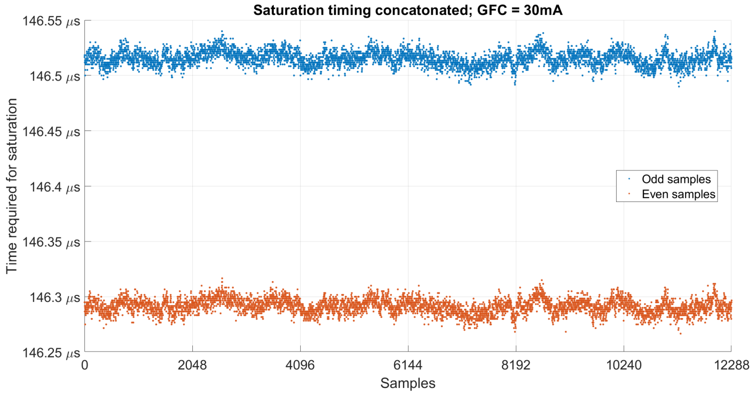


Figure 6.2: Saturation time for odd and even samples with 30mA DC GFC

Increasing the GFC to $30mA$ confirms that the difference in timing will increase as GFC increase. We can clearly see a complete separation between every odd and even sample. In figure 6.3 below, we introduce the data we will use to estimate the GFC. Instead of looking at every sample we instead look at the difference between every odd and even sample. This effectively halves the amount of points of data.

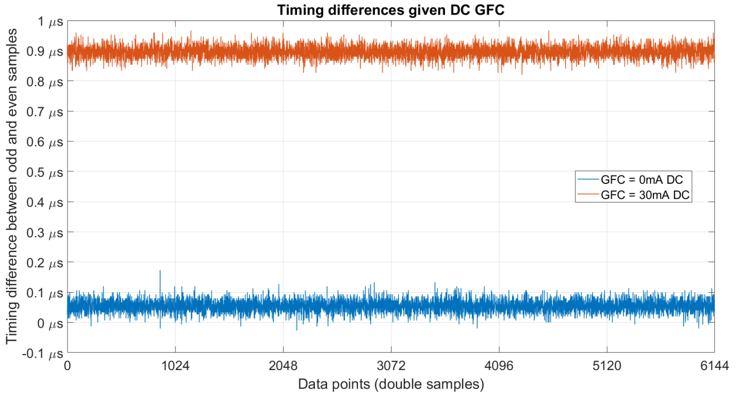


Figure 6.3: Timing difference for different values of DC GFC

6.1.2 Measurement 2: Coil voltage differential

As shown in figure 4.3, the odd and even samples of the CVD will both get lowered by a positive GFC and raised by a negative GFC. The microcontroller is set up to wait a specified amount of time after switching the active coil before ADC1 takes a sample of the CVD. This time delay before sampling is arbitrarily set to minimise the difference between odd and even samples, but since we are interested in the sum, which is a scaled averaging operation, the time delay can be shortened or lengthened without any noticeable effect on the sum of odd and even samples.

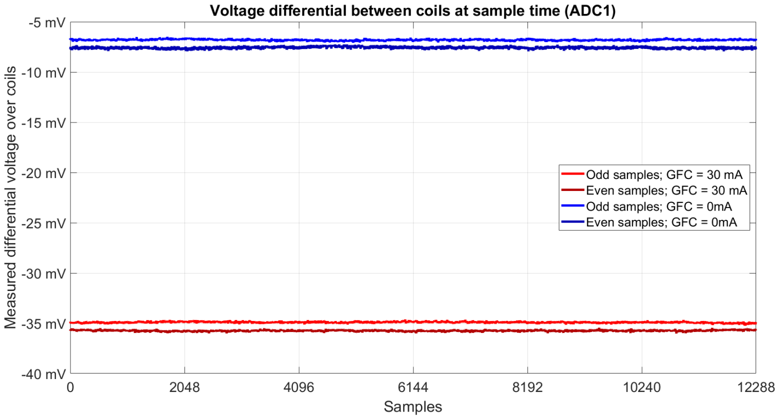


Figure 6.4: Coil voltage differential for different DC GFC

As expected, we get lower values for the CVD as the GFC increases; the blue pair of samples have higher values than the red pair. For this data, the average or sum of odd and even samples will carry the information about the GFC in the system. The value read from ADC1 is in reality a 16-bit integer, but these values have been shifted and scaled in the plot to reflect the physical signal being measured. This is solely for the benefit of human readability as the microcontroller will directly process the data from the ADC-module.

6.1.3 Measurement 3: Coil current draw

From figure 4.6 we expect the difference between odd and even samples to grow larger as the amplitude of the GFC increases. Similar to the CVD-measurements, the CCD-measurement is taken by ADC2 after a set time delay after the coils switch. Since the GFC will effectively shift the transient of the output of the operational amplifier forwards and backwards in time, the time delay is set somewhere in the middle of the transient to minimise the risk of sampling when the operational amplifier is in saturation.

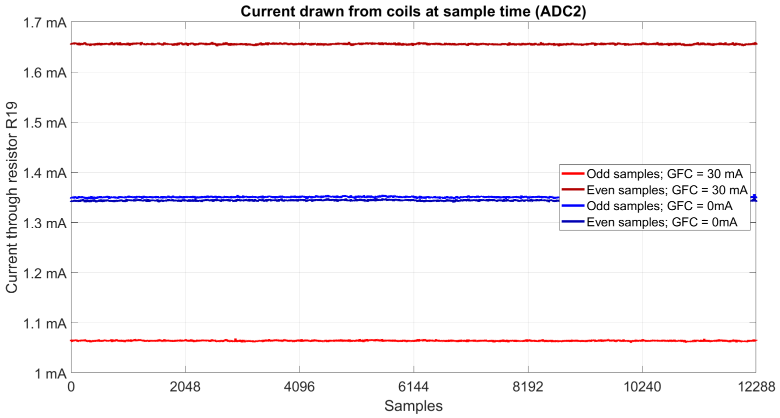


Figure 6.5: Coil current for different values of DC GFC

The distance between the blue pair of samples is a lot smaller than the distance between the red pair. This means that the difference between odd and even samples increase in magnitude as the GFC increase in magnitude which is what we expected. Again, the values from ADC2 is a 16-bit integer, but we transformed these integer values into the current through the resistor for better readability.

6.1.4 Alternating current as GFC

All the previous measurements used a DC GFC. Now we want to analyse how the system behaves as an AC GFC is passed through the system. We generate a 50Hz sine wave that we send through the centre of the MC to simulate an AC GFC. We will only look at TD measurements for now, but equivalent data can be found for the other measurements.

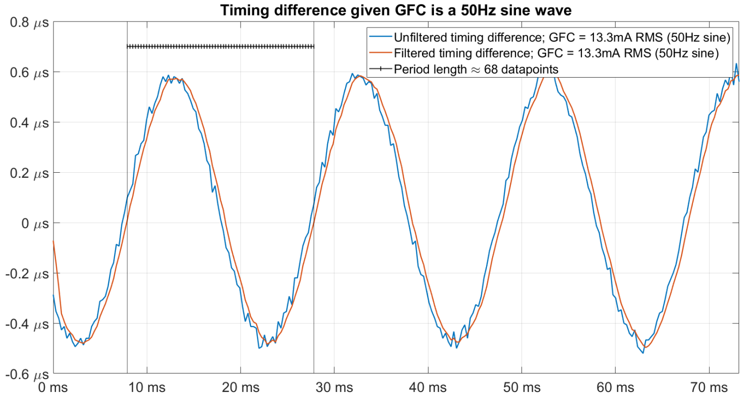


Figure 6.6: Timing difference given a 50Hz sine wave as GFC

Since the saturation process is relatively fast compared to the 50Hz sine, we are able to sample multiple times along the curve. In fact we are able to sample approximately 68 samples of data (68.3 samples) per 50Hz period. The low-pass filter used to smooth out the raw data is a simple 4 sample averaging FIR-filter. This was implemented since it is relatively easy for a microcontroller to execute since it is a sum of 4 elements and a bit shift by 2. This filter only reject the highest frequency components as shown in figure 6.7; these high frequencies are more likely to only contain noise.

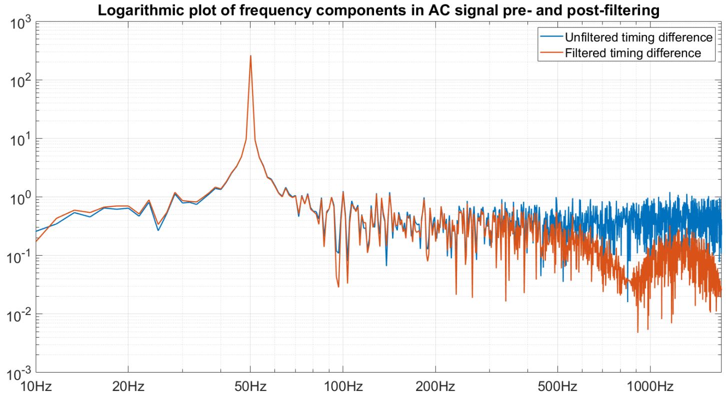


Figure 6.7: Frequency response of signal before and after low pass filtering

6.2 Data response given GFC magnitude

Now we wish to measure how the data changes given a change in GFC. We will generate both DC and AC in a wire through the MC that simulates the GFC and see how the mean and RMS of the data changes as the magnitude of the GFC changes. To calculate the mean and RMS of the 68 point windowed data, the following equations are implemented:

$$d_{\text{mean}} = \frac{1}{68}\sum_{n=0}^{67} d(n), \quad d_{\text{rms}} = \sqrt{\frac{1}{68}\sum_{n=0}^{67} \big(d(n) - d_{\text{mean}}\big)^2}$$

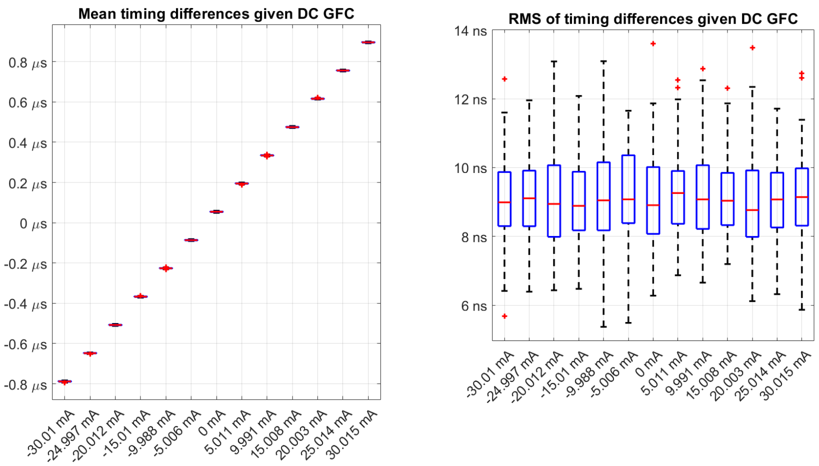
This means that we get one measurement of the mean and RMS every 68 samples. With each data vector being 6144 elements long, we get 90 measurements per data vector. The plots in this section will mainly be in the form of box plots which will give some insight to the distribution of these measurements.

Ideally we would want to see a linear correlation between the mean of the data and the magnitude of the DC GFC; and between the RMS of the data and the RMS of the AC GFC. Additionally, we would want the RMS of the data to have no correlation with the DC GFC and the mean of the data to have no correlation with the AC GFC.

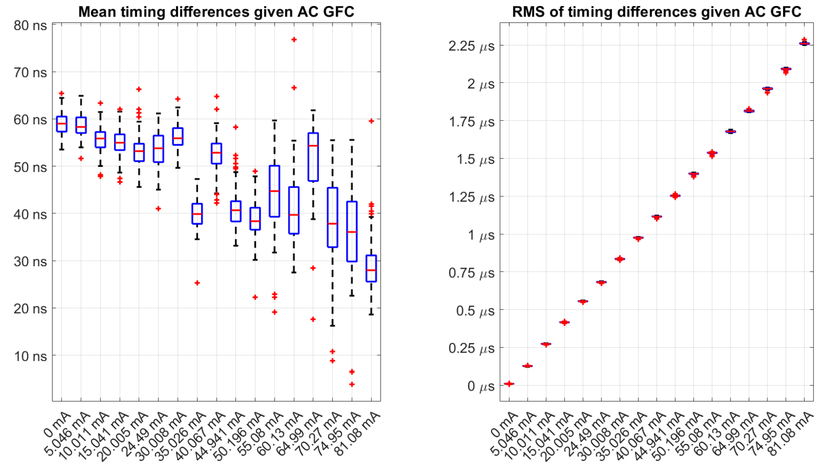
6.2.1 Measurement 1: Timing difference

As can be seen in figure 6.8a, the mean of the TD seem to have a linear relationship to the DC GFC while the RMS seem to be uncorrelated. In figure 6.8b, the RMS is highly correlated to the AC GFC while the mean have a much weaker correlation.

This is close to the ideal outcome, though it is strange that high amplitude AC GFC have an impact on the mean of the TD. According to 6.8a, a mean TD value of 30ns should only yield an estimate of about -2mA DC GFC so this weak correlation should not matter too much.



(a) TD response with DC GFC



(b) TD response with AC GFC

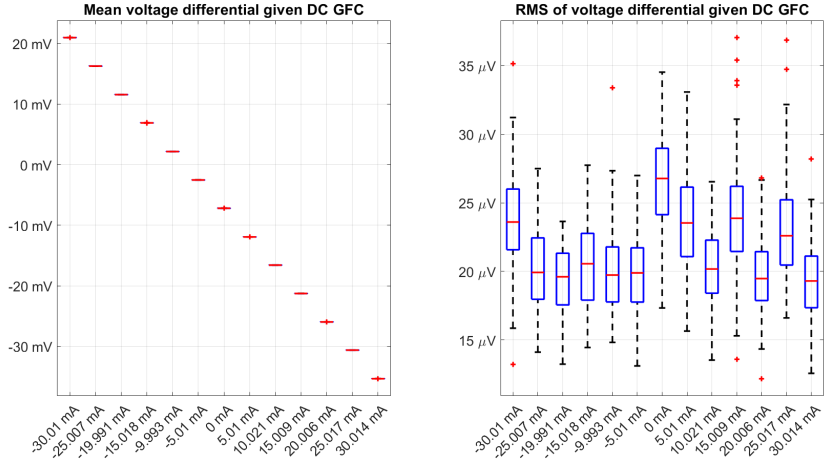
Figure 6.8: TD response given DC and AC GFC

6.2.2 Measurement 2: Coil voltage differential

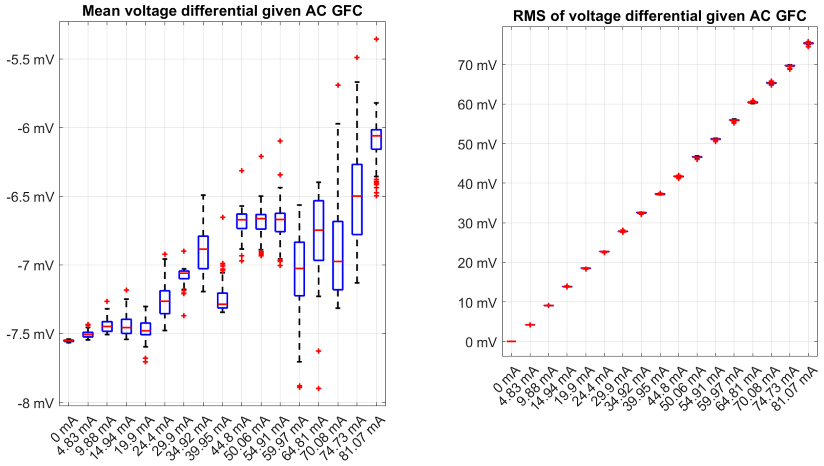
Similarly to TD, the mean and RMS in figure 6.9a are respectively linearly correlated and uncorrelated with the DC GFC. In figure 6.9b, the mean have a weak correlation and the RMS have a strong correlation to the AC GFC.

Again this is close to ideal with the only problem being high magnitude AC

GFC having an effect on the mean. This should also only equate to a couple mA erroneous DC estimates so it should not accidentally trigger a false alarm.



(a) CVD response with DC GFC



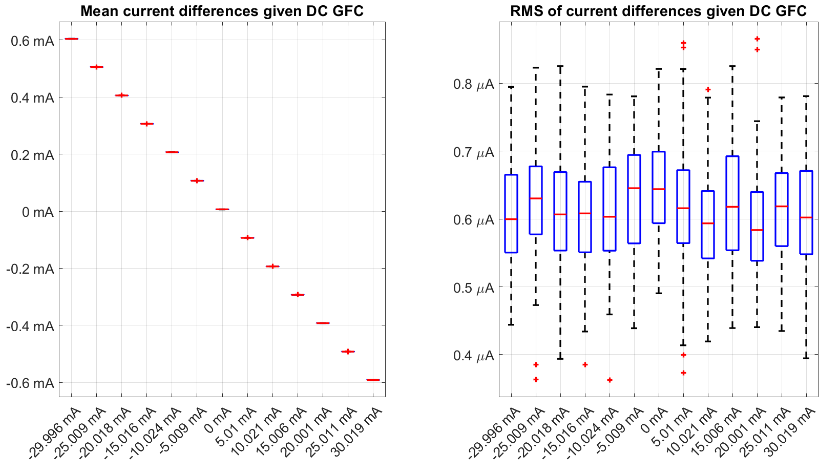
(b) CVD response with AC GFC

Figure 6.9: CVD response given DC and AC GFC

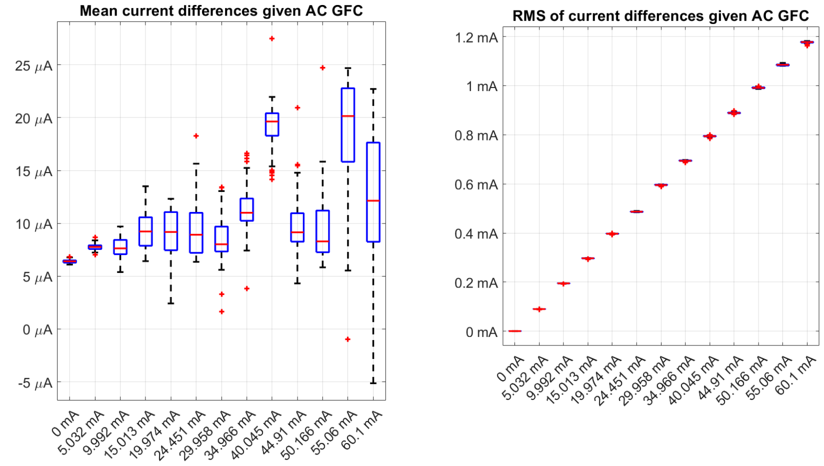
6.2.3 Measurement 3: Coil current draw

Figure 6.10 gives us similar results to the previous two measurements. Strong linear correlations between the mean of the data and a DC GFC, and the

RMS of the data and an AC GFC. Weak to insignificant correlation between the RMS of the data and a DC GFC, and the mean of the data and an AC GFC. High levels of AC GFC do still have an effect on the mean of the data, effectively estimating a small negative DC GFC.



(a) CCD response with DC GFC



(b) CCD response with AC GFC

Figure 6.10: CCD response given DC and AC GFC

6.3 Estimation of the GFC

To estimate the GFC, we will be using the equations in section 6.2 to calculate the mean and RMS of the data and compare them to a linear model relating the two. A demonstration of how the estimation procedure works is shown in figure 6.11.

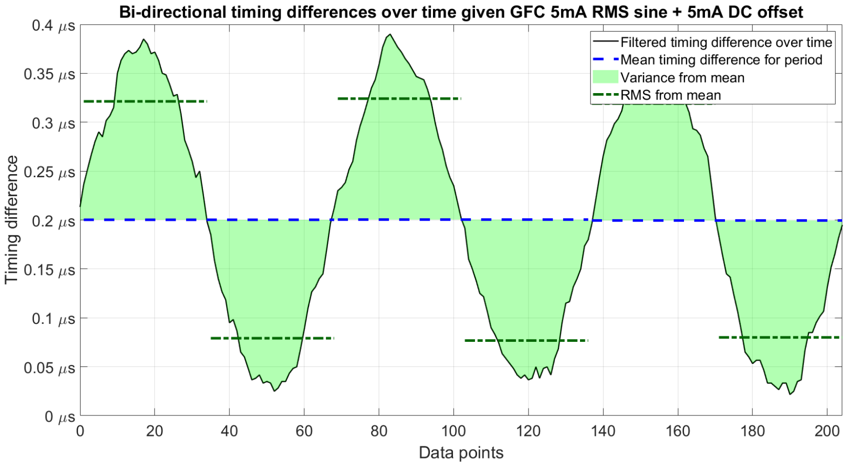


Figure 6.11: How the DC- and AC-GFC estimates are calculated

The black line shows how TD changes over time as a sinusoidal GFC is applied to the system. To estimate the DC component of the GFC we calculate the mean over 68 points of data. This mean is compared to a model based on the historical data found in the previous section. As we can see in the figure, the average timing difference is $0.2\mu s$ which correspond to around 5 mA according to figure 6.8a.

To estimate the AC component, the mean of the 68 points of data is subtracted and the RMS is calculated; this is to estimate the variance around the mean. This RMS value is compared to another model based on historical data. The RMS value in figure 6.11 is approximately $0.125\mu s$ which is approximately 5 mA RMS in figure 6.8b.

6.3.1 Estimation models

The estimation models are based on the historical data displayed in figures 6.8-6.10. To create the models we use the least square method.

$$\min_{\theta_d \in \mathbb{R}^2} \left(\vec{i}_{GFC} - \mathbf{D}{\theta_d}^T \right) \quad \rightarrow \quad \theta_d = (\mathbf{D}^T\mathbf{D})^{-1}\mathbf{D}^T\,\vec{i}_{GFC}$$

The column vector $\vec{i}_{GFC}$ contains the value of the GFC while the matrix $\mathbf{D}$ contains the corresponding data (mean or RMS) at the given GFC as one column and another column of ones. The two-element column vector θ_d contain the slope and intercept of the linear model for the data $d(n)$. This means that we need to find $\theta_{TD(DC)}$, $\theta_{TD(AC)}$, $\theta_{CVD(DC)}$, $\theta_{CVD(AC)}$, $\theta_{CCD(DC)}$, and $\theta_{CCD(AC)}$.

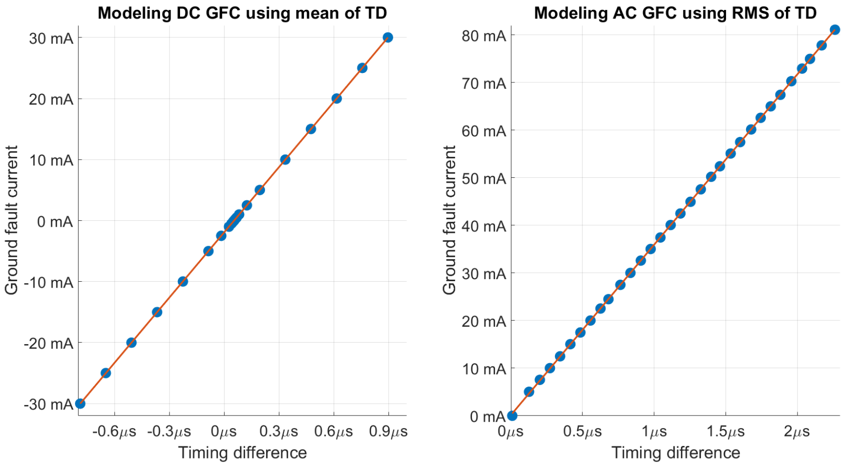


Figure 6.12: Linear model using TD data

$$\theta_{TD(DC)} = \begin{bmatrix} 0.237551004599569 \\ -1.923787269493939 \end{bmatrix} \qquad \theta_{TD(AC)} = \begin{bmatrix} 0.238476342920729 \\ 0.155916345511548 \end{bmatrix}$$

The lines in orange are the linear models and the mean and RMS values of the real data is in blue. The first element of both θ vectors are expecting the raw values read from the timer module, meaning it uses the difference in the amount of ticks since previous rollover instead of the difference in time elapsed. It also outputs the GFC values in milliampere instead of ampere.

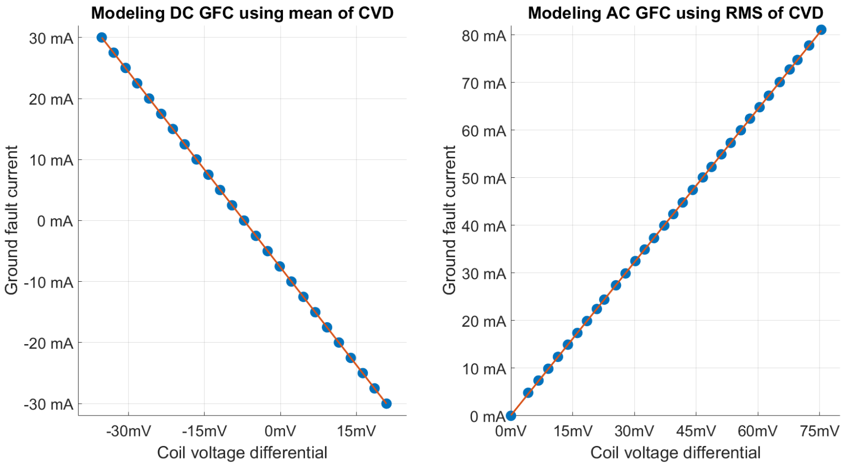


Figure 6.13: Linear model using CVD data

$$\theta_{TD(DC)} = \begin{bmatrix} -0.0065853691401 \\ 422.8862594035857 \end{bmatrix} \qquad \theta_{TD(AC)} = \begin{bmatrix} 0.0066186251570 \\ 0.0948885807896 \end{bmatrix}$$

Again, we see a nice linear relationship between our model in orange and the data in blue. The coefficients in the θ vectors are a bit harder to understand here since the CVD looks at the sum of odd and even samples. The model expect to use the raw ADC values which are quite large 16-bit integers which explains why the coefficients are rather small compared to the other models. This model also outputs the GFC in milliamperes.

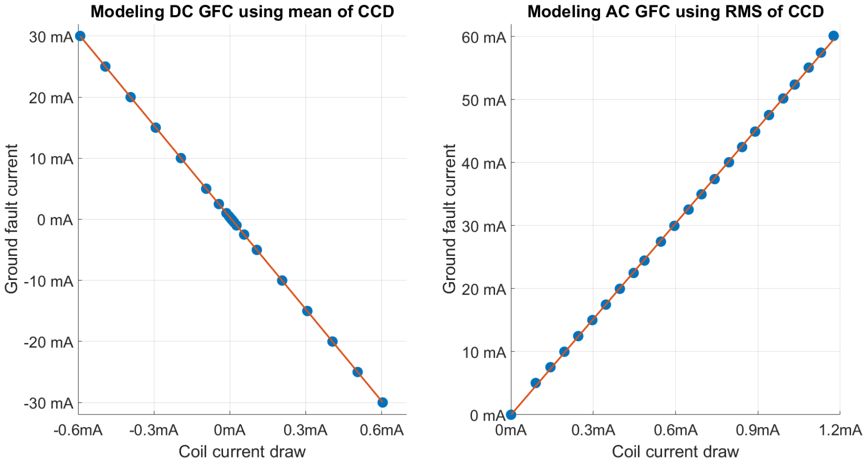


Figure 6.14: Linear model using CCD data

$$\theta_{TD(DC)} = \begin{bmatrix} 0.001757912182488 \\ 0.330065882242458 \end{bmatrix} \qquad \theta_{TD(AC)} = \begin{bmatrix} 0.001774579192702 \\ -0.021088774566089 \end{bmatrix}$$

The model in orange seem to correspond to the data in blue quite well. It might seem strange at first that $\theta_{TD(DC)}$ have a positive slope, but a negative slope in the figure; this is because the measurement is amplified through an inverting operational amplifier and this sign therefore gets flipped. This model uses the difference between the raw 16-bit integers gathered from the ADC2 module.

6.3.2 Running the models on new data

Throughout these test, we will apply a GFC in the form:

$$i_{GFC}(t) = DC + \sqrt{2}AC \cdot \sin\left(2\pi \cdot 50t\right)$$

This is to test the capabilities of simultaneously estimating the DC and AC components of the GFC. In the following diagrams, the dashed lines will represent the measured values of the GFC while the solid lines will be the estimated GFC components. The data sets are multiple runs that are stitched together to form a much longer data set.

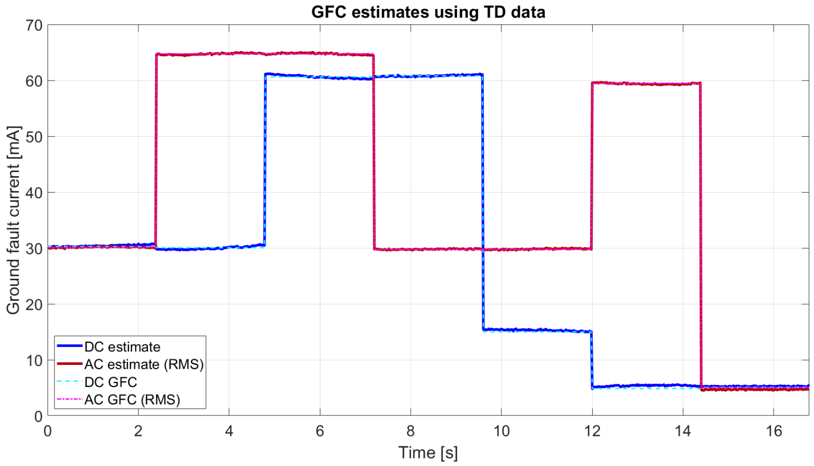


Figure 6.15: Estimates of the GFC using TD data

As we can see, the TD data gives us quite good estimates of the components of the GFC. The error in the estimate are relatively small, though we see the effect of some noise. We are quite happy with this performance and TD seems to give us quite accurate estimates of the GFC; we will look at the estimation error a bit closer in the next section.

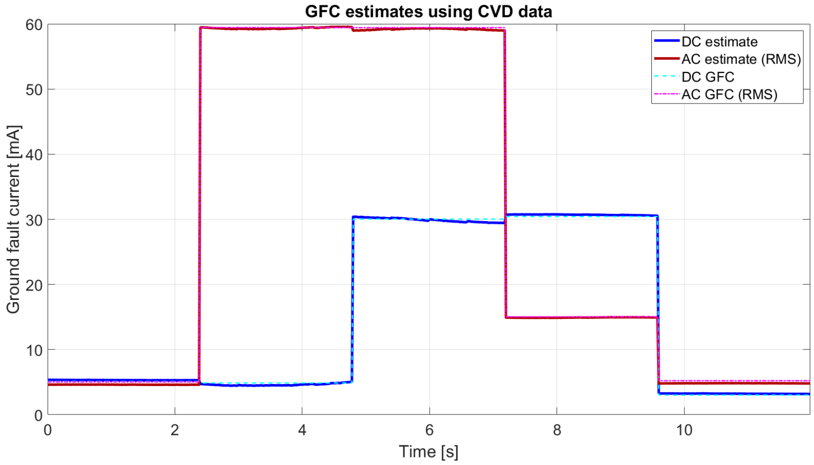


Figure 6.16: Estimates of the GFC using CVD data

The CVD data also give us good estimates of the components of the GFC. We can notice that the estimates drift ever so slightly up or down over time though it is unclear why this is and how big of an issue this may become. This is disappointing to see and even though we will look at estimation errors in the next section, we may need to further investigate this to see if there is anything to be done.

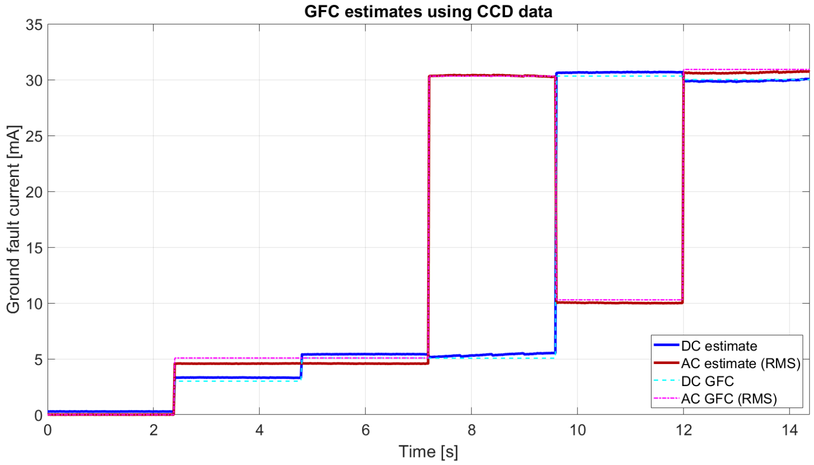


Figure 6.17: Estimates of the GFC using CCD data

The CCD does provide good estimates from the GFC, but we can see some clear differences in the AC estimate around 5mA GFC. This is disappointing to see, but one possible reason for this will get discussed in section 7.1.1. Still these estimation errors do not look to be off by more than a milliampere.

6.4 Performance of the estimates

In the previous section we tried to estimate the GFC using the data from the three measurements. These estimations were generally good, but they were not perfect. To evaluate the performance of the estimates we will introduce the estimation error defined as:

$$e(n) \triangleq \mathbf{D}(n)\theta_d{}^T - i_{GFC}(n)$$

The product $\mathbf{D}(n)\theta_d{}^T$ is the estimate of the GFC and $i_{GFC}(n)$ is the measured GFC at the current sample. This will give us the estimation error at any sample n. Finally, we will find the root mean square error (RMSE) of these runs to give a qualitative result of the performance of each estimator. The RMSE approach was chosen since it punishes large estimation errors more than for example the mean absolute error.

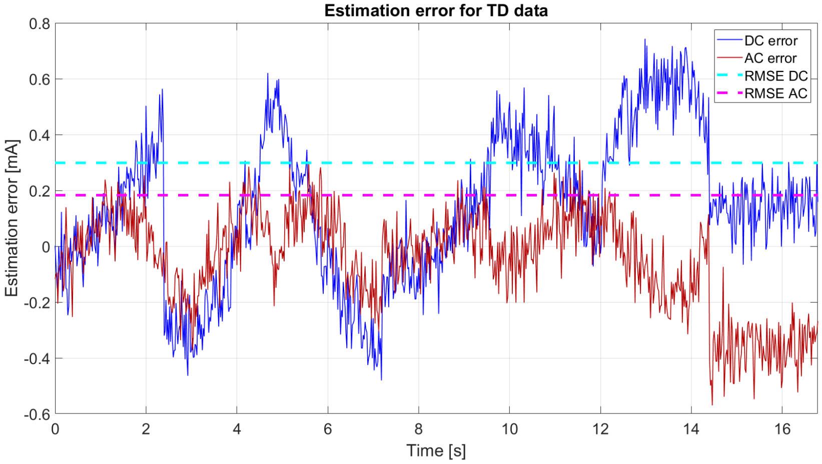


Figure 6.18: Estimation error using TD data

$$RMSE_{DC} = 0.29872mA \quad RMSE_{AC} = 0.18270mA$$

For the TD data, we see that the AC estimate performs extraordinarily good compared to most of the other measurements. The only time we see a drop in performance of the AC estimate is when the AC GFC drops down to 5 milliampere RMS. The DC estimate have some variability, but manage to remain within ±0.8 mA. The AC estimate have a lot less variability, mostly managing to remain within ±0.3 mA, but drops at the end when the RMS of the GFC is low. Why this is will be speculated in section 7.1.1.

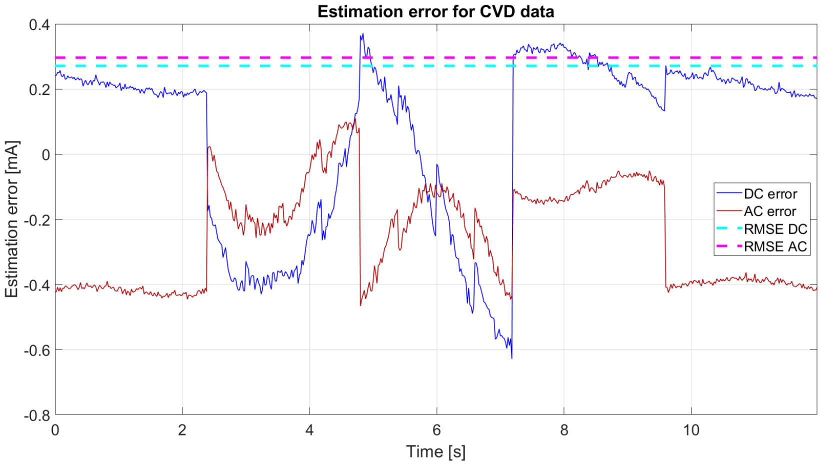


Figure 6.19: Estimation error using CVD data

$$RMSE_{DC} = 0.27124mA \quad RMSE_{AC} = 0.29631mA$$

The CVD estimates does not seem to have too much variance, but we can clearly see that the estimation error changes as the underlying GFC changes. This seems to indicate model errors more than errors due to lack of resolution or noise. We can see that at each step in GFC, the measurement error varies quite little around a local mean (except for the DC estimate between 5 and 7 seconds), but the local means changes quite drastically. Still the RMSE is quite comparable to the DC TD measurements, all being just shy of 0.3 mA RMSE.

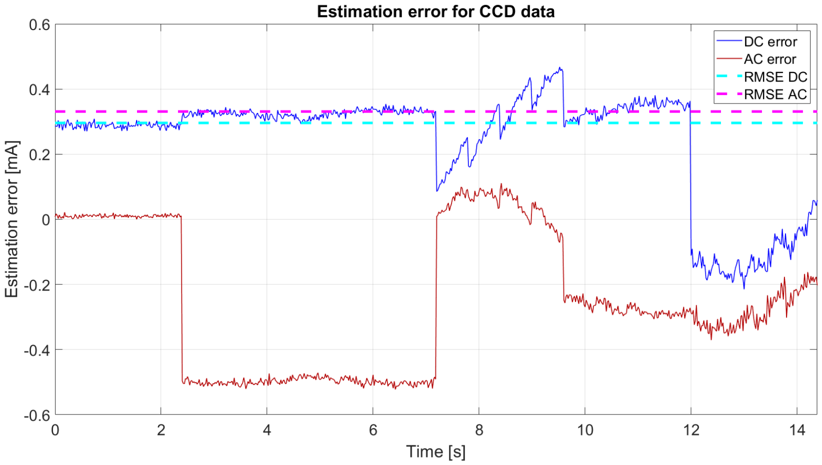


Figure 6.20: Estimation error using CCD data

$$RMSE_{DC} = 0.29582mA \quad RMSE_{AC} = 0.33089mA$$

The estimation error for the CCD estimator also seem to have some dependence on the GFC. Most noticeable is the clear dip of −0.5 milliampere for the AC estimate between 2 and 7 seconds. The DC and AC estimates showed relatively little variance around local means which indicates that they could have performed better with a better model. Still, the RMSE indicate similar, but worse, performance compared to the CVD estimator.

Chapter 7

Conclusion

All three measurement principles gave quite accurate estimates for the ground fault current (GFC). Every estimate was accurate within ±1 milliampere and more often than not, it kept an absolute estimation error lower than 0.5 milliamperes. Using any of the three measurements could ultimately yield a reliable product, though more testing would have to be done to test how these measurements behaved under different temperatures, climates and electromagnetically noisy environments.

Since the performance of all three measurements were similar, the most important factor to think of moving forward would be the cost of implementation. The timing difference (TD) measurements is the most cost effective as it requires no additional external components, but it seems the most noisy of the different measurements. The coil voltage differential (CVD) does show promise given a better model, but it has the highest cost of implementation, especially since it requires a connection to 24V which is not otherwise present in the charger. Finally, the coil current draw (CCD) shows a lot of promise as the estimation error drift very little over time, it has a tolerable cost of implementation, but it would need a better model.

If I had to choose one measurement to solely focus on going forward it would have to be the CCD. It only requires an operational amplifier and some basic components, but give quite good results. Second would be the TD measurement as it requires no additional components, but delivers a reduced performance; a possible reason to this will be given in section 7.1.4. The CVD fall in last place as it delivers a good estimate, but this alone is not sufficient to have a new line voltage implemented in the charger. The rest of this chapter will give more specific details of what could have been improved and what should be done to improve the system in the future.

7.1 What could have been done better?

Before planning what should be left for future work, it is best to reflect on what could already need improvement. The work done in this thesis was not perfect and some issues could not be fixed in time before the deadline. In this section I reflect upon some obvious problems and some more obscure details.

7.1.1 The problem with low-amplitude AC GFCs

A repeating pattern in the estimations was that the AC estimate would yield quite bad estimates whenever the AC component of the GFC reached under 10 mA RMS. Halfway through gathering data I noticed that my multimeter would read a constant 3mA RMS when connected to wire used to simulate the GFC. When I probed this wire with the oscilloscope I saw that it carried voltage reminiscent of a noisy square wave in phase with the saturation circuitry.

It should not have taken this long to realise that magnetically saturating a metal ring at a rate of 3 kHz would also induce a voltage in a wire going through the ring. Because of this, the low-amplitude AC GFCs were probably misread as the induced current accounted for the majority of the current in the system. A better approach would have been to write down the voltages from the signal generator and calculate the GFC based on the measured resistance in the signal generator. Because of this, we never got a clear reading of lower values of the GFC where we should prioritise having better estimates.

7.1.2 More thought put into model creation

We should have prioritised getting better estimates for lower values of the GFC. A standard residual current device (RCD) should cut power at 6 mA DC and

30 mA AC RMS. There is no problem in using a least square method, but we could modify this a bit to suit our needs better.

The simplest trick would be to use more points of data near the points of prioritisation; this was almost done by accident when creating the TD and CCD models as we had more points near 0 mA DC GFC. I moved away from this approach when recording data for the AC GFCs and the CVD model purely because I wanted to evenly space each point of data to produce good looking graphs. Had I been more strategic, I would have recorded multiple points at ±6 mA DC and 30 mA AC RMS. This trick is not as effective in prioritising certain regions, though it would have had a small effect.

A more effective strategy would be to weigh some data higher than others. A weighted least square regression should give us the ability to prioritise minimising specific regions of interest. This could help to give more accurate estimates at lower magnitudes of GFC. We need to make sure that the lower magnitude GFC measurements are correct first though, but a srategy for this has already been provided.

7.1.3 More data for validation

The final sets of data used to validate the estimations and calculate estimation errors could have been a lot better. Not much initial thoughts were put into creating these data sets and it shows. The different GFCs were chosen arbitrarily, they were short, and only tested simultaneous AC and DC. Different GFC ranges should have been chosen to test the responses at smaller and larger GFCs to see if any clear relationship between GFC and estimation error were found.

The tests did have some use, but this was very limited by my lack of planning and doing it properly. When I thought of doing more proper tests, the deadline was uncomfortably close so I decided against it.

7.1.4 Poor time resolution

A problem with the TD estimate and possibly the reason why the estimation error seems to be the noisiest of the three is the poor resolution. The microcontroller was able to provide a clock frequency of 4.8 GHz to the high resolution timer (HRTIM). The problem was that the comparator that notified when the magnetic core was saturated was limited to 150 MHz so the timer was not notified to stop before the next tick of the 150 MHz clock. Because of this, the timer had a great reduction in resolution which degraded the measurement.

When I informed my supervisor about this, the possibility of creating an external analogue comparator was proposed, but this could not be produced and tested before the deadline of this thesis. Since the entire circuitry is dependant on this comparator, we could see a gain in performance for all of these measurements as a quicker comparator could switch the saturation direction more accurately and reliably. Hopefully, this issue could be resolved, but the current situation still give good enough results.

7.2 Plans for improvement

I have already given some plans to improve the previous errors, but there are still a lot of room to improve the system as it stands. It would also be desirable to implement the system onto the microcontroller since all of the work has been done offline in MATLAB [7].

7.2.1 Improved estimates

The linear model created from regressional analysis is a very simple model. This is great for a microcontroller as it requires quite little computing power, but further processing of the data could be a nice thing. This could include any type of filtering of the estimation data to improve stability, use the raw estimates together with a statistical model to improve accuracy, etc. We can also cross-reference measurements meaning that we combine the output of all the estimators to gain a better estimate of the GFC.

7.2.2 Moving window estimate

At the moment, the system will provide an estimate every 68 points of data or approximately 20 milliseconds. To get the next estimate, the system has to wait another 20 milliseconds. One way to fix this would be to create a moving window estimate where the oldest data get replaced with the newest samples and a new estimate can get produced with every new data point. This will give us a refresh rate of approximately 3 kHz, though this will put a larger strain on the microcontroller. A better middle ground could therefore be to update the estimate every $2n$ samples, effectively dividing these 3 kHz by an integer n.

Bibliography

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[3] C. F. Dalziel, J. B. Lagen, and J. L. Thurston, "Electric shock," *Transactions of the American Institute of Electrical Engineers*, vol. 60, no. 12, pp. 1073–1079, 1941.

[4] C. F. Dalziel, E. Ogden, and C. E. Abbott, "Effect of frequency on let-go currents," *Transactions of the American Institute of Electrical Engineers*, vol. 62, no. 12, pp. 745–750, 1943.

[5] C. F. Dalziel, "Effect of wave form on let-go currents," *Transactions of the American Institute of Electrical Engineers*, vol. 62, no. 12, pp. 739–744, 1943.

[6] VACUUMSCHMELZE GmbH & Co. KG, "benvac - all current sensitive differential current sensor." `https://vacuumschmelze.com/benvac`.

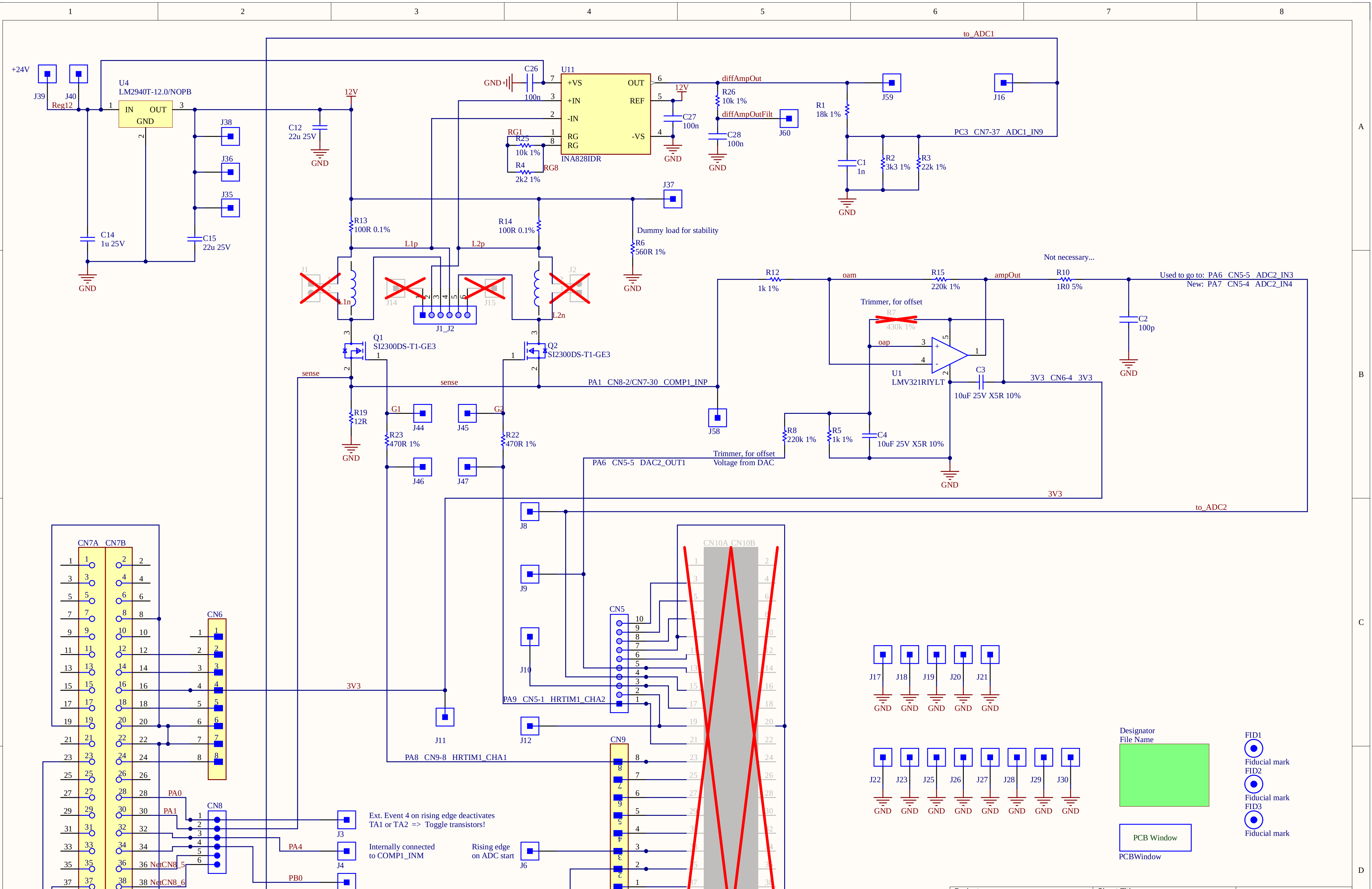
[7] The MathWorks, Inc., "Matlab." `https://se.mathworks.com/products/matlab.html`.

[8] STMicroelectronics N.V., "Integrated development environment for stm32." `https://www.st.com/en/development-tools/stm32cubeide.html`.

Appendix A

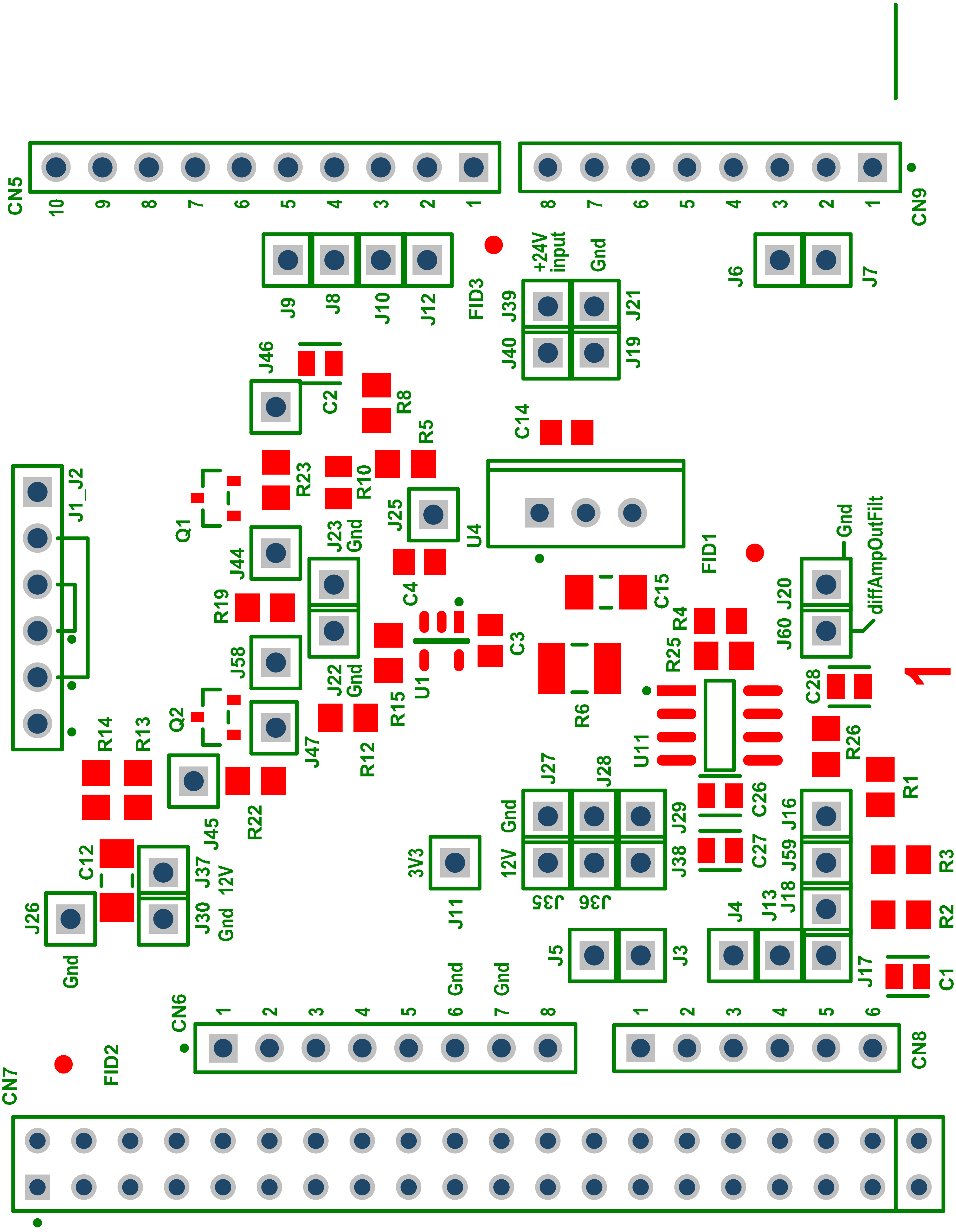
Hardware schematics

A.1 Piggyback circuit board – Schematic



Project:	Sheet Title:		
RCD prototyping board	**RCD circuits**		easee
Drawn by: Erik Grindheim	Doc no:	State: Draft	Easee AS Grenseveien 19 4313 Sandnes Norway
Edited by: *	Version: V1	Approved by:	https://easee.no
BOM Variant: A01	Revision: A	Approved date:	
File: RCD_test_2021.SchDoc	Date: 2021-12-30	Time: 01:27:13	Sheet 1 of 1 Size:A3

A.2 Piggyback circuit board – PCB Layout


CN5
10
9
8
7
6
5
4
3
2
1
8
7
6
5
4
3
2
1
CN9
J9
J8
J10
J12
FID3
+24V input
Gnd
J39
J21
J40
J19
J6
J7
J46
C2
R8
R5
C14
J1_J2
Q1
R23
R10
J25
U4
J44
J23
Gnd
R19
C4
FID1
Gnd
diffAmpOutFilt
J20
J60
C15
R4
R25
C3
U1
J58
J22
Gnd
R15
R6
C28
1
R14
R13
Q2
J47
R12
U11
R26
R22
J45
J27
J28
J29
C26
J16
R1
C12
J37
12V
J30
Gnd
3V3
Gnd
12V
J35
J36
J38
C27
J59
R3
J26
Gnd
J11
J5
J3
J4
J13
J18
R2
J17
C1
Gnd
Gnd
CN6
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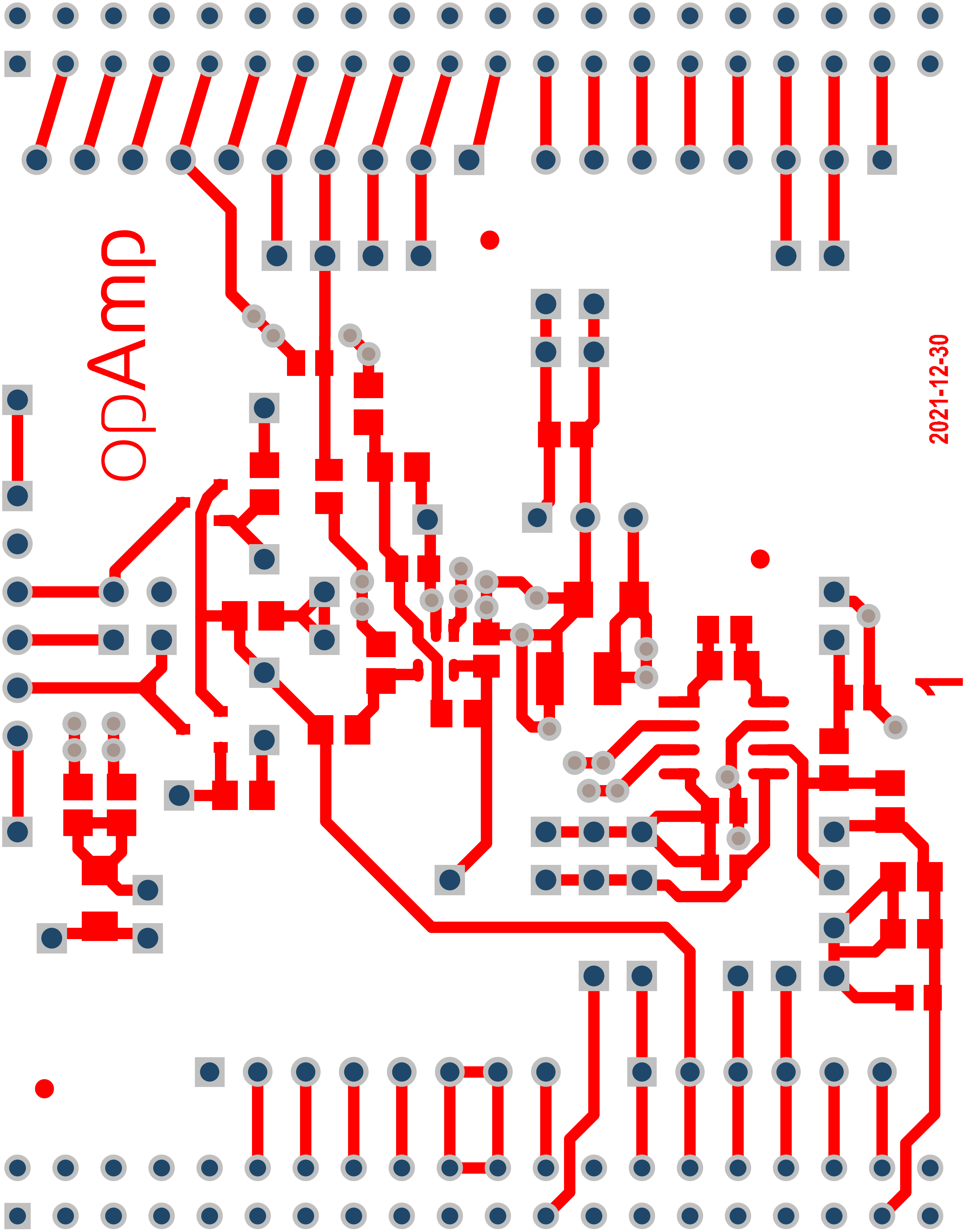
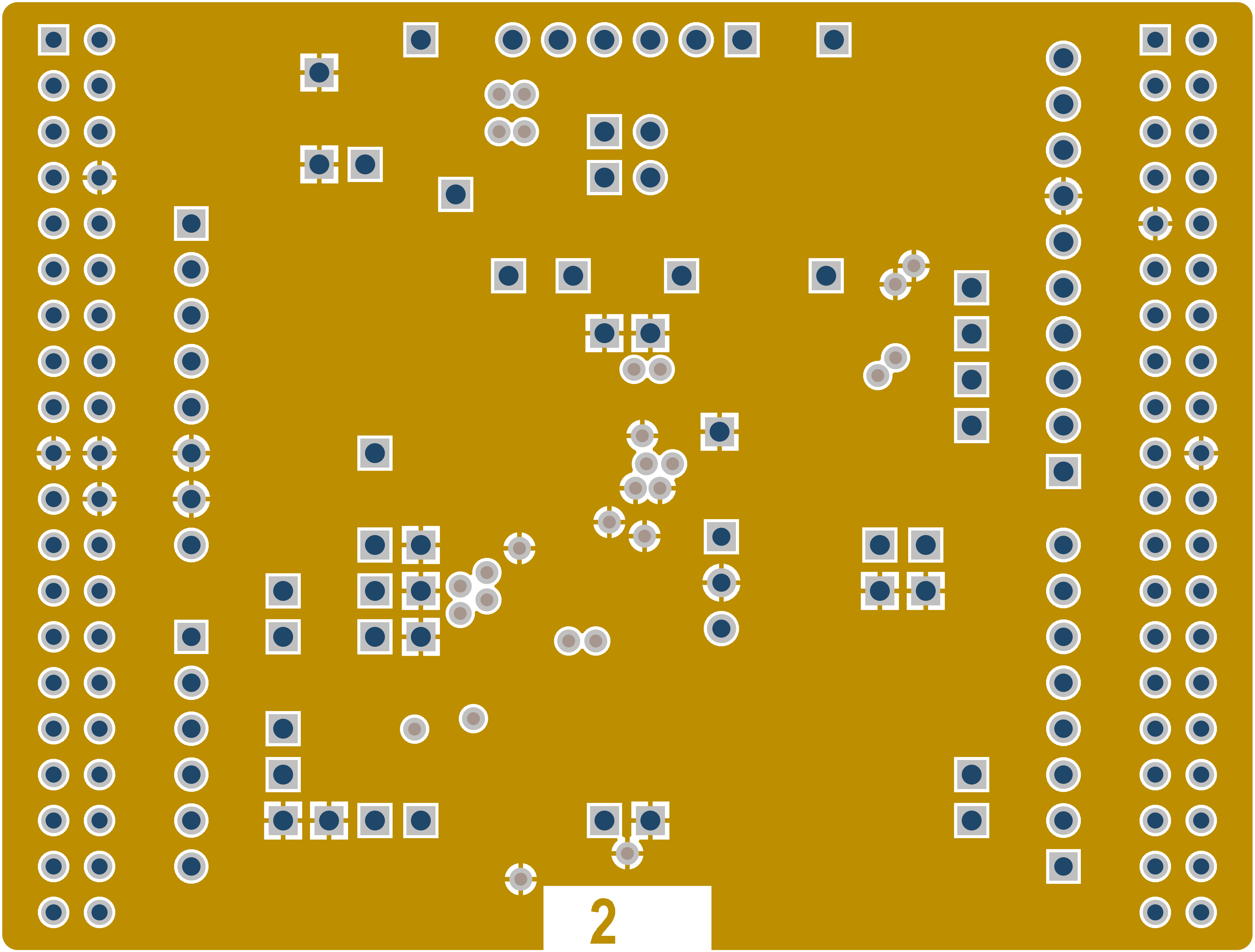
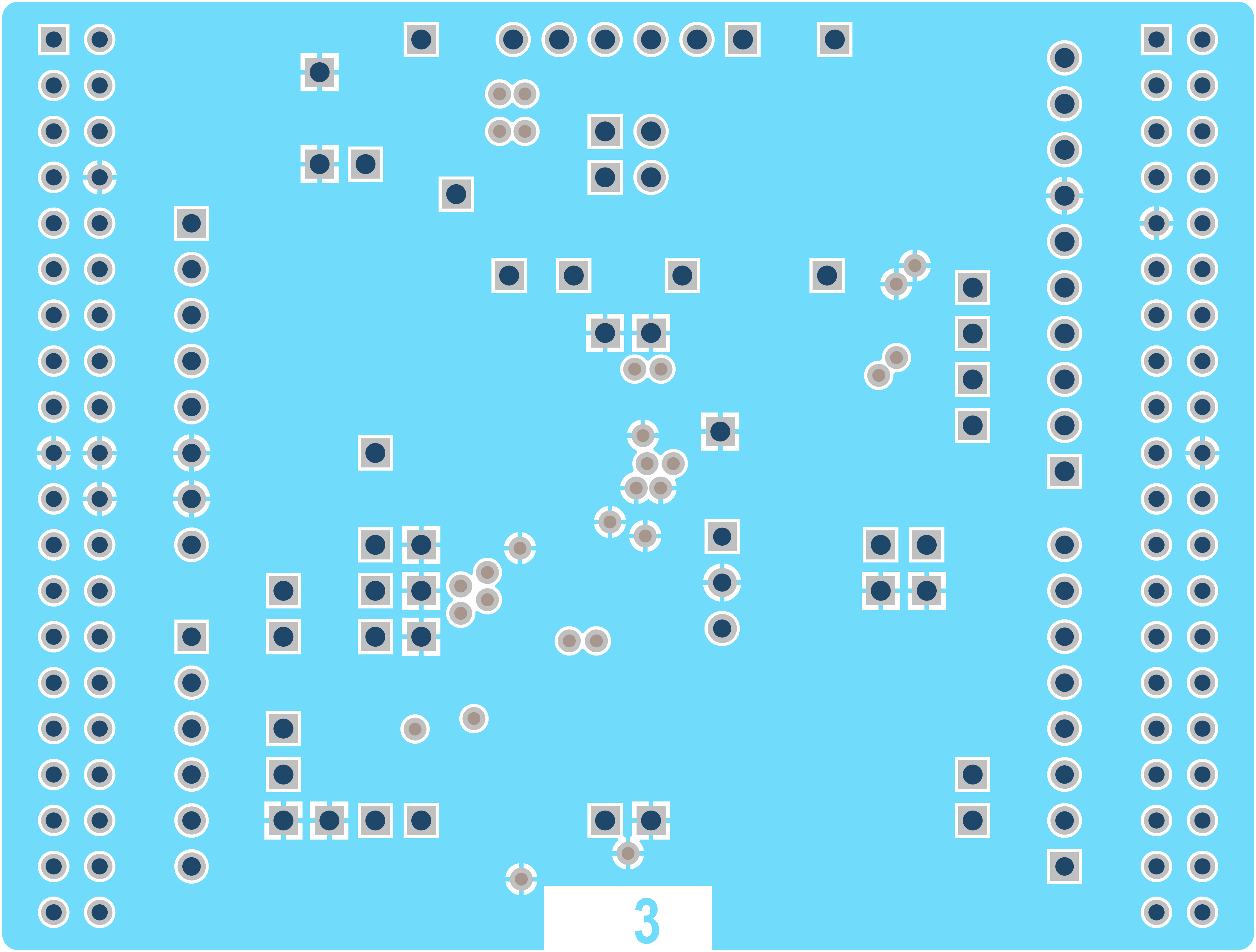
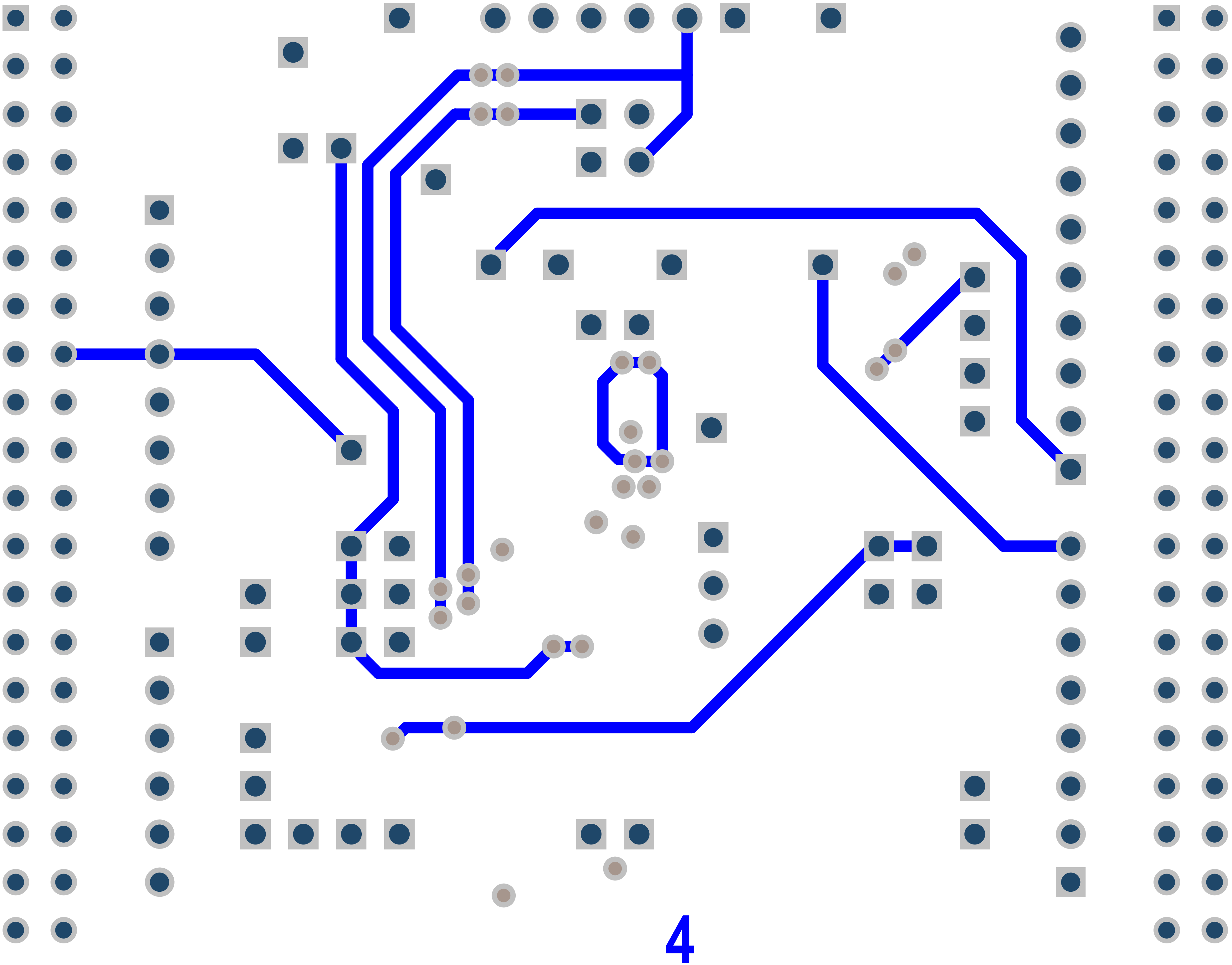
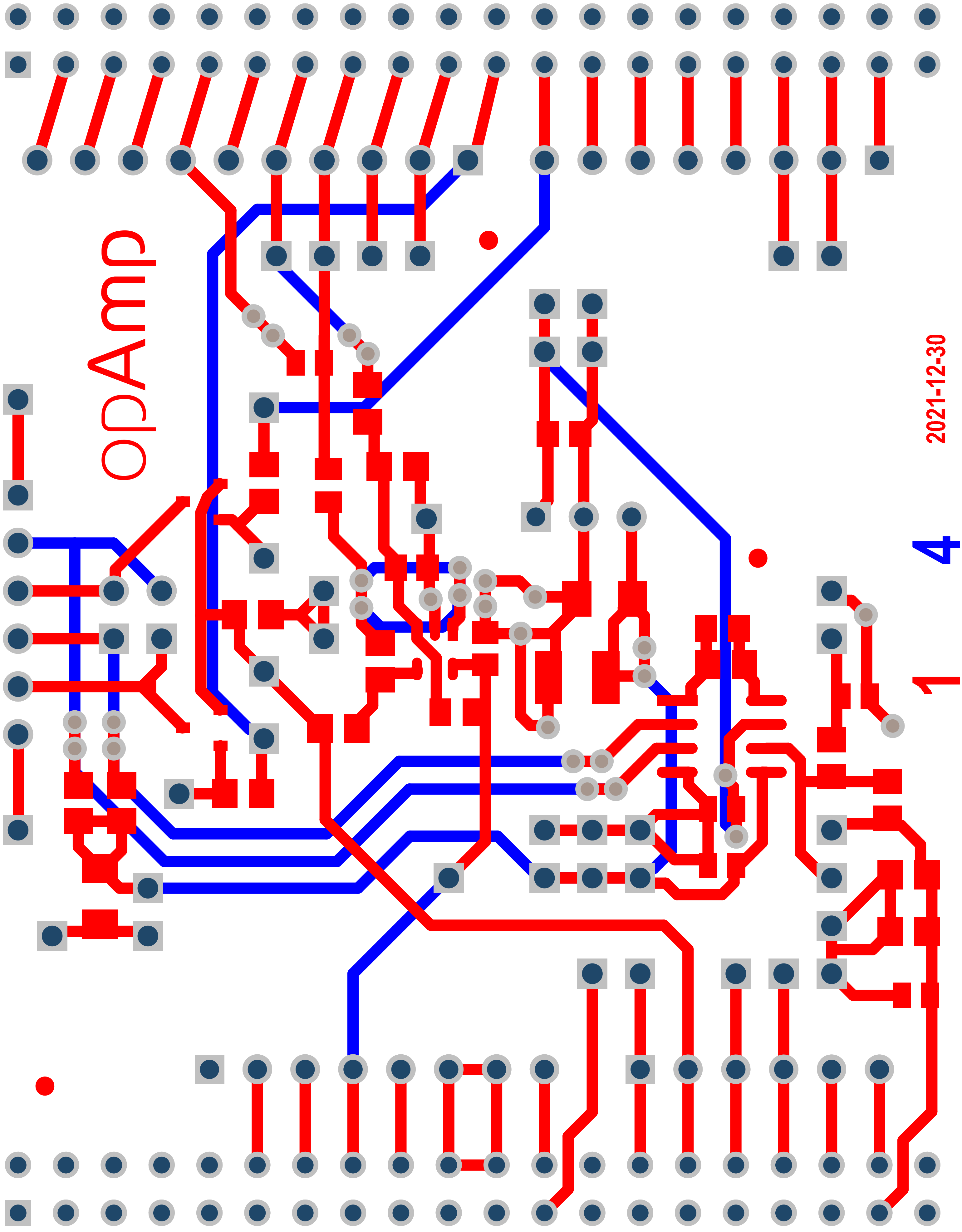
4
5
6
7
8
1
2
3
4
5
6
CN8
FID2
CN7

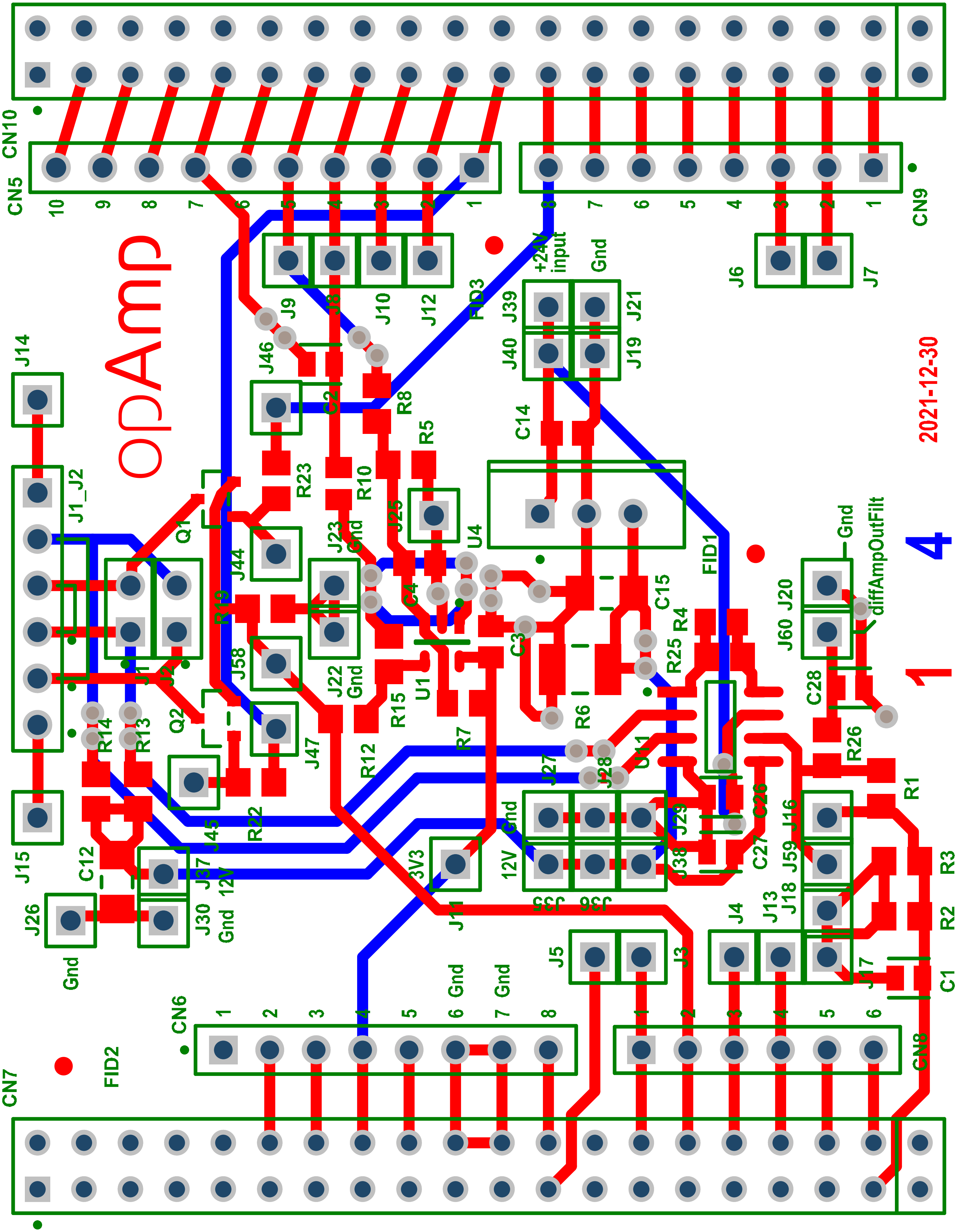

opAmp
2021-12-30
1


2


3


4


opAmp
2021-12-30
4
1


opAmp
2021-12-30
CN10
CN5
CN9
CN6
CN7
CN8
10
9
8
7
6
5
4
3
2
1
+24V input
Gnd
J6
J7
J9
J8
J10
J12
FID3
J39
J21
J40
J19
J46
C21
R8
R5
C14
J14
J1_J2
Q1
R23
R10
J25
U4
FID1
C15
R4
J44
J23
Gnd
C4
R19
C3
R25
J60
J20
diffAmpOutFilt
4
1
J58
J22
Gnd
U1
R15
R6
C28
J1
J2
Q2
R14
R13
J47
R12
R7
J27
J28
U11
R26
R1
J45
R22
J29
C26
J16
C12
J37
12V
3V3
Gnd
12V
J38
C27
J59
R3
J15
J26
J30
Gnd
J11
3V3
3V3
J4
J13
J18
R2
J5
J3
J17
C1
Gnd
Gnd
Gnd
FID2
1
2
3
4
5
6
7
8
1
2
3
4
5
6

Appendix B

Program listing

Listing B.1: gen_thesis_plots.m is used to generate all the plots in this thesis

```
clear; close all;

load("ParsedData.mat", "dat_names", "logs");
plotnames = ["01_datvis" "02_datreal" "03_datsep" ... "04_oddveven30" ...
    "05_oddveven0" "06_timdiff" "07_adc1dat" "08_adc2dat" ...
    "09_fullperiod" "10_periodstat_dc" "11_periodstat_ac" ... "12_AC-GFC" ...
    "13_freq_response" "14_HRTIM_measlin_DC" ... "15_HRTIM_measlin_AC" ...
    "16_ADC1_measlin_DC" "17_ADC1_measlin_AC" ... "18_ADC2_measlin_DC" ...
    "19_ADC2_measlin_AC" "20_GFC-estimation-procedure" ...
    "21_Linear-model_TD" "22_Linear-model_CVD" ... "23_Linear-model_CCD" ...
    "24_TD-estimates" "25_CVD-estimates" "26_CCD-estimates" ...
    "27_Estimation-error_TD" "28_Estimation-error_CVD" ...
    "29_Estimation-error_CCD"];
showplot = false(length(plotnames), 1);
showplot(listdlg("ListString", plotnames, "PromptString", ...
    "Select which plots you want displayed", "CancelString", ...
    "Show no plots", "ListSize", [250 500])) = true;

%% Concatonated vs. gapped sets

sampdat0 = logs(1).data(12).samples; % HRTIM, 0mA DC

% Concatonated
```

```
if(showplot(1))
figure("Name", "01_datvis", "WindowState", "maximized")
plot(0:4096*3-1, sampdat0(:)/150000000, 'LineWidth', 1) % ...
    Divide by 150 MHz to get elapsed time
title("Saturation timing concatonated; GFC = 0mA")
ylabel("Time required for saturation")
xlabel("Samples")
grid("on")
xlim([0 4096*3])
xticks(0:2048:4096*3)
yticks((146.25:0.05:146.55)*10^-6)
yticklabels(string(146.25:0.05:146.55) + " \mus")
set(gca, "FontSize", 18)
end

% Reality
if(showplot(2))
figure("Name", "02_datreal", "WindowState", "maximized")
plot(0:4096-1, sampdat0(:, 1)/150000000, 'LineWidth', 1) % ...
    Divide by 150 MHz to get elapsed time
hold on
plot(4096*2:4096*3-1, sampdat0(:, 2)/150000000, "Color", [0, ...
    0.4470, 0.7410], 'LineWidth', 1)
plot(4096*4:4096*5-1, sampdat0(:, 3)/150000000, "Color", [0, ...
    0.4470, 0.7410], 'LineWidth', 1)
hold off
title("Saturation timing reality; GFC = 0mA")
ylabel("Time required for saturation")
xlabel("Samples")
grid("on")
xlim([0 4096*5])
xticks(0:2048:4096*5)
xticklabels(string(xticks))
yticks((146.25:0.05:146.55)*10^-6)
yticklabels(string(146.25:0.05:146.55) + " \mus")
set(gca, "FontSize", 18)
end

%% Data points

sampdat0  = sampdat0(:);
odd0      = sampdat0(1:2:4096*3);
even0     = sampdat0(2:2:4096*3);

sampdat30 = logs(1).data(end).samples;
sampdat30 = sampdat30(:);
odd30     = sampdat30(1:2:4096*3);
even30    = sampdat30(2:2:4096*3);

if(showplot(3))
```

```
figure("Name", "03_datsep", "WindowState", "maximized")
scatter(0:4096*3-1, sampdat30/150000000, 64, '.') % Divide by ...
    150 MHz to get elapsed time
title("Saturation timing concatonated; GFC = 30mA")
ylabel("Time required for saturation")
xlabel("Samples")
grid("on")
xlim([0 4096*3])
xticks(0:2048:4096*3)
yticks((145.8:0.2:147)*10^-6)
yticklabels(string(146.25:0.05:146.55) + " \mus")
set(gca, "FontSize", 18)
end

if(showplot(4))
figure("Name", "04_oddveven30", "WindowState", "maximized")
scatter(0:2:4096*3-1, odd30/150000000, 64, '.') % Divide by ...
    150 MHz to get elapsed time
hold on
scatter(1:2:4096*3-1, even30/150000000, 64, '.') % Divide by ...
    150 MHz to get elapsed time
title("Saturation timing concatonated; GFC = 30mA")
ylabel("Time required for saturation")
xlabel("Samples")
grid("on")
xlim([0 4096*3])
xticks(0:2048:4096*3)
yticks((145.8:0.2:147)*10^-6)
yticklabels(string(146.25:0.05:146.55) + " \mus")
legend(["Odd samples", "Even samples"], 'Location', 'best')
set(gca, "FontSize", 18)
end

if(showplot(5))
figure("Name", "05_oddveven0", "WindowState", "maximized")
scatter(0:2:4096*3-1, odd0/150000000, 48, 'o', 'filled') % ...
    Divide by 150 MHz to get elapsed time
hold on
scatter(1:2:4096*3-1, even0/150000000, 48, 'o', 'filled') % ...
    Divide by 150 MHz to get elapsed time
title("Saturation timing concatonated; GFC = 0mA")
ylabel("Time required for saturation")
xlabel("Samples")
grid("on")
xlim([0 4096*3])
xticks(0:2048:4096*3)
yticks((146.25:0.05:146.55)*10^-6)
yticklabels(string(146.25:0.05:146.55) + " \mus")
legend(["Odd samples", "Even samples"], 'Location', 'best')
set(gca, "FontSize", 18)
```

```
end

if(showplot(6))
figure("Name", "06_timdiff", "WindowState", "maximized")
plot(0:2048*3-1, (odd0 - even0)/150000000, 'LineWidth', 1) % ...
    Divide by 150 MHz to get elapsed time
hold on
plot(0:2048*3-1, (odd30 - even30)/150000000, 'LineWidth', 1) ...
    % Divide by 150 MHz to get elapsed time
title("Timing differences given DC GFC")
ylabel("Timing difference between odd and even samples")
xlabel("Data points (double samples)")
grid("on")
xlim([0 2048*3])
ylim([-100 1000]*1e-9)
xticks(0:1024:2048*3)
yticks((-100:100:1000)*10^-9)
yticklabels(string(-.1:0.1:1) + " \mus")
legend(["GFC = 0mA DC", "GFC = 30mA DC"], 'Location','best')
set(gca, "FontSize", 18)
end
%% Other data

load("adcs2amps.mat", "theta_AO", "theta_AI")
adc1dat2volt = [3.3/2^12/64*4*theta_AI(1) theta_AI(2)]; % ...
    Oversampled by 64, bitshift by 2
% Convert from ADC2 to voltage, then ADC2 voltage to OpAmp ...
    voltage, then
% divide by resistor to get current
adc2dat2curr = [3.3/2^12/16*1*theta_AO(1) theta_AO(2)]/12;

adc1dath  = logs(8).data(end).samples; % GFC = 30.014 mA
adc1dath  = adc1dath(:)*adc1dat2volt(1) + adc1dat2volt(2);
adc1datho = adc1dath(1:2:end);
adc1dathe = adc1dath(2:2:end);

adc1datn  = logs(8).data(13).samples; % GFC = 0 mA
adc1datn  = adc1datn(:)*adc1dat2volt(1) + adc1dat2volt(2);
adc1datno = adc1datn(1:2:end);
adc1datne = adc1datn(2:2:end);

N = length(adc1dath);

if(showplot(7))
figure("Name", "07_adc1dat", "WindowState", "maximized")
plot(0:2:N-1, adc1datho, 'Color', [1.0 0 0.0], 'LineWidth', 3)
hold on
plot(1:2:N,   adc1dathe, 'Color', [0.7 0 0.0], 'LineWidth', 3)
plot(0:2:N-1, adc1datno, 'Color', [0.0 0 1.0], 'LineWidth', 3)
plot(1:2:N,   adc1datne, 'Color', [0.0 0 0.7], 'LineWidth', 3)
```

```
xlim([0 N])
grid on
legend(["Odd samples; GFC = 30 mA", "Even samples; GFC = 30 ...
    mA", ...
     "Odd samples; GFC = 0mA", "Even samples; GFC = 0mA"], ...
         "Location","east")
title("Voltage differential between coils at sample time (ADC1)")
xlabel("Samples")
xticks(0:2048:4096*3)
ylabel("Measured differential voltage over coils")
yticks(-0.04:0.005:-0.005)
yticklabels((-0.04:0.005:-0.005)*1e3 + " mV")
set(gca, "FontSize", 18)
end

adc2dath  = logs(5).data(end).samples; % GFC = 30.019 mA
adc2dath  = adc2dath(:)*adc2dat2curr(1) + adc2dat2curr(2);
adc2datho = adc2dath(1:2:end);
adc2dathe = adc2dath(2:2:end);

adc2datn  = logs(5).data(12).samples; % GFC = 0 mA
adc2datn  = adc2datn(:)*adc2dat2curr(1) + adc2dat2curr(2);
adc2datno = adc2datn(1:2:end);
adc2datne = adc2datn(2:2:end);

N = length(adc2dath);

if(showplot(8))
figure("Name", "08_adc2dat", "WindowState", "maximized")
plot(0:2:N-1, adc2datho, 'Color', [1.0 0 0.0], 'LineWidth', 3)
hold on
plot(1:2:N,   adc2dathe, 'Color', [0.7 0 0.0], 'LineWidth', 3)
plot(0:2:N-1, adc2datno, 'Color', [0.0 0 1.0], 'LineWidth', 3)
plot(1:2:N,   adc2datne, 'Color', [0.0 0 0.7], 'LineWidth', 3)
xlim([0 N])
grid on
legend(["Odd samples; GFC = 30 mA", "Even samples; GFC = 30 ...
    mA", ...
     "Odd samples; GFC = 0mA", "Even samples; GFC = 0mA"], ...
         "Location","east")
title("Current drawn from coils at sample time (ADC2)")
xlabel("Samples")
ylabel("Current through resistor R19")
xticks(0:2048:4096*3)
yticklabels(yticklabels + " mA")
set(gca, "FontSize", 18)
end

%% Is full period at constant sample time?

```

```
if(showplot(9))
figure("Name", "09_fullperiod", "WindowState","maximized")
plot(0:2048*3-1, (odd0+even0)/150000000, 'LineWidth', 1)
hold on
plot(0:2048*3-1, (odd30+even30)/150000000, 'LineWidth', 1)
plot([0 2048*3-1], ones(2,1)*mean(odd0 + even0)/150000000, ...
    '--', 'LineWidth', 1)
plot([0 2048*3-1], ones(2,1)*mean(odd30+even30)/150000000, ...
    '--', 'LineWidth', 1)
title("Bi-directional saturation time")
ylabel("Time required to saturate in both polarities")
xlabel("Data points (double samples)")
grid("on")
xlim([0 2048*3])
xticks(0:1024:2048*3)
yticks((292.6:0.05:293.1)*10^-6)
yticklabels(string(292.6:0.05:293.1) + " \mus")
legend(["GFC = 0mA", "GFC = 30mA", "Mean period GFC = 0mA", ...
    "Mean period GFC = 30mA"], 'Location', 'best')
set(gca, "FontSize", 18)
end

N1       = length(logs(1).data);
N2       = length(logs(2).data);
gfccurs = [logs(1).data.current logs(2).data.current];
period  = zeros(6144, N1+N2);
cmap       = turbo(512);

if(showplot(10))
figure("Name", "10_periodstat_dc", "WindowState","maximized")
for i=1:N1
    tmpsmp       = logs(1).data(i).samples;
    tmpsmp       = tmpsmp(:)/150000000;
    tmpodd       = tmpsmp(1:2:length(tmpsmp));
    tmpeven      = tmpsmp(2:2:length(tmpsmp));
    tmpsum       = tmpodd+tmpeven;
    period(:,i)  = tmpsum;
end
for i=1:N2
    tmpsmp         = logs(2).data(i).samples;
    tmpsmp         = tmpsmp(:)/150000000;
    tmpodd         = tmpsmp(1:2:length(tmpsmp));
    tmpeven        = tmpsmp(2:2:length(tmpsmp));
    tmpsum         = tmpodd+tmpeven;
    period(:,i+N1)  = tmpsum;
end
colorGroup = cmap(round((gfccurs(1:N1)+35)/70*512), :)*0.8;
bp1 = boxplot(period(:,1:N1), gfccurs(1:N1), 'Notch', 'on', ...
    'Symbol','x', ...
```

```
    'Labels', gfccurs(1:N1) + " mA", 'Color', colorGroup, ...
        'Widths', .9);
title("Bi-directional saturation time given DC GFC")
ylabel("Time required to saturate in both polarities")
xlabel("GFC magnitude")
grid("on")
yticks((292.6:0.1:293.1)*10^-6)
yticklabels(string(292.6:0.1:293.1) + " \mus")
set(gca, "TickLabelInterpreter", "tex")
set(gca, "FontSize", 18)
set(bp1, "LineWidth", 3)
end

if(showplot(11))
figure("Name", "11_periodstat_ac", "WindowState","maximized")
colorGroup = cmap(ceil((gfccurs(N1+1:end)+0.1)/15*512), :)*0.8;
bp2 = boxplot(period(:,N1+1:end), gfccurs(N1+1:end), 'Notch', ...
    'on', 'Symbol','x', ...
    'Labels', gfccurs(N1+1:end) + "mA", 'Color', colorGroup, ...
        'Widths', .9);
title("Bi-directional saturation time given AC GFC")
ylabel("Time required to saturate in both polarities")
xlabel("GFC RMS value")
grid("on")
%ylim([292.7 292.84]*1e-6)
yticks((292.55:0.05:293)*10^-6)
yticklabels(string(292.55:0.05:293) + " \mus")
%sgtitle("Correlation between GFC and bi-directional ...
    saturation period")
set(gca, "TickLabelInterpreter", "tex")
set(gca, "FontSize", 18)
set(bp2, "LineWidth", 3)
end

%% Window-size rationale

acdat   = logs(2).data(end).samples;
acdatt = (cumsum(acdat) - acdat(1))/150000000*2;
acdatd = (acdat(1:2:length(acdat)) - ...
    acdat(2:2:length(acdat)))/150000000*1e9;
acdatf = filter(ones(4,1)/4, 1, acdatd);

if(showplot(12))
figure("Name", "12_AC-GFC", "WindowState","maximized")
plot(acdatt(1:251), acdatd(1:251), 'Linewidth', 1.5, ...
    'DisplayName', "Raw timing difference; GFC = 13.3mA RMS ...
        (50Hz sine)")
hold on
plot(acdatt(1:251), acdatf(1:251), 'Linewidth', 1.5, ...
```

```
 'DisplayName', "Filtered timing difference; GFC = 13.3mA RMS ...
     (50Hz sine)")
plot(acdatt(28:28+68), ones(69,1)*700, '-|k', 'Linewidth', 1, ...
 'DisplayName', "Period length \approx 68 datapoints")
xline(acdatt(28), 'k', 'DisplayName', "Start of period")
xline(acdatt(28+68), 'k', 'DisplayName', "End of period")
title("Timing difference given GFC is a 50Hz sine wave")
xlim([0 acdatt(251)])
grid("on")
xticks(0:0.01:0.07)
xticklabels(string(0:10:70) + " ms")
yticks(-600:200:800)
yticklabels(string(round(-0.6:0.2:0.8, 2)) + " \mus")
axes = get(gca, 'Children');
legend(axes(5:-1:3), [["Unfiltered" "Filtered"] + ...
    " timing difference; GFC = 13.3mA RMS (50Hz sine)", ...
    "Period length \approx 68 datapoints"], 'Location', 'ne');
set(gca, "FontSize", 18)
end

meanper = mean(period, "all");
f  = linspace(0, 0.5/meanper, length(acdatd)/2);
Y  = fft(acdatd);
Yf = fft(acdatf);
if(showplot(13))
figure("Name", "13_freq_response", "WindowState","maximized")
plot(f, abs(Y(1:1024))/length(Y), 'Linewidth', 1.5)
hold on
plot(f, abs(Yf(1:1024)/length(Yf)), 'Linewidth', 1.5)
set(gca, 'YScale', 'log', 'XScale', 'log')
grid on
title("Logarithmic plot of frequency components in AC signal ...
    pre- and post-filtering")
xlim([10 f(end)])
xticks([10 20 50 100 200 500 1000 2000])
xticklabels(string([10 20 50 100 200 500 1000 2000]) + "Hz")
legend(["Unf" "F"] + "iltered timing difference")
set(gca, "FontSize", 18)
end

%% Linearity of data
DC_logs   = logs([1 8 5]);
AC_logs   = logs(9:11);
ftitles   = ["_HRTIM" "_ADC1" "_ADC2"];
sptitles = ["Mean" "RMS of" "Mean" "RMS of"] + " " + ...
    ["timing differences"; "voltage differential"; "current ...
        differences"] + ...
    " given " + ["DC" "DC" "AC" "AC"] + " GFC";
scalef    = [1/150000000 0; adc1dat2volt/2; adc2dat2curr]';
w         = 68;
```

```
lindec   = {[1:6 12 18:23]; 1:2:25; [1:6 12 18:23]};
lindec2  = {[1 3 4 7:2:33]; [32 31:-2:1]; [1 2:2:24]};
ytick    = {(-800:200:800)*1e-9, (6:2:14)*1e-9, ...
    (0:10:80)*1e-9, (0:0.25:2.5)*1e-6; ...
    (-40:10:20)*1e-3, (10:5:40)*1e-6, ...
    (-8:0.5:-5)*1e-3, (0:10:70)*1e-3; ...
    (-0.6:0.2:0.6)*1e-3, (0.4:0.1:0.9)*1e-6, ...
    (-5:5:30)*1e-6, (0:0.2:1.2)*1e-3};
yticklab = {string(-0.8:0.2:0.8) + " \mus", string(6:2:14) + ...
    " ns", ...
    string(0:10:80) + " ns", string(0:0.25:2.5) + " \mus"; ...
    string(-40:10:20) + " mV", string(10:5:40) + " \muV", ...
    string(-8:0.5:-5) + " mV", string(0:10:70) + " mV"; ...
    string(-0.6:0.2:0.6) + " mA", string(0.4:0.1:0.9) + " ...
        \muA", ...
    string(-5:5:30) + " \muA", string(0:0.2:1.2) + " mA"};

for module=1:3
    DC_log  = DC_logs(module);
    AC_log  = AC_logs(module);
    scaling = scalef(:, module);

    tmpmeans = zeros(floor(length(DC_log.data(1).samples)/w), ...
        length(DC_log.data));
    tmprms   = zeros(size(tmpmeans));
    for i=1:length(DC_log.data)
        tmpsmp  = DC_log.data(i).samples;
        % cull the last samples not fitting in the last window
        tmpsmp  = tmpsmp(1:floor(length(tmpsmp)/w/2)*2*w, ...
            :)*scaling(1);
        tmpsmp  = tmpsmp(:) + scaling(2);
        tmpodd  = tmpsmp(1:2:end);
        tmpeven = tmpsmp(2:2:end);
        tmpdat  = tmpodd + tmpeven*(-1)^module;
        tmpdat  = filter(ones(4,1)/4, 1, tmpdat, ...
            tmpdat(1:3)'/4.*[3 2 1]);
        for n=1:floor(length(tmpdat)/w)
            windowdat      = tmpdat((n-1)*w+1:n*w);
            tmpmeans(n, i) = mean(windowdat);
            tmprms(n, i)   = rms(windowdat-tmpmeans(n,i));
        end
    end
    if(showplot(12+2*module))
    figure("Name", string(12+2*module) + ftitles(module) + ...
        "_measlin_DC", ...
        "WindowState","maximized")
    prettify = lindec{module};
    subplot(121)
    bp = boxplot(tmpmeans(:, prettify), ...
        [DC_log.data(prettify).current], ...
```

```
            'Labels', [DC_log.data(prettify).current] + " mA");
        set(bp, "LineWidth", 2)
        title(sptitles(module, 1))
        yticks(ytick{module, 1})
        yticklabels(yticklab{module, 1})
        set(gca, "FontSize", 16, "TickLabelInterpreter", "tex")
        grid on;
        subplot(122)
        bp = boxplot(tmprms(:, prettify), ...
            [DC_log.data(prettify).current], ...
            'Labels', [DC_log.data(prettify).current] + " mA");
        set(bp, "LineWidth", 2)
        title(sptitles(module, 2))
        yticks(ytick{module, 2})
        yticklabels(yticklab{module, 2})
        set(gca, "FontSize", 16, "TickLabelInterpreter", "tex")
        grid on;
        end


        tmpmeans = zeros(floor(length(AC_log.data(1).samples)/w), ...
            length(AC_log.data));
        tmprms   = zeros(size(tmpmeans));
        for i=1:length(AC_log.data)
            tmpsmp  = AC_log.data(i).samples;
            % cull the last samples not fitting in the last window
            tmpsmp  = tmpsmp(1:floor(length(tmpsmp)/w/2)*2*w, ...
                :)*scaling(1);
            tmpsmp  = tmpsmp(:) + scaling(2);
            tmpodd  = tmpsmp(1:2:end);
            tmpeven = tmpsmp(2:2:end);
            tmpdat  = tmpodd + tmpeven*(-1)^module;
            tmpdat  = filter(ones(4,1)/4, 1, tmpdat, ...
                tmpdat(1:3)'/4.*[3 2 1]);
            for n=1:floor(length(tmpdat)/w)
                windowdat      = tmpdat((n-1)*w+1:n*w);
                tmpmeans(n, i) = mean(windowdat);
                tmprms(n, i)   = rms(windowdat-tmpmeans(n,i));
            end
        end
        if(showplot(13+2*module))
        figure("Name", string(13+2*module) + ftitles(module) + ...
            "_measlin_AC", ...
            "WindowState","maximized")
        prettify = lindec2{module};
        subplot(121)
        bp = boxplot(tmpmeans(:, prettify), ...
            [AC_log.data(prettify).current], ...
            'Labels', [AC_log.data(prettify).current] + " mA");
        set(bp, "LineWidth", 2)
```

```
    title(sptitles(module, 3))
    yticks(ytick{module, 3})
    yticklabels(yticklab{module, 3})
    set(gca, "FontSize", 16, "TickLabelInterpreter", "tex")
    grid on;
    subplot(122)
    bp = boxplot(tmprms(:, prettify), ...
        [AC_log.data(prettify).current], ...
        'Labels', [AC_log.data(prettify).current] + " mA");
    set(bp, "LineWidth", 2)
    title(sptitles(module, 4))
    yticks(ytick{module, 4})
    yticklabels(yticklab{module, 4})
    set(gca, "FontSize", 16, "TickLabelInterpreter", "tex")
    grid on;
    end
end

%% Show DC + AC estimate procedure

hybdat  = logs(12).data(end).samples;
hybdat  = (hybdat(:) + 10*65533)/150000000;
hybodd  = hybdat(1:2:end);
hybeven = hybdat(2:2:end);
hybdif  = hybodd-hybeven;

hybdiff = filter(ones(4,1)/4, 1, hybdif);
w       = 68;
if(showplot(20))
figure("Name", "20_GFC-estimation-procedure", "WindowState", ...
    "maximized")
plot(0:3*w, hybdiff(w+50:4*w+50), '-k', 'LineWidth', 1.5)
hold on;
for n=2:4
    interval = ((n-1)*w+1):n*w;
    hybwindm = mean(hybdiff(interval));
    hybwindr = rms(hybdiff(interval)-hybwindm);
    patchx = [interval(1)-1 interval(1)-1 interval ...
        interval(end)]-w;
    patchy = [hybwindm hybdiff(interval(1)+49) ...
        hybdiff(interval(1:w/2-1)+50)' ...
        hybwindm hybdiff(interval(w/2+1:end)+50)' hybwindm];
    patch(patchx, patchy, 'green', 'FaceAlpha', 0.3, ...
        'EdgeColor', 'none')
    plot(interval-w, ones(length(interval))*hybwindm, '--b', ...
        'LineWidth', 3)
    plot(interval(1:w/2)-w, ones(w/2,1)*hybwindr+hybwindm, ...
        '-.', ...
        'Color', [0 0.4 0], 'LineWidth', 3)
```

```
    plot(interval(w/2+1:end)-w, ...
        -ones(w/2,1)*hybwindr+hybwindm, '-.', ...
        'Color', [0 0.4 0], 'LineWidth', 3)
end
title("Bi-directional timing differences over time given GFC ...
    5mA RMS sine + 5mA DC offset")
grid on;
xlim([0 3*w])
xlabel("Data points")
yticklabels(str2double(yticklabels)/10 + " \mus")
ylabel("Timing difference")
axes = get(gca, 'Children');
L    = length(axes);
legend(axes([L L-2 L-1 L-70]), ["Filtered timing difference ...
    over time", ...
    "Mean timing difference for period", "Variance from ...
        mean", ...
    "RMS from mean"]);
set(gca, 'FontSize', 18)
end

%% Create linear models

create_linear_models

%% Estimate on data

TD  = [];
CVD = [];
CCD = [];
TD_GFC  = [];
CVD_GFC = [];
CCD_GFC = [];

for i=1:length(logs(12).data)
    tmp = logs(12).data(i).samples;
    tmp = filter(ones(4,1)/4, 1, tmp(1:2:end,:) - ...
        tmp(2:2:end, :));
    tmp = tmp(end-floor(length(tmp)/w)*w+1:end, :);
    TD  = [TD; tmp(:)];
    TD_GFC = [TD_GFC; ...
        ones(length(tmp(:)),1)*logs(12).data(i).current];
end
for i=1:length(logs(13).data)
    tmp = logs(13).data(i).samples;
    tmp = filter(ones(4,1)/4, 1, tmp(1:2:end,:) + ...
        tmp(2:2:end, :));
    tmp = tmp(end-floor(length(tmp)/w)*w+1:end, :);
    CVD = [CVD; tmp(:)];
```

```
    CVD_GFC = [CVD_GFC; ...
        ones(length(tmp(:)),1)*logs(13).data(i).current];
end
CCD_log = ...
    data_parser("../Data/Raw_Logs/06-13_124844_RCD_HYB_ADC2.txt");
for i=1:length(CCD_log.data)
    tmp = CCD_log.data(i).samples;
    tmp = filter(ones(4,1)/4, 1, tmp(1:2:end,:) - ...
        tmp(2:2:end, :));
    tmp = tmp(end-floor(length(tmp)/w)*w+1:end, :);
    CCD = [CCD; tmp(:)];
    CCD_GFC = [CCD_GFC; ...
        ones(length(tmp(:)),1)*CCD_log.data(i).current];
end

TD_est = zeros(floor(length(TD)/w), 2);
theta_TD = thetamod{1};
for n=1:floor(length(TD)/w)
    window = TD((n-1)*w+1:n*w);
    TD_mean = mean(window);
    DC = TD_mean*theta_TD(1,1) + theta_TD(2,1);
    AC = rms(window-TD_mean)*theta_TD(1,2) + theta_TD(2,2);
    TD_est(n, :) = [DC AC];
end
CVD_est = zeros(floor(length(CVD)/w), 2);
theta_CVD = thetamod{2};
for n=1:floor(length(CVD)/w)
    window = CVD((n-1)*w+1:n*w);
    CVD_mean = mean(window);
    DC = CVD_mean*theta_CVD(1,1) + theta_CVD(2,1);
    AC = rms(window-CVD_mean)*theta_CVD(1,2) + theta_CVD(2,2);
    CVD_est(n, :) = [DC AC];
end
CCD_est = zeros(floor(length(CCD)/w), 2);
theta_CCD = thetamod{3};
for n=1:floor(length(CCD)/w)
    window = CCD((n-1)*w+1:n*w);
    CCD_mean = mean(window);
    DC = CCD_mean*theta_CCD(1,1) + theta_CCD(2,1);
    AC = rms(window-CCD_mean)*theta_CCD(1,2) + theta_CCD(2,2);
    CCD_est(n, :) = [DC AC];
end

if(showplot(24))
figure("Name", "24_TD-estimates", "WindowState","maximized")
time_TD = (0:length(TD_est)-1)*0.02;
plot(time_TD, TD_est(:,1), 'LineWidth', 3, 'Color', [0 0 1])
hold on; grid on;
plot(time_TD, TD_est(:,2), 'LineWidth', 3, 'Color', [.7 0 0])
```

```
plot(time_TD, TD_GFC(1:w:end, 1), '--', 'LineWidth', 1.5, ...
    'Color', [0 1 1])
plot(time_TD, TD_GFC(1:w:end, 2), '-.', 'LineWidth', 1.5, ...
    'Color', [1 0 1])
xlim(time_TD([1 end]))
legend(["DC estimate" "AC estimate (RMS)" "DC GFC" "AC GFC ...
    (RMS)"], ...
    "Location","sw")
xlabel("Time [s]")
ylabel("Ground fault current [mA]")
title("GFC estimates using TD data")
set(gca, "FontSize", 18)
end

if(showplot(25))
figure("Name", "25_CVD-estimates", "WindowState", "maximized")
time_CVD = (0:length(CVD_est)-1)*0.02;
plot(time_CVD, CVD_est(:,1), 'LineWidth', 3, 'Color', [0 0 1])
hold on; grid on;
plot(time_CVD, CVD_est(:,2), 'LineWidth', 3, 'Color', [.7 0 0])
plot(time_CVD, CVD_GFC(1:w:end, 1), '--', 'LineWidth', 1.5, ...
    'Color', [0 1 1])
plot(time_CVD, CVD_GFC(1:w:end, 2), '-.', 'LineWidth', 1.5, ...
    'Color', [1 0 1])
xlim(time_CVD([1 end]))
legend(["DC estimate" "AC estimate (RMS)" "DC GFC" "AC GFC ...
    (RMS)"], ...
    "Location","ne")
xlabel("Time [s]")
ylabel("Ground fault current [mA]")
title("GFC estimates using CVD data")
set(gca, "FontSize", 18)
end

if(showplot(26))
figure("Name", "26_CCD-estimates", "WindowState", "maximized")
time_CCD = (0:length(CCD_est)-1)*0.02;
plot(time_CCD, CCD_est(:,1), 'LineWidth', 3, 'Color', [0 0 1])
hold on; grid on;
plot(time_CCD, CCD_est(:,2), 'LineWidth', 3, 'Color', [.7 0 0])
plot(time_CCD, CCD_GFC(1:w:end, 1), '--', 'LineWidth', 1.5, ...
    'Color', [0 1 1])
plot(time_CCD, CCD_GFC(1:w:end, 2), '-.', 'LineWidth', 1.5, ...
    'Color', [1 0 1])
xlim(time_CCD([1 end]))
legend(["DC estimate" "AC estimate (RMS)" "DC GFC" "AC GFC ...
    (RMS)"], ...
    "Location","se")
xlabel("Time [s]")
ylabel("Ground fault current [mA]")
```

```
title("GFC estimates using CCD data")
set(gca, "FontSize", 18)
end

%% Estimation error

TD_error    =  TD_est -  TD_GFC(1:w:end, :);
CVD_error   = CVD_est - CVD_GFC(1:w:end, :);
CCD_error   = CCD_est - CCD_GFC(1:w:end, :);
TD_error_r  = rms( TD_error);
CVD_error_r = rms(CVD_error);
CCD_error_r = rms(CCD_error);

if(showplot(27))
figure("Name", "27_Estimation-error_TD", ...
    "WindowState","maximized")
colororder([0 0 1; .7 0 0; 0 1 1; 1 0 1; 0 .7 .7; .7 0 .7])
plot(time_TD,  TD_error, "LineWidth", 1)
hold on; grid on;
plot(time_TD([1 end]), ones(2,1)*TD_error_r, '--', ...
    'LineWidth', 3)
xlim(time_TD([1 end]))
legend(["DC error" "AC error" "RMSE DC" "RMSE AC"])
xlabel("Time [s]")
ylabel("Estimation error [mA]")
title("Estimation error for TD data")
set(gca, "FontSize", 18)
disp("TD errors")
disp("    RMSE:")
disp(TD_error_r)
end

if(showplot(28))
figure("Name", "28_Estimation-error_CVD", ...
    "WindowState","maximized")
colororder([0 0 1; .7 0 0; 0 1 1; 1 0 1; 0 .7 .7; .7 0 .7])
plot(time_CVD,  CVD_error, "LineWidth", 1)
hold on; grid on;
plot(time_CVD([1 end]), ones(2,1)*CVD_error_r, '--', ...
    'LineWidth', 3)
xlim(time_CVD([1 end]))
legend(["DC error" "AC error" "RMSE DC" "RMSE AC"], ...
    'Location', 'e')
xlabel("Time [s]")
ylabel("Estimation error [mA]")
title("Estimation error for CVD data")
set(gca, "FontSize", 18)
disp("CVD errors")
disp("    RMSE:")
disp(CVD_error_r)
```

```
end

if(showplot(29))
figure("Name", "29_Estimation-error_CCD", ...
    "WindowState","maximized")
colororder([0 0 1; .7 0 0; 0 1 1; 1 0 1; 0 .7 .7; .7 0 .7])
plot(time_CCD,  CCD_error, "LineWidth", 1)
hold on; grid on;
plot(time_CCD([1 end]), ones(2,1)*CCD_error_r, '--', ...
    'LineWidth', 3)
xlim(time_CCD([1 end]))
legend(["DC error" "AC error" "RMSE DC" "RMSE AC"])
xlabel("Time [s]")
ylabel("Estimation error [mA]")
title("Estimation error for CCD data")
set(gca, "FontSize", 18)
disp("CCD errors")
disp("    RMSE:")
disp(CCD_error_r)
end
```

Listing B.2: create_linear_models.m creates the linear model from data

```
%% Load data

load("ParsedData.mat", "logs")

dat_TD  = logs([1  9]); % Timing Difference
dat_CVD = logs([8 10]); % Coil Voltage Differential
dat_CCD = logs([5 11]); % Coil Current Draw

%% Estimate average values

data = [dat_TD dat_CVD dat_CCD];
avg  = cell(2,3);
w    = 68;

for module=1:length(data)
    mod_DC = data(1, module);
    avg_DC = zeros(length(mod_DC.data), 2);
    for current=1:length(mod_DC.data)
        avg_DC(current, 1) = mod_DC.data(current).current;
        tmp_dat = mod_DC.data(current).samples;
        tmp_dat = tmp_dat(1:2:end, :) + tmp_dat(2:2:end, ...
            :)*(-1)^module;
        tmp_dat = filter(ones(4,1)/4, 1, tmp_dat);
        tmp_dat = ...
            tmp_dat(end-floor(length(tmp_dat)/w)*w+1:end, :);
        avg_DC(current, 2) = mean(tmp_dat, "all");
```

```
    end
    avg{1, module} = avg_DC;
    mod_AC = data(2, module);
    avg_AC = zeros(length(mod_AC.data), 2);
    for current=1:length(mod_AC.data)
        avg_AC(current, 1) = mod_AC.data(current).current;
        tmp_dat = mod_AC.data(current).samples;
        tmp_dat = tmp_dat(1:2:end, :) + tmp_dat(2:2:end, ...
            :)*(-1)^module;
        tmp_dat = filter(ones(4,1)/4, 1, tmp_dat);
        tmp_dat = ...
            tmp_dat(end-floor(length(tmp_dat)/w)*w+1:end, :);
        tmp_dat = tmp_dat - mean(tmp_dat);
        avg_AC(current, 2) = mean(rms(tmp_dat));
    end
    if module==1
        avg_AC(2, :) = []; % Remove erroneous measurement
    end
    avg{2, module} = avg_AC;
end

%% Create regression from averages

thetamod = cell(3,1);
resmod   = cell(3,1);

for module=1:3
    avg_DC = avg{1, module}; avg_AC = avg{2, module};
    [theta_DC, res_DC] = current_regression(avg_DC(:,2), ...
        avg_DC(:,1));
    [theta_AC, res_AC] = current_regression(avg_AC(:,2), ...
        avg_AC(:,1));
    thetamod{module}   = [theta_DC theta_AC];
    resmod{module}     = [res_DC res_AC];
end

%% Display models

modnames = ["TD", "CVD", "CCD"];
load("dat2phys.mat", "scalef");

xtick    = {(-0.9:0.3:0.9)*1e-6, (0:0.5:2.5)*1e-6; ...
    (-45:15:30)*1e-3, (0:15:90)*1e-3; ...
    (-0.6:0.3:0.9)*1e-3, (0:0.3:1.2)*1e-3};
xticklab = {string(-0.9:0.3:0.9)+"\mus", ...
    string(0:0.5:2.5)+"\mus"; ...
    string(-45:15:30)+"mV", string(0:15:90)+"mV"; ...
    string(round(-0.6:0.3:0.9, 2))+"mA", string(0:0.3:1.2)+"mA"};
xlims    = {[-.8 1]*1e-6, [0 2.3]*1e-6;...
    [-40 25]*1e-3, [0 80]*1e-3; ...
```

```
    [-.6 .7]*1e-3, [0 1.2]*1e-3};
ylims    = {[-32 32], [0 82]; ...
    [-32 32], [0 82]; ...
    [-32 32], [0 62]};
xlabels  = ["Timing difference", ...
    "Coil voltage differential", "Coil current draw"];

for module=1:3
    avg_DC = avg{1, module}; avg_AC = avg{2, module};
    scaling = scalef(:, module);
    figure("WindowState","maximized", "Name", ...
        string(20+module) + "_Linear-model_" + modnames(module))
    xdc = avg_DC(:,2); dc = avg_DC(:,1); theta = ...
        thetamod{module};
    ydc = xdc*theta(1,1) + theta(2,1); ddc = xdc*scaling(1);
    if module==2
        ddc = ddc + 2*scaling(2); % Constant only appears in ...
            module 2 (sum)
    end
    subplot(121)
    scatter(ddc, dc, 150, 'filled')
    hold on; grid on;
    plot(ddc, ydc, 'LineWidth', 2)
    xticks(xtick{module, 1})
    xticklabels(xticklab{module, 1})
    yticklabels(yticklabels + " mA")
    xlim(xlims{module, 1})
    ylim(ylims{module, 1})
    xlabel(xlabels(module))
    ylabel("Ground fault current")
    set(gca, "FontSize", 18)
    title("Modeling DC GFC using mean of " + modnames(module))
    xac = avg_AC(:,2); ac = avg_AC(:,1);
    yac = xac*theta(1,2) + theta(2,2); dac = xac*abs(scaling(1));
    subplot(122)
    scatter(dac, ac, 150, 'filled')
    hold on; grid on;
    plot(dac, yac, 'LineWidth', 2)
    xticks(xtick{module, 2})
    xticklabels(xticklab{module, 2})
    yticklabels(yticklabels + " mA")
    xlim(xlims{module, 2})
    ylim(ylims{module, 2})
    xlabel(xlabels(module))
    ylabel("Ground fault current")
    set(gca, "FontSize", 18)
    title("Modeling AC GFC using RMS of " + modnames(module))
end
```

Listing B.3: data_parser.m creates data objects from raw text files

```
function dataarr = data_parser(filenames)
    dataarr = [];
    % Loop through each file
    for i=1:length(filenames)
        filename = strsplit(filenames(i), "/");
        filename = strsplit(filename(end), ".");
        data = struct("name", filename(1), "data", []);
        fileID   = fopen(filenames(i));
        line     = fgetl(fileID);
        datastc  = struct("current", [], "samples", []);
        % Loop through each line in the file
        while ¬strcmp(string(line), "-1")
            info = strsplit(line);
            if length(info) < 3
                if ¬any(isnan(str2double(info)))
                    if ¬isempty(datastc.samples)
                        data.data = [data.data; datastc];
                    end
                    datastc.current = str2double(info);
                    datastc.samples = [];
                end
            else
               try
                    samples = hex2dec(info);
                    datastc.samples = [datastc.samples, samples];
               catch
                   ; % Invalid data
               end
            end
            line = fgetl(fileID);
        end
        data.data = [data.data; datastc];
        dataarr = [dataarr; data];
    end
end
```

Appendix C

Data sheets

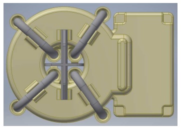
C.1 VACUUMSCHMELZE benvac Differential Current Sensor – Data Sheet

VACUUMSCHMELZE

Specification

Item no.: T60404-N4641-X920

Differential Current Sensor acc. to the standard IEC62752-1:2016



Date: 11.10.2021

K-No.: 26893

Customer: Standard type

Description

- Fluxgate current sensor with toroidal core
- PCB mounting

Characteristics

- Excellent accuracy
- AEC-Q qualified components
- Switching open-collector outputs
- Compact design

Applications

Mainly used for mobile applications:

- IC-CPD acc. to IEC62752

Patents: EP2571128 / US9397494 / CN103001175 // EP2813856

Electrical data – Ratings

		min.	typ.	max.	Unit
I_P	Primary rated current (1phase / 3phase)		32	40	A
$I_{\Delta N1}$	Rated residual operating current 1		6		mA DC
$I_{\Delta N2}$	Rated residual operating current 2		30		mA rms
$I_{\Delta N1,\ \mathrm{tolerance}}$	Trip tolerance 1	4	5	6	mA DC
$I_{\Delta N2,\ \mathrm{tolerance}}$	Trip tolerance 2	20		30(1) / 60(2)	mA rms
$S_{PWM\text{-}OUT}$	Scaling factor of the DC component $I_{\Delta N1}$ **(for monitoring purpose only!)**		3.33		%/mA
$I_{\Delta RI,1/2}$ (Fig.1)	Recovery current level for $I_{\Delta N1}$/$I_{\Delta N2}$ (absolute value dc/rms)		2.5 / 10		mA

(1) f = DC to 1kHz (2) f = 1kHz to 2kHz

Accuracy – Dynamic performance data

		min.	typ.	max.	Unit
$I_{\Delta N,max}$	Measuring range (peak)	-300		+300	mA
X	Resolution (@ $I_{\Delta N}$, Θ_A = 25°C)		< 0.2		mA
t_r (Fig.3)	Response time		According to IEC62752:2016(3)		
f_{BW} (Fig.4)	Frequency range	DC		2	kHz

General data

		min.	typ.	max.	Unit
ϑ_A	Ambient operation temperature	-40		85	°C
$\vartheta_{Storage}$	Ambient storage temperature(4)	-40		85	°C
m	Mass		32		g
V_{CC}	Supply voltage	4.8	5	5.2	V
I_{CC}	Consumption current	38		45	mA rms
$S_{clear,\ pp}$	Clearance (primary to primary)(5)		4.22		mm
$S_{creep,\ pp}$	Creepage (primary to primary)(5)		5.65		mm
$S_{clear,\ ps}$	Clearance (primary to secondary)(6)		6.53		mm
$S_{creep,\ ps}$	Creepage (primary to secondary)(6)		7.75		mm
FIT	EN/IEC 61709 / SN 29500(7) (MIL-HDBK-217F)(7)		1529 (6349)		fit
SW	Firmware		D0462 V1.04		

(3) Switching time of a standard relay (t = 20ms) is considered.

(4) see VAC M-sheet 3101; storage temperature inside cardboard packaging.

(5) Can only be achieved with the isolator; all values acc. to applied standards.

(6) Designed, manufactured and tested in accordance with IEC60664-1:2007. The isolation coordination is according to: Reinforced insulation, Insulation material group 1, Pollution degree 3 and overvoltage category III. Values refer to nominal real clearance and creepage.

(7) The results are valid under following conditions: 55°C mean component ambient temperature by continuous operation (8760h per year); Environment condition: ground mobile, no dust or harmful substances, according to IEC61709; Fit equals one failure per 10^9 component hours.

General description of sensor function:

The Sensor is sensitive to AC and DC current and can be used for fault current detection in IC-CPD applications. The Sensor detects AC and DC fault currents according to IEC62752:2016. In the event of a DC fault current, PIN 3 will change its state from a low level (GND) to high impedance state. In the event of an AC fault current, PINs 3 and 4 will change state from a low level (GND) to a high impedance state.
Error conditions (e.g. an internal error) are signaled by PIN 1 (ERROR-OUT) which changes state to high impedance.

Datum	Name	Index	Änderung
11.10.2021	ZB	82	Patents added on sheet 1. CN-21-290
01.11.19	MB	82	Typo: Add firmware and real creepage/clearance values on pg.1, Correction of readability on pg2/pg3. minor change

Editor.: R&D-PD-NPI D	Designer: MB		MC-PM: BZ		Released by: SB

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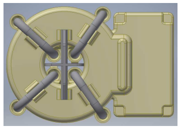
VACUUMSCHMELZE

Specification

Item no.: T60404-N4641-X920

K-No.: 26893

Differential Current Sensor acc. to the standard IEC62752-1:2016



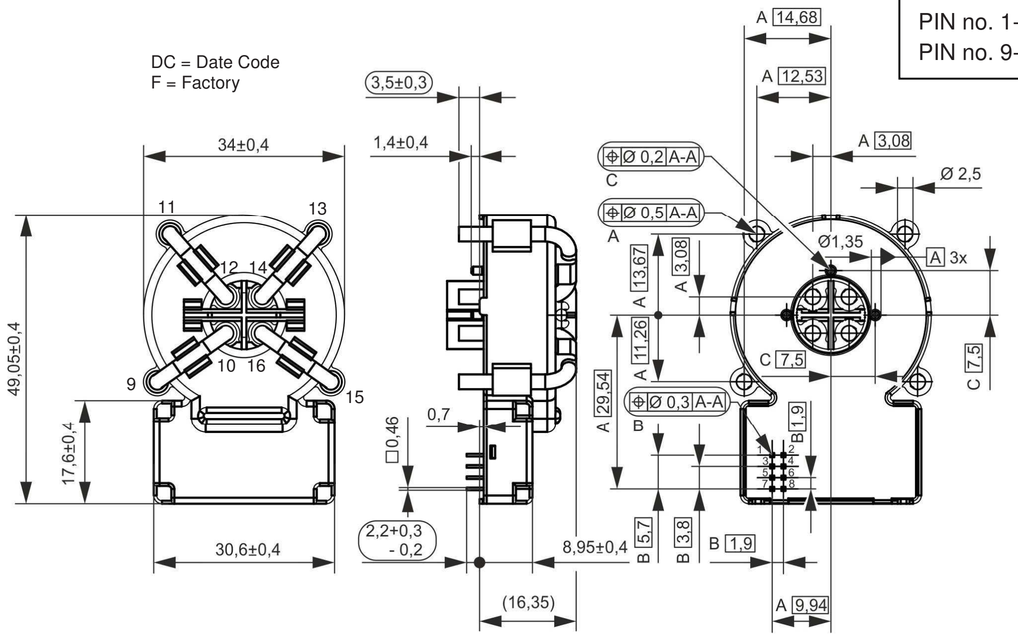
Date: 11.10.2021

Customer: Standard type

Mechanical outline (mm): General tolerances DIN ISO 2768-c

Connections:

PIN no. 1-8: 0.46mm x 0.46mm
PIN no. 9-16: Ø = 2.5mm



Marking:

VAC
4641-X920
F DC

Content of Data-Matrix-Code is: VAC, 4641-X920, F, DC

Datecode Format: [YWW]
Example: J04: 2017, Week 4

PIN description:

PIN no.	Description
PIN 1 → ERROR-OUT (open collector output)	If no system fault is detected, the output PIN 1 is at low level (GND). If a system fault is detected, PIN is at high impedance state. In this case, PINs 3 and 4 will be set to a high impedance state too (see tab.1).
PIN 2 → TEST-IN (refer to Fig. 2)	A function test including an offset measurement (this value is stored in EEPROM for further calculation) is activated if this PIN is connected to GND for a period of 40ms to 1.2s. If the PIN is set to GND less than 40ms or more than 1.2s, no function test will be performed. **Attention:** During the functional test and offset measurement, no differential current shall flow. To ensure high accuracy of the sensor this test shall be activated at regular intervals (e.g. at startup, before measuring…). If a push-pull switch is used, the voltage range must be 0V…5V.
PIN 3 → X6-OUT (open collector output)	If the residual current is below 6mA dc and no system fault occurs the output on PIN 3 is a low level (GND). In any other case output PIN 3 is in a high impedance state. If PIN 4 is high impedance, PIN 3 will also be set to high impedance (see tab. 1).
PIN 4 → X30-OUT (open collector output)	If the residual current is below the 30mA rms and no system fault occurs the output on PIN 4 is a low level (GND). In any other case PINs 3 and 4 are in a high impedance state (see tab. 1).
PIN 5 → GND	Ground connection
PIN 6 → VCC	Positive supply voltage
PIN 7 → PWM-OUT	Acc. to the DC component of residual current a duty-cycle with f=8kHz is generated. This is for monitoring purposes only and shall not be used to switch the power relay. Refer to $S_{PWM\text{-}OUT}$ = 3.33%/mA
PIN 8 → N.C.	Not connected
PIN 9 – 16	For primary wires connection

Editor.: R&D-PD-NPI D	Designer: MB	MC-PM: BZ		Released by: SB

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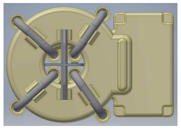
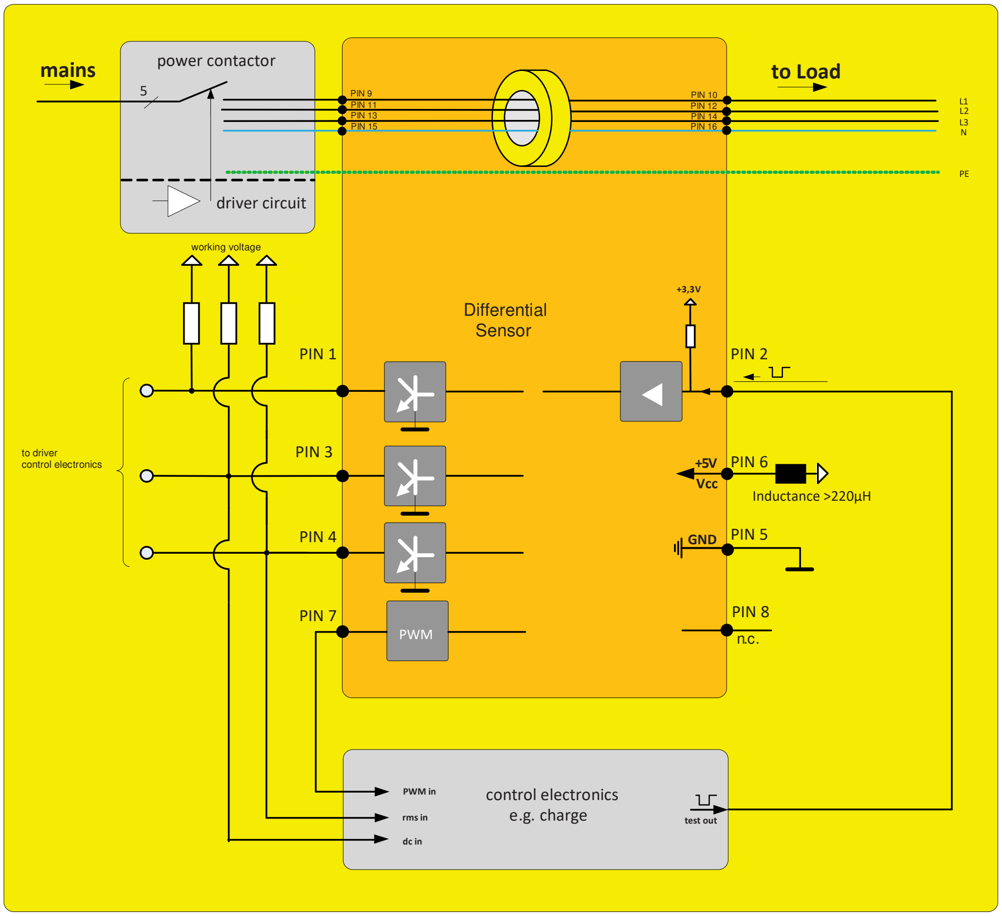


Typical application diagram:



Absolute maximum ratings(8):

		Min	Typ.	Max	Unit
V_{CE}	Collector-Emitter voltage (PINs 1, 3 and 4)			40	V
I_{C}	Collector current (PINs 1, 3 and 4)			50	mA
V_{CC}	Maximum supply voltage (without function)	-0.3		7	V
U_{MAX}	Maximum rated voltage of primary conductors			440	V
$V_{TEST-IN,\ low}$	TEST-IN Input Voltage, low level	0		0.6	V
$V_{TEST-IN,\ high}$	TEST-IN Input Voltage, high level	2.5		5	V

(8) Stresses above these ratings may cause permanent damage. Exposure to these conditions for extended periods may degrade device reliability. Functional operation of the device at these or any other conditions beyond those specified is not supported.

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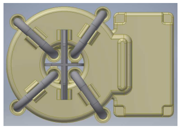
VACUUMSCHMELZE	Specification	Item no.: T60404-N4641-X920
K-No.: 26893	Differential Current Sensor acc. to the standard IEC62752-1:2016	Date: 11.10.2021
Customer: Standard type		Page 4 of 7



Final Tests: (Measurements after temperature balance of the samples at room temperature, SC=significant characteristic)

		Min.	Max.	Unit
Vcc	Supply voltage	4.9	5.1	V
Icc	Supply current	38.0	45.0	mA
TEST-IN (SC)	TEST-IN voltage	2.8	3.4	V
X6-OUT (normal)	X6-OUT voltage	0	0.6	V
X30-OUT (normal)	X30-OUT voltage	0	0.6	V
ERROR-OUT (normal)	ERROR-OUT voltage	0	0.6	V
X6-OUT (activated)	X6-OUT voltage activated @5V, 1kΩ (pull-up)*	4.9	5.1	V
X30-OUT (activated)	X30-OUT voltage activated @5V, 1kΩ (pull-up)*	4.9	5.1	V
ERROR-OUT (activated)	ERROR-OUT voltage activated @5V, 1kΩ (pull-up)*	4.9	5.1	V
TC1	Trip current 1 – X6	4.1	5.4	mA
TC2	Trip current 2 – X6	-5.4	-4.1	mA
TC3	Trip current 3 – X30@50Hz	20	30	mA
PWM-OUT (frequency)	PWM-OUT frequency	7.8	8.2	kHz
PWM-OUT (duty-cycle)	PWM-OUT duty-cycle @6mA DC	18	22	%
LV1	Limit values of break time - X6-OUT@6mA DC	0	700	ms
LV2	Limit values of break time - X6-OUT@30mA DC	0	500	ms
LV3	Limit values of break time - X30-OUT@30mA, 50Hz	0	300	ms
LV4	Limit values of break time - X30-OUT@150mA,50Hz	0	40	ms

* the maximum values of collector-emitter voltage and current see “Absolute maximum ratings”

Product Tests:

	Acc. to VAC sheet M3238 Following tests differ from M3238: 3.4a: Rapid change of temperature for 300 cycles 4.5a: Damp heat, steady state. Duration: 1000 h	passed	
PD	IEC61000-4-1, EN60270, M3024 UPDE M3024, Partial discharge voltage (extinction) *acc. to table 24	1.5	kV rms
ESD	Air- and contact discharge; U=±2000V, R=1500Ω, C=100pF Acc. to Human Body Model JESD22-A114	±2.0	kV
EMC	IEC61000-4-3 (Radiated, radio-frequency, electromagnetic field immunity) 20V/m 80MHz – 1GHz 80%AM 1kHz, recommend with the use of inductance of >220µH in series of Vcc input.	passed	
	CISPR14-1 (Immunity to conducted disturbances), recommend with the use of inductance of >220µH in series of Vcc input.	passed	
	IEC61000-6-4 (Emission standard for industrial environments, conducted disturbances)	Should be done in end application	
A(f), Φ(f)	Amplitude and phase response over frequency 1% of I_{PN} or $I_{\Delta n}$	passed	
Impulse test	Monitoring of CS function during the current phase test 100A to 5kA	passed	

Editor.: R&D-PD-NPI D	Designer: MB		MC-PM: BZ			Released by: SB

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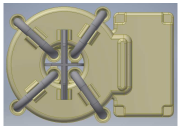

Requalification Tests: (replicated every year, Precondition acc. to M3238)

$\hat{U}_{W,\ prim\text{-}sec}$	M3064	Impulse test (1.2µs/50µs waveform) PIN 1-8 vs. PIN 9-14 5 pulse ➔ polarity +, 5 pulse ➔ polarity -	5.5	kV
$\hat{U}_{W,\ prim\text{-}prim}$	M3064	Impulse test (1.2µs/50µs waveform) PIN 9 vs. PIN 11, PIN 11 vs. PIN 13, PIN 13 vs. PIN 15, PIN 15 vs. PIN 9 5 pulse ➔ polarity +, 5 pulse ➔ polarity -	4.0	kV
U_d	M3014	Test voltage, 60s PIN 1-8 vs. PIN 9-16	1.5	kV
$U_{d,\ prim\text{-}prim}$	M3014	Test voltage between primary conductors, 5s PIN 9 vs. PIN 11,PIN 11 vs. PIN 13, PIN 13 vs. PIN 15, PIN 15 vs. PIN 9	1.5	kV
U_{PDE}	M3024	Partial discharge voltage (extinction) PIN 1-8 vs. PIN 9-16 *acc. to table 24	1.2	kV rms
U_{PD} x 1.875	M3024	Partial discharge voltage (extinction) PIN 1-8 vs. PIN 9-16 *acc. to table 24	1.5	kV rms

* IEC 61800-5-1:2007

Other instructions:

- Temperature of the primary conductor should not exceed 105°C.
- Vcc during Test-IN function test must be in rated range.
- Fall- and rise-time of Vcc: t > 10µs/V

Figures:

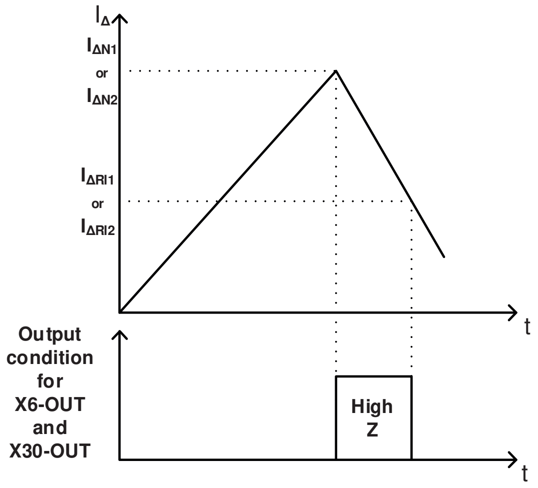

Fig. 1: Meaning of switching recovery level

If the trip-level $I_{\Delta N1}/I_{\Delta N2}$ is accomplished the corresponding output X6-OUT/X30-OUT will change its state from low-level (GND) to high impedance. Depending on the existence of the differential current I_{Δ}, the outputs X6-OUT/X30-OUT will remain in their states until I_{Δ} is below the recovery threshold $I_{\Delta RI1}/I_{\Delta RI2}$.

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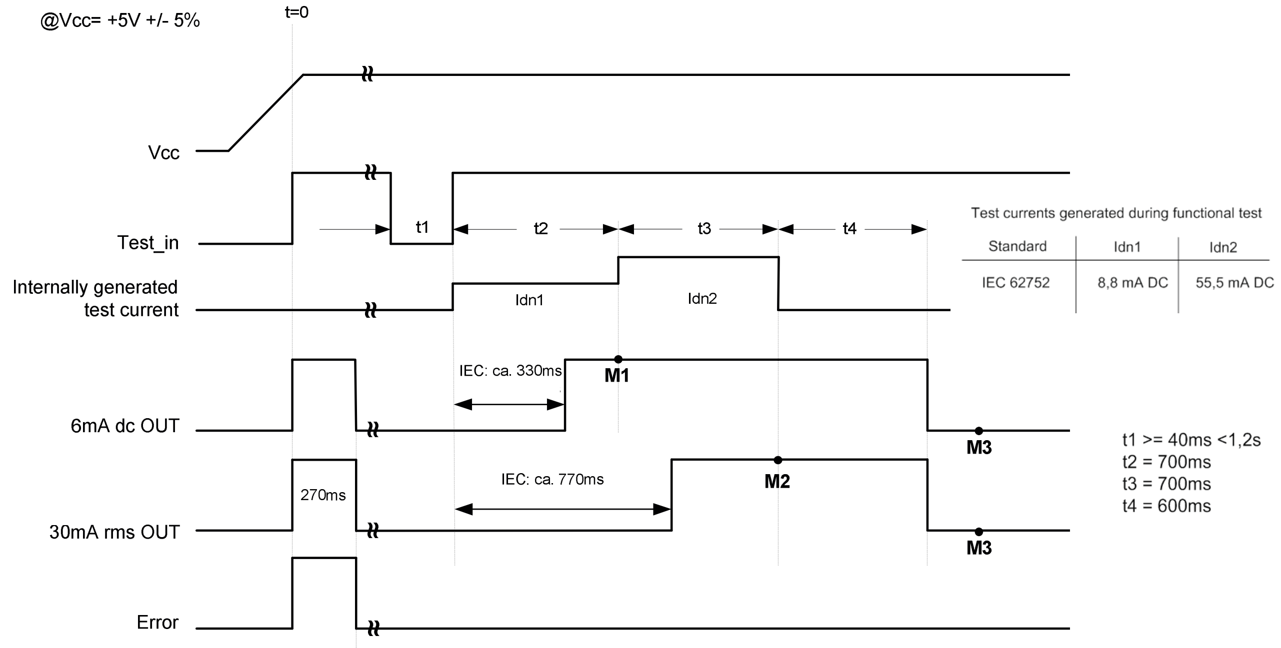

Test currents generated during functional test

Standard	Idn1	Idn2
IEC 62752	8,8 mA DC	55,5 mA DC

t1 >= 40ms <1,2s
t2 = 700ms
t3 = 700ms
t4 = 600ms

After activating the test sequence, the end product has to monitor the correct state of the switching outputs being used at the following points in time

M1:	check that 6mA dc OUT is disabled (latest time)
M2:	check that 30mA rms OUT is disabled
M3:	check that 30mA rms OUT resp. 6mA dc out is enabled

Fig. 2: Power-Up timing diagram

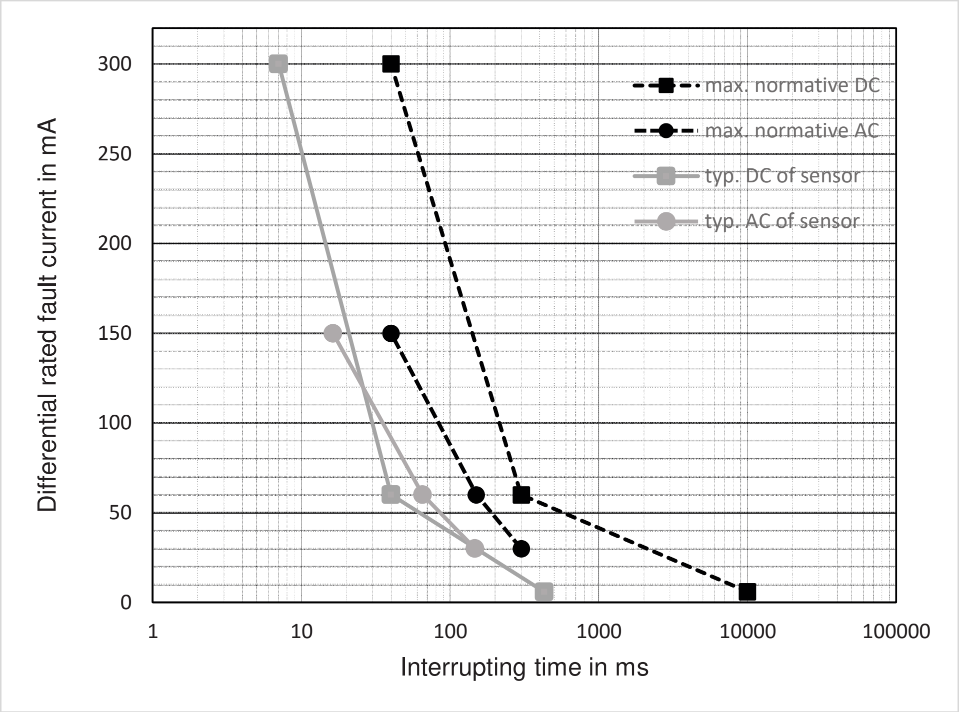

Fig. 3: Interrupting Time according to IEC62752 (E)-1:2016 Table 2 + 3 and typical values of sensor

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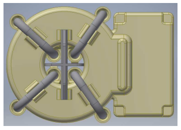

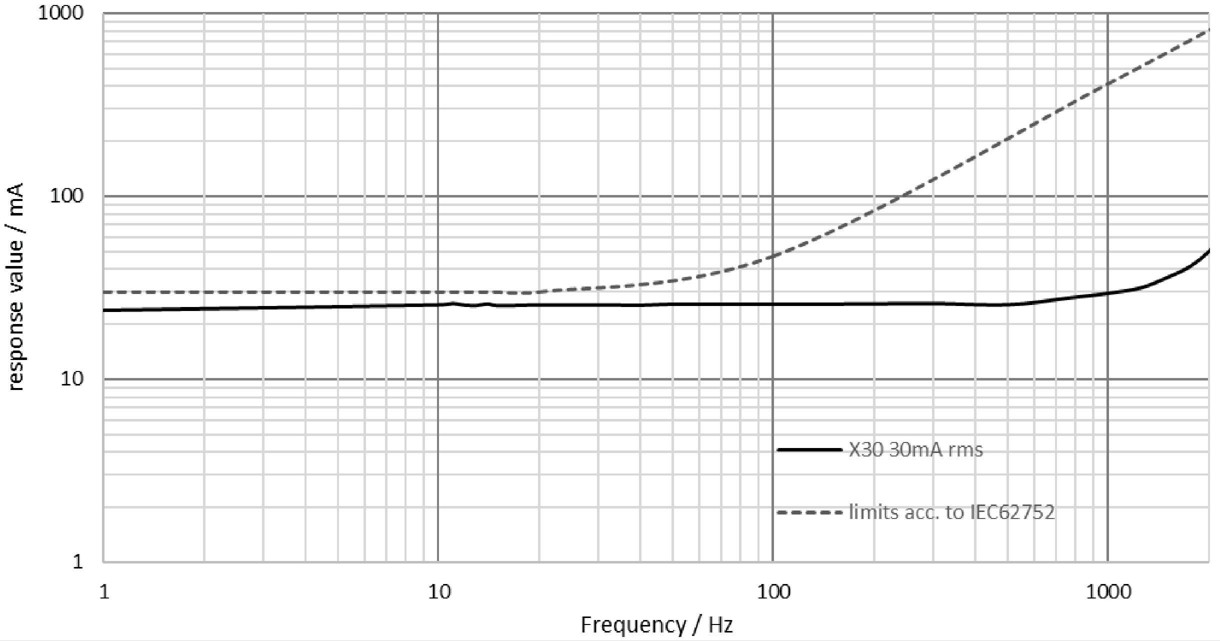

Fig. 4: Response value over frequency

X6-OUT	X30-OUT	ERROR-OUT	State
GND	GND	GND	Normal condition
High impedance	GND	GND	$I_{\Delta N1} \geq 6mA_{DC}$
High impedance	High impedance	GND	$I_{\Delta N2} \geq 30mA_{rms}$
High impedance	High impedance	High impedance	Error, system fault
All other conditions not mentioned in the table are not possible. If these conditions occur, the sensor is in unknown state and describes an Error.			

Table 1: Possible output states

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C.2 STM32 NUCLEO-G474RE – User Manual

UM2505

User manual

STM32G4 Nucleo-64 boards (MB1367)

Introduction

The STM32G4 Nucleo-64 boards based on the MB1367 reference board (NUCLEO-G431RB, NUCLEO-G474RE, NUCLEO-G491RE) provide an affordable and flexible way for users to try out new concepts and build prototypes with the STM32G4 Series microcontrollers, choosing from the various combinations of performance, power consumption and features. The ARDUINO® Uno V3 connectivity and the ST morpho headers provide an easy means of expanding the functionality of the Nucleo open development platform with a wide choice of specialized shields. The STM32G4 Nucleo-64 boards do not require any separate probe as they integrate the STLINK-V3E debugger/programmer. The STM32G4 Nucleo-64 boards come with the comprehensive free software libraries and examples available with the STM32CubeG4 MCU Package.

Figure 1. **NUCLEO-G474RE top view**

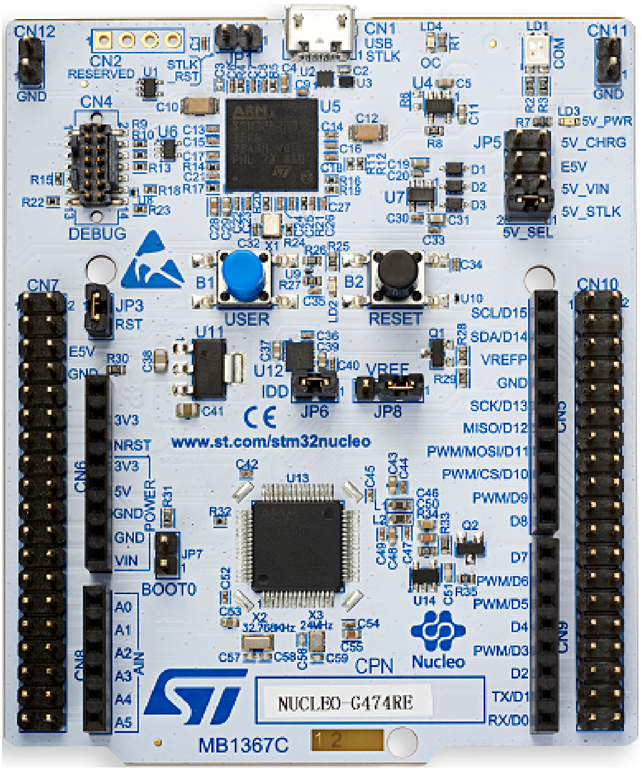
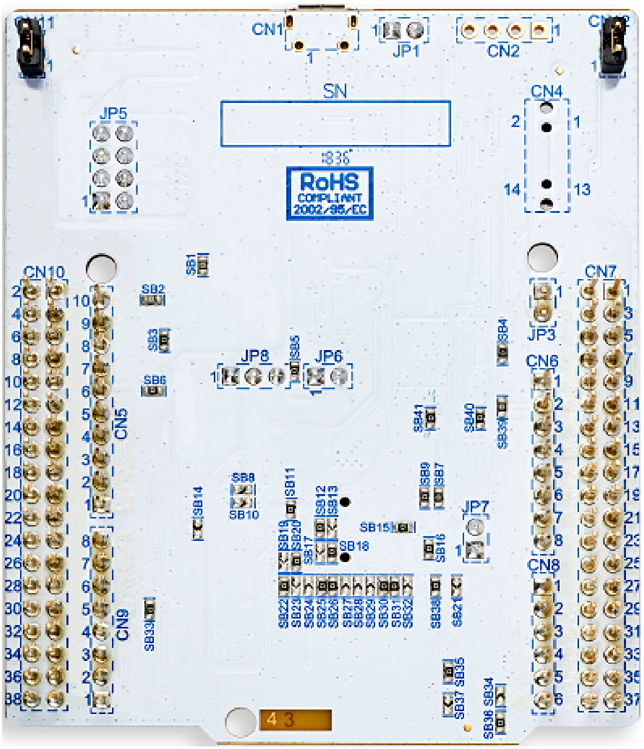


Figure 2. **NUCLEO-G474RE bottom view**



Pictures are not contractual.

1 Features

- STM32G4 microcontroller (Arm® Cortex®-M4 at 170 MHz) in LQFP64 package featuring:
  - 128 KBytes of Flash memory and 32 Kbytes of SRAM for STM32G431RBT6
  - 512 KBytes of Flash memory and 96 Kbytes of SRAM for STM32G491RET6
  - 512 KBytes of Flash memory and 128 Kbytes of SRAM for STM32G474RET6
- Fully compatible with STM32G473RET6 (512 Kbytes of Flash memory and 128 Kbytes of SRAM)
- 1 user LED
- 1 user and 1 reset push-buttons
- 32.768 kHz LSE crystal oscillator
- 24 MHz HSE on-board oscillator
- Board connectors:
  - USB with Micro-AB
  - MIPI® debug connector
  - ARDUINO® Uno V3 expansion connector
  - ST morpho extension pin headers for full access to all STM32G4 I/Os
- Flexible power-supply options: ST-LINK, USB V_{BUS}, or external sources
- On-board STLINK-V3E debugger/programmer with USB re-enumeration capability: mass storage, Virtual COM port, and debug port
- Comprehensive free software libraries and examples available with the STM32CubeG4 MCU Package
- Support of a wide choice of Integrated Development Environments (IDEs) including IAR Embedded Workbench®, MDK-ARM, and STM32CubeIDE

Note: *Arm is a registered trademark of Arm Limited (or its subsidiaries) in the US and/or elsewhere.*

2 Ordering information

To order an STM32G4 Nucleo-64 board, refer to Table 1. Additional information is available from the datasheet and reference manual of the target STM32.

Table 1. List of available products

Order code	Board reference	Target STM32
NUCLEO-G431RB	MB1367	STM32G431RBT6
NUCLEO-G474RE		STM32G474RET6
NUCLEO-G491RE		STM32G491RET6

2.1 Codification

The meaning of the codification is explained in Table 2.

Table 2. Codification explanation

NUCLEO-G4XXRY	Description	Example: NUCLEO-G474RE
G4	MCU series in STM32 Arm Cortex MCUs	STM32G4 Series
XX	MCU line in the series	STM32G474 line
R	STM32 package pin count	64 pins
Y	STM32 Flash memory size: • B for 128 Kbytes • E for 512 Kbytes	512 Kbytes

3 Development environment

3.1 System requirements

- Windows® OS (7, 8, or 10), Linux® 64-bit, or macOS®
- USB Type-A or USB Type-C® to Micro-B cable

Note: *macOS® is a trademark of Apple Inc. registered in the U.S. and other countries.*

Linux® is a registered trademark of Linus Torvalds.
All other trademarks are the property of their respective owners.

3.2 Development toolchains

- IAR Systems® - IAR Embedded Workbench®(1)
- Keil® - MDK-ARM(1)
- STMicroelectronics - STM32CubeIDE

1. *On Windows® only.*

3.3 Demonstration software

The demonstration software, included in the STM32Cube MCU Package corresponding to the on-board microcontroller, is preloaded in the STM32 Flash memory for easy demonstration of the device peripherals in standalone mode. The latest versions of the demonstration source code and associated documentation can be downloaded from *www.st.com*.

4 Conventions

Table 3 provides the conventions used for the ON and OFF settings in the present document.

Table 3. **ON/OFF convention**

Convention	Definition
Jumper JPx ON	Jumper fitted
Jumper JPx OFF	Jumper not fitted
Jumper JPx [1-2]	Jumper fitted between Pin 1 and Pin 2
Solder bridge SBx ON	SBx connections closed by 0 Ω resistor
Solder bridge SBx OFF	SBx connections left open
Resistor Rx ON	Resistor soldered
Resistor Rx OFF	Resistor not soldered

5 Quick start

The STM32G4 Nucleo-64 board is a low-cost and easy-to-use development kit, used to evaluate and start a development quickly with an STM32G4 Series microcontroller in LQFP64 package. Before installing and using the product, accept the Evaluation Product License Agreement from the www.st.com/epla webpage. For more information on the STM32G4 Nucleo-64 and for demonstration software, visit the www.st.com/stm32nucleo webpage.

5.1 Getting started

Follow the sequence below to configure the STM32G4 Nucleo-64 board and launch the demonstration application (refer to Figure 4 for component location):

1. Check the jumper position on the board (refer to Table 4)
2. For the correct identification of the device interfaces from the host PC and before connecting the board, install the Nucleo USB driver available on the www.st.com/stm32nucleo website
3. To power the board, connect the STM32G4 Nucleo-64 board to a PC with a USB cable (USB Type-A or USB Type-C® to Micro-B) through the USB connector CN1 of the board
4. Then, green LED LD3 (5V_PWR) and red LED LD1 (COM) light up, green LED LD2 (USER) blinks
5. Press user button B1 (left blue USER button)
6. Observe how the blinking of the green LED LD2 changes according to the clicks on button B1
7. The software demonstration and the several software examples that allow users to exercise Nucleo features, are available on the www.st.com/stm32nucleo webpage
8. Develop your own application using the available examples

Table 4. **Jumper configuration**

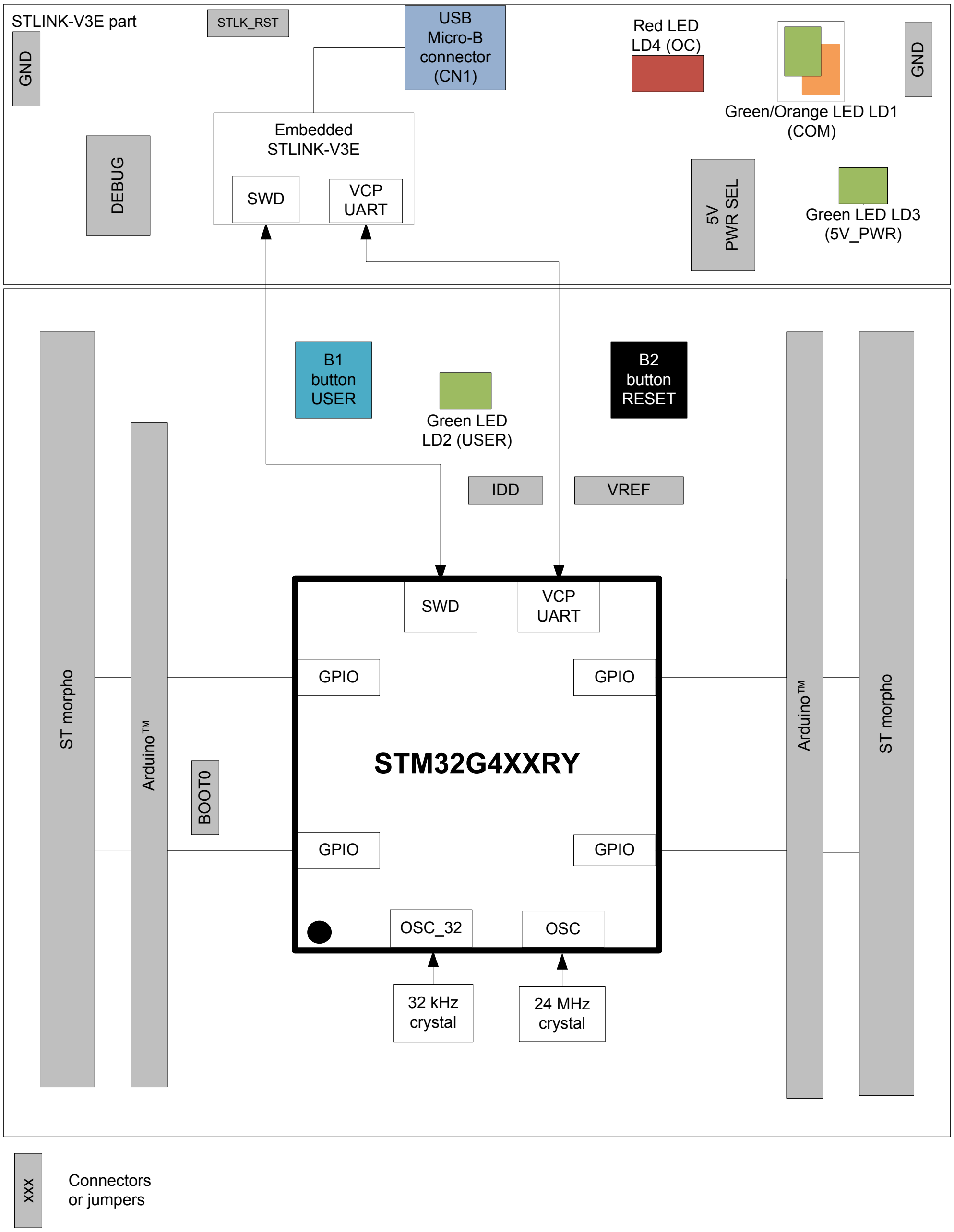
Jumper	Definition	Position[1]	Comment[1]
JP1	NRST	OFF	STLINK-V3E reset
JP3	T_RST	ON	-
JP5	5 V power-source selection	**ON [1-2] (Default)**	**5V_USB_STLK (from ST-LINK)**
		ON [3-4] (optional)	5V_VIN
		ON [5-6] (optional)	E5V
		ON [7-8] (optional)	5V_USB_CHGR
JP6	IDD	ON	-
JP7	BOOT0	OFF	-
JP8	VREF+ selection (VREF or VDD voltage supply selection)	**ON [1-2] (Default)**	**VREF+ supplied with VREF**
		ON [2-3] (optional)	VREF+ supplied with VDD

1. *Default jumper state is shown in bold.*

6 Hardware layout and configuration

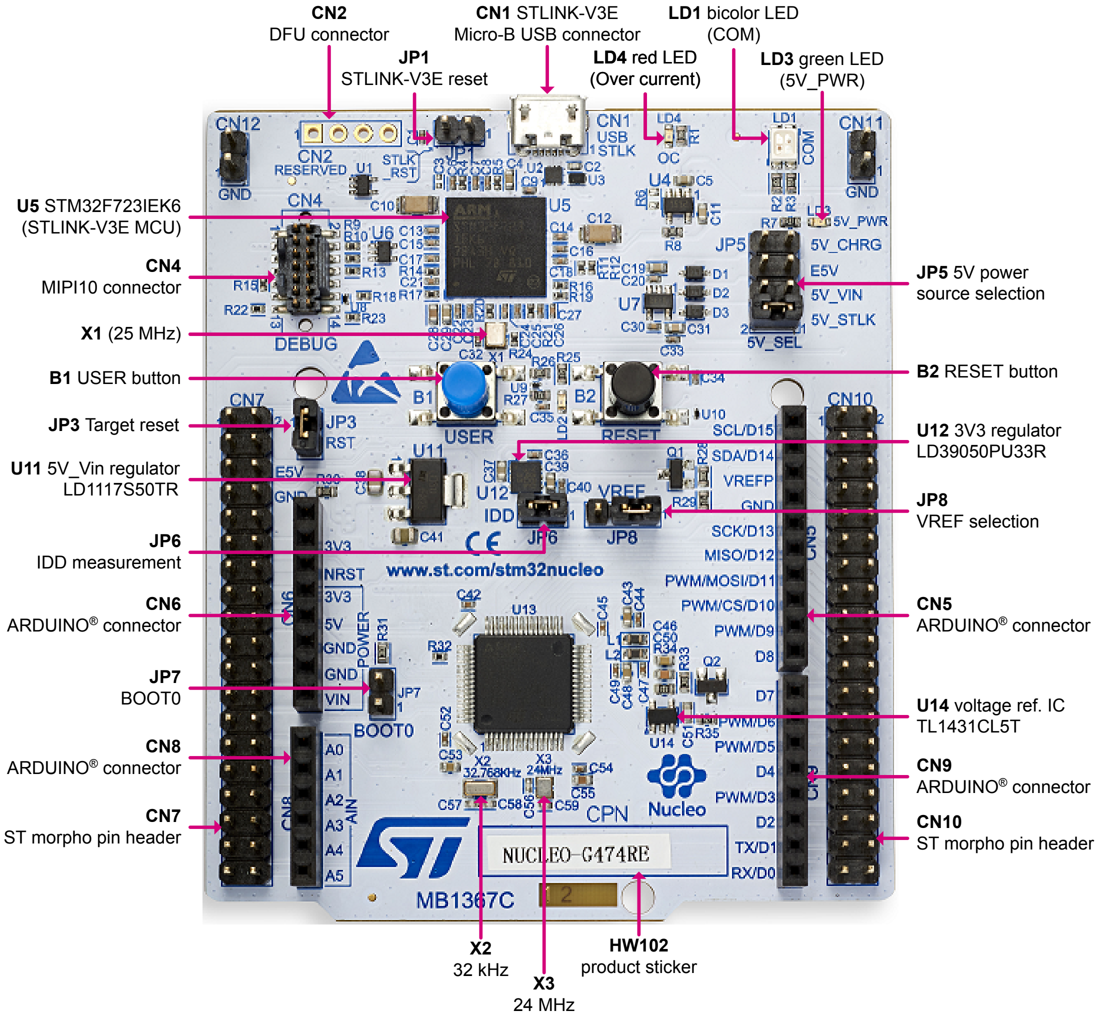
The STM32G4 Nucleo-64 board is designed around the STM32 microcontrollers in a 64-pin LQFP package. Figure 3 shows the connections between the STM32 and its peripherals (STLINK-V3E, push-buttons, LEDs, USB, ARDUINO® Uno and ST morpho headers). Figure 4 and Figure 5 show the location of these features on the STM32G4 Nucleo-64 board. The mechanical dimensions of the board are shown in Figure 6.

Figure 3. Hardware block diagram



6.1 PCB layout

Figure 4. Top layout



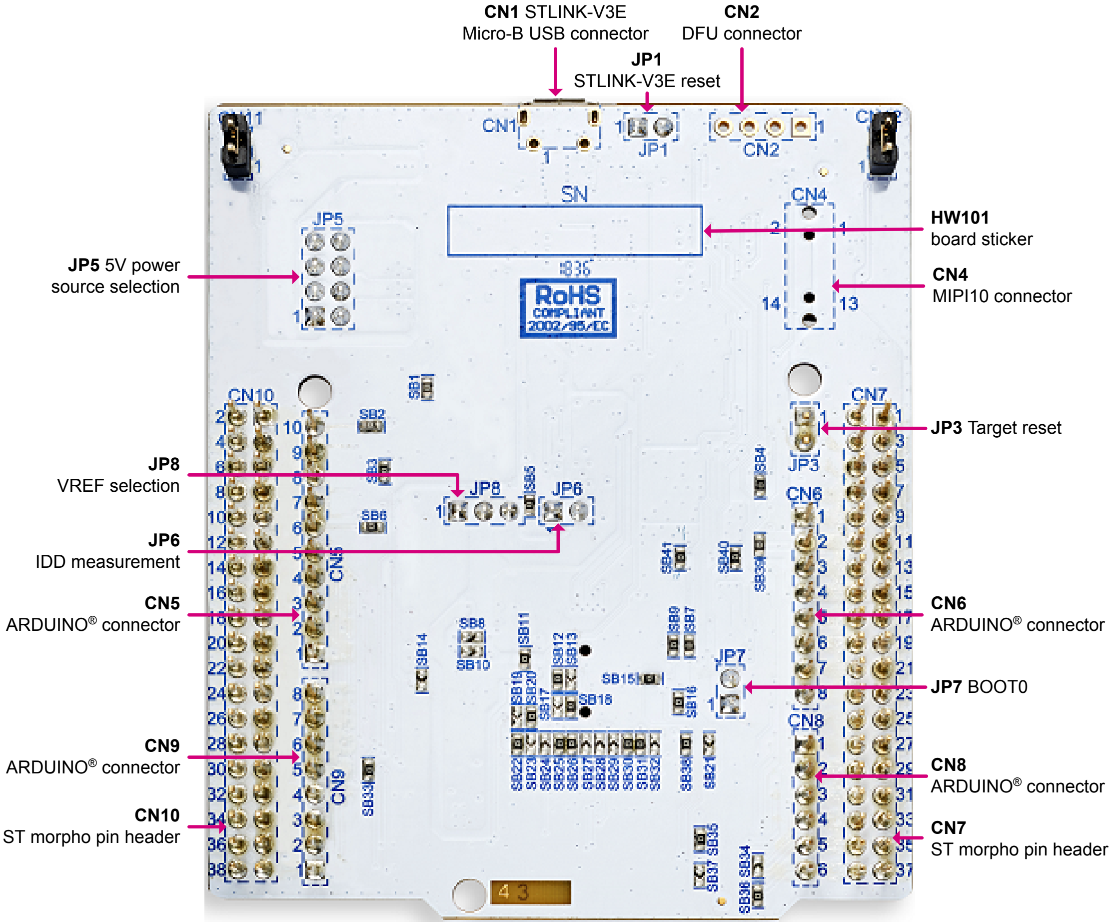
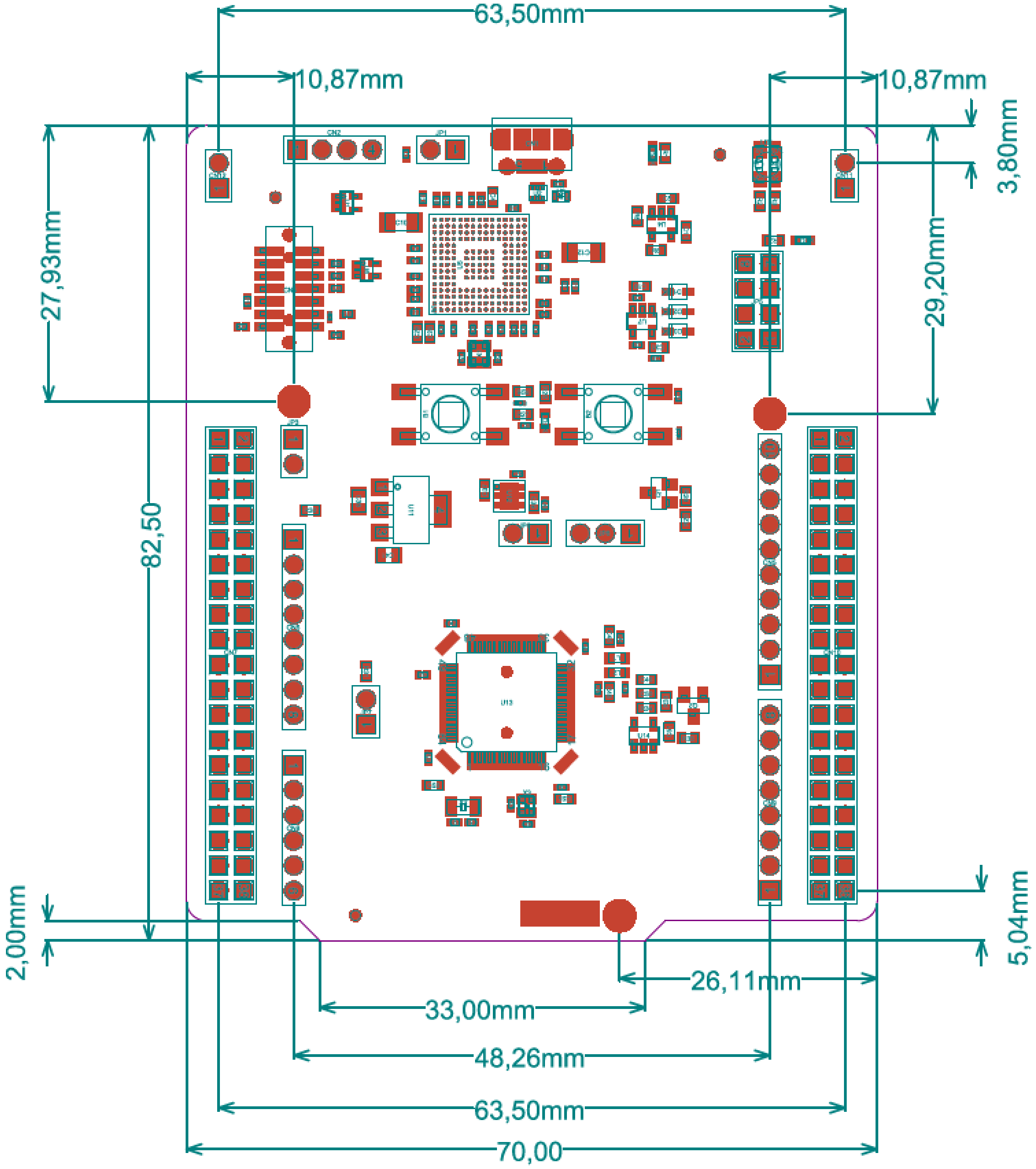


Figure 5. Bottom layout

6.2 Mechanical drawing

Figure 6. STM32G4 Nucleo 64 board mechanical drawing (in millimeter)



6.3 Embedded STLINK-V3E

There are two different ways to program and debug the onboard STM32 MCU:

- Using the embedded STLINK-V3E
- Using an external debug tool connected to the CN4 MIPI10 connector.

The STLINK-V3E programming and debugging tool is integrated in the STM32G4 Nucleo-64 board.

The embedded STLINK-V3E supports only SWD and VCP for STM32 devices. For information about debugging and programming features of STLINK-V3, refer to the *STLINK-V3SET debugger/programmer for STM8 and STM32* user manual (UM2448), which describes in details all the STLINK-V3 features.

Features supported on STLINK-V3E:

- 5V power supplied by USB connector (CN1)
- USB 2.0 high-speed-compatible interface
- JTAG/serial wire debugging (SWD) specific features:
  - 3 V to 3.6 V application voltage on the JTAG/SWD interface and 5 V tolerant inputs
  - JTAG
  - SWD and serial viewer (SWV) communication
- MIPI10 connector (CN4)
- Status LED LD1 (COM) that blinks during communication with the PC
- Fault red LED LD4 (OC) alerting on USB overcurrent request
- 5 V / 300 mA output power supply capability (U4) with current limitation and LED
- 5 V power green LED LD3 (5V_PWR)

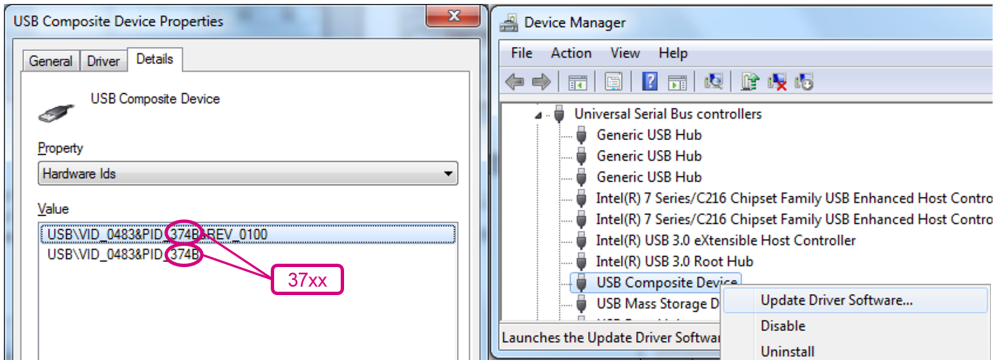
6.3.1 Drivers

Before connecting the STM32G4 Nucleo-64 board to a Windows 7®, Windows 8® or Windows 10® PC via USB, a driver for the STLINK-V3E must be installed (not required for Windows 10®) . It is available at the *www.st.com* website.

In case the STM32G4 Nucleo-64 board is connected to the PC before the driver is installed, some STM32G4 Nucleo-64 interfaces may be declared as “Unknown” in the PC device manager. In this case, the user must install the dedicated driver files, and update the driver of the connected device from the device manager a shown in Figure 7.

Note: *Prefer using the USB Composite Device handle for a full recovery.*

Figure 7. **USB composite device**



Property: Hardware Ids

Value:
USB\VID_0483&PID_374B&REV_0100
USB\VID_0483&PID_374B

Note: *37xx:*

- *374E for STLINK-V3E without bridge functions*
- *374F for STLINK-V3E with bridge functions*

6.3.2 STLINK-V3E firmware upgrade

The STLINK-V3E embeds a firmware upgrade mechanism for in-situ upgrade through the USB port. As the firmware may evolve during the lifetime of the STLINK-V3E product (for example new functionalities, bug fixes, support for new microcontroller families), it is recommended to visit the www.st.com website before starting to use the STM32G4 Nucleo-64 board and periodically, to stay up-to-date with the latest firmware version.

6.3.3 Using an external debug tool to program and debug the on-board STM32

There are two basic ways to support an external debug tool:

1. Keep the embedded STLINK-V3E running. Power on the STLINK-V3E at first until the COM LED turns red. Then connect the external debug tool through the CN4 STDC14/MIPI-10 debug connector
2. Set the embedded STLINK-V3E in hig-impedance state: when jumper JP1 (STLK_RST) is ON, the embedded STLINK-V3E is in RESET state and all GPIOs are in high-impedance; then, connect the external debug tool to debug connector CN4.

Figure 8. Connecting an external debug tool to program the on-board STM32G4

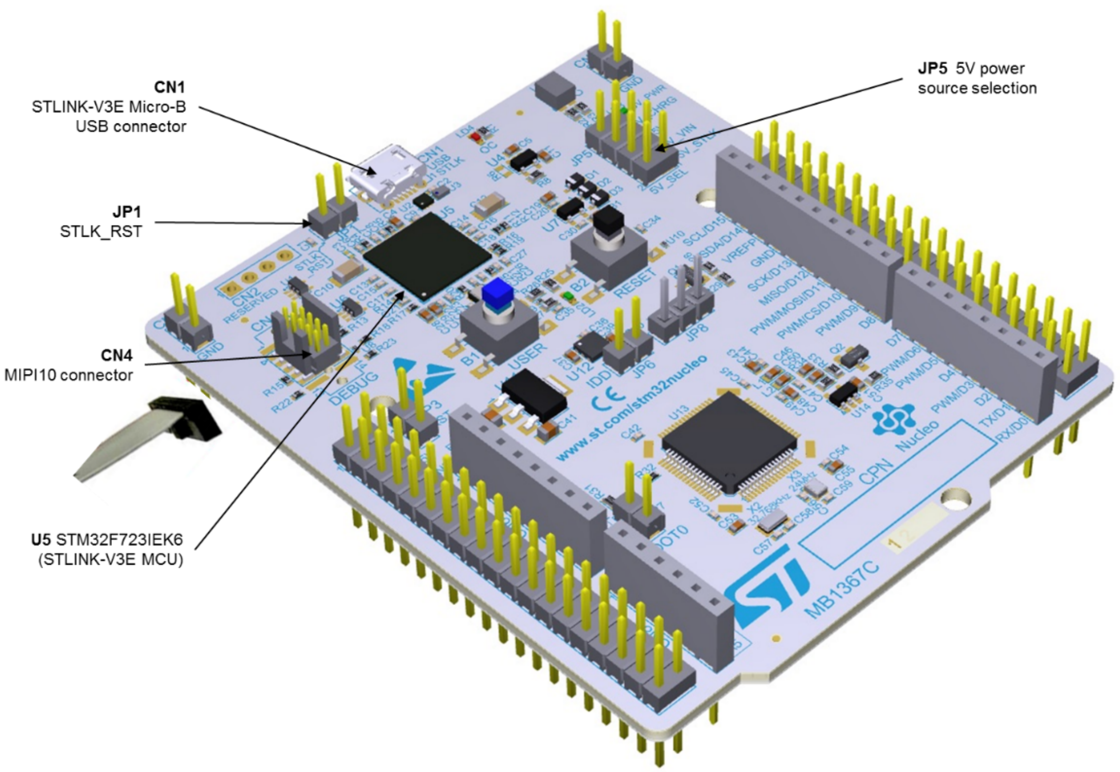


Table 5. MIPI10 / STDC14 debug connector (CN4)

MIPI10 pin	STDC14 pin	CN4	Function
-	1	NC	Reserved
-	2	NC	Reserved
1	3	3V3	Target VCC
2	4	T_SWDIO	Target SWDIO using SWD protocol or Target JTMS (T_JTMS) using JTAG protocol
3	5	GND	Ground
4	6	T_SWCLK	Target SWCLK using SWD protocol or Target JCLK (T_JCLK) using JTAG protocol
5	7	GND	Ground
6	8	T_SWO	Target SWO using SWD protocol or Target JTDO (T_JTMS) using JTAG protocol
7	9	NC	Not connected

MIPI10 pin	STDC14 pin	CN4	Function
8	10	T_JTDI	Not used by SWD protocol, Target JTDI (T_JTDI) using JTAG protocol, only for external tools
9	11	GNDDetect	GND detect for plug indicator, used on SWD and JTAG neither
10	12	T_NRST	Target NRST using SWD protocol or Target JTMS (T_JTMS) using JTAG protocol
-	13	T_VCP_RX	Target RX used for VCP (must be UART dedicated to bootloader)
-	14	T_VCP_TX	Target TX used for VCP (must be UART dedicated to bootloader)

6.4 Power supply

The power supply can be provided by five different sources:

- A host PC connected to CN1 through a USB cable (default setting)
- An external 7 V - 12 V (VIN) power supply connected to CN7 pin 24
- An external 5 V (E5V) power supply connected to CN7 pin 6
- An external 5 V USB charger (5V_USB_CHGR) connected to CN1
- An external 3.3 V power supply (3V3) connected to CN7 pin 16

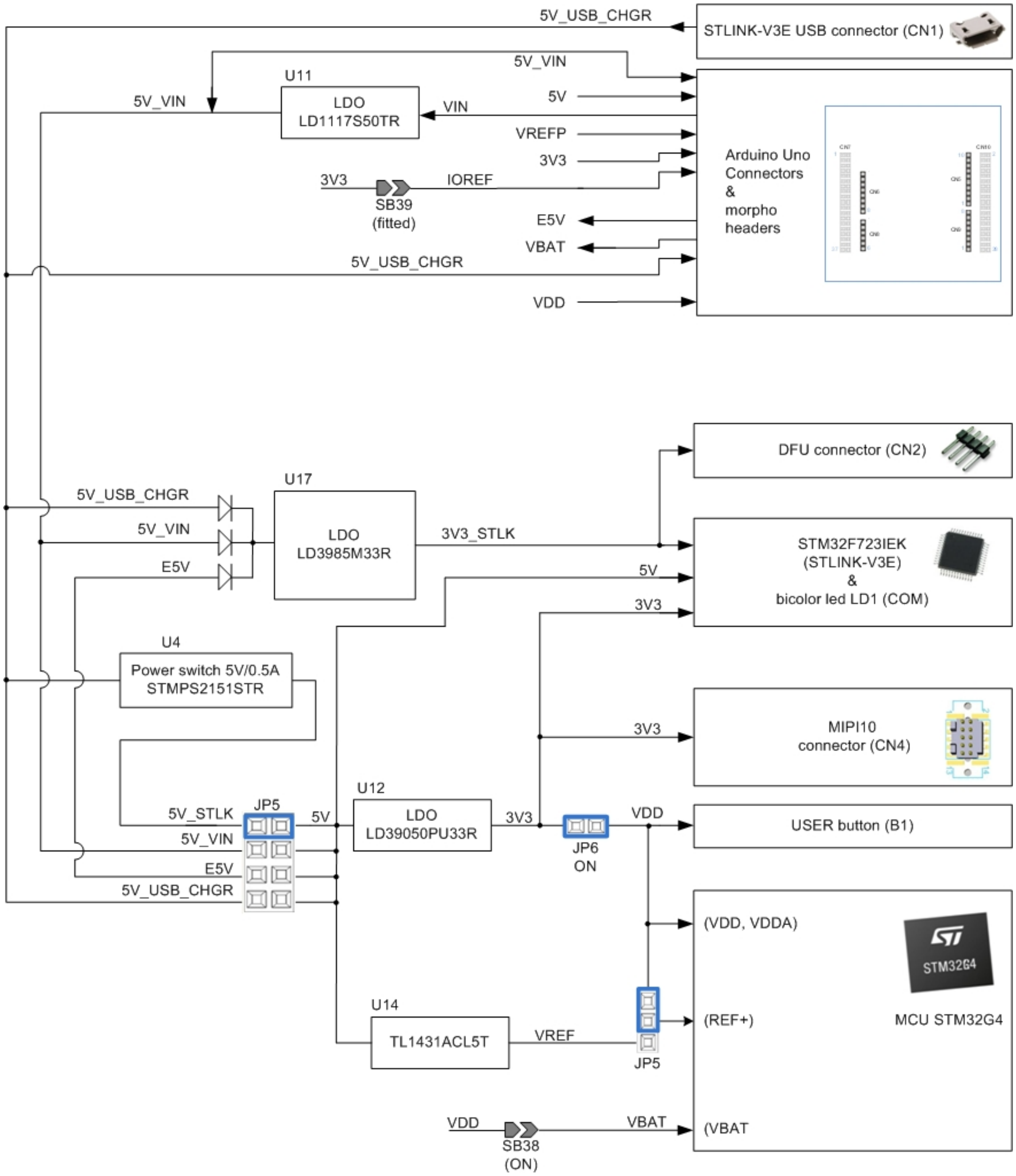


Figure 9. **STM32G4 Nucleo-64 board power tree**

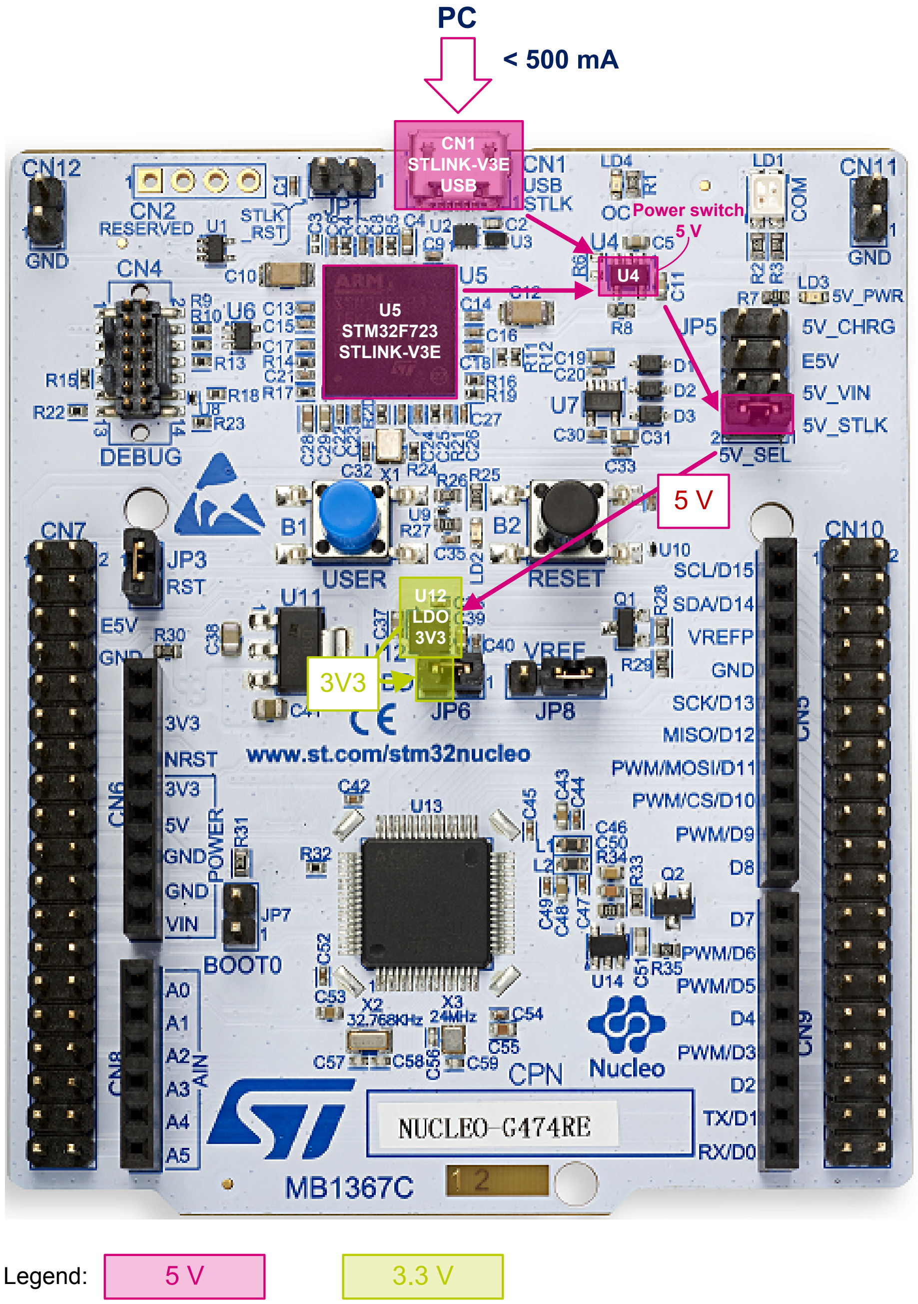
In case 5V_VIN, E5V, 5V_USB_CHGR, or 3V3 is used to power the STM32G4 Nucleo-64 board, this power source must comply with the EN-60950-1: 2006+A11/2009 standard and must be Safety Extra Low Voltage (SELV) with limited power capability.

If the power supply is 3V3, the ST-LINK is not powered and cannot be used.

Power supply input from STLINK-V3E USB connector (default setting)

The STM32G4 Nucleo-64 board and shield can be powered from STLINK-V3E connector CN1 (5 V) by placing a jumper between pins 1-2 of JP5, “5V_SEL”, as illustrated in Figure 10. This is the default setting.

Figure 10. **Power supply input from STLINK-V3E USB connector with PC (5 V, 500 mA max)**



If the USB enumeration succeeds, the 5V_USB_STLK power is enabled, by asserting the T_PWR_EN signal from STM32F723IEK6 “STLINK V3” (U5). This pin is connected to a power switch STMPS2151STR (U4), which powers the board. The power switch STMPS2151STR (U4) features also a current limitation to protect the PC in case of short-circuit on board. If an overcurrent (more than 500 mA) happens on board, the red LED LD4 is lit.

The Nucleo board and its shield can be powered from ST-LINK USB connector CN1, but only ST-LINK circuit gets power before USB enumeration, because the host PC only provides 100 mA to the board at that time.

During the USB enumeration, the Nucleo board requires 500 mA power from the host PC:

- If the host is able to provide the required power, the enumeration finishes by a “SetConfiguration” command and then, the power switch STMPS2151STR is switched ON, the green LED LD3 (5V_PWR) is turned ON, thus Nucleo board and its shield on it can consume 500 mA at the maximum.
- If the host is not able to provide the requested current, the enumeration fails. Therefore, the STMPS2151STR power switch (U4) remains OFF and the MCU part including the extension board is not powered. As a consequence, the green LED LD5 remains turned OFF. In this case, it is mandatory to use an external power supply.

Caution: If the maximum current consumption of the STM32G4 Nucleo-64 board and its shield boards exceeds 300 mA, it is mandatory to power the STM32G4 Nucleo-64 board with an external power supply connected to E5V, VIN or 3.3 V.

External power supply input from VIN (7 V - 12 V, 800 mA max)

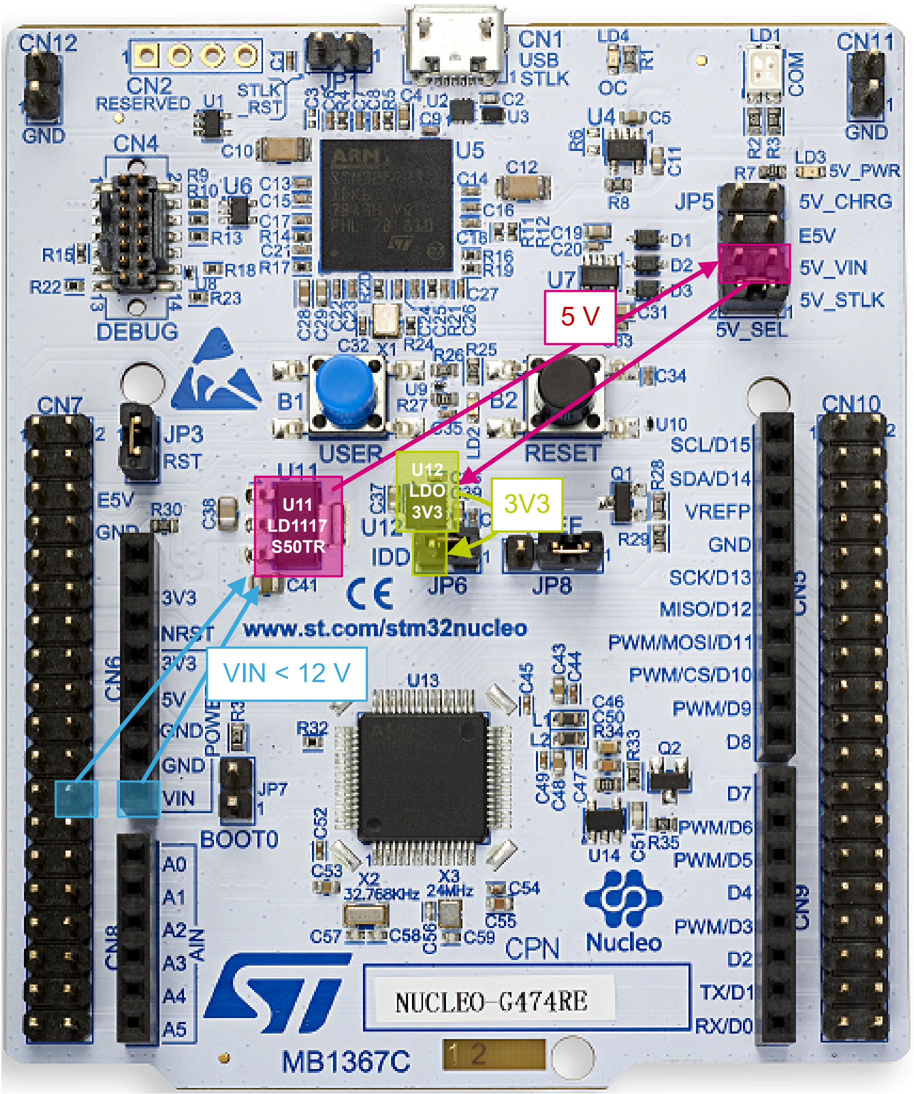
When the STM32G4 Nucleo-64 board is power-supplied by VIN (refer to Table 6 and Figure 11), the jumper configuration must be the following: jumper JP2 on pins 3-4 “5V_VIN”.

The STM32G4 Nucleo-64 board and its shield boards can be powered in three different ways from an external power supply, depending on the voltage used. The three cases are summarized in Table 6.

Table 6. **External power sources: VIN (7 V - 12 V)**

Input power name	Connector pins	Voltage range	Maximum current	Limitation
VIN	CN6 pin 8 CN7 pin 24	7 V to 12 V	800 mA	From 7 V to 12 V only and input current capability is linked to input voltage: • 800 mA input current when VIN = 7 V • 450 mA input current when 7 V < VIN < 9 V • 250 mA input current when 9 V < VIN < 12 V

Figure 11. Power supply input from VIN (7 V - 12 V, 800 mA max)



Legend: VIN < 12 V 5 V 3.3 V

Refer to Section 6.4.1 for debugging when using an external power supply.

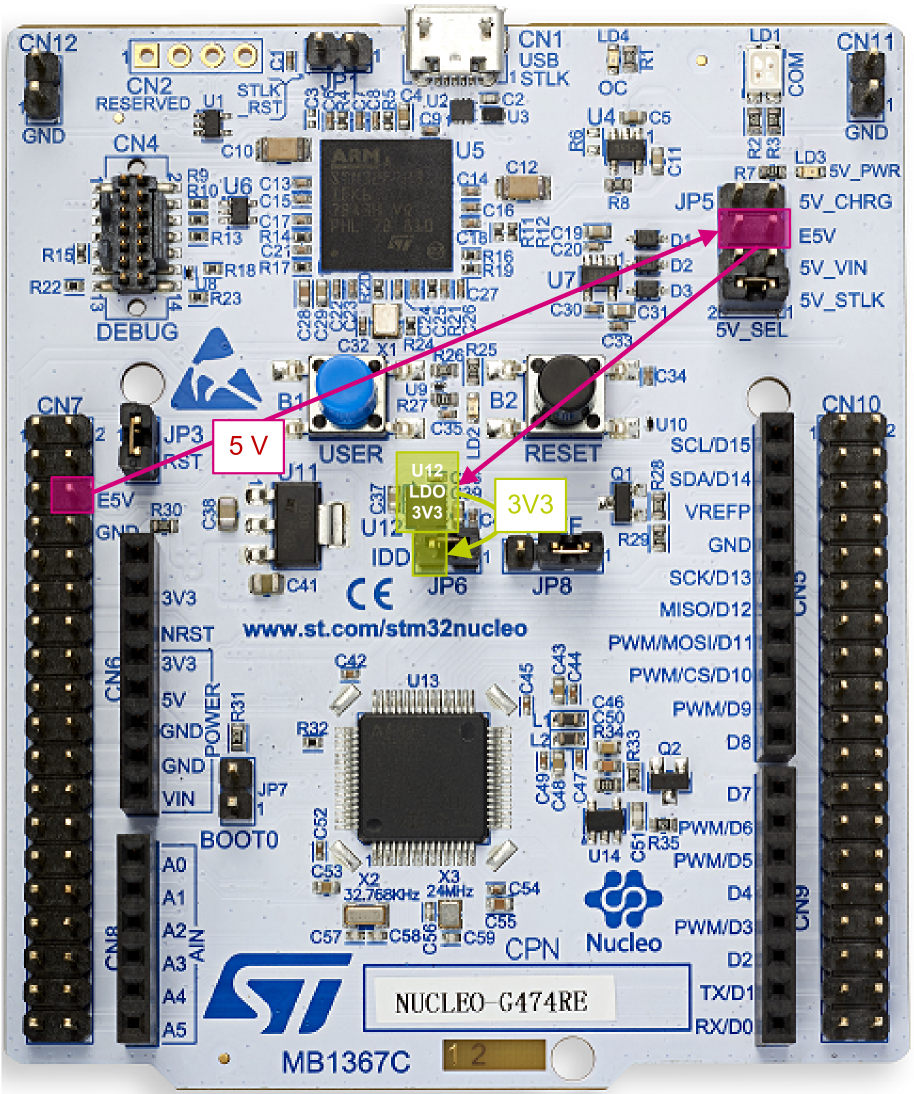
External power supply input from E5V (5 V, 500 mA max)

When the STM32G4 Nucleo-64 board is power-supplied by E5V (refer to Table 7 and Figure 12), the jumper configuration must be the following: jumper JP5 on pins 5-6 “E5V”.

Table 7. **External power sources: E5V (5 V)**

Input power name	Connector pins	Voltage range	Maximum current
E5V	CN7 pin 6	4.75 V to 5.25 V	500 mA

Figure 12. **Power supply input from 5V_EXT (5 V, 500 mA max)**



Legend: 🟥 5 V 🟩 3.3 V

Refer to Section 6.4.1 for debugging when using an external power supply.

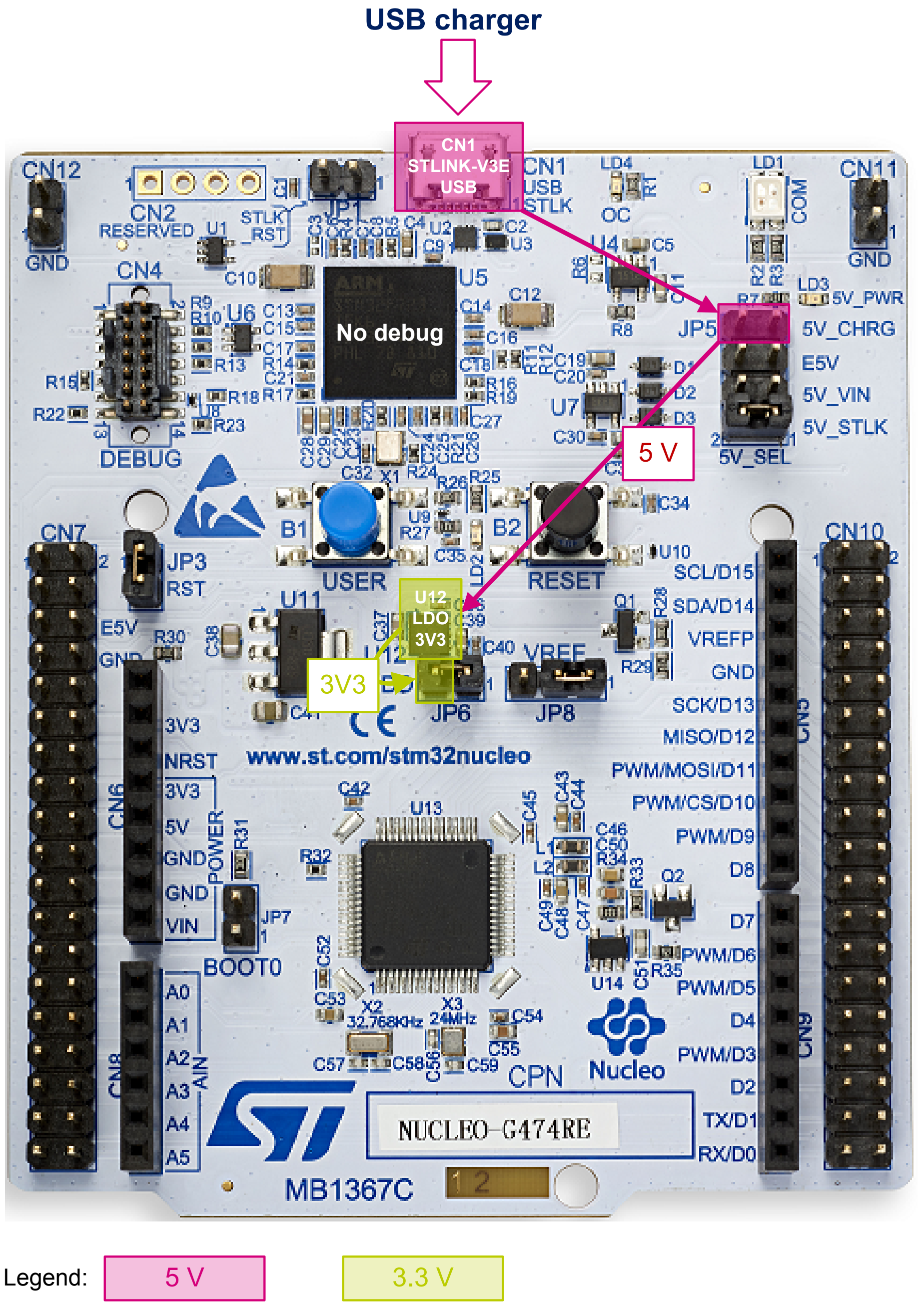
External power supply input from USB charger (5 V)

When the STM32G4 Nucleo-64 board is power-supplied by a USB charger on CN1 (refer to Table 8 and Figure 13), the jumper configuration must be the following: jumper JP2 on pins 7-8 “5V_CHGR”.

Table 8. **External power sources: 5V_CHGR (5 V)**

Input power name	Connector pins	Voltage range	Maximum current
5V_CHGR	CN1	5 V	-

Figure 13. **Power supply input from ST-LINK USB connector with USB charger (5 V)**



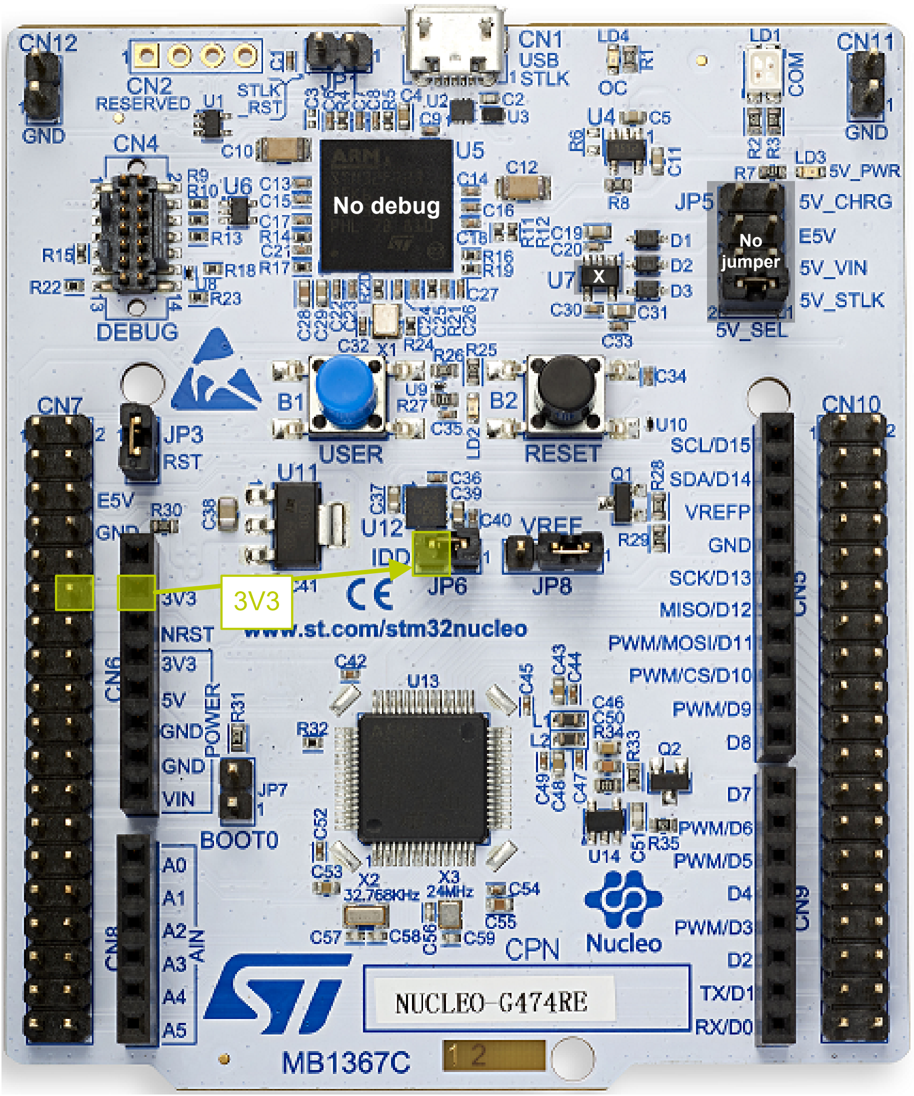
External power supply input from external 3.3 V

When the 3.3 V is provided by a shield board, it is interesting to use the 3.3 V (CN6 pin 4 or CN7 pin 16) directly as power input (refer to Table 9 and Figure 14). In this case, the programming and debugging features are not available, since the ST-LINK is not powered.

Table 9. External power sources: 3V3

Input power name	Connector pins	Voltage range	Maximum current
3V3	CN6 pin 4 CN7 pin 16	3 V to 3.6 V	1.3 A

Figure 14. Power supply input from external 3V3



Legend: 3.3 V

6.4.1 Debugging while using VIN or EXT as an external power supply

When powered by VIN or E5V, it is still possible to use the ST-LINK for programming or debugging only, but it is mandatory to power the board first using VIN or EXT, then to connect the USB cable to the PC. In this way the enumeration succeeds, thanks to the external power source.

The following power-sequence procedure must be respected:

1. Connect jumper JP5 between pins 5 & 6 for E5V or between pins 3 & 4 for VIN
2. Connect the external power source to VIN or E5V
3. Power on the external power supply 7V < VIN < 12 V for VIN, or 5V for E5V
4. Check that the green LED LD3 is turned ON
5. Connect the PC to the USB connector CN1

If this order is not respected, the board may be powered by USB first, then by VIN or E5V as the following risks may be encountered:

1. If more than 300 mA current is needed by the board, the PC may be damaged or the current supplied can be limited by the PC. As a consequence, the board is not powered correctly.
2. 300 mA is requested at enumeration so there is risk that the request is rejected and the enumeration does not succeed if the PC cannot provide such current. Consequently, the board is not power supplied (LED LD3 remains OFF).

6.5 Clock sources

6.5.1 HSE clock (high-speed external clock)

There are four ways to configure the pins corresponding to the high-speed external clock (HSE):

- **MCO from ST-LINK**: MCO output of ST-LINK is used as input clock. This frequency cannot be changed, it is fixed at 8 MHz and connected to the PF0-OSC_IN of the STM32 microcontroller. The configuration must be:
  - SB27 ON
  - SB25 and SB26 OFF
  - SB24 and SB28 OFF
- **HSE on-board oscillator from X3 crystal (default)**: For typical frequencies and its capacitors and resistors, refer to the STM32 microcontroller datasheet and to the Oscillator design guide for STM8S, STM8A and STM32 microcontrollers Application note (AN2867) for the oscillator design guide. The X3 crystal has the following characteristics: 24 MHz, 6 pF load capacitance, 20 ppm. It is recommended to use NX2016SA-24MHz-EXS00A-CS10820 manufactured by NDK. The configuration must be:
  - SB25 and SB26 ON
  - SB24 and SB28 OFF
  - SB27 OFF
  - C56 and C59 soldered with 6.8 pF capacitors
- **Oscillator from external PF0**: from an external oscillator through the pin 29 of the CN7 connector. The configuration must be:
  - SB28 ON
  - SB24 OFF
  - SB25 and SB26 OFF
  - SB27 OFF
- **HSE not used**: PF0 and PF1 are used as GPIOs instead of as clock. The configuration must be:
  - SB24 and SB28 ON
  - SB27 OFF
  - SB25 and SB26 OFF

6.5.2 LSE clock (low-speed external clock) – 32.768 kHz

There are three ways to configure the pins corresponding to the low-speed clock (LSE):

- **On-board oscillator (default)**: X2 crystal. Refer to the *Oscillator design guide for STM8S, STM8A and STM32 microcontrollers* application note (AN2867). It is recommended to use NX3215SA-32.768kHz-EXS00A-MU00525 (32.768 kHz, 6 pF load capacitance, 20 ppm) from NDK.
  - SB30 and SB31 ON
  - SB29 and SB32 OFF
- **Oscillator from external PC14**: from external oscillator through the pin 25 of CN7 connector. The configuration must be:
  - SB29 and SB32 ON
  - SB30 and SB31 OFF
- **LSE not used**: PC14 and PC15 are used as GPIOs instead of low-speed clock. The configuration must be:
  - SB29 and SB32 ON
  - SB30 and SB31 OFF

6.6 Board functions

6.6.1 LEDs

LD1 STLINK-V3E COM LED

The bicolor LED LD1 (green, red) provides information about STLINK-V3E communication status. LD1 default color is red. LD1 turns to green to indicate that communication is in progress between the PC and the STLINK-V3E, with the following setup:

- Blinking red: the first USB enumeration with the PC is taking place
- Red on: when the initialization between the PC and STLINK-V3E is complete
- Blinking red/green: during communication with target
- Green on: communication finished and successful
- Orange on: communication failure

LD2 USER

This green LED is a user LED connected to STM32G4 I/O PA5 (SB6 ON) corresponding to the ARDUINO® D13. To light LED LD2, a high logic state “1” must be written in the corresponding GPIO PA5. A transistor is used to drive the LED LD2. LD2 consumption does not impact the VDD STM32G4 power measurement, since LD2 is isolated from it.

LD3 PWR

The green LED indicates that the STM32G4 part is powered and +5 V power is available on CN6 pin 5 and CN7 pin 18.

LD4 USB power fault (OC, overcurrent)

LD4 indicates that the board power consumption on USB ST-LINK exceeds 500 mA. Consequently, the user must power the board using an external power supply.

6.6.2 Push-buttons

B1 USER (blue button)

The user button is connected to the STM32G4 I/O PC13 by default (Tamper support, SB16 ON and SB21 OFF) or PA0 (Wakeup support, SB21 ON and SB16 OFF) of the STM32G4 microcontroller.

B2 RESET (black button)

This push-button is connected to NRST (PG10-NRST) and is used to RESET the STM32G4 microcontroller.

6.6.3 MCU voltage selection on VREF+

The STM32G4 Nucleo-64 board offers the possibility to supply the STM32G4 microcontroller with either VREF or VDD on its VREF+ input voltage pin.

VREF+ is targeted to offer high-end analog device, especially for precise analog applications (ADC converters usage) with the STM32G4 microcontroller.

In the STM32G4 Nucleo-64 board, the VREF+ can be supplied with a very stable output voltage provided by the TL1431CL5T. The TL1431CL5T is an adjustable shunt voltage reference with guaranteed temperature stability over the entire operating temperature range. The output voltage may be set to any value between 2.5 V and up to 36 V with two external resistors. The TL1431CL5T operates with a wide current range from 1 mA to 100 mA with a typical dynamic impedance of 0.2 Ω.

JP8 jumper is used to select either the VREF or VDD voltage for VREF+.

- Place the JP8 jumper on [1-2] to supply the MCU VREF+ with VREF
  - To have VREF at 2.5 V, then SB14 is fitted and R34 is not fitted
  - To have VREF at 3.25 V, then SB14 is not fitted. VREF = 2,5 × (1 + (R33 / R34)) = 2,5 × (1 + (10k / 33k)).
- Place the JP8 jumper on [2-3] to supply the MCU VREF+ with VDD

6.6.4 Current consumption measurement (IDD)

Jumper JP6, labeled IDD, is used to measure the STM32G4 microcontroller consumption by removing the jumper and by connecting an ammeter:

- JP6 ON: STM32 is powered with 3V3 voltage (default)
- JP6 OFF: an ammeter must be connected to measure the STM32G4 current. If there is no ammeter, the STM32 is not powered.

To get a correct and complete current consumption of the STM32G4, jumper JP8 must be set to [2-3] to supply the MCU VREF+ with VDD, otherwise, the current consumption at pin VREF+ is not taken into account in the IDD (through jumper JP6).

6.6.5 Virtual COM port (VCP): LPUART and USART

The STM32G4 Nucleo-64 board offers the possibility to connect an LPUART or a USART interface to the STLINK-V3E, ARDUINO® Uno V3 connector (CN9 pins 2 and 1), or ST morpho connector (CN10 pins 35 and 37).

The selection is done by setting the related solder bridges as detailed in Table 10 and Table 11.

Table 10. **USART1 connection**

Solder bridge configuration(1)	Feature(1)
SB13, SB19: ON **SB12, SB20, SB18, SB22: OFF**	**USART1 (PC4/PC5) connected to ARDUINO® (D1 & D0) and ST morpho connector (CN10 pin 35 & 37).**
SB12, SB20: ON SB13, SB19, SB17, SB23: OFF	USART1 (PC4/PC5) connected to STLINK-V3E Virtual COM port.

1. *The default configuration is shown in bold*

Table 11. **LPUART1 connection**

Solder bridge configuration(1)	Feature(1)
SB17, SB23: ON **SB18, SB22, SB12, SB20: OFF**	**LPUART1 (PA2/PA3) connected to STLINK-V3E Virtual COM port.**
SB18, SB22: ON SB17, SB23, SB13, SB19: OFF	LPUART1 (PA2/PA3) connected to ARDUINO® (D1 & D0) and ST morpho connector (CN10 pin 35 & 37).

1. *The default configuration is shown in bold*

By default:

- Communication between the target STM32G4 and the STLINK-V3E MCU is enabled on LPUART1 to support the Virtual COM port
- Communication between the target STM32G4 and ARDUINO® (and ST morpho) connectors is enabled on USART1

6.7 Solder bridges

All 41 solder bridges are located on the bottom layer of the STM32G4 Nucleo-64 board.

Table 12. **Solder bridge configuration**

Solder bridge control	Solder bridge (SB)	State(1)	Description(1)
100 nF on PG10-NRST	SB1	**ON**	**100 nF capacitor grounded to PG10-NRST of the STM32G4**
		OFF	100 nF capacitor disconnected from PG10-NRST of the STM32G4
PB8 on ARD_D14	SB2	**ON**	**PB8 connected to ARDUINO® D14**
		OFF	PB8 not connected to ARDUINO® D14
PC5 on ST morpho	SB3	**ON**	**PC5 connected to ST morpho CN10 pin 6**
		OFF	PC5 not connected to ST morpho CN10 pin 6
PB8 on Morpho	SB4	**ON**	**PB8 connected to ST morpho CN7 pin 7**
		OFF	PB8 not connected to ST morpho CN7 pin 7
3.3 V LDO output	SB5	**ON**	**U12 LDO output provides 3.3 V**
		OFF	U12 LDO output does NOT provide 3.3 V, user must connect an external 3.3 V source.
User LED LD2	SB6	**ON**	**User LED driven by PA5 (ARD_D13)**
		OFF	User LED not driven
PA15 on Morpho	SB7	**ON**	**PA15 connected to ST morpho CN7 pin 17**
		OFF	PA15 not connected to ST morpho CN7 pin 17
SMD ferrite bead L1	SB8	ON	SMD ferrite bead L1 shunted. VDDA connected on VDD voltage supply
		OFF	**SMD ferrite bead L1 on STM32G4 VDDA voltage supply**
JTDI on MIPI10	SB9	**ON**	**JTDI connected to MIPI10 connector (CN4 pin 10)**
		OFF	JTDI not connected to MIPI10 connector (CN4 pin 10)
SMD ferrite bead L2	SB10	ON	SMD ferrite bead L2 shunted. VREF+ connected to either VREF or VDD depending on the jumper position on JP8
		OFF	**SMD ferrite bead L2 on VREF+ (either VREF or VDD voltage supply (depending on the jumper position on JP8)).**
AGND	SB11	**ON**	**AGND connected to GND. Reserved, do not modify.**
		OFF	AGND not connected to GND.
PC4 USART1 TX	SB12	ON	STLINK_TX (T_VCP_TX) connected to USART1 TX PC4
		OFF	**STLINK_TX (T_VCP_TX) not connected to USART1 TX PC4**
	SB13	**ON**	**ARD_D1_TX connected to USART1 TX PC4**
		OFF	ARD_D1_TX not connected to USART1 TX PC4

Solder bridge control	Solder bridge (SB)	State(1)	Description(1)
VREF voltage (3.25 V or 2.5 V)	SB14	ON	R33 = 10 kΩ is shunted. Then VREF = 2.5 V. Do not forget to remove in that case R34 = 33 kΩ.
		OFF	**R33 = 10 kΩ is not shunted. Then VREF = 3.25 V. In that case, R34 = 33 kΩ must be fitted.**
T_SWO on PB3	SB15	**ON**	**T_SWO connected to PB3.**
		OFF	T_SWO not connected to PB3 and isolated from ARD_D3.
PA2 LPUART1 TX	SB17	**ON**	**STLINK_TX (T_VCP_TX) connected to LPUART1 TX PA2.**
		OFF	STLINK_TX (T_VCP_TX) not connected to LPUART1 TX PA2.
	SB18	ON	ARD_D1_TX connected to LPUART1 TX PA2.
		OFF	**ARD_D1_TX not connected to LPUART1 TX PA2.**
PA3 LPUART1 RX	SB23	**ON**	**STLINK_RX (T_VCP_RX) connected to LPUART1 RX PA3.**
		OFF	STLINK_RX (T_VCP_RX) not connected to LPUART1 RX PA3.
	SB22	ON	ARD_D0_RX connected to LPUART1 RX PA3.
		OFF	**ARD_D0_RX not connected to LPUART1 RX PA3.**
PC5 USART1 RX	SB20	ON	STLINK_RX (T_VCP_RX) connected to USART1 RX PC5.
		OFF	**STLINK_RX (T_VCP_RX) not connected to USART1 RX PC5.**
	SB19	**ON**	**ARD_D0_RX connected to USART1 RX PC5.**
		OFF	ARD_D0_RX not connected to USART1 RX PC5.
USER button	SB16	**ON**	**USER button connected to PC13.**
		OFF	USER button not connected to PC13.
	SB21	ON	USER button connected to PA0.
		OFF	**USER button not connected to PA0.**
HSE CLK selection	SB25 & SB26	**ON**	**HSE provided by external HSE 24 MHz CLK X3.**
		OFF	HSE not provided by external HSE 24 MHz CLK X3.
	SB24	ON	PF1-OSC_IN connected to ST morpho connector I/O usage (CN7 pin 31).
		OFF	**PF1-OSC_IN not connected to ST morpho connector.**
	SB28	ON	PF0-OSC_OUT connected to ST morpho connector I/O usage (CN7 pin 29).
		OFF	**PF0-OSC_OUT not connected to ST morpho connector.**
	SB27	ON	ST-LINK MCO used for HSE CLK.
		OFF	**ST-LINK MCO not used for HSE CLK.**
PC4 on ST morpho	SB33	**ON**	**PC4 connected to Morpho CN10 pin 34.**
		OFF	PC4 not connected to Morpho CN10 pin 34.
VBAT	SB38	**ON**	**VBAT (pin1 of STM32G4) powered by VDD.**
		OFF	VBAT (pin1 of STM32G4) supplied separately (through morpho connector CN7 pin 33).
LSE CLK selection	SB31 & SB30	**ON**	**LSE provided by external LSE 32.768 kHz CLK X2.**
		OFF	LSE not provided by external LSE 32.768 kHz CLK X2.

Solder bridge control	Solder bridge (SB)	State[(1)]	Description[(1)]
LSE CLK selection	SB32	ON	PC14-OSC32_IN connected to ST morpho connector I/O usage (CN7 pin 25).
		OFF	**PC14-OSC32_IN not connected to ST morpho connector.**
	SB29	ON	PC15-OSC32_OUT connected to ST morpho connector I/O usage (CN7 pin 27).
		OFF	**PC15-OSC32_OUT not connected to ST morpho connector.**
PB9 on ARD_A4	SB34	ON	PB9 connected to ARD_A4 and connected to CN7 pin 36.
		OFF	**PB9 not connected to ARD_A4 and connected to CN7 pin 36.**
PC1 on ARD_A4	SB35	**ON**	**PC1 connected to ARD_A4 and connected to CN7 pin 36.**
		OFF	PC1 not connected to ARD_A4 and connected to CN7 pin 36.
PC0 on ARD_A5	SB36	**ON**	**PC0 connected to ARD_A5 and connected to CN7 pin 38.**
		OFF	PC0 not connected to ARD_A5 and connected to CN7 pin 38.
PA15 on ARD_A5	SB37	ON	PA15 connected to ARD_A5 and connected to CN7 pin 38.
		OFF	**PA15 not connected to ARD_A5 and connected to CN7 pin 38.**
IOREF and 3V3 connection	SB39	**ON**	**IOREF connected to 3V3 power supply.**
		OFF	IOREF not connected to 3V3 power supply.
T_SWDIO on PA13	SB40	**ON**	**T_SWDIO connected to PA13.**
		OFF	T_SWO not connected to PA13.
T_SWCLK on PA14	SB41	**ON**	**T_SWCLK connected to PA14.**
		OFF	T_SWCLK not connected to PA14.

1. *The default SB state is in bold.*

All the other solder bridges present on the STM32G4 Nucleo-64 board are used to configure several I/Os and power-supply pins for compatibility of features and pinout with the target STM32G4 supported.

7 Board connectors

Several connectors are implemented on the STM32G4 Nucleo-64 board.

7.1 STLINK-V3E USB Micro-B connector CN1

The USB connector CN1 is used to connect the embedded STLINK-V3E to the PC for the programming and debugging purposes.

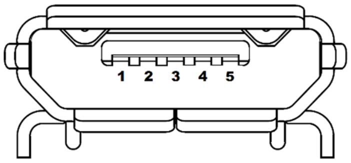


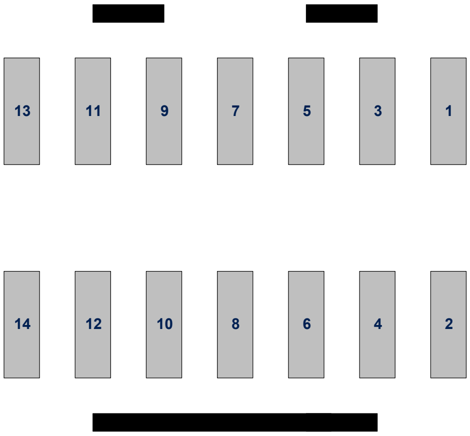
Figure 15. **USB Micro-B connector CN1 (front view)**

Table 13. **USB Micro-B connector CN1 pinout**

Connector	Pin number	Pin name	Signal name	STLINK-V3E MCU pin	Function
CN1	1	VBUS	5V_USB_CHGR	-	5 V power
	2	DM	USB_DEV_HS_CN_N	R14	USB diff pair N
	3	DP	USB_DEV_HS_CN_P	R15	USB diff pair P
	4	ID	-	-	-
	5	GND	-	-	GND

7.2 MIPI10 connector CN4

Figure 16. **MIPI10 connector CN4**



The MIPI10 connector is implemented with a footprint compatible with the STDC14 footprint. The related pinout for the MIPI10 connector is listed in Table 14.

Table 14. MIPI10 connector CN4 pinout (STDC14 pinout compatible)

Connector	Pin number	Description	Pin number	Description
CN4	1	-	2	-
	3	VDD (3V3)	4	T_SWDIO (PA13)
	5	GND	6	T_SWCLK (PA14)
	7	KEY (connected to GND)	8	T_SWO (PB3)
	9	-	10	T_JTDI (PA15)
	11	GNDDetect (connected to GND through a 100 Ω resistor)	12	T_NRST
	13	T_VCP_RX (PA3 by default or PC5)	14	T_VCP_TX (PA2 by default or PC4)

7.3 ARDUINO® Uno V3 connectors CN5, CN6, CN8 and CN9

The ARDUINO® connectors CN5, CN6, CN8 and CN9 are female connectors compatible with the ARDUINO® standard. Most shields designed for ARDUINO® can fit with the STM32G4 Nucleo-64 board.

The ARDUINO® connectors on the STM32G4 Nucleo-64 board support the ARDUINO® Uno V3.

Figure 17. ARDUINO® connectors

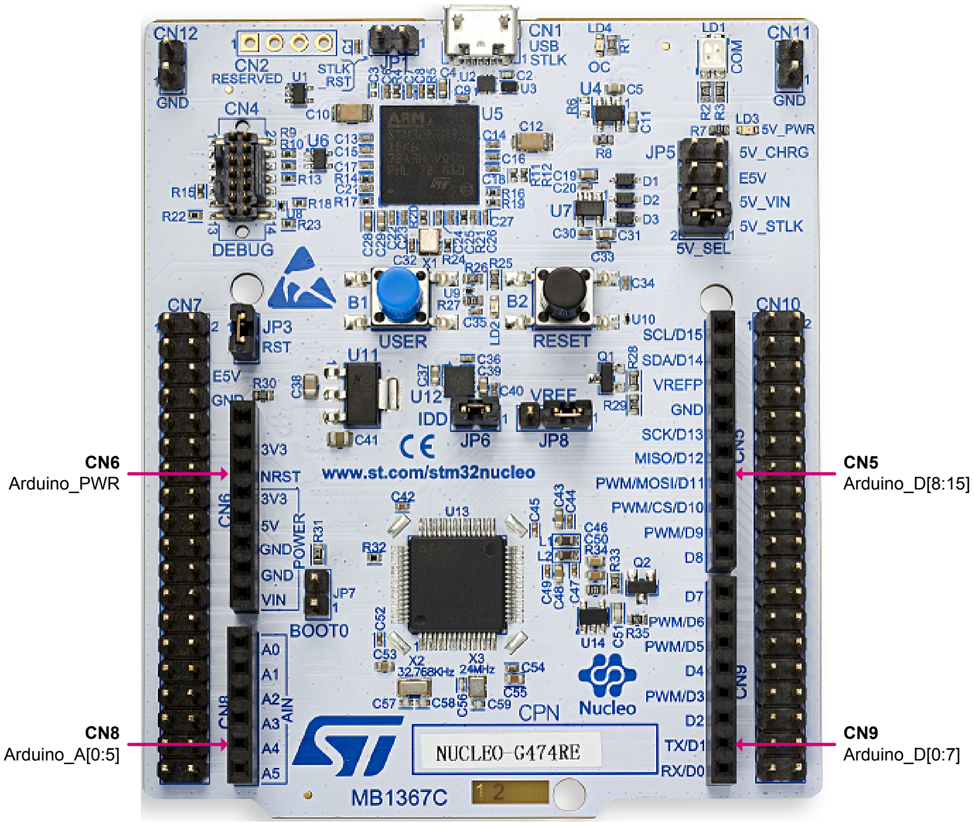
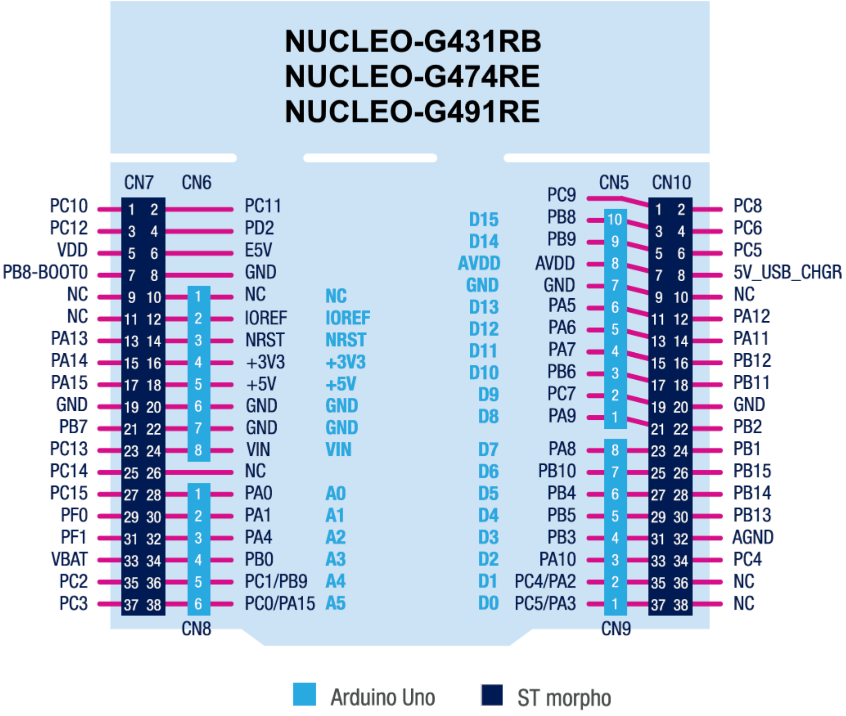


Figure 18. **ARDUINO® and ST morpho connectors pinout**



Note: *ARDUINO® Uno V3 D0 and D1 signals are connected by default on USART1 (MCU I/O PC4 and PC5). For details about how to modify the UART interface, refer to Section 6.6.5 Virtual COM port (VCP): LPUART and USART.*

Table 15. **ARDUINO® connectors pinout**

Connector	Pin number	Pin name	Signal name	STM32 pin[(1)]	Function[(1)]
CN6	1	NC	-	-	Reserved for test
	2	IOREF	-	-	I/O reference
	3	NRST	NRST	PG10-NRST	RESET
	4	3V3	-	-	3V3 input / output
	5	5V	-	-	5 V output
	6	GND	-	-	GND
	7	GND	-	-	GND
	8	VIN	-	-	7 V - 12 V input power
CN8	1	A0	ADC	PA0	ADC12_IN1
	2	A1	ADC	PA1	ADC12_IN2
	3	A2	ADC	PA4	ADC2_IN17
	4	A3	ADC	PB0	ADC3_IN12 or ADC1_IN15
	5	A4	ADC	**PC1** / PB9	**ADC12_IN7** / I2C1_SDA
	6	A5	ADC	**PC0** / PA15	**ADC12_IN6** / I2C1_SCL

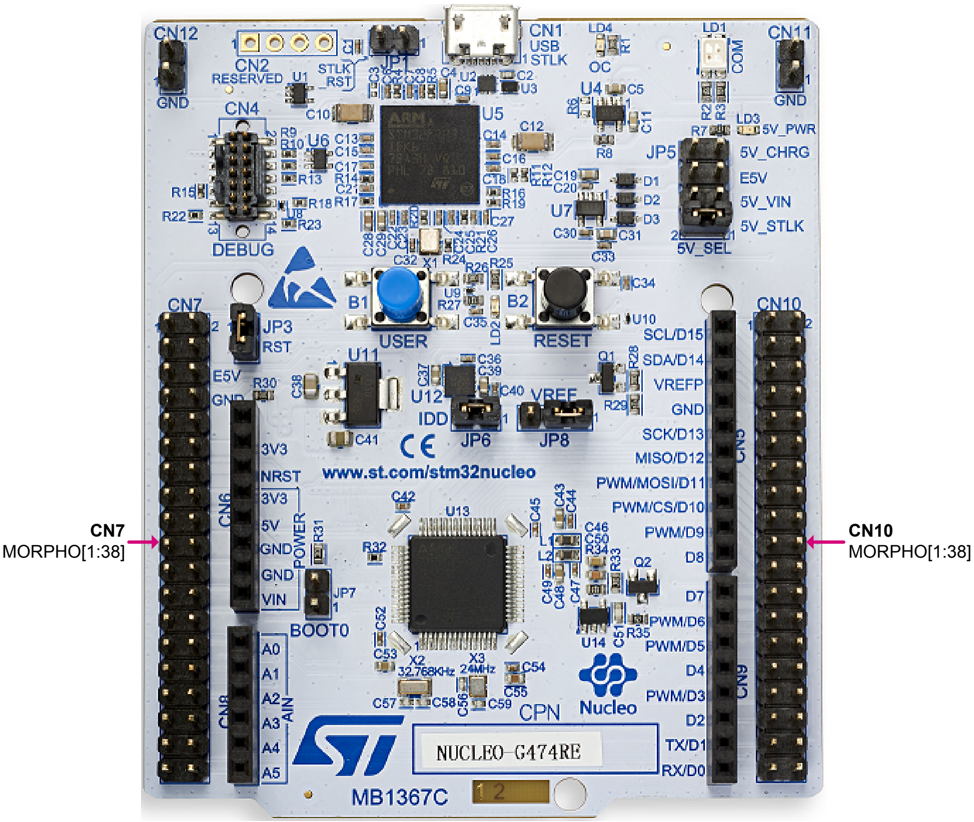
Connector	Pin number	Pin name	Signal name	STM32 pin[(1)]	Function[(1)]
CN5	10	SCL/D15	ARD_D15	PB8	I2C1_SCL
	9	SDA/D14	ARD_D14	PB9	I2C1_SDA
	8	VREFP	VREFP	VREF+	Voltage reference
	7	GND	-	-	GND
	6	SCK/D13	ARD_D13	PA5	SPI1_SCK
	5	MISO/D12	ARD_D12	PA6	SPI1_MISO
	4	PWM/MOSI/D11	ARD_D11	PA7	TIM3_CH2 / SPI1_MOSI
	3	PWM/CS/D10	ARD_D10	PB6	TIM4_CH1 / SPIx_CS
	2	PWM/D9	ARD_D9	PC7	TIM3_CH2 or TIM8_CH2
	1	D8	ARD_D8	PA9	IO
CN9	8	D7	ARD_D7	PA8	IO
	7	PWM/D6	ARD_D6	PB10	TIM2_CH3
	6	PWM/D5	ARD_D5	PB4	TIM3_CH1
	5	D4	ARD_D4	PB5	IO
	4	PWM/D3	ARD_D3	PB3	TIM2_CH2
	3	D2	ARD_D2	PA10	IO
	2	TX/D1	ARD_D1	PA2 / **PC4**	LPUSART1_TX / **USART1_TX**
	1	RX/D0	ARD_D0	PA3 / **PC5**	LPUSART1_RX / **USART1_RX**

1. *Default configuration is in bold.*

7.4 ST morpho connectors CN7 and CN10

ST morpho connectors CN7 and CN10 are male pin headers accessible on both sides of the board. All signals and power pins of the STM32G4 MCU are available on the ST morpho connectors. These connectors can also be probed by an oscilloscope, logical analyzer, or voltmeter.

Figure 19. ST morpho connectors



The pinout of ST morpho connectors CN7 and CN10 is shown in Figure 18. ARDUINO® and ST morpho connectors pinout.

Note: *The D0 and D1 signals are connected by default to USART1 (MCU I/O PC4 and PC5). For details about how to modify the UART interface, refer to Section 6.6.5 Virtual COM port (VCP): LPUART and USART.*

Table 16 shows the pin assignment of each STM32G4 I/O on the ST morpho connector.

Table 16. Pin assignment of the ST morpho connectors

CN7 odd pins		CN7 even pins		CN10 odd pins		CN10 even pins	
Pin nbr	Pin name	Pin nbr	Pin name[1]	Pin nbr	Pin name[1]	Pin nbr	Pin name
1	PC10	2	PC11	1	PC9	2	PC8
3	PC12	4	PD2	3	PB8	4	PC6
5	VDD	6	E5V	5	PB9	6	PC5
7	BOOT0[2]	8	GND	7	VREFP[3]	8	5V_USB_CHGR[4]
9	NC	10	NC	9	GND	10	NC
11	NC	12	IOREF	11	PA5	12	PA12
13	PA13[5]	14	NRST	13	PA6	14	PA11
15	PA14[5]	16	3V3	15	PA7	16	PB12
17	PA15	18	5V	17	PB6	18	PB11

CN7 odd pins		CN7 even pins		CN10 odd pins		CN10 even pins	
Pin nbr	Pin name	Pin nbr	Pin name(1)	Pin nbr	Pin name(1)	Pin nbr	Pin name
19	GND	20	GND	19	PC7	20	GND
21	PB7	22	GND	21	PA9	22	PB2
23	PC13	24	VIN	23	PA8	24	PB1
25	PC14	26	NC	25	PB10	26	PB15
27	PC15	28	PA0	27	PB4	28	PB14
29	PF0	30	PA1	29	PB5	30	PB13
31	PF1	32	PA4	31	PB3	32	AGND
33	VBAT	34	PB0	33	PA10	34	PC4
35	PC2	36	**PC1**/PB9	35	PA2 / **PC4**	36	NC
37	PC3	38	**PC0**/PA15	37	PA3 / **PC5**	38	NC

1. *Default configuration in bold.*
2. *BOOT0 is not connected by default. The BOOT0 function is done by SW:*
   - *Option byte nSWBOOT0 must be set to 0 (in that case, BOOT0 is taken from the Option byte nBOOT0)*
   - *Option byte nBOOT0 must be set to 1 (in that case BOOT0 is active low).*

   If nSWBOOT0 is set to 0, the BOOT0 is taken from pin PB8 / BOOT0.
3. *AVDD connected to VREF+*
4. *5V_USB_CHGR is the 5 V power from the STLINK-V3E USB connector that rises first. It rises before the 5 V rising on the board.*
5. *PA13 and PA14 are shared with SWD signals connected to STLINK-V3E. It is not recommended to use them as I/O pins.*

8 STM32G4 Nucleo-64 I/O assignment

Table 17. **Nucleo-64 I/O assignment**

Pin	Pin name	Signal or label	Main feature / optional feature / (SB)[(1)]
1	VBAT	VBAT	VBAT voltage supply
2	PC13	PC13	**USER button** / IO
3	PC14-OSC32_IN	OSC32_IN / PC14	**LSE CLK** / IO
4	PC15-OSC32_OUT	OSC32_OUT / PC15	**LSE CLK** / IO
5	PF0-OSC_IN	OSC_IN / PF0	**HSE CLK** / I
6	PF1-OSC_OUT	OSC_OUT / PF1	**HSE CLK** / O
7	PG10-NRST	T_NRST	STM32G4 RESET
8	PC0	PC0	ARD_A5 - ADC12_IN6
9	PC1	PC1	ARD_A4 - ADC12_IN7
10	PC2	PC2	IO
11	PC3	PC3	IO
12	PA0	PA0	**ARD_A0 - ADC12_IN1** / User Button
13	PA1	PA1	ARD_A1 - ADC12_IN2
14	PA2	LPUART1_TX	ARD_D1 / **STLINK_TX (T_VCP_TX)**
15	VSS	GND	PWR GND
16	VDD	VDD	PWR VDD supply
17	PA3	LPUART1_RX	ARD_D0 / **STLINK_RX (T_VCP_RX)**
18	PA4	PA4	ARD_A2 - ADC2_IN17
19	PA5	PA5	ARD_D13 - SPI1_CLK
20	PA6	PA6	ARD_D12 - SPI1_MISO
21	PA7	PA7	ARD_D11 - TIM3_CH2 / SPI1_MOSI
22	PC4	PC4	IO
23	PC5	PC5	IO
24	PB0	PB0	ARD_A3 - ADC3_IN12
25	PB1	PB1	IO
26	PB2	PB2	IO
27	VSSA	AGND	AGND
28	VREF+	VREFP	Reference voltage supply
29	VDDA	AVDD	Analog voltage supply
30	PB10	PB10	ARD_D6 / TIM2_CH3
31	VSS	GND	GND
32	VDD	VDD	VDD voltage supply
33	PB11	PB11	IO
34	PB12	PB12	IO
35	PB13	PB13	IO
36	PB14	PB14	IO
37	PB15	PB15	IO

Pin	Pin name	Signal or label	Main feature / optional feature / (SB)[1]
38	PC6	PC6	IO
39	PC7	PC7	ARD_D9-TIM3_CH2 (or TIM8_CH2) / IO
40	PC8	PC8	IO
41	PC9	PC9	IO
42	PA8	PA8	ARD_D7 - IO
43	PA9	PA9	ARD_D8 - IO
44	PA10	PA10	ARD_D2 - IO
45	PA11	PA11	IO
46	PA12	PA12	IO
47	VSS	GND	GND
48	VDD	VDD	VDD voltage supply
49	PA13	T_SWDIO	T_SWDIO
50	PA14	T_SWCLK	T_SWCLK
51	PA15	T_JTDI	**T_JTDI** / I2C1_SCL
52	PC10	PC10	IO
53	PC11	PC11	IO
54	PC12	PC12	IO
55	PD2	D2	IO
56	PB3	PB3	ARD_D3 - TIM2_CH2 / T_SWO
57	PB4	PB4	ARD_D5 - TIM3_CH1 / IO
58	PB5	PB5	ARD_D4 - IO
59	PB6	PB6	ARD_D10 - SPIx_CS / TIM4_CH1
60	PB7	PB7	IO
61	PB8-BOOT0	BOOT0	BOOT0
62	PB9	PB9	ARD_D14 - I2C1_SDA
63	VSS	GND	GND
64	VDD	VDD	VDD voltage supply

1. *The default configuration is shown in bold.*

9 STM32G4 Nucleo-64 product information

9.1 Product marking

The stickers located on the top or bottom side of the PCB provide product information:

- Product order code and product identification for the first sticker
- Board reference with revision, and serial number for the second sticker

On the first sticker, the first line provides the product order code, and the second line the product identification.

On the second sticker, the first line has the following format: “MBxxxx-Variant-yzz”, where “MBxxxx” is the board reference, “Variant” (optional) identifies the mounting variant when several exist, "y" is the PCB revision and "zz" is the assembly revision, for example B01. The second line shows the board serial number used for traceability.

Evaluation tools marked as “ES” or “E” are not yet qualified and therefore not ready to be used as reference design or in production. Any consequences deriving from such usage will not be at ST charge. In no event, ST will be liable for any customer usage of these engineering sample tools as reference designs or in production.

“E” or “ES” marking examples of location:

- On the targeted STM32 that is soldered on the board (For an illustration of STM32 marking, refer to the STM32 datasheet “Package information” paragraph at the *www.st.com* website).
- Next to the evaluation tool ordering part number that is stuck or silk-screen printed on the board.

Some boards feature a specific STM32 device version, which allows the operation of any bundled commercial stack/library available. This STM32 device shows a "U" marking option at the end of the standard part number and is not available for sales.

In order to use the same commercial stack in his application, a developer may need to purchase a part number specific to this stack/library. The price of those part numbers includes the stack/library royalties.

9.2 NUCLEO-G431RB product history

9.2.1 Product identification NUG431RB$AT1

This product identification is based on the mother board MB1367-G431RB-C04.

It embeds the STM32G431RBT6 microcontroller with silicon revision code "Z". The limitations of this silicon revision are detailed in errata sheet *STM32G431xx/441xx device errata* (ES0431).

Product limitations

No limitation identified for this product identification.

9.2.2 Product identification NUG431RB$AT2

This product identification is based on the mother board MB1367-G431RB-C04.

It embeds the STM32G431RBT6 microcontroller with silicon revision code "Y". The limitations of this silicon revision are detailed in errata sheet *STM32G431xx/441xx device errata* (ES0431).

Product limitations

No limitation identified for this product identification.

9.2.3 Product identification NUG431RB$AT3

This product identification is based on the mother board MB1367-G431RB-C04.

It embeds the STM32G431RBT6 microcontroller with silicon revision code "X". The limitations of this silicon revision are detailed in errata sheet *STM32G431xx/441xx device errata* (ES0431).

Product limitations

No limitation identified for this product identification.

9.3 NUCLEO-G474RE product history

9.3.1 Product identification NUG474RE$AT1

This product identification is based on the mother board MB1367-G474RE-C04.

It embeds the STM32G474RET6 microcontroller with silicon revision code "Z". The limitations of this silicon revision are detailed in errata sheet *STM32G471xx/473xx/474xx/483xx/484xx device errata* (ES0430).

9.3.1.1 NUG474RE$AT1 known limitations

Issue observed

The OPAMP offset value is minimized using a trimming circuitry. At startup, the trimming values are initialized with the preset factory trimming values. The trimming values of OPAMP1, OPAMP2 and OPAMP4 are not programmed correctly, resulting in a large offset compared to the one specified.

Proposed workaround

The offset values of OPAMP1, OPAMP2 and OPAMP4 must be calibrated by software, applying the calibration procedure described in the *STM32G4 Series advanced Arm®-based 32-bit MCUs* reference manual (RM0440), in the *Calibration* section of the *Operational amplifiers (OPAMP)* chapter. Such a procedure is already implemented in the STM32CubeG4 MCU Package.

Parts impacted

This applies only to the MB1367-based NUCLEO-G474RE boards within the following range of serial numbers: A191300001-A191304602.

9.3.2 Product identification NUG474RE$AT2

This product identification is based on the mother board MB1367-G474RE-C04.

It embeds the STM32G474RET6 microcontroller with silicon revision code "Y". The limitations of this silicon revision are detailed in errata sheet *STM32G471xx/473xx/474xx/483xx/484xx device errata* (ES0430).

Product limitations

No limitation identified for this product identification.

9.3.3 Product identification NUG474RE$AT3

This product identification is based on the mother board MB1367-G474RE-C04.

It embeds the STM32G474RET6 microcontroller with silicon revision code "X". The limitations of this silicon revision are detailed in errata sheet *STM32G471xx/473xx/474xx/483xx/484xx device errata* (ES0430).

Product limitations

No limitation identified for this product identification.

9.4 NUCLEO-G491RE product history

9.4.1 Product identification NUG491RE$AT1

This product identification is based on the mother board MB1367-G491RE-C04.

It embeds the STM32G491RET6 microcontroller with silicon revision code "Z". The limitations of this silicon revision are detailed in errata sheet *STM32G491xx/4A1xx device errata* (ES0523).

Product limitations

No limitation identified for this product identification.

9.5 Board revision history

9.5.1 Board MB1367 revision C-04

The revision C-04 is the initial release of master board MB1367.

Board limitations

No limitation identified for this board revision.

10 Federal Communications Commission (FCC) and ISED Canada Compliance Statements

10.1 FCC Compliance Statement

Part 15.19

This device complies with Part 15 of the FCC Rules. Operation is subject to the following two conditions: (1) this device may not cause harmful interference, and (2) this device must accept any interference received, including interference that may cause undesired operation.

Part 15.21

Any changes or modifications to this equipment not expressly approved by STMicroelectronics may cause harmful interference and void the user's authority to operate this equipment.

Part 15.105

This equipment has been tested and found to comply with the limits for a Class B digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference in a residential installation. This equipment generates uses and can radiate radio frequency energy and, if not installed and used in accordance with the instruction, may cause harmful interference to radio communications. However, there is no guarantee that interference will not occur in a particular installation. If this equipment does cause harmful interference to radio or television reception which can be determined by turning the equipment off and on, the user is encouraged to try to correct interference by one or more of the following measures:

- Reorient or relocate the receiving antenna.
- Increase the separation between the equipment and receiver.
- Connect the equipment into an outlet on circuit different from that to which the receiver is connected.
- Consult the dealer or an experienced radio/TV technician for help.

Note: *Use only shielded cables.*

Responsible party (in the USA)

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10.2 ISED Compliance Statement

ISED Canada ICES-003 Compliance Label: *CAN ICES-3 (B) / NMB-3 (B)*.

Étiquette de conformité à la NMB-003 d'ISDE Canada: *CAN ICES-3 (B) / NMB-3 (B)*.

Revision history

Table 18. **Document revision history**

Date	Revision	Changes
28-Mar-2019	1	Initial release.
17-Apr-2019	2	Added the *Limitation* section.
26-Nov-2020	3	Extended the document scope to the NUCLEO-G491RE board: updated sections *Introduction*, *Features*, *Ordering information* and *Development environment*. Added the *STM32G4 Nucleo-64 board information* section.
11-Feb-2021	4	Updated the Embedded STLINK-V3E section. Updated the STM32G4 Nucleo-64 product information chapter.

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C.3 STM32G474RE – Data Sheet

STM32G474xB STM32G474xC STM32G474xE

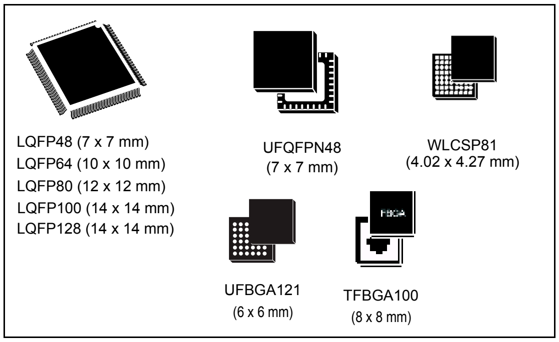
Arm® Cortex®-M4 32-bit MCU+FPU, 170 MHz / 213 DMIPS, 128 KB SRAM, rich analog, math acc, 184 ps 12 chan Hi-res timer

Datasheet - production data

Features

Includes ST state-of-the-art patented technology

- Core: Arm® 32-bit Cortex®-M4 CPU with FPU, Adaptive real-time accelerator (ART Accelerator) allowing 0-wait-state execution from Flash memory, frequency up to 170 MHz with 213 DMIPS, MPU, DSP instructions
- Operating conditions:
  - V_{DD}, V_{DDA} voltage range: 1.71 V to 3.6 V
- Mathematical hardware accelerators
  - CORDIC for trigonometric functions acceleration
  - FMAC: filter mathematical accelerator
- Memories
  - 512 Kbytes of Flash memory with ECC support, two banks read-while-write, proprietary code readout protection (PCROP), securable memory area, 1 Kbyte OTP
  - 96 Kbytes of SRAM, with hardware parity check implemented on the first 32 Kbytes
  - Routine booster: 32 Kbytes of SRAM on instruction and data bus, with hardware parity check (CCM SRAM)
  - External memory interface for static memories FSMC supporting SRAM, PSRAM, NOR and NAND memories
  - Quad-SPI memory interface
- Reset and supply management
  - Power-on/power-down reset (POR/PDR/BOR)
  - Programmable voltage detector (PVD)
  - Low-power modes: sleep, stop, standby and shutdown
  - V_{BAT} supply for RTC and backup registers



- Clock management
  - 4 to 48 MHz crystal oscillator
  - 32 kHz oscillator with calibration
  - Internal 16 MHz RC with PLL option (± 1%)
  - Internal 32 kHz RC oscillator (± 5%)
- Up to 107 fast I/Os
  - All mappable on external interrupt vectors
  - Several I/Os with 5 V tolerant capability
- Interconnect matrix
- 16-channel DMA controller
- 5 x 12-bit ADCs 0.25 µs, up to 42 channels. Resolution up to 16-bit with hardware oversampling, 0 to 3.6 V conversion range
- 7 x 12-bit DAC channels
  - 3 x buffered external channels 1 MSPS
  - 4 x unbuffered internal channels 15 MSPS
- 7 x ultra-fast rail-to-rail analog comparators
- 6 x operational amplifiers that can be used in PGA mode, all terminals accessible
- Internal voltage reference buffer (VREFBUF) supporting three output voltages (2.048 V, 2.5 V, 2.9 V)
- 17 timers:
  - HRTIM (Hi-Resolution and complex waveform builder): 6 x16-bit counters, 184 ps resolution, 12 PWM

This is information on a product in full production. www.st.com

  - 2 x 32-bit timer and 2 x 16-bit timers with up to four IC/OC/PWM or pulse counter and quadrature (incremental) encoder input
  - 3 x 16-bit 8-channel advanced motor control timers, with up to 8 x PWM channels, dead time generation and emergency stop
  - 1 x 16-bit timer with 2 x IC/OCs, one OCN/PWM, dead time generation and emergency stop
  - 2 x 16-bit timers with IC/OC/OCN/PWM, dead time generation and emergency stop
  - 2 x watchdog timers (independent, window)
  - 1 x SysTick timer: 24-bit downcounter
  - 2 x 16-bit basic timers
  - 1 x low-power timer
- Calendar RTC with alarm, periodic wakeup from stop/standby
- Communication interfaces
  - 3 x FDCAN controller supporting flexible data rate
  - 4 x I^2C Fast mode plus (1 Mbit/s) with 20 mA current sink, SMBus/PMBus, wakeup from stop
  - 5 x USART/UARTs (ISO 7816 interface, LIN, IrDA, modem control)
  - 1 x LPUART
  - 4 x SPIs, 4 to 16 programmable bit frames, 2 x with multiplexed half duplex I^2S interface
  - 1 x SAI (serial audio interface)
  - USB 2.0 full-speed interface with LPM and BCD support
  - IRTIM (infrared interface)
  - USB Type-C™ /USB power delivery controller (UCPD)
- True random number generator (RNG)
- CRC calculation unit, 96-bit unique ID
- Development support: serial wire debug (SWD), JTAG, Embedded Trace Macrocell™

Table 1. Device summary

Reference	Part number
STM32G474xB	STM32G474CB, STM32G474MB, STM32G474RB, STM32G474VB, STM32G474QB, STM32G474PB
STM32G474xC	STM32G474CC, STM32G474MC, STM32G474RC, STM32G474VC, STM32G474QC, STM32G474PC
STM32G474xE	STM32G474CE, STM32G474ME, STM32G474RE, STM32G474VE, STM32G474QE, STM32G474PE

Contents

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1 Introduction

This datasheet provides the ordering information and mechanical device characteristics of the STM32G474xB/xC/xE microcontrollers.

This document should be read in conjunction with the reference manual RM0440 “STM32G4 Series advanced Arm® 32-bit MCUs”. The reference manual is available from the STMicroelectronics website *www.st.com*.

For information on the Arm®[a] Cortex®-M4 core, refer to the Cortex®-M4 technical reference manual, available from the www.arm.com website.

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[a] Arm is a registered trademark of Arm Limited (or its subsidiaries) in the US and/or elsewhere.

2 Description

The STM32G474xB/xC/xE devices are based on the high-performance Arm® Cortex®-M4 32-bit RISC core. They operate at a frequency of up to 170 MHz.

The Cortex-M4 core features a single-precision floating-point unit (FPU), which supports all the Arm single-precision data-processing instructions and all the data types. It also implements a full set of DSP (digital signal processing) instructions and a memory protection unit (MPU) which enhances the application's security.

These devices embed high-speed memories (up to 512 Kbytes of Flash memory, and 128 Kbytes of SRAM), a flexible external memory controller (FSMC) for static memories (for devices with packages of 100 pins and more), a Quad-SPI Flash memory interface, and an extensive range of enhanced I/Os and peripherals connected to two APB buses, two AHB buses and a 32-bit multi-AHB bus matrix.

The devices also embed several protection mechanisms for embedded Flash memory and SRAM: readout protection, write protection, securable memory area and proprietary code readout protection.

The devices embed peripherals allowing mathematical/arithmetic function acceleration (CORDIC for trigonometric functions and FMAC unit for filter functions).

They offer five fast 12-bit ADCs (4 Msps), seven comparators, six operational amplifiers, seven DAC channels (3 external and 4 internal), an internal voltage reference buffer, a low-power RTC, two general-purpose 32-bit timers, three 16-bit PWM timers dedicated to motor control, seven general-purpose 16-bit timers, and one 16-bit low-power timer, and high resolution timer with 184 ps resolution.

They also feature standard and advanced communication interfaces such as:

- Four I2Cs
- Four SPIs multiplexed with two half duplex I2Ss
- Three USARTs, two UARTs and one low-power UART.
- Three FDCANs
- One SAI
- USB device
- UCPD

The devices operate in the -40 to +85 °C (+105 °C junction) and -40 to +125 °C (+130 °C junction) temperature ranges from a 1.71 to 3.6 V power supply. A comprehensive set of power-saving modes allows the design of low-power applications.

Some independent power supplies are supported including an analog independent supply input for ADC, DAC, OPAMPs and comparators. A V_{BAT} input allows backup of the RTC and the registers.

The STM32G474xB/xC/xE family offers 9 packages from 48-pin to 128-pin.

Table 2. STM32G474xB/xC/xE features and peripheral counts

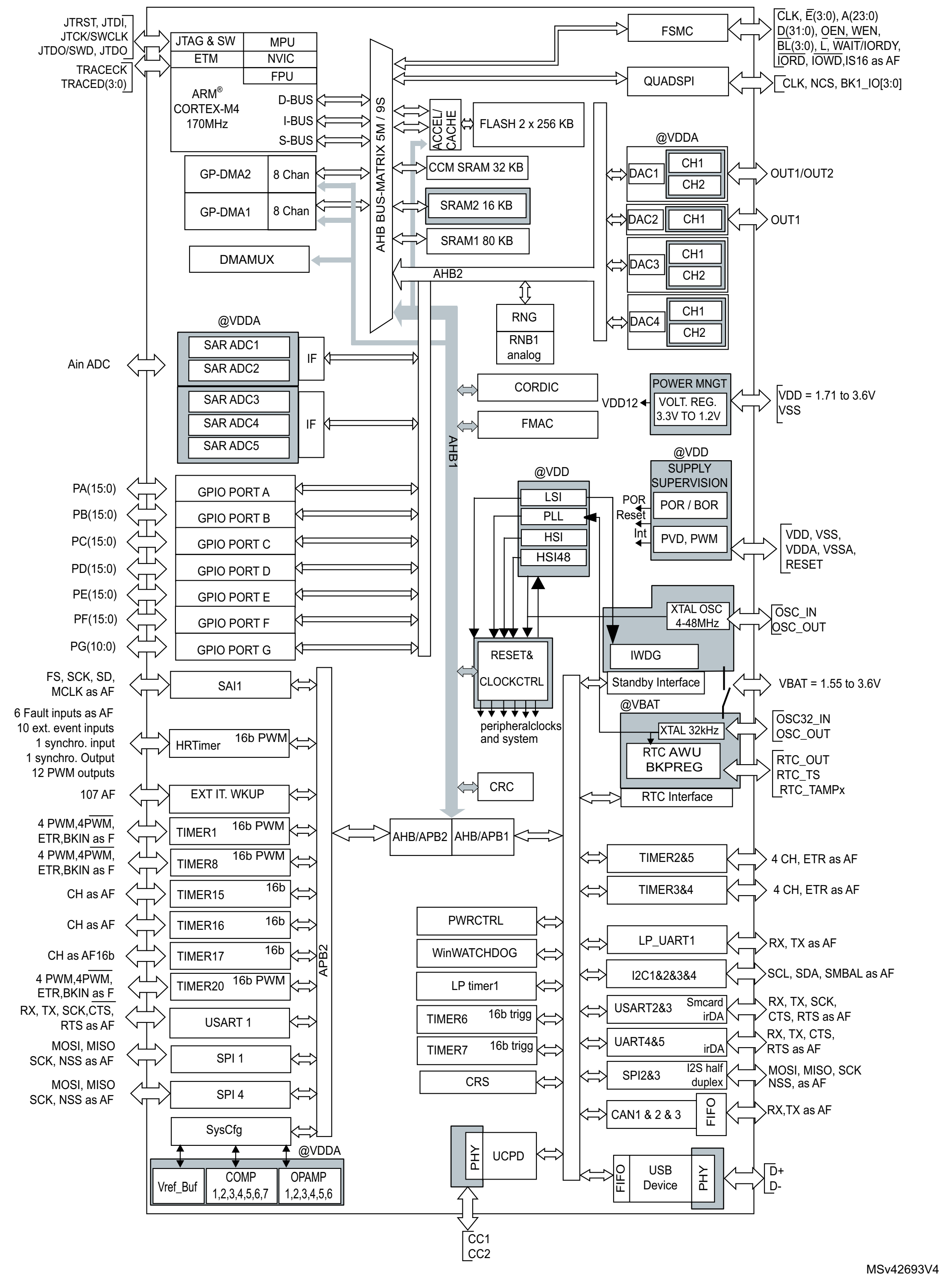
Peripheral		STM32G474Cx			STM32G474Rx			STM32G474Mx			STM32G474Vx			STM32G474Px			STM32G474Qx		
Flash memory		128 KB	256 KB	512 KB	128 KB	256 KB	512 KB	128 KB	256 KB	512 KB	128 KB	256 KB	512 KB	128 KB	256 KB	512 KB	128 KB	256 KB	512 KB
SRAM		128 (80 + 16+ 32) KB																	
External memory controller for static memories (FSMC)		No			No			No			Yes[1]			Yes[2]			Yes		
QUADSPI		1																	
Timers	Advanced motor control	3 (16-bit)																	
	HRTIM	1																	
	General purpose	5 (16-bit) 2 (32-bit)																	
	Basic	2 (16-bit)																	
	Low power	1 (16-bit)																	
	SysTick timer	1																	
	Watchdog timers (independent, window)	2																	
Comm. interfaces	SPI(I2S)[3]	3 (2)						4 (2)											
	I^{2}C	4																	
	USART	3																	
	UART	0			2														
	LPUART	1																	
	FDCANs	3																	
	USB device	Yes																	
	UCPD	Yes																	
	SAI	Yes																	
RTC		Yes																	
Tamper pins		2						3											
Random number generator		Yes																	
CORDIC		Yes																	
FMAC		Yes																	

Table 2. STM32G474xB/xC/xE features and peripheral counts (continued)

Peripheral	STM32G474Cx	STM32G474Rx	STM32G474Mx	STM32G474Vx	STM32G474Px	STM32G474Qx
GPIOs	38 in LQFP48 42 in UFQFPN48	52	67 in WLCSP81 66 in LQFP80	86	102	107
Wakeup pins	3	4	4	5	5	5
12-bit ADCs	5					
Number of channels	20 in LQFP48 21 in UFQFPN48	26	42 in WLCSP81 41 in LQFP80	42	42	42
12-bit DAC	4					
Number of channels	7 (3 external + 4 internal)					
Internal voltage reference buffer	Yes					
PWM channels (all)	33	41	42	48	48	48
PWM channels (except complementary)	28	30	32	33	33	33
Analog comparator	7					
Operational amplifiers	6					
Max. CPU frequency	170 MHz					
Operating voltage	1.71 V to 3.6 V					
Operating temperature	Ambient operating temperature: -40 to 85 °C /-40 to 125 °C					
Packages	LQFP48/ UFQFPN48	LQFP64	WLCSP81 LQFP80	LQFP100/ TFBGA100	UFBGA121	LQFP128

1. For the LQFP100 package, only FMC bank1 and NAND bank are available. Bank1 can only support a multiplexed NOR/PSRAM memory using the NE1 chip select.
2. For the UFBGA121 package, only FMC bank1/bank4 and NAND bank are available. Bank1/Bank4 can only support a multiplexed NOR/PSRAM memory using the NE1/NE4 chip select.
3. The SPI2/3 interfaces can work in an exclusive way in either the SPI mode or the I2S audio mode.

Figure 1. STM32G474xB/xC/xE block diagram



1. AF: alternate function on I/O pins.

3 Functional overview

3.1 Arm® Cortex®-M4 core with FPU

The Arm® Cortex®-M4 with FPU processor is the latest generation of Arm processors for embedded systems. It was developed to provide a low-cost platform that meets the needs of the MCU implementation, with a reduced pin count and with low-power consumption, while delivering outstanding computational performance and an advanced response to interrupts.

The Arm® Cortex®-M4 with FPU 32-bit RISC processor features an exceptional code-efficiency, delivering the expected high-performance from an Arm core in a memory size usually associated with 8-bit and 16-bit devices.

The processor supports a set of DSP instructions which allows an efficient signal processing and a complex algorithm execution. Its single precision FPU speeds up the software development by using metalanguage development tools to avoid saturation.

With its embedded Arm core, the STM32G474xB/xC/xE family is compatible with all Arm tools and software.

Figure 1 shows the general block diagram of the STM32G474xB/xC/xE devices.

3.2 Adaptive real-time memory accelerator (ART accelerator)

The ART accelerator is a memory accelerator that is optimized for the STM32 industry-standard Arm® Cortex®-M4 processors. It balances the inherent performance advantage of the Arm® Cortex®-M4 over Flash memory technologies, which normally requires the processor to wait for the Flash memory at higher frequencies.

3.3 Memory protection unit

The memory protection unit (MPU) is used to manage the CPU accesses to the memory and to prevent one task to accidentally corrupt the memory or the resources used by any other active task. This memory area is organized into up to 8 protected areas, which can be divided in up into 8 subareas each. The protection area sizes range between 32 bytes and the whole 4 gigabytes of addressable memory.

The MPU is especially helpful for applications where some critical or certified code has to be protected against the misbehavior of other tasks. It is usually managed by an RTOS (real-time operating system). If a program accesses a memory location that is prohibited by the MPU, the RTOS can detect it and take action. In an RTOS environment, the kernel can dynamically update the MPU area setting based on the process to be executed.

The MPU is optional and can be bypassed for applications that do not need it.

3.4 Embedded Flash memory

The STM32G474xB/xC/xE devices feature up to 512 Kbytes of embedded Flash memory which is available for storing programs and data.

The Flash interface features:

- Single or dual bank operating modes
- Read-while-write (RWW) in dual bank mode

This feature allows to perform a read operation from one bank while an erase or program operation is performed to the other bank. The dual bank boot is also supported.

Flexible protections can be configured thanks to the option bytes:

- Readout protection (RDP) to protect the whole memory. Three levels of protection are available:
  - Level 0: no readout protection
  - Level 1: memory readout protection; the Flash memory cannot be read from or written to if either the debug features are connected or the boot in RAM or bootloader are selected
  - Level 2: chip readout protection; the debug features (Cortex-M4 JTAG and serial wire), the boot in RAM and the bootloader selection are disabled (JTAG fuse). This selection is irreversible.
- Write protection (WRP): the protected area is protected against erasing and programming.
- Proprietary code readout protection (PCROP): a part of the Flash memory can be protected against read and write from third parties. The protected area is execute-only and it can only be reached by the STM32 CPU as an instruction code, while all other accesses (DMA, debug and CPU data read, write and erase) are strictly prohibited. An additional option bit (PCROP_RDP) allows to select if the PCROP area is erased or not when the RDP protection is changed from Level 1 to Level 0.
- Securable memory area: a part of Flash memory can be configured by option bytes to be securable. After reset this securable memory area is not secured and it behaves like the remainder of main Flash memory (execute, read, write access). When secured, any access to this securable memory area generates corresponding read/write error. Purpose of the Securable memory area is to protect sensitive code and data (secure keys storage) which can be executed only once at boot, and never again unless a new reset occurs.

The Flash memory embeds the error correction code (ECC) feature supporting:

- Single error detection and correction
- Double error detection
- The address of the ECC fail can be read in the ECC register
- 1 Kbyte (128 double word) OTP (one-time programmable) for user data. The OTP area is available in Bank 1 only. The OTP data cannot be erased and can be written only once.

3.5 Embedded SRAM

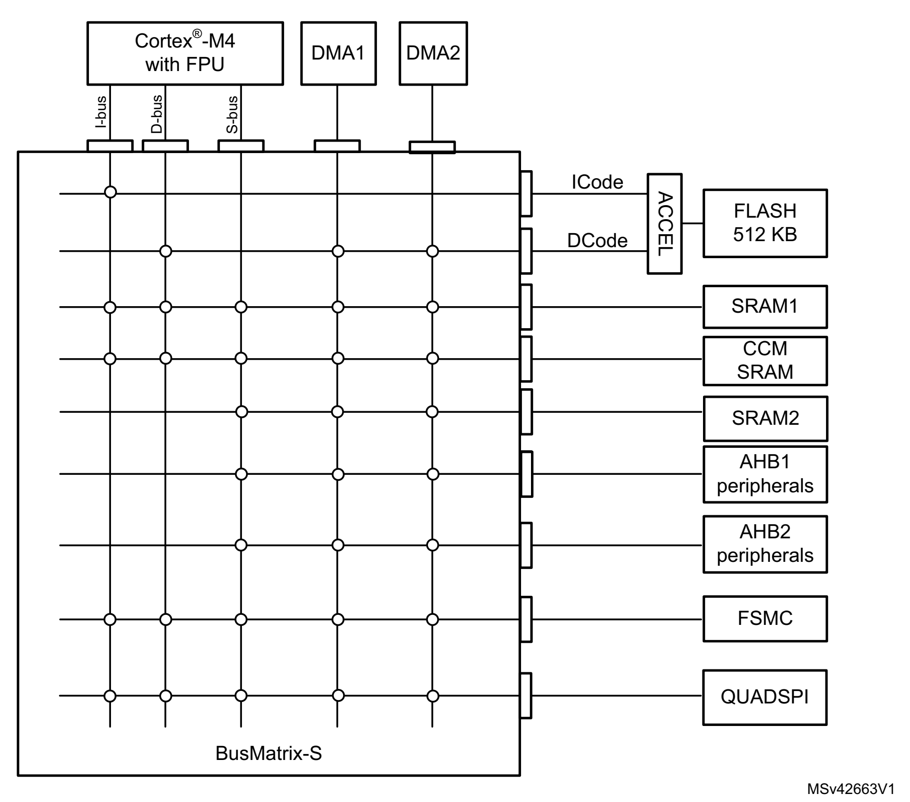
STM32G474xB/xC/xE devices feature 128 Kbytes of embedded SRAM. This SRAM is split into three blocks:

- 80 Kbytes mapped at address 0x2000 0000 (SRAM1). The CM4 can access the SRAM1 through the System Bus (or through the I-Code/D-Code buses when boot from SRAM1 is selected or when physical remap is selected by SYSCFG_MEMRMP register). The first 32 Kbytes of SRAM1 support hardware parity check.
- 16 Kbytes mapped at address 0x2001 4000 (SRAM2). The CM4 can access the SRAM2 through the System bus. SRAM2 can be retained in standby modes.
- 32 Kbytes mapped at address 0x1000 0000 (CCM SRAM). It is accessed by the CPU through I-Code/D-Code bus for maximum performance.
  It is also aliased at 0x2001 8000 address to be accessed by all masters (CPU, DMA1, DMA2) through SBUS contiguously to SRAM1 and SRAM2. The CCM SRAM supports hardware parity check and can be write-protected with 1-Kbyte granularity.
- The memory can be accessed in read/write at max CPU clock speed with 0 wait states.

3.6 Multi-AHB bus matrix

The 32-bit multi-AHB bus matrix interconnects all the masters (CPU, DMAs) and the slaves (Flash memory, RAM, FSMC, QUADSPI, AHB and APB peripherals). It also ensures a seamless and efficient operation even when several high-speed peripherals work simultaneously.

Figure 2. Multi-AHB bus matrix



3.7 Boot modes

At startup, a BOOT0 pin (or nBOOT0 option bit) and an nBOOT1 option bit are used to select one of three boot options:

- Boot from user Flash
- Boot from system memory
- Boot from embedded SRAM

The BOOT0 value may come from the PB8-BOOT0 pin or from an nBOOT0 option bit depending on the value of a user nBOOT_SEL option bit to free the GPIO pad if needed.

The boot loader is located in the system memory. It is used to reprogram the Flash memory by using USART, I2C, SPI, and USB through the DFU (device firmware upgrade).

3.8 CORDIC

The CORDIC provides hardware acceleration of certain mathematical functions, notably trigonometric, commonly used in motor control, metering, signal processing and many other applications.

It speeds up the calculation of these functions compared to a software implementation, allowing a lower operating frequency, or freeing up processor cycles in order to perform other tasks.

Cordic features

- 24-bit CORDIC rotation engine
- Circular and Hyperbolic modes
- Rotation and Vectoring modes
- Functions: Sine, Cosine, Sinh, Cosh, Atan, Atan2, Atanh, Modulus, Square root, Natural logarithm
- Programmable precision up to 20-bit
- Fast convergence: 4 bits per clock cycle
- Supports 16-bit and 32-bit fixed point input and output formats
- Low latency AHB slave interface
- Results can be read as soon as ready without polling or interrupt
- DMA read and write channels

3.9 Filter mathematical accelerator (FMAC)

The filter mathematical accelerator unit performs arithmetic operations on vectors. It comprises a multiplier/accumulator (MAC) unit, together with address generation logic, which allows it to index vector elements held in local memory.

The unit includes support for circular buffers on input and output, which allows digital filters to be implemented. Both finite and infinite impulse response filters can be realized.

The unit allows frequent or lengthy filtering operations to be offloaded from the CPU, freeing up the processor for other tasks. In many cases it can accelerate such calculations compared to a software implementation, resulting in a speed-up of time critical tasks.

FMAC features

- 16 x 16-bit multiplier
- 24+2-bit accumulator with addition and subtraction
- 16-bit input and output data
- 256 x 16-bit local memory
- Up to three areas can be defined in memory for data buffers (two input, one output), defined by programmable base address pointers and associated size registers
- Input and output sample buffers can be circular
- Buffer “watermark” feature reduces overhead in interrupt mode
- Filter functions: FIR, IIR (direct form 1)
- AHB slave interface
- DMA read and write data channels

3.10 Cyclic redundancy check calculation unit (CRC)

The CRC (cyclic redundancy check) calculation unit is used to get a CRC code using a configurable generator with polynomial value and size.

Among other applications, the CRC-based techniques are used to verify data transmission or storage integrity. In the scope of the EN/IEC 60335-1 standard, they offer a mean to verify the Flash memory integrity.

The CRC calculation unit helps to compute a signature of the software during runtime, which can be ulteriorly compared with a reference signature generated at link-time and which can be stored at a given memory location.

3.11 Power supply management

3.11.1 Power supply schemes

The STM32G474xB/xC/xE devices require a 1.71 V to 3.6 V V_{DD} operating voltage supply. Several independent supplies, can be provided for specific peripherals:

- V_{DD} = 1.71 V to 3.6 V

  V_{DD} is the external power supply for the I/Os, the internal regulator and the system analog such as reset, power management and internal clocks. It is provided externally through the VDD pins.
- V_{DDA} = 1.62 V to 3.6 V (see *Section 5: Electrical characteristics* for the minimum V_{DDA} voltage required for ADC, DAC, COMP, OPAMP, VREFBUF operation).
  V_{DDA} is the external analog power supply for A/D converters, D/A converters, voltage reference buffer, operational amplifiers and comparators. The V_{DDA} voltage level is independent from the V_{DD} voltage and should preferably be connected to V_{DD} when these peripherals are not used.
- V_{BAT} = 1.55 V to 3.6 V

  V_{BAT} is the power supply for RTC, external clock 32 kHz oscillator and backup registers (through power switch) when V_{DD} is not present.

- VREF-, VREF+

  V_{REF+} is the input reference voltage for ADCs and DACs. It is also the output of the internal voltage reference buffer when enabled.

  When $V_{DDA} < 2$ V V_{REF+} must be equal to V_{DDA}.

  When $V_{DDA} \geq 2$ V V_{REF+} must be between 2 V and V_{DDA}.

  The internal voltage reference buffer supports three output voltages, which are configured with VRS bits in the VREFBUF_CSR register:

  - $V_{REF+} = 2.048$ V
  - $V_{REF+} = 2.5$ V
  - $V_{REF+} = 2.9$ V

  V_{REF-} is double bonded with V_{SSA}.

3.11.2 Power supply supervisor

The device has an integrated ultra-low-power brown-out reset (BOR) active in all modes (except for Shutdown mode). The BOR ensures proper operation of the device after power-on and during power down. The device remains in reset mode when the monitored supply voltage V_{DD} is below a specified threshold, without the need for an external reset circuit.

The lowest BOR level is 1.71 V at power on, and other higher thresholds can be selected through option bytes.The device features an embedded programmable voltage detector (PVD) that monitors the V_{DD} power supply and compares it to the VPVD threshold. An interrupt can be generated when V_{DD} drops below the VPVD threshold and/or when V_{DD} is higher than the VPVD threshold. The interrupt service routine can then generate a warning message and/or put the MCU into a safe state. The PVD is enabled by software.

In addition, the device embeds a peripheral voltage monitor which compares the independent supply voltages V_{DDA}, with a fixed threshold in order to ensure that the peripheral is in its functional supply range.

3.11.3 Voltage regulator

Two embedded linear voltage regulators, main regulator (MR) and low-power regulator (LPR), supply most of digital circuitry in the device. The MR is used in Run and Sleep modes. The LPR is used in Low-power run, Low-power sleep and Stop modes. In Standby and Shutdown modes, both regulators are powered down and their outputs set in high-impedance state, such as to bring their current consumption close to zero.

The device supports dynamic voltage scaling to optimize its power consumption in Run mode. the voltage from the main regulator that supplies the logic (VCORE) can be adjusted according to the system's maximum operating frequency.

The main regulator (MR) operates in the following ranges:

- Range 1 boost mode with the CPU running at up to 170 MHz.
- Range 1 normal mode with CPU running at up to 150 MHz.
- Range 2 with a maximum CPU frequency of 26 MHz.

3.11.4 Low-power modes

By default, the microcontroller is in Run mode after system or power Reset. It is up to the user to select one of the low-power modes described below:

- **Sleep mode**: In Sleep mode, only the CPU is stopped. All peripherals continue to operate and can wake up the CPU when an interrupt/event occurs.
- **Low-power run mode:** This mode is achieved with VCORE supplied by the low-power regulator to minimize the regulator's operating current. The code can be executed from SRAM or from Flash, and the CPU frequency is limited to 2 MHz. The peripherals with independent clock can be clocked by HSI16.
- **Low-power sleep mode:** This mode is entered from the low-power run mode. Only the CPU clock is stopped. When wakeup is triggered by an event or an interrupt, the system reverts to the Low power run mode.
- **Stop mode:** In Stop mode, the device achieves the lowest power consumption while retaining the SRAM and register contents. All clocks in the VCORE domain are stopped. The PLL, as well as the HSI16 RC oscillator and the HSE crystal oscillator are disabled. The LSE or LSI keep running. The RTC can remain active (Stop mode with RTC, Stop mode without RTC). Some peripherals with wakeup capability can enable the HSI16 RC during Stop mode, so as to get clock for processing the wakeup event.
- **Standby mode:** The Standby mode is used to achieve the lowest power consumption with brown-out reset, BOR. The internal regulator is switched off to power down the VCORE domain. The PLL, as well as the HSI16 RC oscillator and the HSE crystal oscillator are also powered down. The RTC can remain active (Standby mode with RTC, Standby mode without RTC). The BOR always remains active in Standby mode. For each I/O, the software can determine whether a pull-up, a pull-down or no resistor shall be applied to that I/O during Standby mode. Upon entering Standby mode, SRAM and register contents are lost except for registers in the RTC domain and standby circuitry. The device exits Standby mode upon external reset event (NRST pin), IWDG reset event, wakeup event (WKUP pin, configurable rising or falling edge) or RTC event (alarm, periodic wakeup, timestamp, tamper), or when a failure is detected on LSE (CSS on LSE).
- **Shutdown mode:** The Shutdown mode allows to achieve the lowest power consumption. The internal regulator is switched off to power down the VCORE domain. The PLL, as well as the HSI16 and LSI RC-oscillators and HSE crystal oscillator are also powered down. The RTC can remain active (Shutdown mode with RTC, Shutdown mode without RTC). The BOR is not available in Shutdown mode. No power voltage monitoring is possible in this mode. Therefore, switching to RTC domain is not supported. SRAM and register contents are lost except for registers in the RTC domain. The device exits Shutdown mode upon external reset event (NRST pin), IWDG reset event, wakeup event (WKUP pin, configurable rising or falling edge) or RTC event (alarm, periodic wakeup, timestamp, tamper).

3.11.5 Reset mode

In order to improve the consumption under reset, the I/Os state under and after reset is “analog state” (the I/O schmitt trigger is disabled). In addition, the internal reset pull-up is deactivated when the reset source is internal.

3.11.6 V_{BAT} operation

The V_{BAT} pin allows to power the device V_{BAT} domain from an external battery, an external supercapacitor, or from V_{DD} when there is no external battery and when an external supercapacitor is present. The V_{BAT} pin supplies the RTC with LSE and the backup registers. Three anti-tamper detection pins are available in V_{BAT} mode.

The V_{BAT} operation is automatically activated when V_{DD} is not present. An internal V_{BAT} battery charging circuit is embedded and can be activated when V_{DD} is present.

Note: When the microcontroller is supplied from V_{BAT}*, neither external interrupts nor RTC alarm/events exit the microcontroller from the* V_{BAT} *operation.*

3.12 Interconnect matrix

Several peripherals have direct connections between them. This allows autonomous communication between peripherals, saving CPU resources thus power supply consumption. In addition, these hardware connections allow fast and predictable latency.

Depending on peripherals, these interconnections can operate in Run, Sleep and Stop modes.

Table 3. STM32G474xB/xC/xE peripherals interconnect matrix

Interconnect source	Interconnect destination	Interconnect action	Run	Sleep	Low-power run	Low-power sleep	Stop
TIMx	TIMx	Timers synchronization or chaining	Y	Y	Y	Y	-
	ADCx DACx	Conversion triggers	Y	Y	Y	Y	-
	DMA	Memory to memory transfer trigger	Y	Y	Y	Y	-
	COMPx	Comparator output blanking	Y	Y	Y	Y	-
TIM16/TIM17	IRTIM	Infrared interface output generation	Y	Y	Y	Y	-
COMPx	TIM1, 8, 20 TIM2, 3, 4, 5	Timer input channel, trigger, break from analog signals comparison	Y	Y	Y	Y	-
	LPTIMER1	Low-power timer triggered by analog signals comparison	Y	Y	Y	Y	Y
	HRTIM	COMPx Output is an input event or a fault input for HRTIM	Y	Y	Y	Y	-
ADCx	TIM1, 8, 20	Timer triggered by analog watchdog	Y	Y	Y	Y	-
	HRTIM	HRTIM external event source can be ADCx analog watchdog	Y	Y	Y	Y	-
RTC	TIM16	Timer input channel from RTC events	Y	Y	Y	Y	-
	LPTIMER1	Low-power timer triggered by RTC alarms or tampers	Y	Y	Y	Y	Y
All clocks sources (internal and external)	TIM5, TIM15, 16, 17	Clock source used as input channel for RC measurement and trimming	Y	Y	Y	Y	-
USB	TIM2	Timer triggered by USB SOF	Y	Y	-	-	-
CSS RAM (parity error) Flash memory (ECC error) COMPx PVD	TIM1,8, 20 TIM15,16,17 HRTIM	Timer break HRTIM SYSFLT	Y	Y	Y	Y	-

Table 3. STM32G474xB/xC/xE peripherals interconnect matrix (continued)

Interconnect source	Interconnect destination	Interconnect action	Run	Sleep	Low-power run	Low-power sleep	Stop
CPU (hard fault)	TIM1,8,20 TIM15/16/17 HRTIM	Timer break HRTIM SYSFLT	Y	Y	Y	Y	-
GPIO	TIMx	External trigger	Y	Y	Y	Y	-
	LPTIMER1	External trigger	Y	Y	Y	Y	Y
	HRTIM	External fault/event/Synchro inputs for HRTIM	Y	Y	Y	Y	-
	ADCx DACx	Conversion external trigger	Y	Y	Y	Y	-
HRTIM	DACx/ADCx	Conversion trigger	Y	Y	Y	Y	-
	GPIO	Synchro output for HRTIM	Y	Y	Y	Y	-

3.13 Clocks and startup

The clock controller distributes the clocks coming from different oscillators to the core and the peripherals. It also manages clock gating for low-power modes and ensures clock robustness. It features:

- **Clock prescaler:** to get the best trade-off between speed and current consumption, the clock frequency to the CPU and peripherals can be adjusted by a programmable prescaler
- **Safe clock switching:** clock sources can be changed safely on the fly in run mode through a configuration register.
- **Clock management:** to reduce power consumption, the clock controller can stop the clock to the core, individual peripherals or memory.
- **System clock source:** three different sources can deliver SYSCLK system clock:
  - 4 - 48 MHz high-speed oscillator with external crystal or ceramic resonator (HSE). It can supply clock to system PLL. The HSE can also be configured in bypass mode for an external clock.
  - 16 MHz high-speed internal RC oscillator (HSI16), trimmable by software. It can supply clock to system PLL.
  - System PLL with maximum output frequency of 170 MHz. It can be fed with HSE or HSI16 clocks.
- **RC48 with clock recovery system (HSI48):** internal HSIRC48 MHz clock source can be used to drive the USB or the RNG peripherals.
- **Auxiliary clock source:** two ultra-low-power clock sources for the real-time clock (RTC):
  - 32.768 kHz low-speed oscillator with external crystal (LSE), supporting four drive capability modes. The LSE can also be configured in bypass mode for using an external clock.
  - 32 kHz low-speed internal RC oscillator (LSI) with ±5% accuracy, also used to clock an independent watchdog.
- **Peripheral clock sources:** several peripherals (I2S, USART, I2C, LPTimer, ADC, SAI, RNG) have their own clock independent of the system clock.
- **Clock security system (CSS):** in the event of HSE clock failure, the system clock is automatically switched to HSI16 and, if enabled, a software interrupt is generated. LSE clock failure can also be detected and generate an interrupt.
- Clock-out capability:
  - **MCO:** microcontroller clock output: it outputs one of the internal clocks for external use by the application
  - **LSCO: low speed clock output:** it outputs LSI or LSE in all low-power modes.

Several prescalers allow to configure the AHB frequency, the High-speed APB (APB2) and the low speed APB (APB1) domains. The maximum frequency of the AHB and the APB domains is 170 MHz.

3.14 General-purpose inputs/outputs (GPIOs)

Each of the GPIO pins can be configured by software as output (push-pull or open-drain), as input (with or without pull-up or pull-down) or as peripheral alternate function. Most of the GPIO pins are shared with digital or analog alternate functions. Fast I/O toggling can be achieved thanks to their mapping on the AHB2 bus.

The I/Os alternate function configuration can be locked if needed following a specific sequence in order to avoid spurious writing to the I/Os registers.

3.15 Direct memory access controller (DMA)

The device embeds 2 DMAs. Refer to *Table 4: DMA implementation* for the features implementation.

Direct memory access (DMA) is used in order to provide a high-speed data transfer between peripherals and memory as well as from memory to memory. Data can be quickly moved by DMA without any CPU actions. This keeps the CPU resources free for other operations.

The two DMA controllers have 16 channels in total, each one dedicated to manage memory access requests from one or more peripherals. Each controller has an arbiter for handling the priority between DMA requests.

The DMA supports:

- 16 independently configurable channels (requests)
  - Each channel is connected to a dedicated hardware DMA request, a software trigger is also supported on each channel. This configuration is done by software.
- Priorities between requests from channels of one DMA are both software programmable (4 levels: very high, high, medium, low) or hardware programmable in case of equality (request 1 has priority over request 2, etc.)
- Independent source and destination transfer size (byte, half word, word), emulating packing and unpacking. Source/destination addresses must be aligned on the data size.
- Support for circular buffer management
- 3 event flags (DMA half transfer, DMA transfer complete and DMA transfer error) logically ORed together in a single interrupt request for each channel
- Memory-to-memory transfer
- Peripheral-to-memory, memory-to-peripheral, and peripheral-to-peripheral transfers
- Access to Flash, SRAM, APB and AHB peripherals as source and destination
- Programmable number of data to be transferred: up to 65536.

Table 4. DMA implementation

DMA features	DMA1	DMA2
Number of regular channels	8	8

3.16 DMA request router (DMAMUX)

When a peripheral indicates a request for DMA transfer by setting its DMA request line, the DMA request is pending until it is served and the corresponding DMA request line is reset. The DMA request router allows to route the DMA control lines between the peripherals and the DMA controllers of the product.

An embedded multi-channel DMA request generator can be considered as one of such peripherals. The routing function is ensured by a multi-channel DMA request line multiplexer. Each channel selects a unique set of DMA control lines, unconditionally or synchronously with events on synchronization inputs.

For simplicity, the functional description is limited to DMA request lines. The other DMA control lines are not shown in figures or described in the text. The DMA request generator produces DMA requests following events on DMA request trigger inputs.

3.17 Interrupts and events

3.17.1 Nested vectored interrupt controller (NVIC)

The STM32G474xB/xC/xE devices embed a nested vectored interrupt controller which is able to manage 16 priority levels, and to handle up to 102 maskable interrupt channels plus the 16 interrupt lines of the Cortex®-M4.

The NVIC benefits are the following:

- Closely coupled NVIC gives low latency interrupt processing
- Interrupt entry vector table address passed directly to the core
- Allows early processing of interrupts
- Processing of late arriving higher priority interrupts
- Support for tail chaining
- Processor state automatically saved
- Interrupt entry restored on interrupt exit with no instruction overhead

The NVIC hardware block provides flexible interrupt management features with minimal interrupt latency.

3.17.2 Extended interrupt/event controller (EXTI)

The extended interrupt/event controller consists of 44 edge detector lines used to generate interrupt/event requests and to wake-up the system from the Stop mode. Each external line can be independently configured to select the trigger event (rising edge, falling edge, both) and can be masked independently.

A pending register maintains the status of the interrupt requests. The internal lines are connected to peripherals with wakeup from Stop mode capability. The EXTI can detect an external line with a pulse width shorter than the internal clock period. Up to 107 GPIOs can be connected to the 16 external interrupt lines.

3.18 Analog-to-digital converter (ADC)

The device embeds five successive approximation analog-to-digital converters with the following features:

- 12-bit native resolution, with built-in calibration
- 4 Msps maximum conversion rate with full resolution
  - Down to 41.67 ns sampling time
  - Increased conversion rate for lower resolution (up to 6.66 Msps for 6-bit resolution)
- One external reference pin is available on all packages, allowing the input voltage range to be independent from the power supply
- Single-ended and differential mode inputs
- Low-power design
  - Capable of low-current operation at low conversion rate (consumption decreases linearly with speed)
  - Dual clock domain architecture: ADC speed independent from CPU frequency
- Highly versatile digital interface
  - Single-shot or continuous/discontinuous sequencer-based scan mode: 2 groups of analog signals conversions can be programmed to differentiate background and high-priority real-time conversions
  - Each ADC support multiple trigger inputs for synchronization with on-chip timers and external signals
  - Results stored into a data register or in RAM with DMA controller support
  - Data pre-processing: left/right alignment and per channel offset compensation
  - Built-in oversampling unit for enhanced SNR
  - Channel-wise programmable sampling time
  - Analog watchdog for automatic voltage monitoring, generating interrupts and trigger for selected timers
  - Hardware assistant to prepare the context of the injected channels to allow fast context switching
  - Flexible sample time control
  - Hardware gain and offset compensation

3.18.1 Temperature sensor

The temperature sensor (TS) generates a voltage V_{TS} that varies linearly with temperature. The temperature sensor is internally connected to the ADCs input channels which is used to convert the sensor output voltage into a digital value.

The sensor provides good linearity but it has to be calibrated to obtain good overall accuracy of the temperature measurement. As the offset of the temperature sensor varies from chip to chip due to process variation, the uncalibrated internal temperature sensor is suitable for applications that detect temperature changes only.

To improve the accuracy of the temperature sensor measurement, each device is individually factory-calibrated by ST. The temperature sensor factory calibration data are stored by ST in the system memory area, accessible in read-only mode.

Table 5. Temperature sensor calibration values

Calibration value name	Description	Memory address
TS_CAL1	TS ADC raw data acquired at a temperature of 30 °C (± 5 °C), $V_{DDA} = V_{REF+} = 3.0$ V (± 10 mV)	0x1FFF 75A8 - 0x1FFF 75A9
TS_CAL2	TS ADC raw data acquired at a temperature of 130 °C (± 5 °C), $V_{DDA} = V_{REF+} = 3.0$ V (± 10 mV)	0x1FFF 75CA - 0x1FFF 75CB

3.18.2 Internal voltage reference (V_{REFINT})

The internal voltage reference (VREFINT) provides a stable (bandgap) voltage output for the ADC and the comparators. The VREFINT is internally connected to the ADCx_IN18, x = 1,3,4,5 input channel. The precise voltage of VREFINT is individually measured for each part by ST during production test and stored in the system memory area. It is accessible in read-only mode.

Table 6. Internal voltage reference calibration values

Calibration value name	Description	Memory address
VREFINT	Raw data acquired at a temperature of 30 °C (± 5 °C), $V_{DDA} = V_{REF+} = 3.0$ V (± 10 mV)	0x1FFF 75AA - 0x1FFF 75AB

3.18.3 V_{BAT} battery voltage monitoring

This embedded hardware enables the application to measure the V_{BAT} battery voltage using the internal ADC1_IN17 channel. As the V_{BAT} voltage may be higher than the V_{DDA}, and thus outside the ADC input range, the VBAT pin is internally connected to a bridge divider by 3. As a consequence, the converted digital value is one third of the V_{BAT} voltage.

3.18.4 Operational amplifier internal output (OPAMPxINT):

The OPAMPx (x = 1...6) output OPAMPxINT can be sampled using an ADCx (x = 1...5) internal input channel. In this case, the I/O on which the OPAMPx output is mapped can be used as GPIO.

3.19 Digital to analog converter (DAC)

Seven 12 bit DAC channels (3 external buffered and 4 internal unbuffered) can be used to convert digital signals into analog voltage signal outputs. The chosen design structure is composed of integrated resistor strings and an amplifier in inverting configuration.

This digital interface supports the following features:

- Up to two DAC output channels
- 8-bit or 12-bit output mode
- Buffer offset calibration (factory and user trimming)
- Left or right data alignment in 12-bit mode
- Synchronized update capability
- Noise-wave generation
- Triangular-wave generation
- Saw tooth wave generation
- Dual DAC channel independent or simultaneous conversions
- DMA capability for each channel
- External triggers for conversion
- Sample and hold low-power mode, with internal or external capacitor
- Up to 1 Msps for external output and 15 Msps for internal output

The DAC channels are triggered through the timer update outputs that are also connected to different DMA channels.

3.20 Voltage reference buffer (V_{REFBUF})

The STM32G474xB/xC/xE devices embed a voltage reference buffer which can be used as voltage reference for ADC, DACs and also as voltage reference for external components through the VREF+ pin.

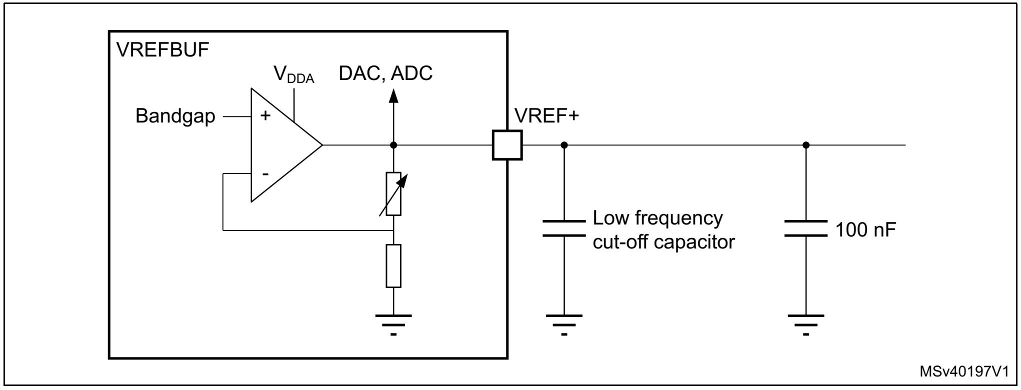
The internal voltage reference buffer supports three voltages:

- 2.048 V
- 2.5 V
- 2.9 V

An external voltage reference can be provided through the VREF+ pin when the internal voltage reference buffer is off.

The VREF+ pin is double-bonded with V_{DDA} on some packages. In these packages the internal voltage reference buffer is not available.

Figure 3. Voltage reference buffer



3.21 Comparators (COMP)

The STM32G474xB/xC/xE devices embed seven rail-to-rail comparators with programmable reference voltage (internal or external), hysteresis.

The reference voltage can be one of the following:

- External I/O
- DAC output channels
- Internal reference voltage or submultiple (1/4, 1/2, 3/4).

All comparators can wake up from Stop mode, generate interrupts and breaks for the timers.

3.22 Operational amplifier (OPAMP)

The STM32G474xB/xC/xE devices embed six operational amplifiers with external or internal follower routing and PGA capability.

The operational amplifier features:

- 13 MHz bandwidth
- Rail-to-rail input/output
- PGA with a non-inverting gain ranging of 2, 4, 8, 16, 32 or 64 or inverting gain ranging of -1, -3, -7, -15, -31 or -63

3.23 Random number generator (RNG)

All devices embed an RNG that delivers 32-bit random numbers generated by an integrated analog circuit.

3.24 Timers and watchdogs

The STM32G474xB/xC/xE devices include One High Resolution time, three advanced motor control timers, up to nine general-purpose timers, two basic timers, one low-power timer, two watchdog timers and a SysTick timer. The table below compares the features of the advanced motor control, general purpose and basic timers.

Table 7. Timer feature comparison

Timer type	Timer	Counter resolution	Counter type	Prescaler factor	DMA request generation	Capture/ compare channels	Complementary outputs
High resolution timer	HRTIM	16-bit	Up	/1 /2 /4 (x2 x4 x8 x16 x32, with DLL)	Yes	12	Yes
Advanced motor control	TIM1, TIM8, TIM20	16-bit	Up, down, Up/down	Any integer between 1 and 65536	Yes	4	4
General-purpose	TIM2, TIM5	32-bit	Up, down, Up/down	Any integer between 1 and 65536	Yes	4	No

Table 7. Timer feature comparison (continued)

Timer type	Timer	Counter resolution	Counter type	Prescaler factor	DMA request generation	Capture/ compare channels	Complementary outputs
General-purpose	TIM3, TIM4	16-bit	Up, down, Up/down	Any integer between 1 and 65536	Yes	4	No
General-purpose	TIM15	16-bit	Up	Any integer between 1 and 65536	Yes	2	1
General-purpose	TIM16, TIM17	16-bit	Up	Any integer between 1 and 65536	Yes	1	1
Basic	TIM6, TIM7	16-bit	Up	Any integer between 1 and 65536	Yes	0	No

3.24.1 High-resolution timer (HRTIM)

The high-resolution timer (HRTIM) allows generating digital signals with high-accuracy timings, such as PWM or phase-shifted pulses.

It consists of 7 timers, 1 master and 6 slaves, totaling 12 high-resolution outputs, which can be coupled by pairs for deadtime insertion. It also features 6 fault inputs for protection purposes and 10 inputs to handle external events such as current limitation, zero voltage or zero current switching.

HRTIM timer is made of a digital kernel clocked at 170 MHz followed by delay lines. Delay lines with closed loop control guarantee a 184 ps resolution whatever the voltage, temperature or chip-to-chip manufacturing process deviation. The high-resolution is available on the 12 outputs in all operating modes: variable duty cycle, variable frequency, and constant ON time.

The slave timers can be combined to control multiswitch complex converters or operate independently to manage multiple independent converters.

The waveforms are defined by a combination of user-defined timings and external events such as analog or digital feedbacks signals.

HRTIM timer includes options for blanking and filtering out spurious events or faults. It also offers specific modes and features to offload the CPU: DMA requests, burst mode controller, push-pull and resonant mode.

It supports many topologies including LLC, Full bridge phase shifted, buck or boost converters, either in voltage or current mode, as well as lighting application (fluorescent or LED). It can also be used as a general purpose timer, for instance to achieve high-resolution PWM-emulated DAC.

In debug mode, the HRTIM counters can be frozen and the PWM outputs enter safe state.

3.24.2 Advanced motor control timer (TIM1, TIM8, TIM20)

The advanced motor control timers can each be seen as a four-phase PWM multiplexed on 8 channels. They have complementary PWM outputs with programmable inserted dead-times. They can also be seen as complete general-purpose timers.

The 4 independent channels can be used for:

- Input capture
- Output compare
- PWM generation (edge or center-aligned modes) with full modulation capability (0-100%)
- One-pulse mode output

In debug mode, the advanced motor control timer counter can be frozen and the PWM outputs disabled in order to turn off any power switches driven by these outputs.

Many features are shared with the general-purpose TIMx timers (described in *Section 3.24.3*) using the same architecture, so the advanced motor control timers can work together with the TIMx timers via the Timer Link feature for synchronization or event chaining.

3.24.3 General-purpose timers (TIM2, TIM3, TIM4, TIM5, TIM15, TIM16, TIM17)

There are up to seven synchronizable general-purpose timers embedded in the STM32G474xB/xC/xE devices (see *Table 7* for differences). Each general-purpose timer can be used to generate PWM outputs, or act as a simple time base.

- TIM2, TIM3, TIM4 and TIM5

  They are full-featured general-purpose timers:

  - TIM2 and TIM5 have a 32-bit auto-reload up/downcounter and 32-bit prescaler
  - TIM3 and TIM4 have 16-bit auto-reload up/downcounter and 16-bit prescaler.

  These timers feature 4 independent channels for input capture/output compare, PWM or one-pulse mode output. They can work together, or with the other general-purpose timers via the Timer Link feature for synchronization or event chaining.

  The counters can be frozen in debug mode.

  All have independent DMA request generation and support quadrature encoders.

- TIM15, 16 and 17

  They are general-purpose timers with mid-range features:

  They have 16-bit auto-reload upcounters and 16-bit prescalers.

  - TIM15 has 2 channels and 1 complementary channel
  - TIM16 and TIM17 have 1 channel and 1 complementary channel

  All channels can be used for input capture/output compare, PWM or one-pulse mode output.

  The timers can work together via the Timer Link feature for synchronization or event chaining. The timers have independent DMA request generation.

  The counters can be frozen in debug mode.

3.24.4 Basic timers (TIM6 and TIM7)

The basic timers are mainly used for DAC trigger generation. They can also be used as generic 16-bit timebases.

3.24.5 Low-power timer (LPTIM1)

The devices embed a low-power timer. This timer has an independent clock and are running in Stop mode if it is clocked by LSE, LSI or an external clock. It is able to wakeup the system from Stop mode.

LPTIM1 is active in Stop mode.

This low-power timer supports the following features:

- 16-bit up counter with 16-bit autoreload register
- 16-bit compare register
- Configurable output: pulse, PWM
- Continuous/ one shot mode
- Selectable software/hardware input trigger
- Selectable clock source
  - Internal clock sources: LSE, LSI, HSI16 or APB clock
  - External clock source over LPTIM input (working even with no internal clock source running, used by pulse counter application).
- Programmable digital glitch filter
- Encoder mode

3.24.6 Independent watchdog (IWDG)

The independent watchdog is based on a 12-bit downcounter and an 8-bit prescaler. It is clocked from an independent 32 kHz internal RC (LSI) and as it operates independently from the main clock, it can operate in Stop and Standby modes. It can be used either as a watchdog to reset the device when a problem occurs, or as a free running timer for application timeout management. It is hardware or software configurable through the option bytes. The counter can be frozen in debug mode.

3.24.7 System window watchdog (WWDG)

The window watchdog is based on a 7-bit downcounter that can be set as free running. It can be used as a watchdog to reset the device when a problem occurs. It is clocked from the main clock. It has an early warning interrupt capability and the counter can be frozen in debug mode.

3.24.8 SysTick timer

This timer is dedicated to real-time operating systems, but could also be used as a standard down counter. It features:

- A 24-bit down counter
- Autoreload capability
- Maskable system interrupt generation when the counter reaches 0.
- Programmable clock source

3.25 Real-time clock (RTC) and backup registers

The RTC supports the following features:

- Calendar with subsecond, seconds, minutes, hours (12 or 24 format), week day, date, month, year, in BCD (binary-coded decimal) format.
- Automatic correction for 28, 29 (leap year), 30, and 31 days of the month.
- Two programmable alarms.
- On-the-fly correction from 1 to 32767 RTC clock pulses. This can be used to synchronize it with a master clock.
- Reference clock detection: a more precise second source clock (50 or 60 Hz) can be used to enhance the calendar precision.
- Digital calibration circuit with 0.95 ppm resolution, to compensate for quartz crystal inaccuracy.
- Timestamp feature which can be used to save the calendar content. This function can be triggered by an event on the timestamp pin, or by a tamper event, or by a switch to V_{BAT} mode.
- 17-bit auto-reload wakeup timer (WUT) for periodic events with programmable resolution and period.

The RTC is supplied through a switch that takes power either from the V_{DD} supply when present or from the VBAT pin.

The RTC clock sources can be:

- A 32.768 kHz external crystal (LSE)
- An external resonator or oscillator (LSE)
- The internal low power RC oscillator (LSI, with typical frequency of 32 kHz)
- The high-speed external clock (HSE) divided by 32.

The RTC is functional in V_{BAT} mode and in all low-power modes when it is clocked by the LSE. When clocked by the LSI, the RTC is not functional in V_{BAT} mode, but is functional in all low-power modes except Shutdown mode.

All RTC events (Alarm, WakeUp Timer, Timestamp) can generate an interrupt and wakeup the device from the low-power modes.

3.26 Tamper and backup registers (TAMP)

- 32 32-bit backup registers, retained in all low-power modes and also in V_{BAT} mode. They can be used to store sensitive data as their content is protected by an tamper detection circuit. They are not reset by a system or power reset, or when the device wakes up from Standby or Shutdown mode.
- Up to three tamper pins for external tamper detection events. The external tamper pins can be configured for edge detection, edge and level, level detection with filtering.
- Five internal tampers events.
- Any tamper detection can generate a RTC timestamp event.
- Any tamper detection erases the backup registers.
- Any tamper detection can generate an interrupt and wake-up the device from all low-power modes.

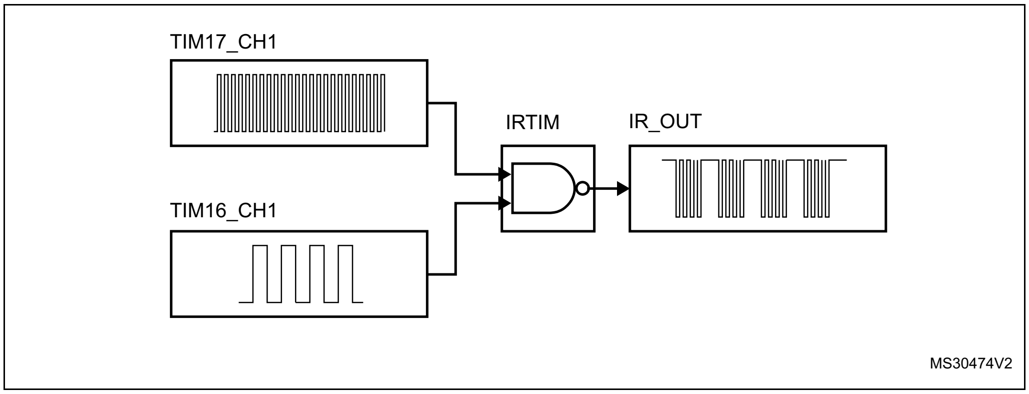
3.27 Infrared transmitter

The STM32G474xB/xC/xE devices provide an infrared transmitter solution. The solution is based on internal connections between TIM16 and TIM17 as shown in the figure below.

TIM17 is used to provide the carrier frequency and TIM16 provides the main signal to be sent. The infrared output signal is available on PB9 or PA13.

To generate the infrared remote control signals, TIM16 channel 1 and TIM17 channel 1 must be properly configured to generate correct waveforms. All standard IR pulse modulation modes can be obtained by programming the two timers output compare channels.

Figure 4. Infrared transmitter



3.28 Inter-integrated circuit interface (I^2C)

The device embeds four I2Cs. Refer to *Table 8: I2C implementation* for the features implementation.

The I^2C bus interface handles communications between the microcontroller and the serial I^2C bus. It controls all I^2C bus-specific sequencing, protocol, arbitration and timing.

The I2C peripheral supports:

- I^2C-bus specification and user manual rev. 5 compatibility:
  - Slave and master modes, multimaster capability
  - Standard-mode (Sm), with a bitrate up to 100 kbit/s
  - Fast-mode (Fm), with a bitrate up to 400 kbit/s
  - Fast-mode Plus (Fm+), with a bitrate up to 1 Mbit/s and 20 mA output drive I/Os
  - 7-bit and 10-bit addressing mode, multiple 7-bit slave addresses
  - Programmable setup and hold times
  - Optional clock stretching
- System management bus (SMBus) specification rev 2.0 compatibility:
  - Hardware PEC (packet error checking) generation and verification with ACK control
  - Address resolution protocol (ARP) support
  - SMBus alert
- Power system management protocol (PMBus^{TM}) specification rev 1.1 compatibility
- Independent clock: a choice of independent clock sources allowing the I2C communication speed to be independent from the PCLK reprogramming.
- Wakeup from Stop mode on address match
- Programmable analog and digital noise filters
- 1-byte buffer with DMA capability

Table 8. I2C implementation

I2C features(1)	I2C1	I2C2	I2C3	I2C4
Standard-mode (up to 100 kbit/s)	X	X	X	X
Fast-mode (up to 400 kbit/s)	X	X	X	X
Fast-mode Plus with 20mA output drive I/Os (up to 1 Mbit/s)	X	X	X	X
Programmable analog and digital noise filters	X	X	X	X
SMBus/PMBus hardware support	X	X	X	X
Independent clock	X	X	X	X
Wakeup from Stop mode on address match	X	X	X	X

1. X: supported

3.29 Universal synchronous/asynchronous receiver transmitter (USART)

The STM32G474xB/xC/xE devices have three embedded universal synchronous receiver transmitters (USART1, USART2 and USART3) and two universal asynchronous receiver transmitters (UART4, USART5).

These interfaces provide asynchronous communication, IrDA SIR ENDEC support, multiprocessor communication mode, single-wire half-duplex communication mode and have LIN master/slave capability. They provide hardware management of the CTS and RTS signals, and RS485 driver enable.

The USART1, USART2 and USART3 also provide a Smartcard mode (ISO 7816 compliant) and an SPI-like communication capability.

The USART comes with a Transmit FIFO (TXFIFO) and a Receive FIFO (RXFIFO). FIFO mode is enabled by software and is disabled by default.

All USART have a clock domain independent from the CPU clock, allowing the U(S)ARTx (x=1,2,3,4,5) to wake up the MCU from Stop mode. The wakeup from Stop mode can be done on:

- Start bit detection
- Any received data frame
- A specific programmed data frame
- Some specific TXFIFO/RXFIFO status interrupts when FIFO mode is enabled

All USART interfaces can be served by the DMA controller.

Table 9. USART/UART/LPUART features

USART modes/features(1)	USART1	USART2	USART3	UART4	UART5	LPUART1
Hardware flow control for modem	X	X	X	X	X	X
Continuous communication using DMA	X	X	X	X	X	X
Multiprocessor communication	X	X	X	X	X	X
Synchronous mode	X	X	X	-	-	-
Smartcard mode	X	X	X	-	-	-
Single-wire half-duplex communication	X	X	X	X	X	X
IrDA SIR ENDEC block	X	X	X	X	X	-
LIN mode	X	X	X	X	X	-
Dual clock domain	X	X	X	X	X	X
Wakeup from Stop mode	X	X	X	X	X	X
Receiver timeout interrupt	X	X	X	X	X	-
Modbus communication	X	X	X	X	X	-
Auto baud rate detection	X (4 modes)					-
Driver Enable	X	X	X	X	X	X
LPUART/USART data length	7, 8 and 9 bits					

Table 9. USART/UART/LPUART features (continued)

USART modes/features[1]	USART1	USART2	USART3	UART4	UART5	LPUART1
Tx/Rx FIFO	X					
Tx/Rx FIFO size	8					

1. X = supported.

3.30 Low-power universal asynchronous receiver transmitter (LPUART)

The STM32G474xB/xC/xE devices embed one Low-Power UART. The LPUART supports asynchronous serial communication with minimum power consumption. It supports half-duplex single-wire communication and modem operations (CTS/RTS). It allows multiprocessor communication.

The LPUART comes with a Transmit FIFO (TXFIFO) and a Receive FIFO (RXFIFO). FIFO mode is enabled by software and is disabled by default. It has a clock domain independent from the CPU clock, and can wakeup the system from Stop mode. The wake up from Stop mode can be done on:

- Start bit detection
- Any received data frame
- A specific programmed data frame
- Some specific TXFIFO/RXFIFO status interrupts when FIFO mode is enabled

Only a 32.768 kHz clock (LSE) is needed to allow LPUART communication up to 9600 baud. Therefore, even in Stop mode, the LPUART can wait for an incoming frame while having an extremely low energy consumption. Higher speed clock can be used to reach higher baudrates.

The LPUART interface can be served by the DMA controller.

3.31 Serial peripheral interface (SPI)

Four SPI interfaces allow communication up to 75 Mbits/s in master and up to 41 Mbits/s in slave, half-duplex, full-duplex and simplex modes. The 3-bit prescaler gives 8 master mode frequencies and the frame size is configurable from 4 bits to 16 bits. The SPI interfaces support NSS pulse mode, TI mode and hardware CRC calculation.

Two standard I^2S interfaces (multiplexed with SPI2 and SPI3) supporting four different audio standards can operate as master or slave at half-duplex communication modes. They can be configured to transfer 16 and 24 or 32 bits with 16-bit or 32-bit data resolution and synchronized by a specific signal. Audio sampling frequency from 8 kHz up to 192 kHz can be set by 8-bit programmable linear prescaler. When operating in master mode it can output a clock for an external audio component at 256 times the sampling frequency.

All SPI interfaces can be served by the DMA controller.

3.32 Serial audio interfaces (SAI)

The device embeds 1 SAI. The SAI bus interface handles communications between the microcontroller and the serial audio protocol.

SAI peripheral supports:

- Two independent audio sub-blocks which can be transmitters or receivers with their respective FIFO.
- 8-word integrated FIFOs for each audio sub-block.
- Synchronous or asynchronous mode between the audio sub-blocks.
- Master or slave configuration independent for both audio sub-blocks.
- Clock generator for each audio block to target independent audio frequency sampling when both audio sub-blocks are configured in master mode.
- Data size configurable: 8-, 10-, 16-, 20-, 24-, 32-bit.
- Peripheral with large configurability and flexibility allowing to target as example the following audio protocol: I2S, LSB or MSB-justified, PCM/DSP, TDM, AC’97 and SPDIF out.
- Up to 16 slots available with configurable size and with the possibility to select which ones are active in the audio frame.
- Number of bits by frame may be configurable.
- Frame synchronization active level configurable (offset, bit length, level).
- First active bit position in the slot is configurable.
- LSB first or MSB first for data transfer.
- Mute mode.
- Stereo/Mono audio frame capability.
- Communication clock strobing edge configurable (SCK).
- Error flags with associated interrupts if enabled respectively.
  - Overrun and underrun detection.
  - Anticipated frame synchronization signal detection in slave mode.
  - Late frame synchronization signal detection in slave mode.
  - Codec not ready for the AC’97 mode in reception.
- Interruption sources when enabled:
  - Errors.
  - FIFO requests.
- DMA interface with 2 dedicated channels to handle access to the dedicated integrated FIFO of each SAI audio sub-block.

Table 10. SAI features implementation

SAI features	Support[1]
I2S, LSB or MSB-justified, PCM/DSP, TDM, AC’97	X
Mute mode	X
Stereo/Mono audio frame capability	X
16 slots	X

Table 10. SAI features implementation (continued)

SAI features	Support[1]
Data size configurable: 8-, 10-, 16-, 20-, 24-, 32-bit	X
FIFO size	X (8 word)
SPDIF	X

1. X: supported.

3.33 Controller area network (FDCAN1, FDCAN2, FDCAN3)

The controller area network (CAN) subsystem consists of three CAN modules and a shared message RAM memory.

The three CAN modules (FDCAN1, FDCAN2 and FDCAN3) are compliant with ISO 11898-1 (CAN protocol specification version 2.0 part A, B) and CAN FD protocol specification version 1.0.

A 3-Kbyte message RAM memory implements filters, receive FIFOs, receive buffers, transmit event FIFOs, transmit buffers. This message RAM is shared between the three FDCAN modules.

3.34 Universal serial bus (USB)

The STM32G474xB/xC/xE devices embed a full-speed USB device peripheral compliant with the USB specification version 2.0. The internal USB PHY supports USB FS signaling, embedded DP pull-up and also battery charging detection according to Battery Charging Specification Revision 1.2. The USB interface implements a full-speed (12 Mbit/s) function interface with added support for USB 2.0 Link Power Management. It has software-configurable endpoint setting with packet memory up-to 1 Kbyte and suspend/resume support. It requires a precise 48 MHz clock which can be generated from the internal main PLL (the clock source must use a HSE crystal oscillator) or by the internal 48 MHz oscillator in automatic trimming mode. The synchronization for this oscillator can be taken from the USB data stream itself (SOF signalization) which allows crystal less operation.

3.35 USB Type-C™ / USB Power Delivery controller (UCPD)

The device embeds one controller (UCPD) compliant with USB Type-C Rev. 1.2 and USB Power Delivery Rev. 3.0 specifications.

The controller uses specific I/Os supporting the USB Type-C and USB Power Delivery requirements, featuring:

- USB Type-C pull-up (Rp, all values) and pull-down (Rd) resistors
- “Dead battery” support
- USB Power Delivery message transmission and reception
- FRS (fast role swap) support

The digital controller handles notably:

- USB Type-C level detection with de-bounce, generating interrupts
- FRS detection, generating an interrupt
- Byte-level interface for USB Power Delivery payload, generating interrupts (DMA compatible)
- USB Power Delivery timing dividers (including a clock pre-scaler)
- CRC generation/checking
- 4b5b encode/decode
- Ordered sets (with a programmable ordered set mask at receive)
- Frequency recovery in receiver during preamble

The interface offers low-power operation compatible with Stop mode, maintaining the capacity to detect incoming USB Power Delivery messages and FRS signaling.

3.36 Clock recovery system (CRS)

The devices embed a special block which allows automatic trimming of the internal 48 MHz oscillator to guarantee its optimal accuracy over the whole device operational range. This automatic trimming is based on the external synchronization signal, which could be either derived from USB SOF signalization, from LSE oscillator, from an external signal on CRS_SYNC pin or generated by user software. For faster lock-in during startup it is also possible to combine automatic trimming with manual trimming action.

3.37 Flexible static memory controller (FSMC)

The Flexible static memory controller (FSMC) includes two memory controllers:

- The NOR/PSRAM memory controller
- The NAND/memory controller

This memory controller is also named Flexible memory controller (FMC).

The main features of the FMC controller are the following:

- Interface with static-memory mapped devices including:
  - Static random access memory (SRAM)
  - NOR Flash memory/OneNAND Flash memory
  - PSRAM (4 memory banks)
  - NAND Flash memory with ECC hardware to check up to 8 Kbytes of data
  - Ferroelectric RAM (FRAM)
- 8-,16- bit data bus width
- Independent Chip Select control for each memory bank
- Independent configuration for each memory bank
- Write FIFO
- The Maximum FMC_CLK frequency for synchronous accesses is HCLK/2.

LCD parallel interface

The FMC can be configured to interface seamlessly with most graphic LCD controllers. It supports the Intel 8080 and Motorola 6800 modes, and is flexible enough to adapt to specific LCD interfaces. This LCD parallel interface capability makes it easy to build cost effective graphic applications using LCD modules with embedded controllers or high performance solutions using external controllers with dedicated acceleration.

3.38 Quad-SPI memory interface (QUADSPI)

The Quad-SPI is a specialized communication interface targeting single, dual or quad SPI Flash memories. It can operate in any of the three following modes:

- Indirect mode: all the operations are performed using the QUADSPI registers
- Status polling mode: the external Flash status register is periodically read and an interrupt can be generated in case of flag setting
- Memory-mapped mode: the external Flash is memory mapped and is seen by the system as if it were an internal memory.

Both throughput and capacity can be increased two-fold using dual-flash mode, where two quad SPI Flash memories are accessed simultaneously.

The Quad-SPI interface supports:

- Indirect mode: all the operations are performed using the QUADSPI registers
- Status polling mode: the external Flash status register is periodically read and an interrupt can be generated in case of flag setting
- Memory-mapped mode: the external Flash is memory mapped and is seen by the system as if it were an internal memory
- Three functional modes: indirect, status-polling, and memory-mapped
- SDR and DDR support
- Fully programmable opcode for both indirect and memory mapped mode
- Fully programmable frame format for both indirect and memory mapped mode
  - Each of the 5 following phases can be configured independently (enable, length, single/dual/quad communication)
  - Instruction phase
  - Address phase
  - Alternate bytes phase
  - Dummy cycles phase
  - Data phase
- Integrated FIFO for reception and transmission
- 8, 16, and 32-bit data accesses are allowed
- DMA channel for indirect mode operations
- Programmable masking for external Flash flag management
- Timeout management
- Interrupt generation on FIFO threshold, timeout, status match, operation complete, and access error

3.39 Development support

3.39.1 Serial wire JTAG debug port (SWJ-DP)

The Arm SWJ-DP interface is embedded, and is a combined JTAG and serial wire debug port that enables either a serial wire debug or a JTAG probe to be connected to the target.

Debug is performed using 2 pins only instead of 5 required by the JTAG (JTAG pins could be re-use as GPIO with alternate function): the JTAG TMS and TCK pins are shared with SWDIO and SWCLK, respectively, and a specific sequence on the TMS pin is used to switch between JTAG-DP and SW-DP.

3.39.2 Embedded trace macrocell™

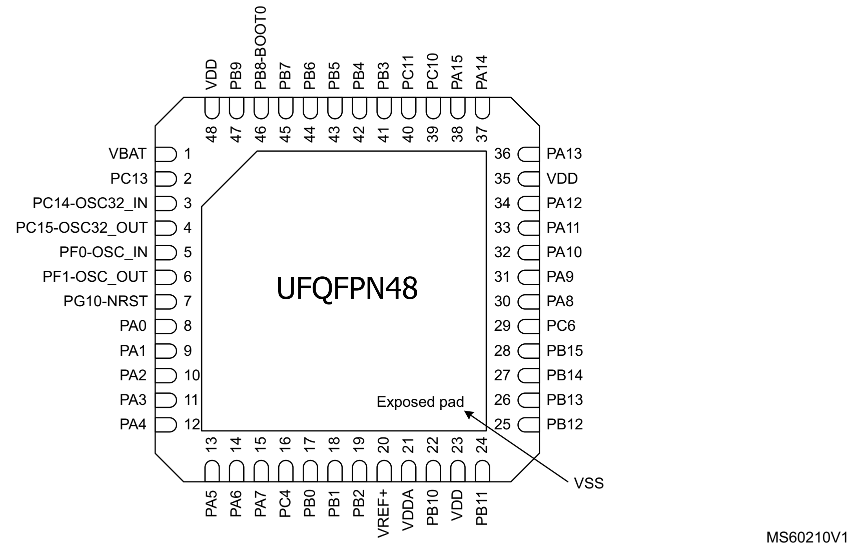
The Arm embedded trace macrocell provides a greater visibility of the instruction and data flow inside the CPU core by streaming compressed data at a very high rate from the STM32G474xB/xC/xE devices through a small number of ETM pins to an external hardware trace port analyzer (TPA) device. Real-time instruction and data flow activity be recorded and then formatted for display on the host computer that runs the debugger software. TPA hardware is commercially available from common development tool vendors.

The Embedded trace macrocell operates with third party debugger software tools.

4 Pinouts and pin description

4.1 UFQFPN48 pinout description

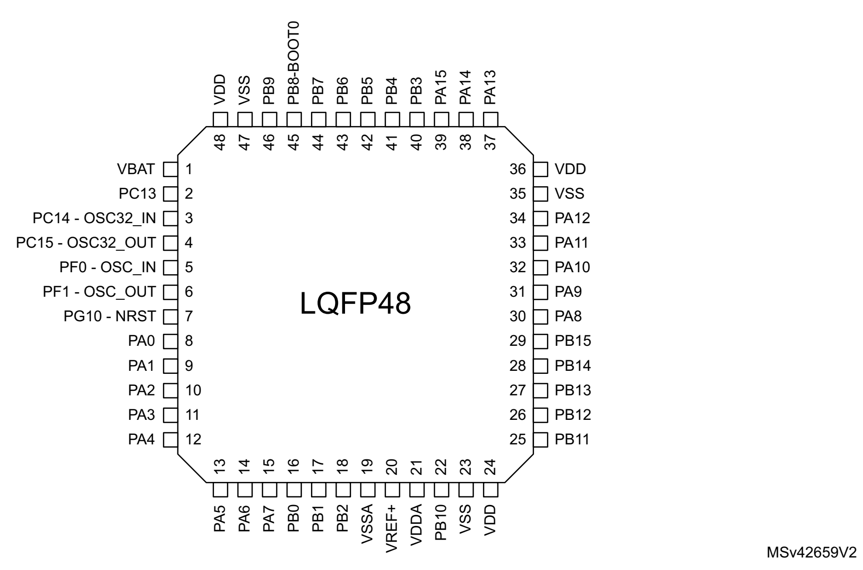
Figure 5. STM32G474xB/xC/xE UFQFPN48 pinout



1. The above figure shows the package top view.
2. VSS pads are connected to the exposed pad.

4.2 LQFP48 pinout description

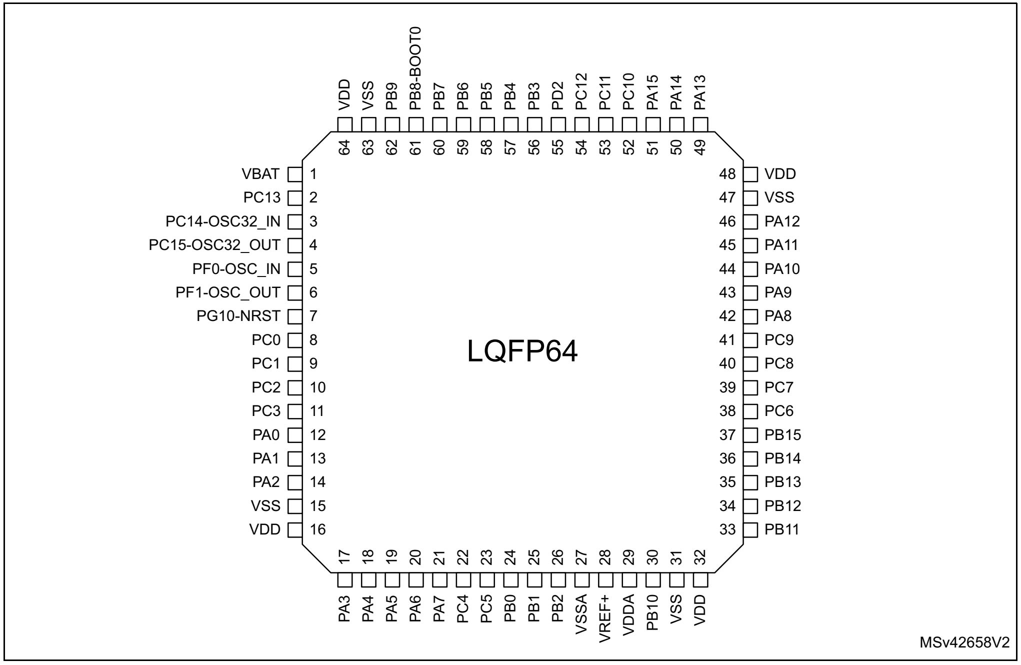
Figure 6. STM32G474xB/xC/xE LQFP48 pinout



1. The above figure shows the package top view.

4.3 LQFP64 pinout description

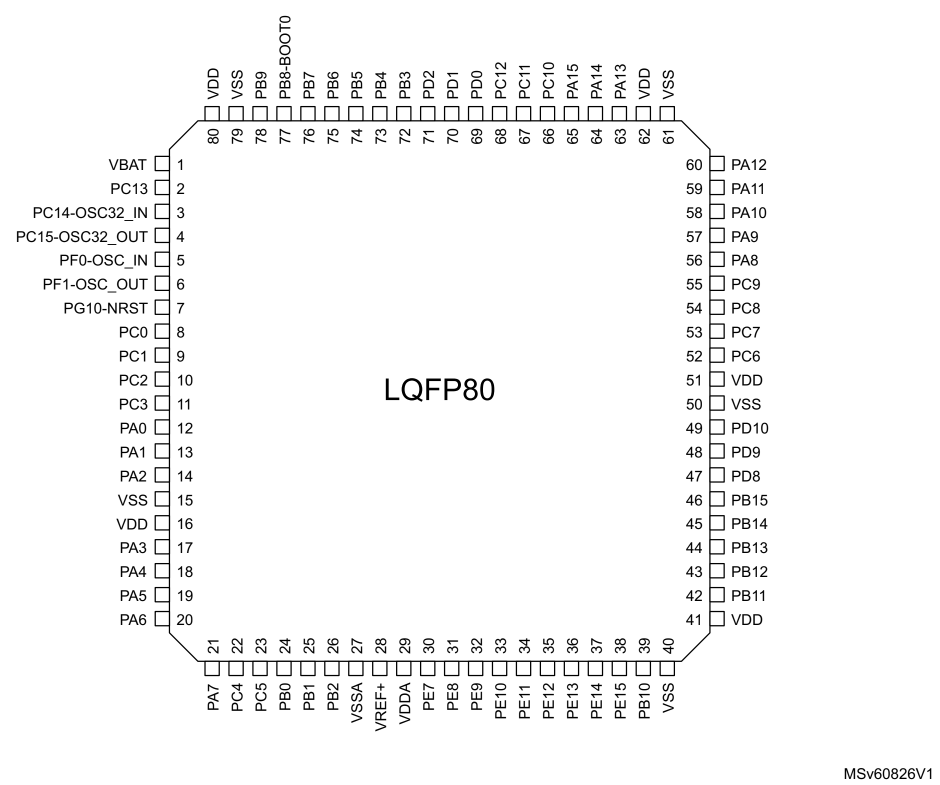
Figure 7. STM32G474xB/xC/xE LQFP64 pinout



1. The above figure shows the package top view.

4.4 LQFP80 pinout description

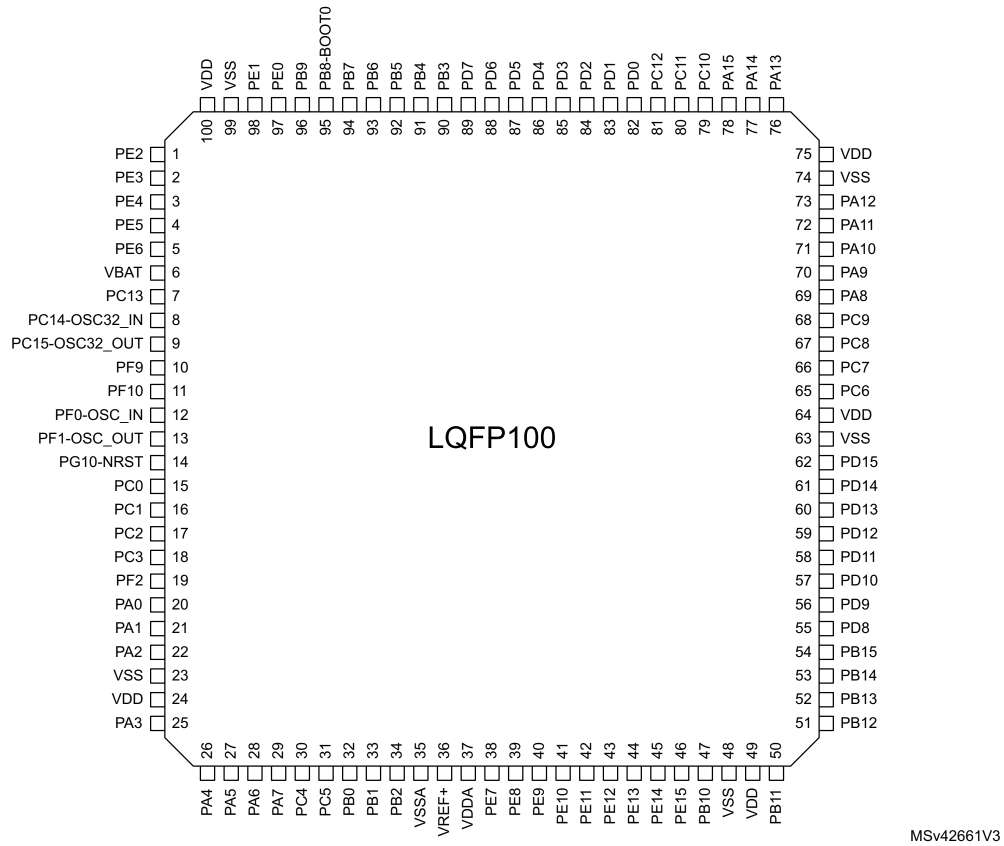
Figure 8. STM32G474xB/xC/xE LQFP80 pinout



1. The above figure shows the package top view.

4.5 LQFP100 pinout description

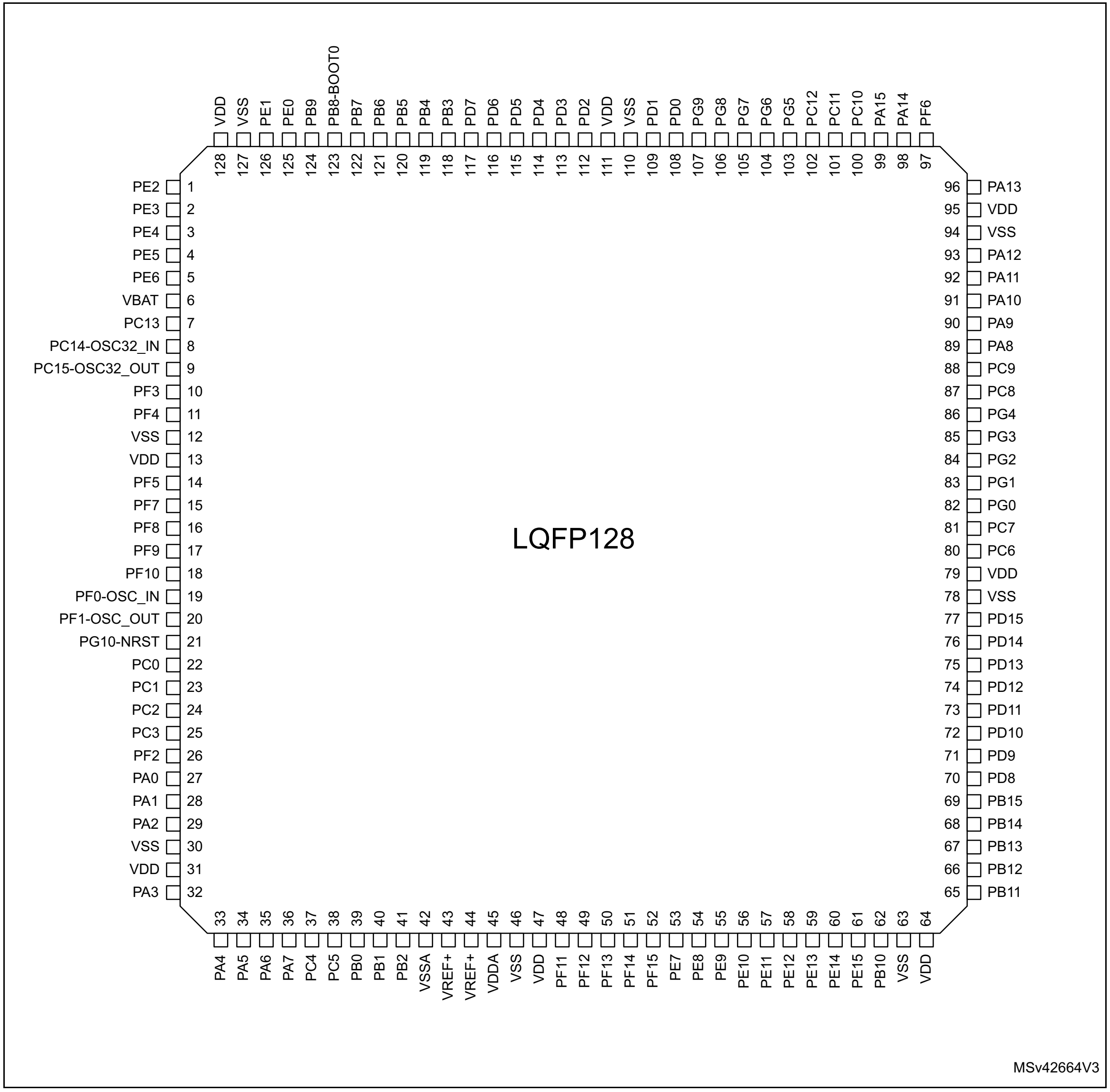
Figure 9. STM32G474xB/xC/xE LQFP100 pinout



1. The above figure shows the package top view.

4.6 LQFP128 pinout description

Figure 10. STM32G474xB/xC/xE LQFP128 pinout



1. The above figure shows the package top view.

4.7 WLCSP81 pinout description

Figure 11. STM32G474xB/xC/xE WLCSP81 pinout

	1	2	3	4	5	6	7	8	9
A	VDD	PA15	PC12	PD1	PB3	PB5	PB9	VSS	VDD
B	VSS	PA13	PC10	PD0	PD2	PB6	PB8-BOOT0	PC13	VBAT
C	PA12	PA11	PA14	PC11	PC8	PB4	PB7	PC1	PC14-OSC32_IN
D	PA8	PC9	PA10	PA9	PC7	PA4	PA0	PG10-NRST	PC15-OSC32_OUT
E	VDD	PD11	PC6	PB15	PE12	PC4	PA1	PC0	PF0-OSC_IN
F	VSS	PD10	PD9	PE15	PE9	PB0	PA5	PC2	PF1-OSC_OUT
G	PD8	PB14	PB12	PE13	PE8	PB1	PA6	PA2	PC3
H	PB13	PB11	PB10	PE11	PE7	VSSA	PC5	PA3	VSS
J	VDD	VSS	PE14	PE10	VDDA	VREF+	PB2	PA7	VDD

MSv48046V1

1. The above figure shows the package top view.

4.8 TFBGA100 pinout description

Figure 12. STM32G474xB/xC/xE TFBGA100 pinout

	1	2	3	4	5	6	7	8	9	10
A	PE4	PB9	PB8-BOOT0	PB6	PB3	PD6	PD5	PD4	PD1	PC12
B	PE5	PE3	PE1	PB7	PB5	PD7	PD2	PD0	PA15	PA14
C	PC14-OSC32_IN	PE6	PE2	PE0	PB4	PD3	PC11	PC10	PA12	PA11
D	PC15-OSC32_OUT	VSS	VBAT	PC13	VDD	VSS	VDD	PA13	PA10	PA9
E	PF0-OSC_IN	PF1-OSC_OUT	PF9	PF10	VSS	VSS	VSS	PC8	PC9	PA8
F	PC2	PC0	PG10-NRST	PC1	VDD	VSS	VDD	PD14	PC6	PC7
G	PC3	PA1	PF2	PA0	PE7	PE12	PD10	PD9	PD13	PD15
H	PA2	PA4	PA3	PB0	PE8	PE9	PE15	PB11	PB14	PD11
J	PA5	PA6	PC5	PB2	VDDA	PE11	PE14	PB10	PB13	PD12
K	PA7	PC4	PB1	VSSA	VREF+	PE10	PE13	PB12	PB15	PD8

MS48951V1

1. The above figure shows the package top view.

4.9 UFBGA121 pinout description

Figure 13. STM32G474xB/xC/xE UFBGA121 pinout

	1	2	3	4	5	6	7	8	9	10	11
A	PE4	PE2	VDD	PB9	PB6	PB3	PD4	VDD	PD1	PA15	PF6
B	PE5	PE3	VSS	PE0	PB5	PD7	PD3	VSS	PD0	PA14	PA13
C	PC13	VBAT	PE6	PE1	PB7	PB4	PD2	PC11	PC10	VSS	VDD
D	PC14-OSC32_IN	PC15-OSC32_OUT	PF3	PF4	PB8-BOOT0	PD6	PC12	PA9	PA10	PA12	PA11
E	VDD	VSS	PF5	PF7	PF8	PD5	PA8	PC9	PC8	PG4	PG3
F	PF0-OSC_IN	PF1-OSC_OUT	PF9	PF10	PG10-NRST	PD15	PG2	PG1	PG0	PC6	PC7
G	PC1	PC0	PC2	PA0	PB1	PF15	PD11	PD12	PD13	PD14	VDD
H	PC3	PF2	PA1	PC5	PF12	PF14	PE10	PB15	PD8	PD9	PD10
J	VDD	VSS	PA2	PB0	PF11	PF13	PE9	PE13	PB12	PB14	PB13
K	PA3	PA5	PA7	PB2	VSSA	VSS	PE8	PE12	PE14	VSS	VDD
L	PA4	PA6	PC4	VREF+	VDDA	VDD	PE7	PE11	PE15	PB10	PB11

MS52876V1

1. The above figure shows the package top view.

4.10 Pin definition

Table 11. Legend/abbreviations used in the pinout table

Name	Abbreviation	Definition
Pin name	Unless otherwise specified in brackets below the pin name, the pin function during and after reset is the same as the actual pin name	
Pin type	S	Supply pin
	I	Input only pin
	I/O	Input / output pin
I/O structure	FT	5 V tolerant I/O
	TT	3.6 V tolerant I/O
	B	Dedicated BOOT0 pin
	NRST	Bidirectional reset pin with embedded weak pull-up resistor
	Option for TT or FT I/Os	
	_a(1)	I/O, with Analog switch function supplied by V_{DDA}
	_c	I/O, USB Type-C PD capable
	_d	I/O, USB Type-C PD Dead Battery function
	_f(2)	I/O, Fm+ capable
	_u(3)	I/O, with USB function
Notes	Unless otherwise specified by a note, all I/Os are set as floating inputs during and after reset	
Pin functions	Alternate functions	Functions selected through GPIOx_AFR registers
	Additional functions	Functions directly selected/enabled through peripheral registers

1. The related I/O structures in *Table 12* are: FT_a, FT_fa, TT_a.
2. The related I/O structures in *Table 12* are: FT_f, FT_fa.
3. The related I/O structures in *Table 12* are FT_u.

Table 12. STM32G474xB/xC/xE pin definition

Pin Number									Pin name (function after reset)(1)	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
-	-	-	-	-	C3	1	A2	1	PE2	I/O	FT	-	TRACECK, TIM3_CH1, SAI1_CK1, SPI4_SCK, TIM20_CH1, FMC_A23, SAI1_MCLK_A, EVENTOUT	-
-	-	-	-	-	B2	2	B2	2	PE3	I/O	FT	-	TRACED0, TIM3_CH2, SPI4_NSS, TIM20_CH2, FMC_A19, SAI1_SD_B, EVENTOUT	-
-	-	-	-	-	A1	3	A1	3	PE4	I/O	FT	-	TRACED1, TIM3_CH3, SAI1_D2, SPI4_NSS, TIM20_CH1N, FMC_A20, SAI1_FS_A, EVENTOUT	-
-	-	-	-	-	B1	4	B1	4	PE5	I/O	FT	-	TRACED2, TIM3_CH4, SAI1_CK2, SPI4_MISO, TIM20_CH2N, FMC_A21, SAI1_SCK_A, EVENTOUT	-
-	-	-	-	-	C2	5	C3	5	PE6	I/O	FT	-	TRACED3, SAI1_D1, SPI4_MOSI, TIM20_CH3N, FMC_A22, SAI1_SD_A, EVENTOUT	WKUP3, RTC_TAMP3
B9	1	1	1	1	D3	6	C2	6	VBAT	S	-	-	-	-
B8	2	2	2	2	D4	7	C1	7	PC13	I/O	FT	(2) (3)	TIM1_BKIN, TIM1_CH1N, TIM8_CH4N, EVENTOUT	WKUP2, RTC_TAMP1, RTC_TS, RTC_OUT1
C9	3	3	3	3	C1	8	D1	8	PC14-OSC32_IN	I/O	FT	(2) (3)	EVENTOUT	OSC32_IN
D9	4	4	4	4	D1	9	D2	9	PC15-OSC32_OUT	I/O	FT	(2) (3)	EVENTOUT	OSC32_OUT
-	-	-	-	-	-	-	D3	10	PF3	I/O	FT_f	-	TIM20_CH4, I2C3_SCL, FMC_A3, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)(1)	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
-	-	-	-	-	-	-	D4	11	PF4	I/O	FT_f	-	COMP1_OUT, TIM20_CH1N, I2C3_SDA, FMC_A4, EVENTOUT	-
F1	-	-	-	-	D2	-	E2	12	VSS	S	-	-	-	-
A9	-	-	-	-	D5	-	E1	13	VDD	S	-	-	-	-
-	-	-	-	-	-	-	E3	14	PF5	I/O	FT	-	TIM20_CH2N, FMC_A5, EVENTOUT	-
-	-	-	-	-	-	-	E4	15	PF7	I/O	FT	-	TIM20_BKIN, TIM5_CH2, QUADSPI1_BK1_IO2, FMC_A1, SAI1_MCLK_B, EVENTOUT	-
-	-	-	-	-	-	-	E5	16	PF8	I/O	FT	-	TIM20_BKIN2, TIM5_CH3, QUADSPI1_BK1_IO0, FMC_A24, SAI1_SCK_B, EVENTOUT	-
-	-	-	-	-	E3	10	F3	17	PF9	I/O	FT	-	TIM20_BKIN, TIM15_CH1, SPI2_SCK, TIM5_CH4, QUADSPI1_BK1_IO1, FMC_A25, SAI1_FS_B, EVENTOUT	-
-	-	-	-	-	E4	11	F4	18	PF10	I/O	FT	-	TIM20_BKIN2, TIM15_CH2, SPI2_SCK, QUADSPI1_CLK, FMC_A0, SAI1_D3, EVENTOUT	-
E9	5	5	5	5	E1	12	F1	19	PF0-OSC_IN	I/O	FT_fa	-	I2C2_SDA, SPI2_NSS/I2S2_WS, TIM1_CH3N, EVENTOUT	ADC1_IN10, OSC_IN
F9	6	6	6	6	E2	13	F2	20	PF1-OSC_OUT	I/O	FT_a	-	SPI2_SCK/I2S2_CK, EVENTOUT	ADC2_IN10, COMP3_INM, OSC_OUT
D8	7	7	7	7	F3	14	F5	21	PG10-NRST	I/O	NRST (4)	-	MCO, EVENTOUT	NRST

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)(1)	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
E8	-	-	8	8	F2	15	G2	22	PC0	I/O	FT_a	-	LPTIM1_IN1, TIM1_CH1, LPUART1_RX, EVENTOUT	ADC12_IN6, COMP3_INM
C8	-	-	9	9	F4	16	G1	23	PC1	I/O	TT_a	-	LPTIM1_OUT, TIM1_CH2, LPUART1_TX, QUADSPI1_BK2_IO0, SAI1_SD_A, EVENTOUT	ADC12_IN7, COMP3_INP
F8	-	-	10	10	F1	17	G3	24	PC2	I/O	FT_a	-	LPTIM1_IN2, TIM1_CH3, COMP3_OUT, TIM20_CH2, QUADSPI1_BK2_IO1, EVENTOUT	ADC12_IN8
G9	-	-	11	11	G1	18	H1	25	PC3	I/O	TT_a	-	LPTIM1_ETR, TIM1_CH4, SAI1_D1, TIM1_BKIN2, QUADSPI1_BK2_IO2, SAI1_SD_A, EVENTOUT	ADC12_IN9, OPAMP5_VINP
-	-	-	-	-	G3	19	H2	26	PF2	I/O	FT	-	TIM20_CH3, I2C2_SMBA, FMC_A2, EVENTOUT	-
D7	8	8	12	12	G4	20	G4	27	PA0	I/O	TT_a	-	TIM2_CH1, TIM5_CH1, USART2_CTS, COMP1_OUT, TIM8_BKIN, TIM8_ETR, TIM2_ETR, EVENTOUT	ADC12_IN1, COMP1_INM, COMP3_INP, RTC_TAMP2,WKUP1
E7	9	9	13	13	G2	21	H3	28	PA1	I/O	TT_a	-	RTC_REFIN, TIM2_CH2, TIM5_CH2, USART2_RTS_DE, TIM15_CH1N, EVENTOUT	ADC12_IN2, COMP1_INP, OPAMP1_VINP, OPAMP3_VINP, OPAMP6_VINM
G8	10	10	14	14	H1	22	J3	29	PA2	I/O	FT_a	-	TIM2_CH3, TIM5_CH3, USART2_TX, COMP2_OUT, TIM15_CH1, QUADSPI1_BK1_NCS, LPUART1_TX, UCPD1_FRSTX, EVENTOUT	ADC1_IN3, COMP2_INM, OPAMP1_VOUT, WKUP4/LSCO

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)(1)	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
H9	-	-	15	15	D6	23	J2	30	VSS	S	-	-	-	-
J9	-	-	16	16	D7	24	J1	31	VDD	S	-	-	-	-
H8	11	11	17	17	H3	25	K1	32	PA3	I/O	TT_a	-	TIM2_CH4, TIM5_CH4, SAI1_CK1, USART2_RX, TIM15_CH2, QUADSPI1_CLK, LPUART1_RX, SAI1_MCLK_A, EVENTOUT	ADC1_IN4, COMP2_INP, OPAMP1_VINM/ OPAMP 1_VINP, OPAMP5_VINM
D6	12	12	18	18	H2	26	L1	33	PA4	I/O	TT_a	-	TIM3_CH2, SPI1_NSS, SPI3_NSS/I2S3_WS, USART2_CK, SAI1_FS_B, EVENTOUT	ADC2_IN17, DAC1_OUT1, COMP1_INM
F7	13	13	19	19	J1	27	K2	34	PA5	I/O	TT_a	-	TIM2_CH1, TIM2_ETR, SPI1_SCK, UCPD1_FRSTX, EVENTOUT	ADC2_IN13, DAC1_OUT2, COMP2_INM, OPAMP2_VINM
G7	14	14	20	20	J2	28	L2	35	PA6	I/O	TT_a	-	TIM16_CH1, TIM3_CH1, TIM8_BKIN, SPI1_MISO, TIM1_BKIN, COMP1_OUT, QUADSPI1_BK1_IO3, LPUART1_CTS, EVENTOUT	ADC2_IN3, DAC2_OUT1, OPAMP2_VOUT
J8	15	15	21	21	K1	29	K3	36	PA7	I/O	TT_a	-	TIM17_CH1, TIM3_CH2, TIM8_CH1N, SPI1_MOSI, TIM1_CH1N, COMP2_OUT, QUADSPI1_BK1_IO2, UCPD1_FRSTX, EVENTOUT	ADC2_IN4, COMP2_INP, OPAMP1_VINP, OPAMP2_VINP
E6	16	-	22	22	K2	30	L3	37	PC4	I/O	FT_fa	-	TIM1_ETR, I2C2_SCL, USART1_TX, QUADSPI1_BK2_IO3, EVENTOUT	ADC2_IN5

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)(1)	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
H7	-	-	23	23	J3	31	H4	38	PC5	I/O	TT_a	-	TIM15_BKIN, SAI1_D3, TIM1_CH4N, USART1_RX, HRTIM1_EEV10, EVENTOUT	ADC2_IN11, OPAMP1_VINM, OPAMP2_VINM, WKUP5
F6	17	16	24	24	H4	32	J4	39	PB0	I/O	TT_a	-	TIM3_CH3, TIM8_CH2N, TIM1_CH2N, QUADSPI1_BK1_IO1, HRTIM1_FLT5, UCPD1_FRSTX, EVENTOUT	ADC3_IN12/ ADC1_IN15, COMP4_INP, OPAMP2_VINP, OPAMP3_VINP
G6	18	17	25	25	K3	33	G5	40	PB1	I/O	TT_a	-	TIM3_CH4, TIM8_CH3N, TIM1_CH3N, COMP4_OUT, QUADSPI1_BK1_IO0, LPUART1_RTS_DE,HRTIM1_SCOUT, EVENTOUT	ADC3_IN1/ ADC1_IN12, COMP1_INP, OPAMP3_VOUT, OPAMP6_VINM
J7	19	18	26	26	J4	34	K4	41	PB2	I/O	TT_a	-	RTC_OUT2, LPTIM1_OUT, TIM5_CH1, TIM20_CH1, I2C3_SMBA, QUADSPI1_BK2_IO1, HRTIM1_SCIN, EVENTOUT	ADC2_IN12, COMP4_INM, OPAMP3_VINM
H6	-	19	27	27	K4	35	K5	42	VSSA	S	-	-	-	-
J6	20	20	28	28	K5	36	L4	43	VREF+	S	-	-	-	VREFBUF_OUT
-	-	-	-	-	-	-	-	44	VREF+	S	-	-	-	VREFBUF_OUT
J5	21	21	29	29	J5	37	L5	45	VDDA	S	-	-	-	-
H9	-	-	-	-	E5	-	K6	46	VSS	S	-	-	-	-
J1	-	-	-	-	F5	-	L6	47	VDD	S	-	-	-	-
-	-	-	-	-	-	-	J5	48	PF11	I/O	FT	-	TIM20_ETR, FMC_NE4, EVENTOUT	-
-	-	-	-	-	-	-	H5	49	PF12	I/O	FT	-	TIM20_CH1, FMC_A6, EVENTOUT	-
-	-	-	-	-	-	-	J6	50	PF13	I/O	FT	-	TIM20_CH2, I2C4_SMBA, FMC_A7, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)[(1)]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
-	-	-	-	-	-	-	H6	51	PF14	I/O	FT_f	-	TIM20_CH3, I2C4_SCL, FMC_A8, EVENTOUT	-
-	-	-	-	-	-	-	G6	52	PF15	I/O	FT_f	-	TIM20_CH4, I2C4_SDA, FMC_A9, EVENTOUT	-
H5	-	-	-	30	G5	38	L7	53	PE7	I/O	TT_a	-	TIM1_ETR, FMC_D4, SAI1_SD_B, EVENTOUT	ADC3_IN4, COMP4_INP
G5	-	-	-	31	H5	39	K7	54	PE8	I/O	FT_a	-	TIM5_CH3, TIM1_CH1N, FMC_D5, SAI1_SCK_B, EVENTOUT	ADC345_IN6, COMP4_INM
F5	-	-	-	32	H6	40	J7	55	PE9	I/O	FT_a	-	TIM5_CH4, TIM1_CH1, FMC_D6, SAI1_FS_B, EVENTOUT	ADC3_IN2
J4	-	-	-	33	K6	41	H7	56	PE10	I/O	FT_a	-	TIM1_CH2N, QUADSPI1_CLK, FMC_D7, SAI1_MCLK_B, EVENTOUT	ADC345_IN14
H4	-	-	-	34	J6	42	L8	57	PE11	I/O	FT_a	-	TIM1_CH2, SPI4_NSS, QUADSPI1_BK1_NCS, FMC_D8, EVENTOUT	ADC345_IN15
E5	-	-	-	35	G6	43	K8	58	PE12	I/O	FT_a	-	TIM1_CH3N, SPI4_SCK, QUADSPI1_BK1_IO0, FMC_D9, EVENTOUT	ADC345_IN16
G4	-	-	-	36	K7	44	J8	59	PE13	I/O	FT_a	-	TIM1_CH3, SPI4_MISO, QUADSPI1_BK1_IO1, FMC_D10, EVENTOUT	ADC3_IN3
J3	-	-	-	37	J7	45	K9	60	PE14	I/O	FT_a	-	TIM1_CH4, SPI4_MOSI, TIM1_BKIN2, QUADSPI1_BK1_IO2, FMC_D11, EVENTOUT	ADC4_IN1

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)[1]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
F4	-	-	-	38	H7	46	L9	61	PE15	I/O	FT_a	-	TIM1_BKIN, TIM1_CH4N, USART3_RX, QUADSPI1_BK1_IO3, FMC_D12, EVENTOUT	ADC4_IN2
H3	22	22	30	39	J8	47	L10	62	PB10	I/O	TT_a	-	TIM2_CH3, USART3_TX, LPUART1_RX, QUADSPI1_CLK, TIM1_BKIN, HRTIM1_FLT3, SAI1_SCK_A, EVENTOUT	COMP5_INM, OPAMP3_VINM, OPAMP4_VINM
J2	-	23	31	40	E6	48	K10	63	VSS	S	-	-	-	-
J1	23	24	32	41	F7	49	K11	64	VDD	S	-	-	-	-
H2	24	25	33	42	H8	50	L11	65	PB11	I/O	TT_a	-	TIM2_CH4, USART3_RX, LPUART1_TX, QUADSPI1_BK1_NCS, HRTIM1_FLT4, EVENTOUT	ADC12_IN14, COMP6_INP, OPAMP4_VINP, OPAMP6_VOUT
G3	25	26	34	43	K8	51	J9	66	PB12	I/O	TT_a	-	TIM5_ETR, I2C2_SMBA, SPI2_NSS/I2S2_WS, TIM1_BKIN, USART3_CK, LPUART1_RTS_DE, FDCAN2_RX, HRTIM1_CHC1, EVENTOUT	ADC4_IN3/ ADC1_IN11, COMP7_INM, OPAMP4_VOUT, OPAMP6_VINP
H1	26	27	35	44	J9	52	J11	67	PB13	I/O	TT_a	-	SPI2_SCK/I2S2_CK, TIM1_CH1N, USART3_CTS, LPUART1_CTS, FDCAN2_TX, HRTIM1_CHC2, EVENTOUT	ADC3_IN5, COMP5_INP, OPAMP3_VINP, OPAMP4_VINP, OPAMP6_VINP
G2	27	28	36	45	H9	53	J10	68	PB14	I/O	TT_a	-	TIM15_CH1, SPI2_MISO, TIM1_CH2N, USART3_RTS_DE, COMP4_OUT, HRTIM1_CHD1, EVENTOUT	ADC4_IN4/ ADC1_IN5, COMP7_INP, OPAMP2_VINP, OPAMP5_VINP

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)[1]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
E4	28	29	37	46	K9	54	H8	69	PB15	I/O	TT_a	-	RTC_REFIN, TIM15_CH2, TIM15_CH1N, COMP3_OUT, TIM1_CH3N, SPI2_MOSI/I2S2_SD, HRTIM1_CHD2, EVENTOUT	ADC4_IN5/ ADC2_IN15, COMP6_INM, OPAMP5_VINM
G1	-	-	-	47	K10	55	H9	70	PD8	I/O	TT_a	-	USART3_TX, FMC_D13, EVENTOUT	ADC4_IN12/ ADC5_IN12, OPAMP4_VINM
F3	-	-	-	48	G8	56	H10	71	PD9	I/O	TT_a	-	USART3_RX, FMC_D14, EVENTOUT	ADC4_IN13/ ADC5_IN13, OPAMP6_VINP
F2	-	-	-	49	G7	57	H11	72	PD10	I/O	FT_a	-	USART3_CK, FMC_D15, EVENTOUT	ADC345_IN7, COMP6_INM
E2	-	-	-	-	H10	58	G7	73	PD11	I/O	TT_a	-	TIM5_ETR, I2C4_SMBA, USART3_CTS, FMC_A16, EVENTOUT	ADC345_IN8, COMP6_INP, OPAMP4_VINP
-	-	-	-	-	J10	59	G8	74	PD12	I/O	TT_a	-	TIM4_CH1, USART3_RTS_DE, FMC_A17, EVENTOUT	ADC345_IN9, COMP5_INP, OPAMP5_VINP
-	-	-	-	-	G9	60	G9	75	PD13	I/O	FT_a	-	TIM4_CH2, FMC_A18, EVENTOUT	ADC345_IN10, COMP5_INM
-	-	-	-	-	F8	61	G10	76	PD14	I/O	TT_a	-	TIM4_CH3, FMC_D0, EVENTOUT	ADC345_IN11, COMP7_INP, OPAMP2_VINP
-	-	-	-	-	G10	62	F6	77	PD15	I/O	FT_a	-	TIM4_CH4, SPI2_NSS, FMC_D1, EVENTOUT	COMP7_INM
B1	-	-	-	50	E7	63	-	78	VSS	S	-	-	-	-
E1	-	-	-	51	-	64	G11	79	VDD	S	-	-	-	-
E3	29	-	38	52	F9	65	F10	80	PC6	I/O	FT_f	-	TIM3_CH1, HRTIM1_EEV10, TIM8_CH1, I2S2_MCK, COMP6_OUT, I2C4_SCL, HRTIM1_CHF1, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)[(1)]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
D5	-	-	39	53	F10	66	F11	81	PC7	I/O	FT_f	-	TIM3_CH2, HRTIM1_FLT5, TIM8_CH2, I2S3_MCK, COMP5_OUT, I2C4_SDA, HRTIM1_CHF2, EVENTOUT	-
-	-	-	-	-	-	-	F9	82	PG0	I/O	FT	-	TIM20_CH1N, FMC_A10, EVENTOUT	-
-	-	-	-	-	-	-	F8	83	PG1	I/O	FT	-	TIM20_CH2N, FMC_A11, EVENTOUT	-
-	-	-	-	-	-	-	F7	84	PG2	I/O	FT	-	TIM20_CH3N, SPI1_SCK, FMC_A12, EVENTOUT	-
-	-	-	-	-	-	-	E11	85	PG3	I/O	FT_f	-	TIM20_BKIN, I2C4_SCL, SPI1_MISO, TIM20_CH4N, FMC_A13, EVENTOUT	-
-	-	-	-	-	-	-	E10	86	PG4	I/O	FT_f	-	TIM20_BKIN2, I2C4_SDA, SPI1_MOSI, FMC_A14, EVENTOUT	-
C5	-	-	40	54	E8	67	E9	87	PC8	I/O	FT_f	-	TIM3_CH3, HRTIM1_CHE1, TIM8_CH3, TIM20_CH3, COMP7_OUT, I2C3_SCL, EVENTOUT	-
D2	-	-	41	55	E9	68	E8	88	PC9	I/O	FT_f	-	TIM3_CH4, HRTIM1_CHE2, TIM8_CH4, I2SCKIN, TIM8_BKIN2, I2C3_SDA, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)(1)	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
D1	30	30	42	56	E10	69	E7	89	PA8	I/O	FT_a	-	MCO, I2C3_SCL, I2C2_SDA, I2S2_MCK, TIM1_CH1, USART1_CK, COMP7_OUT, TIM4_ETR, FDCAN3_RX, SAI1_CK2, HRTIM1_CHA1, SAI1_SCK_A, EVENTOUT	ADC5_IN1, OPAMP5_VOUT
D4	31	31	43	57	D10	70	D8	90	PA9	I/O	FT_fda	-	I2C3_SMBA, I2C2_SCL, I2S3_MCK, TIM1_CH2, USART1_TX, OMP5_OUT, TIM15_BKIN, TIM2_CH3, HRTIM1_CHA2, SAI1_FS_A, EVENTOUT	ADC5_IN2, UCPD1_DBCC1
D3	32	32	44	58	D9	71	D9	91	PA10	I/O	FT_fda	-	TIM17_BKIN, USB_CRS_SYNC, I2C2_SMBA, SPI2_MISO, TIM1_CH3, USART1_RX, COMP6_OUT, TIM2_CH4, TIM8_BKIN, SAI1_D1, HRTIM1_CHB1, SAI1_SD_A, EVENTOUT	UCPD1_DBCC2, PVD_IN
C2	33	33	45	59	C10	72	D11	92	PA11	I/O	FT_u	-	SPI2_MOSI/I2S2_SD, TIM1_CH1N, USART1_CTS, COMP1_OUT, FDCAN1_RX, TIM4_CH1, TIM1_CH4, TIM1_BKIN2, HRTIM1_CHB2, EVENTOUT	USB_DM

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)[1]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
C1	34	34	46	60	C9	73	D10	93	PA12	I/O	FT_u	-	TIM16_CH1, I2SCKIN, TIM1_CH2N, USART1_RTS_DE, COMP2_OUT, FDCAN1_TX, TIM4_CH2, TIM1_ETR, HRTIM1_FLT1, EVENTOUT	USB_DP
A8	-	35	47	61	F6	74	C10	94	VSS	S	-	-	-	-
A1	35	36	48	62	-	75	C11	95	VDD	S	-	-	-	-
B2	36	37	49	63	D8	76	B11	96	PA13	I/O	FT_f	(5)	SWDIO-JTMS, TIM16_CH1N, I2C4_SCL, I2C1_SCL, IR_OUT, USART3_CTS, TIM4_CH3, SAI1_SD_B, EVENTOUT	-
-	-	-	-	-	-	-	A11	97	PF6	I/O	FT_f	-	TIM5_ETR, TIM4_CH4, SAI1_SD_B, I2C2_SCL, TIM5_CH1, USART3_RTS, QUADSPI1_BK1_IO3, EVENTOUT	-
C3	37	38	50	64	B10	77	B10	98	PA14	I/O	FT_f	(5)	SWCLK-JTCK, LPTIM1_OUT, I2C4_SMBA, I2C1_SDA, TIM8_CH2, TIM1_BKIN, USART2_TX, SAI1_FS_B, EVENTOUT	-
A2	38	39	51	65	B9	78	A10	99	PA15	I/O	FT_f	(5)	JTDI, TIM2_CH1, TIM8_CH1, I2C1_SCL, SPI1_NSS, SPI3_NSS/I2S3_WS, USART2_RX, UART4_RTS_DE, TIM1_BKIN, FDCAN3_TX, HRTIM1_FLT2, TIM2_ETR, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)[1]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
B3	39	-	52	66	C8	79	C9	100	PC10	I/O	FT	-	TIM8_CH1N, UART4_TX, SPI3_SCK/I2S3_CK, USART3_TX, HRTIM1_FLT6, EVENTOUT	-
C4	40	-	53	67	C7	80	C8	101	PC11	I/O	FT_f	-	HRTIM1_EEV2, TIM8_CH2N, UART4_RX, SPI3_MISO, USART3_RX, I2C3_SDA, EVENTOUT	-
A3	-	-	54	68	A10	81	D7	102	PC12	I/O	FT	-	TIM5_CH2, HRTIM1_EEV1, TIM8_CH3N, UART5_TX, SPI3_MOSI/I2S3_SD, USART3_CK, UCPD1_FRSTX, EVENTOUT	-
-	-	-	-	-	-	-	-	103	PG5	I/O	FT	-	TIM20_ETR, SPI1_NSS, LPUART1_CTS, FMC_A15, EVENTOUT	-
-	-	-	-	-	-	-	-	104	PG6	I/O	FT	-	TIM20_BKIN, I2C3_SMBA, LPUART1_RTS_DE, FMC_INT, EVENTOUT	-
-	-	-	-	-	-	-	-	105	PG7	I/O	FT_f	-	SAI1_CK1, I2C3_SCL, LPUART1_TX, FMC_INT, SAI1_MCLK_A, EVENTOUT	-
-	-	-	-	-	-	-	-	106	PG8	I/O	FT_f	-	I2C3_SDA, LPUART1_RX, FMC_NE3, EVENTOUT	-
-	-	-	-	-	-	-	-	107	PG9	I/O	FT	-	SPI3_SCK, USART1_TX, FMC_NCE/FMC_NE2, TIM15_CH1N, EVENTOUT	-
B4	-	-	-	69	B8	82	B9	108	PD0	I/O	FT	-	TIM8_CH4N, FDCAN1_RX, FMC_D2, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)[(1)]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
A4	-	-	-	70	A9	83	A9	109	PD1	I/O	FT	-	TIM8_CH4, TIM8_BKIN2, FDCAN1_TX, FMC_D3, EVENTOUT	-
-	-	-	-	-	-	-	B8	110	VSS	S	-	-	-	-
A1	-	-	-	-	-	-	A8	111	VDD	S	-	-	-	-
B5	-	-	55	71	B7	84	C7	112	PD2	I/O	FT	-	TIM3_ETR, TIM8_BKIN, UART5_RX, EVENTOUT	-
-	-	-	-	-	C6	85	B7	113	PD3	I/O	FT	-	TIM2_CH1/ TIM2_ETR, USART2_CTS, QUADSPI1_BK2_NCS , FMC_CLK, EVENTOUT	-
-	-	-	-	-	A8	86	A7	114	PD4	I/O	FT	-	TIM2_CH2, USART2_RTS_DE, QUADSPI1_BK2_IO0, FMC_NOE, EVENTOUT	-
-	-	-	-	-	A7	87	E6	115	PD5	I/O	FT	-	USART2_TX, QUADSPI1_BK2_IO1, FMC_NWE, EVENTOUT	-
-	-	-	-	-	A6	88	D6	116	PD6	I/O	FT	-	TIM2_CH4, SAI1_D1, USART2_RX, QUADSPI1_BK2_IO2, FMC_NWAIT, SAI1_SD_A, EVENTOUT	-
-	-	-	-	-	B6	89	B6	117	PD7	I/O	FT	-	TIM2_CH3, USART2_CK, QUADSPI1_BK2_IO3, FMC_NCE/FMC_NE1, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)(1)	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
A5	41	40	56	72	A5	90	A6	118	PB3	I/O	FT	(5)	JTDO-TRACESWO, TIM2_CH2, TIM4_ETR, UCPD1_CRS_SYNC, TIM8_CH1N, SPI1_SCK, SPI3_SCK/I2S3_CK, USART2_TX, TIM3_ETR, FDCAN3_RX, HRTIM1_SCOUT, HRTIM1_EEV9, SAI1_SCK_B, EVENTOUT	-
C6	42	41	57	73	C5	91	C6	119	PB4	I/O	FT_c	(5) (6)	JTRST, TIM16_CH1, TIM3_CH1, TIM8_CH2N, SPI1_MISO, SPI3_MISO, USART2_RX, UART5_RTS_DE, TIM17_BKIN, FDCAN3_TX, HRTIM1_EEV7, SAI1_MCLK_B, EVENTOUT	UCPD1_CC2
A6	43	42	58	74	B5	92	B5	120	PB5	I/O	FT_f	-	TIM16_BKIN, TIM3_CH2, TIM8_CH3N, I2C1_SMBA, SPI1_MOSI, SPI3_MOSI/I2S3_SD, USART2_CK, I2C3_SDA, FDCAN2_RX, TIM17_CH1, LPTIM1_IN1, SAI1_SD_B, HRTIM1_EEV6, UART5_CTS, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)[1]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
B6	44	43	59	75	A4	93	A5	121	PB6	I/O	FT_c	(6)	TIM16_CH1N, TIM4_CH1, TIM8_CH1, TIM8_ETR, USART1_TX, COMP4_OUT, FDCAN2_TX, TIM8_BKIN2, LPTIM1_ETR, HRTIM1_SCIN, HRTIM1_EEV4, SAI1_FS_B, EVENTOUT	UCPD1_CC1
C7	45	44	60	76	B4	94	C5	122	PB7	I/O	FT_f	-	TIM17_CH1N, TIM4_CH2, I2C4_SDA, I2C1_SDA, TIM8_BKIN, USART1_RX, COMP3_OUT, TIM3_CH4, LPTIM1_IN2, FMC_NL, HRTIM1_EEV3, UART4_CTS, EVENTOUT	-
B7	46	45	61	77	A3	95	D5	123	PB8-BOOT0	I/O	FT_f	(7)	TIM16_CH1, TIM4_CH3, SAI1_CK1, I2C1_SCL, USART3_RX, COMP1_OUT, FDCAN1_RX, TIM8_CH2, TIM1_BKIN, HRTIM1_EEV8, SAI1_MCLK_A, EVENTOUT	-
A7	47	46	62	78	A2	96	A4	124	PB9	I/O	FT_f	-	TIM17_CH1, TIM4_CH4, SAI1_D2, I2C1_SDA, IR_OUT, USART3_TX, COMP2_OUT, FDCAN1_TX, TIM8_CH3, TIM1_CH3N, HRTIM1_EEV5, SAI1_FS_A, EVENTOUT	-

Table 12. STM32G474xB/xC/xE pin definition (continued)

Pin Number									Pin name (function after reset)(1)	Pin type	I/O structure	Notes	Alternate functions	Additional functions
WLCSP81	UFQFPN48	LQFP48	LQFP64	LQFP80	TFBGA100	LPQF100	UFBGA121	LPQF128						
-	-	-	-	-	C4	97	B4	125	PE0	I/O	FT	-	TIM4_ETR, TIM20_CH4N, TIM16_CH1, TIM20_ETR, USART1_TX, FMC_NBL0, EVENTOUT	-
-	-	-	-	-	B3	98	C4	126	PE1	I/O	FT	-	TIM17_CH1, TIM20_CH4, USART1_RX, FMC_NBL1, EVENTOUT	-
-	-	47	63	79	-	99	B3	127	VSS	S	-	-	-	-
A9	48	48	64	80	-	100	A3	128	VDD	S	-	-	-	-

1. Function availability depends on the chosen device.
2. PC13, PC14 and PC15 are supplied through the power switch. Since the switch only sinks a limited amount of current (3 mA), the use of GPIOs PC13 to PC15 in output mode is limited:
   - The speed should not exceed 2 MHz with a maximum load of 30 pF
   - These GPIOs must not be used as current sources (e.g. to drive an LED).
3. After a backup domain power-up, PC13, PC14 and PC15 operate as GPIOs. Their function then depends on the content of the RTC registers which are not reset by the system reset. For details on how to manage these GPIOs, refer to the Backup domain and RTC register descriptions in the reference manual RM0440 "STM32G4 Series advanced Arm®-based 32-bit MCUs”.
4. PG10-NRST pin is FT tolerant if it is configured as PG10 GPIO by option bytes except for the startup time until option bytes are loaded.
5. After reset, these pins are configured as JTAG/SW debug alternate functions, and the internal pull-up on PA15, PA13, PB4 pins and the internal pull-down on PA14 pin are activated.
6. After reset, a pull-down resistor (Rd = 5.1kΩ from UCPD peripheral) can be activated on PB6, PB4 (UCPD1_CC1, UCPD1_CC2). The pull-down on PB6 (UCPD1_CC1) is activated by high level on PA9 (UCPD1_DBCC1). The pull-down on PB4 (UCPD1_CC2) is activated by high level on PA10 (UCPD1_DBCC2). This pull-down control (dead battery support on UCPD peripheral) can be disabled by setting bit UCPD1_DBDIS=1 in the PWR_CR3 register. PB4, PB6 have UCPD_CC functionality which implements an internal pull-down resistor (5.1kΩ) which is controlled by the voltage on the UCPD_DBCC pin (PA10, PA9). A high level on the UCPD_DBCC pin activates the pull-down on the UCPD_CC pin. The pull-down effect on the CC lines can be removed by using the bit UCPD1_DBDIS =1 (USB Type-C and power delivery dead battery disable) in the PWR_CR3 register.
7. It is recommended to set PB8 in another mode than analog mode after startup to limit consumption if the pin is left unconnected.

4.11 Alternate functions

Table 13. Alternate function

Port		AF0	AF1	AF2	AF3	AF4	AF5	AF6	AF7	AF8	AF9	AF10	AF11	AF12	AF13	AF14	AF15
		I2C4/SYS_AF	**LPTIM1/TIM2/5/15/16/17**	**I2C1/3/TIM1/2/3/4/5/8/20/15/COMP1**	**QUADSPI1/I2C3/4/SAI1/USB/HRTIM1/TIM8/20/15/COMP3**	**I2C1/2/3/4/TIM1/8/16/17**	**QUADSPI1/SPI1/2/3/4/I2S2/3/I2C4/UART4/5/TIM8/Infrared**	**QUADSPI1/SPI2/3/I2S2/3/TIM1/5/8/20/Infrared**	**USART1/2/3/FDCAN/COMP7/5/6**	**I2C3/4/UART4/5/LPUART1/COMP1/2/7/4/5/6/3**	**FDCAN/TIM1/8/15/FDCAN1/2**	**QUADSPI1/TIM2/3/4/8/17**	**LPTIM1/TIM1/8/FDCAN1/3**	**FMC/LPUART1/SAI1/HRTIM1/TIM1**	**SAI1SAI1/HRTIM1/OPAMP2**	**UART4/5/SAI1/TIM2/15/UCPD1**	**EVENT**
Port A	PA0	-	TIM2_CH1	TIM5_CH1	-	-	-	-	USART2_CTS	COMP1_OUT	TIM8_BKIN	TIM8_ETR	-	-	-	TIM2_ETR	EVENTOUT
	PA1	RTC_REFIN	TIM2_CH2	TIM5_CH2	-	-	-	-	USART2_RTS_DE	-	TIM15_CH1N	-	-	-	-	-	EVENTOUT
	PA2	-	TIM2_CH3	TIM5_CH3	-	-	-	-	USART2_TX	COMP2_OUT	TIM15_CH1	QUADSPI1_BK1_NCS	-	LPUART1_TX	-	UCPD1_FRSTX	EVENTOUT
	PA3	-	TIM2_CH4	TIM5_CH4	SAI1_CK1	-	-	-	USART2_RX	-	TIM15_CH2	QUADSPI1_CLK	-	LPUART1_RX	SAI1_MCLK_A	-	EVENTOUT
	PA4	-	-	TIM3_CH2	-	-	SPI1_NSS	SPI3_NSS/I2S3_WS	USART2_CK	-	-	-	-	-	SAI1_FS_B	-	EVENTOUT
	PA5	-	TIM2_CH1	TIM2_ETR	-	-	SPI1_SCK	-	-	-	-	-	-	-	-	UCPD1_FRSTX	EVENTOUT
	PA6	-	TIM16_CH1	TIM3_CH1	-	TIM8_BKIN	SPI1_MISO	TIM1_BKIN	-	COMP1_OUT	-	QUADSPI1_BK1_IO3	-	LPUART1_CTS	-	-	EVENTOUT
	PA7	-	TIM17_CH1	TIM3_CH2	-	TIM8_CH1N	SPI1_MOSI	TIM1_CH1N	-	COMP2_OUT	-	QUADSPI1_BK1_IO2	-	-	-	UCPD1_FRSTX	EVENTOUT
	PA8	MCO	-	I2C3_SCL	-	I2C2_SDA	I2S2_MCK	TIM1_CH1	USART1_CK	COMP7_OUT	-	TIM4_ETR	FDCAN3_RX	SAI1_CK2	HRTIM1_CHA1	SAI1_SCK_A	EVENTOUT
	PA9	-	-	I2C3_SMBA	-	I2C2_SCL	I2S3_MCK	TIM1_CH2	USART1_TX	COMP5_OUT	TIM15_BKIN	TIM2_CH3	-	-	HRTIM1_CHA2	SAI1_FS_A	EVENTOUT
	PA10	-	TIM17_BKIN	-	USB_CRS_SYNC	I2C2_SMBA	SPI2_MISO	TIM1_CH3	USART1_RX	COMP6_OUT	-	TIM2_CH4	TIM8_BKIN	SAI1_D1	HRTIM1_CHB1	SAI1_SD_A	EVENTOUT
	PA11	-	-	-	-	-	SPI2_MOSI/I2S2_SD	TIM1_CH1N	USART1_CTS	COMP1_OUT	FDCAN1_RX	TIM4_CH1	TIM1_CH4	TIM1_BKIN2	HRTIM1_CHB2	-	EVENTOUT
	PA12	-	TIM16_CH1	-	-	-	I2SCKIN	TIM1_CH2N	USART1_RTS_DE	COMP2_OUT	FDCAN1_TX	TIM4_CH2	TIM1_ETR	-	HRTIM1_FLT1	-	EVENTOUT
	PA13	SWDIO-JTMS	TIM16_CH1N	-	I2C4_SCL	I2C1_SCL	IR_OUT	-	USART3_CTS	-	-	TIM4_CH3	-	-	SAI1_SD_B	-	EVENTOUT
	PA14	SWCLK-JTCK	LPTIM1_OUT	-	I2C4_SMBA	I2C1_SDA	TIM8_CH2	TIM1_BKIN	USART2_TX	-	-	-	-	-	SAI1_FS_B	-	EVENTOUT
	PA15	JTDI	TIM2_CH1	TIM8_CH1	-	I2C1_SCL	SPI1_NSS	SPI3_NSS/I2S3_WS	USART2_RX	UART4_RTS_DE	TIM1_BKIN	-	FDCAN3_TX	-	HRTIM1_FLT2	TIM2_ETR	EVENTOUT

Table 13. Alternate function (continued)

Port		AF0	AF1	AF2	AF3	AF4	AF5	AF6	AF7	AF8	AF9	AF10	AF11	AF12	AF13	AF14	AF15
		I2C4/ SYS_AF	LPTIM1/ TIM2/5/ 15/16/17	I2C1/3/ TIM1/2/3/4/5/8/ 20/15/ COMP1	QUADSPI1/ I2C3/4/SAI1/US B/HRTIM1/ TIM8/20/15/ COMP3	I2C1/2/3/ 4/TIM1/8/ 16/17	QUADSPI1 /SPI1/2/3/4/ I2S2/3/I2C4/ UART4/5/ TIM8/ Infrared	QUADSPI1/ SPI2/3/I2S2 /3/TIM1/5/8/ 20/Infrared	USART1/2/3 /FDCAN/CO MP7/5/6	I2C3/4/UAR T4/5/LPUA RT1/COMP 1/2/7/4/5/6/ 3	FDCAN/T IM1/8/15/ FDCAN1/ 2	QUADSPI1/ TIM2/3/4/8/1 7	LPTIM1/ TIM1/8/F DCAN1/3	FMC/LPUART1 /SAI1/HRTIM1/ TIM1	SAI1SAI1/HR TIM1/OPAMP 2	UART4/5/ SAI1/TIM 2/15/ UCPD1	EVENT
Port B	PB0	-	-	TIM3_CH3	-	TIM8_ CH2N	-	TIM1_ CH2N	-	-	-	QUADSPI1_ BK1_IO1	-	-	HRTIM1_ FLT5	UCPD1_ FRSTX	EVENT OUT
	PB1	-	-	TIM3_CH4	-	TIM8_ CH3N	-	TIM1_ CH3N	-	COMP4_ OUT	-	QUADSPI1_ BK1_IO0	-	LPUART1_ RTS_DE	HRTIM1_ SCOUT	-	EVENT OUT
	PB2	RTC_OUT2	LPTIM1_OUT	TIM5_CH1	TIM20_CH1	I2C3_ SMBA	-	-	-	-	-	QUADSPI1_ BK2_IO1	-	-	HRTIM1_ SCIN	-	EVENT OUT
	PB3	JTDO- TRACESWO	TIM2_CH2	TIM4_ETR	USB_CRS_ SYNC	TIM8_ CH1N	SPI1_SCK	SPI3_SCK/ I2S3_CK	USART2_ TX	-	-	TIM3_ETR	FDCAN3 _RX	HRTIM1_ SCOUT	HRTIM1_ EEV9	SAI1_ SCK_B	EVENT OUT
	PB4	JTRST	TIM16_CH1	TIM3_CH1	-	TIM8_ CH2N	SPI1_MISO	SPI3_MISO	USART2_ RX	UART5_ RTS_DE	-	TIM17_BKIN	FDCAN3 _TX	-	HRTIM1_ EEV7	SAI1_ MCLK_B	EVENT OUT
	PB5	-	TIM16_BKIN	TIM3_CH2	TIM8_CH3N	I2C1_ SMBA	SPI1_MOSI	SPI3_MOSI /I2S3_SD	USART2_ CK	I2C3_SDA	FDCAN2 _RX	TIM17_CH1	LPTIM1_ IN1	SAI1_SD_B	HRTIM1_ EEV6	UART5_ CTS	EVENT OUT
	PB6	-	TIM16_CH1N	TIM4_CH1	-	-	TIM8_CH1	TIM8_ETR	USART1_ TX	COMP4_ OUT	FDCAN2 _TX	TIM8_BKIN2	LPTIM1_ ETR	HRTIM1_SCIN	HRTIM1_ EEV4	SAI1_FS _B	EVENT OUT
	PB7	-	TIM17_CH1N	TIM4_CH2	I2C4_SDA	I2C1_ SDA	TIM8_BKIN	-	USART1_ RX	COMP3_ OUT	-	TIM3_CH4	LPTIM1_ IN2	FMC_NL	HRTIM1_ EEV3	UART4_ CTS	EVENT OUT
	PB8	-	TIM16_CH1	TIM4_CH3	SAI1_CK1	I2C1_ SCL	-	-	USART3_ RX	COMP1_ OUT	FDCAN1 _RX	TIM8_CH2	-	TIM1_BKIN	HRTIM1_ EEV8	SAI1_ MCLK_A	EVENT OUT
	PB9	-	TIM17_CH1	TIM4_CH4	SAI1_D2	I2C1_ SDA	-	IR_OUT	USART3_ TX	COMP2_ OUT	FDCAN1 _TX	TIM8_CH3	-	TIM1_CH3N	HRTIM1_ EEV5	SAI1_FS _A	EVENT OUT
	PB10	-	TIM2_CH3	-	-	-	-	-	USART3_ TX	LPUART1_ RX	-	QUADSPI1_ CLK	-	TIM1_BKIN	HRTIM1_ FLT3	SAI1_SC K_A	EVENT OUT
	PB11	-	TIM2_CH4	-	-	-	-	-	USART3_ RX	LPUART1_ TX	-	QUADSPI1_ BK1_NCS	-	-	HRTIM1_ FLT4	-	EVENT OUT
	PB12	-	-	TIM5_ETR	-	I2C2_ SMBA	SPI2_NSS/ I2S2_WS	TIM1_BKIN	USART3_ CK	LPUART1_ RTS_DE	FDCAN2 _RX	-	-	-	HRTIM1_ CHC1	-	EVENT OUT
	PB13	-	-	-	-	-	SPI2_SCK/ I2S2_CK	TIM1_ CH1N	USART3_ CTS	LPUART1_ CTS	FDCAN2 _TX	-	-	-	HRTIM1_ CHC2	-	EVENT OUT
	PB14	-	TIM15_CH1	-	-	-	SPI2_MISO	TIM1_ CH2N	USART3_ RTS_DE	COMP4_ OUT	-	-	-	-	HRTIM1_ CHD1	-	EVENT OUT
	PB15	RTC_REFIN	TIM15_CH2	TIM15_CH1N	COMP3_OUT	TIM1_ CH3N	SPI2_MOSI/ I2S2_SD	-	-	-	-	-	-	-	HRTIM1_ CHD2	-	EVENT OUT

Table 13. Alternate function (continued)

Port		AF0	AF1	AF2	AF3	AF4	AF5	AF6	AF7	AF8	AF9	AF10	AF11	AF12	AF13	AF14	AF15
		I2C4/ SYS_AF	LPTIM1/ TIM2/5/ 15/16/17	I2C1/3/ TIM1/2/3/4/5/8/ 20/15/ COMP1	QUADSPI1/ I2C3/4/SAI1/US B/HRTIM1/ TIM8/20/15/ COMP3	I2C1/2/3/ 4/TIM1/8/ 16/17	QUADSPI1 /SPI1/2/3/4/ I2S2/3/I2C4/ UART4/5/ TIM8/ Infrared	QUADSPI1/ SPI2/3/I2S2 /3/TIM1/5/8/ 20/Infrared	USART1/2/3 /FDCAN/CO MP7/5/6	I2C3/4/UAR T4/5/LPUA RT1/COMP 1/2/7/4/5/6/ 3	FDCAN/T IM1/8/15/ FDCAN1/ 2	QUADSPI1/ TIM2/3/4/8/1 7	LPTIM1/ TIM1/8/F DCAN1/3	FMC/LPUART1 /SAI1/HRTIM1/ TIM1	SAI1SAI1/HR TIM1/OPAMP 2	UART4/5/ SAI1/TIM 2/15/ UCPD1	EVENT
Port C	PC0	-	LPTIM1_IN1	TIM1_CH1	-	-	-	-	-	LPUART1_ RX	-	-	-	-	-	-	EVENT OUT
	PC1	-	LPTIM1_OUT	TIM1_CH2	-	-	-	-	-	LPUART1_ TX	-	QUADSPI1_ BK2_IO0	-	-	SAI1_SD_A	-	EVENT OUT
	PC2	-	LPTIM1_IN2	TIM1_CH3	COMP3_OUT	-	-	TIM20_CH2	-	-	-	QUADSPI1_ BK2_IO1	-	-	-	-	EVENT OUT
	PC3	-	LPTIM1_ETR	TIM1_CH4	SAI1_D1	-	-	TIM1_ BKIN2	-	-	-	QUADSPI1_ BK2_IO2	-	-	SAI1_SD_A	-	EVENT OUT
	PC4	-	-	TIM1_ETR	-	I2C2_ SCL	-	-	USART1_ TX	-	-	QUADSPI1_ BK2_IO3	-	-	-	-	EVENT OUT
	PC5	-	-	TIM15_BKIN	SAI1_D3	-	-	TIM1_ CH4N	USART1_ RX	-	-	-	-	-	HRTIM1_ EEV10	-	EVENT OUT
	PC6	-	-	TIM3_CH1	HRTIM1_EEV10	TIM8_ CH1	-	I2S2_MCK	COMP6_ OUT	I2C4_SCL	-	-	-	-	HRTIM1_ CHF1	-	EVENT OUT
	PC7	-	-	TIM3_CH2	HRTIM1_FLT5	TIM8_ CH2	-	I2S3_MCK	COMP5_ OUT	I2C4_SDA	-	-	-	-	HRTIM1_ CHF2	-	EVENT OUT
	PC8	-	-	TIM3_CH3	HRTIM1_CHE1	TIM8_ CH3	-	TIM20_CH3	COMP7_ OUT	I2C3_SCL	-	-	-	-	-	-	EVENT OUT
	PC9	-	-	TIM3_CH4	HRTIM1_CHE2	TIM8_ CH4	I2SCKIN	TIM8_ BKIN2	-	I2C3_SDA	-	-	-	-	-	-	EVENT OUT
	PC10	-	-	-	-	TIM8_ CH1N	UART4_TX	SPI3_SCK/ I2S3_CK	USART3_ TX	-	-	-	-	-	HRTIM1_ FLT6	-	EVENT OUT
	PC11	-	-	-	HRTIM1_EEV2	TIM8_ CH2N	UART4_RX	SPI3_MISO	USART3_ RX	I2C3_SDA	-	-	-	-	-	-	EVENT OUT
	PC12	-	TIM5_CH2	-	HRTIM1_EEV1	TIM8_ CH3N	UART5_TX	SPI3_MOSI /I2S3_SD	USART3_ CK	-	-	-	-	-	-	UCPD1_ FRSTX	EVENT OUT
	PC13	-	-	TIM1_BKIN	-	TIM1_ CH1N	-	TIM8_ CH4N	-	-	-	-	-	-	-	-	EVENT OUT
	PC14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	EVENT OUT
	PC15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	EVENT OUT

Table 13. Alternate function (continued)

Port		AF0	AF1	AF2	AF3	AF4	AF5	AF6	AF7	AF8	AF9	AF10	AF11	AF12	AF13	AF14	AF15
		I2C4/ SYS_AF	LPTIM1/ TIM2/5/ 15/16/17	I2C1/3/ TIM1/2/3/4/5/8/ 20/15/ COMP1	QUADSPI1/ I2C3/4/SAI1/US B/HRTIM1/ TIM8/20/15/ COMP3	I2C1/2/3/ 4/TIM1/8/ 16/17	QUADSPI1 /SPI1/2/3/4/ I2S2/3/I2C4/ UART4/5/ TIM8/ Infrared	QUADSPI1/ SPI2/3/I2S2 /3/TIM1/5/8/ 20/Infrared	USART1/2/3 /FDCAN/CO MP7/5/6	I2C3/4/UAR T4/5/LPUA RT1/COMP 1/2/7/4/5/6/ 3	FDCAN/T IM1/8/15/ FDCAN1/ 2	QUADSPI1/ TIM2/3/4/8/1 7	LPTIM1/ TIM1/8/F DCAN1/3	FMC/LPUART1 /SAI1/HRTIM1/ TIM1	SAI1SAI1/HR TIM1/OPAMP 2	UART4/5/ SAI1/TIM 2/15/ UCPD1	EVENT
Port D	PD0	-	-	-	-	-	-	TIM8_ CH4N	-	-	FDCAN1 _RX	-	-	FMC_D2	-	-	EVENT OUT
	PD1	-	-	-	-	TIM8_ CH4	-	TIM8_ BKIN2	-	-	FDCAN1 _TX	-	-	FMC_D3	-	-	EVENT OUT
	PD2	-	-	TIM3_ETR	-	TIM8_ BKIN	UART5_RX	-	-	-	-	-	-	-	-	-	EVENT OUT
	PD3	-	-	TIM2_CH1/ TIM2_ETR	-	-	-	-	USART2_ CTS	-	-	QUADSPI1 _BK2_NCS	-	FMC_CLK	-	-	EVENT OUT
	PD4	-	-	TIM2_CH2	-	-	-	-	USART2_ RTS_DE	-	-	QUADSPI1_ BK2_IO0	-	FMC_NOE	-	-	EVENT OUT
	PD5	-	-	-	-	-	-	-	USART2_ TX	-	-	QUADSPI1_ BK2_IO1	-	FMC_NWE	-	-	EVENT OUT
	PD6	-	-	TIM2_CH4	SAI1_D1	-	-	-	USART2_ RX	-	-	QUADSPI1_ BK2_IO2	-	FMC_NWAIT	SAI1_SD_A	-	EVENT OUT
	PD7	-	-	TIM2_CH3	-	-	-	-	USART2_ CK	-	-	QUADSPI1_ BK2_IO3	-	FMC_NCE/ FMC_NE1	-	-	EVENT OUT
	PD8	-	-	-	-	-	-	-	USART3_ TX	-	-	-	-	FMC_D13	-	-	EVENT OUT
	PD9	-	-	-	-	-	-	-	USART3_ RX	-	-	-	-	FMC_D14	-	-	EVENT OUT
	PD10	-	-	-	-	-	-	-	USART3_ CK	-	-	-	-	FMC_D15	-	-	EVENT OUT
	PD11	-	TIM5_ETR	-	-	I2C4_ SMBA	-	-	USART3_ CTS	-	-	-	-	FMC_A16	-	-	EVENT OUT
	PD12	-	-	TIM4_CH1	-	-	-	-	USART3_ RTS_DE	-	-	-	-	FMC_A17	-	-	EVENT OUT
	PD13	-	-	TIM4_CH2	-	-	-	-	-	-	-	-	-	FMC_A18	-	-	EVENT OUT
	PD14	-	-	TIM4_CH3	-	-	-	-	-	-	-	-	-	FMC_D0	-	-	EVENT OUT
	PD15	-	-	TIM4_CH4	-	-	-	SPI2_NSS	-	-	-	-	-	FMC_D1	-	-	EVENT OUT

Table 13. Alternate function (continued)

Port		AF0	AF1	AF2	AF3	AF4	AF5	AF6	AF7	AF8	AF9	AF10	AF11	AF12	AF13	AF14	AF15
		I2C4/ SYS_AF	LPTIM1/ TIM2/5/ 15/16/17	I2C1/3/ TIM1/2/3/4/5/8/ 20/15/ COMP1	QUADSPI1/ I2C3/4/SAI1/US B/HRTIM1/ TIM8/20/15/ COMP3	I2C1/2/3/ 4/TIM1/8/ 16/17	QUADSPI1 /SPI1/2/3/4/ I2S2/3/I2C4/ UART4/5/ TIM8/ Infrared	QUADSPI1/ SPI2/3/I2S2 /3/TIM1/5/8/ 20/Infrared	USART1/2/3 /FDCAN/CO MP7/5/6	I2C3/4/UAR T4/5/LPUA RT1/COMP 1/2/7/4/5/6/ 3	FDCAN/T IM1/8/15/ FDCAN1/ 2	QUADSPI1/ TIM2/3/4/8/1 7	LPTIM1/ TIM1/8/F DCAN1/3	FMC/LPUART1 /SAI1/HRTIM1/ TIM1	SAI1SAI1/HR TIM1/OPAMP 2	UART4/5/ SAI1/TIM 2/15/ UCPD1	EVENT
Port E	PE0	-	-	TIM4_ETR	TIM20_CH4N	TIM16_ CH1	-	TIM20_ETR	USART1_ TX	-	FDCAN1 _RXFD	-	-	FMC_NBL0	-	-	EVENT OUT
	PE1	-	-	-	-	TIM17_ CH1	-	TIM20_CH4	USART1_ RX	-	-	-	-	FMC_NBL1	-	-	EVENT OUT
	PE2	TRACECK	-	TIM3_CH1	SAI1_CK1	-	SPI4_SCK	TIM20_CH1	-	-	-	-	-	FMC_A23	SAI1_MCLK_ A	-	EVENT OUT
	PE3	TRACED0	-	TIM3_CH2	-	-	SPI4_NSS	TIM20_CH2	-	-	-	-	-	FMC_A19	SAI1_SD_B	-	EVENT OUT
	PE4	TRACED1	-	TIM3_CH3	SAI1_D2	-	SPI4_NSS	TIM20_ CH1N	-	-	-	-	-	FMC_A20	SAI1_FS_A	-	EVENT OUT
	PE5	TRACED2	-	TIM3_CH4	SAI1_CK2	-	SPI4_MISO	TIM20_ CH2N	-	-	-	-	-	FMC_A21	SAI1_SCK_A	-	EVENT OUT
	PE6	TRACED3	-	-	SAI1_D1	-	SPI4_MOSI	TIM20_ CH3N	-	-	-	-	-	FMC_A22	SAI1_SD_A	-	EVENT OUT
	PE7	-	-	TIM1_ETR	-	-	-	-	-	-	-	-	-	FMC_D4	SAI1_SD_B	-	EVENT OUT
	PE8	-	TIM5_CH3	TIM1_CH1N	-	-	-	-	-	-	-	-	-	FMC_D5	SAI1_SCK_B	-	EVENT OUT
	PE9	-	TIM5_CH4	TIM1_CH1	-	-	-	-	-	-	-	-	-	FMC_D6	SAI1_FS_B	-	EVENT OUT
	PE10	-	-	TIM1_CH2N	-	-	-	-	-	-	-	QUADSPI1_ CLK	-	FMC_D7	SAI1_MCLK_ B	-	EVENT OUT
	PE11	-	-	TIM1_CH2	-	-	SPI4_NSS	-	-	-	-	QUADSPI1_ BK1_NCS	-	FMC_D8	-	-	EVENT OUT
	PE12	-	-	TIM1_CH3N	-	-	SPI4_SCK	-	-	-	-	QUADSPI1_ BK1_IO0	-	FMC_D9	-	-	EVENT OUT
	PE13	-	-	TIM1_CH3	-	-	SPI4_MISO	-	-	-	-	QUADSPI1_ BK1_IO1	-	FMC_D10	-	-	EVENT OUT
	PE14	-	-	TIM1_CH4	-	-	SPI4_MOSI	TIM1_ BKIN2	-	-	-	QUADSPI1_ BK1_IO2	-	FMC_D11	-	-	EVENT OUT
	PE15	-	-	TIM1_BKIN	-	-	-	TIM1_ CH4N	USART3_ RX	-	-	QUADSPI1_ BK1_IO3	-	FMC_D12	-	-	EVENT OUT

Table 13. Alternate function (continued)

Port		AF0	AF1	AF2	AF3	AF4	AF5	AF6	AF7	AF8	AF9	AF10	AF11	AF12	AF13	AF14	AF15
		I2C4/ SYS_AF	LPTIM1/ TIM2/5/ 15/16/17	I2C1/3/ TIM1/2/3/4/5/8/ 20/15/ COMP1	QUADSPI1/ I2C3/4/SAI1/US B/HRTIM1/ TIM8/20/15/ COMP3	I2C1/2/3/ 4/TIM1/8/ 16/17	QUADSPI1 /SPI1/2/3/4/ I2S2/3/I2C4/ UART4/5/ TIM8/ Infrared	QUADSPI1/ SPI2/3/I2S2 /3/TIM1/5/8/ 20/Infrared	USART1/2/3 /FDCAN/CO MP7/5/6	I2C3/4/UAR T4/5/LPUA RT1/COMP 1/2/7/4/5/6/ 3	FDCAN/T IM1/8/15/ FDCAN1/ 2	QUADSPI1/ TIM2/3/4/8/1 7	LPTIM1/ TIM1/8/F DCAN1/3	FMC/LPUART1 /SAI1/HRTIM1/ TIM1	SAI1SAI1/HR TIM1/OPAMP 2	UART4/5/ SAI1/TIM 2/15/ UCPD1	EVENT
Port F	PF0	-	-	-	-	I2C2_ SDA	SPI2_NSS/ I2S2_WS	TIM1_ CH3N	-	-	-	-	-	-	-	-	EVENT OUT
	PF1	-	-	-	-	-	SPI2_SCK/ I2S2_CK	-	-	-	-	-	-	-	-	-	EVENT OUT
	PF2	-	-	TIM20_CH3	-	I2C2_ SMBA	-	-	-	-	-	-	-	FMC_A2	-	-	EVENT OUT
	PF3	-	-	TIM20_CH4	-	I2C3_ SCL	-	-	-	-	-	-	-	FMC_A3	-	-	EVENT OUT
	PF4	-	-	COMP1_OUT	TIM20_CH1N	I2C3_ SDA	-	-	-	-	-	-	-	FMC_A4	-	-	EVENT OUT
	PF5	-	-	TIM20_CH2N	-	-	-	-	-	-	-	-	-	FMC_A5	-	-	EVENT OUT
	PF6	-	TIM5_ETR	TIM4_CH4	SAI1_SD_B	I2C2_ SCL	-	TIM5_CH1	USART3_ RTS	-	-	QUADSPI1_ BK1_IO3	-	-	-	-	EVENT OUT
	PF7	-	-	TIM20_BKIN	-	-	-	TIM5_CH2	-	-	-	QUADSPI1_ BK1_IO2	-	FMC_A1	SAI1_MCLK_ B	-	EVENT OUT
	PF8	-	-	TIM20_BKIN2	-	-	-	TIM5_CH3	-	-	-	QUADSPI1_ BK1_IO0	-	FMC_A24	SAI1_SCK_B	-	EVENT OUT
	PF9	-	-	TIM20_BKIN	TIM15_CH1	-	SPI2_SCK	TIM5_CH4	-	-	-	QUADSPI1_ BK1_IO1	-	FMC_A25	SAI1_FS_B	-	EVENT OUT
	PF10	-	-	TIM20_BKIN2	TIM15_CH2	-	SPI2_SCK	-	-	-	-	QUADSPI1_ CLK	-	FMC_A0	SAI1_D3	-	EVENT OUT
	PF11	-	-	TIM20_ETR	-	-	-	-	-	-	-	-	-	FMC_NE4	-	-	EVENT OUT
	PF12	-	-	TIM20_CH1	-	-	-	-	-	-	-	-	-	FMC_A6	-	-	EVENT OUT
	PF13	-	-	TIM20_CH2	-	I2C4_ SMBA	-	-	-	-	-	-	-	FMC_A7	-	-	EVENT OUT
	PF14	-	-	TIM20_CH3	-	I2C4_ SCL	-	-	-	-	-	-	-	FMC_A8	-	-	EVENT OUT
	PF15	-	-	TIM20_CH4	-	I2C4_ SDA	-	-	-	-	-	-	-	FMC_A9	-	-	EVENT OUT

Table 13. Alternate function (continued)

Port		AF0	AF1	AF2	AF3	AF4	AF5	AF6	AF7	AF8	AF9	AF10	AF11	AF12	AF13	AF14	AF15
		I2C4/ SYS_AF	LPTIM1/ TIM2/5/ 15/16/17	I2C1/3/ TIM1/2/3/4/5/8/ 20/15/ COMP1	QUADSPI1/ I2C3/4/SAI1/US B/HRTIM1/ TIM8/20/15/ COMP3	I2C1/2/3/ 4/TIM1/8/ 16/17	QUADSPI1 /SPI1/2/3/4/ I2S2/3/I2C4/ UART4/5/ TIM8/ Infrared	QUADSPI1/ SPI2/3/I2S2 /3/TIM1/5/8/ 20/Infrared	USART1/2/3 /FDCAN/CO MP7/5/6	I2C3/4/UAR T4/5/LPUA RT1/COMP 1/2/7/4/5/6/ 3	FDCAN/T IM1/8/15/ FDCAN1/ 2	QUADSPI1/ TIM2/3/4/8/1 7	LPTIM1/ TIM1/8/F DCAN1/3	FMC/LPUART1 /SAI1/HRTIM1/ TIM1	SAI1SAI1/HR TIM1/OPAMP 2	UART4/5/ SAI1/TIM 2/15/ UCPD1	EVENT
Port G	PG0	-	-	TIM20_CH1N	-	-	-	-	-	-	-	-	-	FMC_A10	-	-	EVENT OUT
	PG1	-	-	TIM20_CH2N	-	-	-	-	-	-	-	-	-	FMC_A11	-	-	EVENT OUT
	PG2	-	-	TIM20_CH3N	-	-	SPI1_SCK	-	-	-	-	-	-	FMC_A12	-	-	EVENT OUT
	PG3	-	-	TIM20_BKIN	-	I2C4_ SCL	SPI1_MISO	TIM20_ CH4N	-	-	-	-	-	FMC_A13	-	-	EVENT OUT
	PG4	-	-	TIM20_BKIN2	-	I2C4_ SDA	SPI1_MOSI	-	-	-	-	-	-	FMC_A14	-	-	EVENT OUT
	PG5	-	-	TIM20_ETR	-	-	SPI1_NSS	-	-	LPUART1_ CTS	-	-	-	FMC_A15	-	-	EVENT OUT
	PG6	-	-	TIM20_BKIN	-	I2C3_ SMBA	-	-	-	LPUART1_ RTS_DE	-	-	-	FMC_INT	-	-	EVENT OUT
	PG7	-	-	-	SAI1_CK1	I2C3_ SCL	-	-	-	LPUART1_ TX	-	-	-	FMC_INT	SAI1_MCLK_ A	-	EVENT OUT
	PG8	-	-	-	-	I2C3_ SDA	-	-	-	LPUART1_ RX	-	-	-	FMC_NE3	-	-	EVENT OUT
	PG9	-	-	-	-	-	-	SPI3_SCK	USART1_TX	-	-	-	-	FMC_NCE/ FMC_NE2	-	TIM15_ CH1N	EVENT OUT
	PG10	MCO	-	-	-	-	-	-	-	-	-	-	-	-	-	-	EVENT OUT

5 Electrical characteristics

5.1 Parameter conditions

Unless otherwise specified, all voltages are referenced to V_{SS}.

5.1.1 Minimum and maximum values

Unless otherwise specified, the minimum and maximum values are guaranteed in the worst conditions of ambient temperature, supply voltage and frequencies by tests in production on 100% of the devices with an ambient temperature at T_A = 25 °C and $T_A = T_A$max (given by the selected temperature range).

Data based on characterization results, design simulation and/or technology characteristics are indicated in the table footnotes and are not tested in production. Based on characterization, the minimum and maximum values refer to sample tests and represent the mean value plus or minus three times the standard deviation (mean ±3σ).

5.1.2 Typical values

Unless otherwise specified, typical data are based on T_A = 25 °C, $V_{DD} = V_{DDA}$ = 3 V. They are given only as design guidelines and are not tested.

Typical ADC accuracy values are determined by characterization of a batch of samples from a standard diffusion lot over the full temperature range, where 95% of the devices have an error less than or equal to the value indicated (mean ±2σ).

5.1.3 Typical curves

Unless otherwise specified, all typical curves are given only as design guidelines and are not tested.

5.1.4 Loading capacitor

The loading conditions used for pin parameter measurement are shown in *Figure 14*.

5.1.5 Pin input voltage

The input voltage measurement on a pin of the device is described in *Figure 15*.

Figure 14. Pin loading conditions

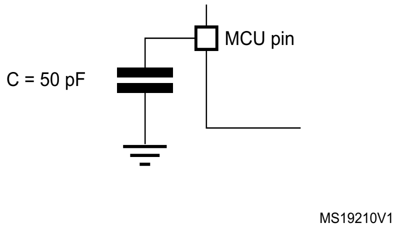
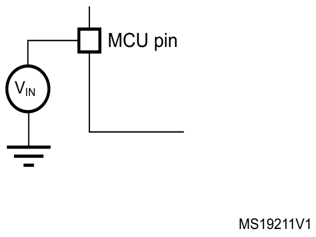
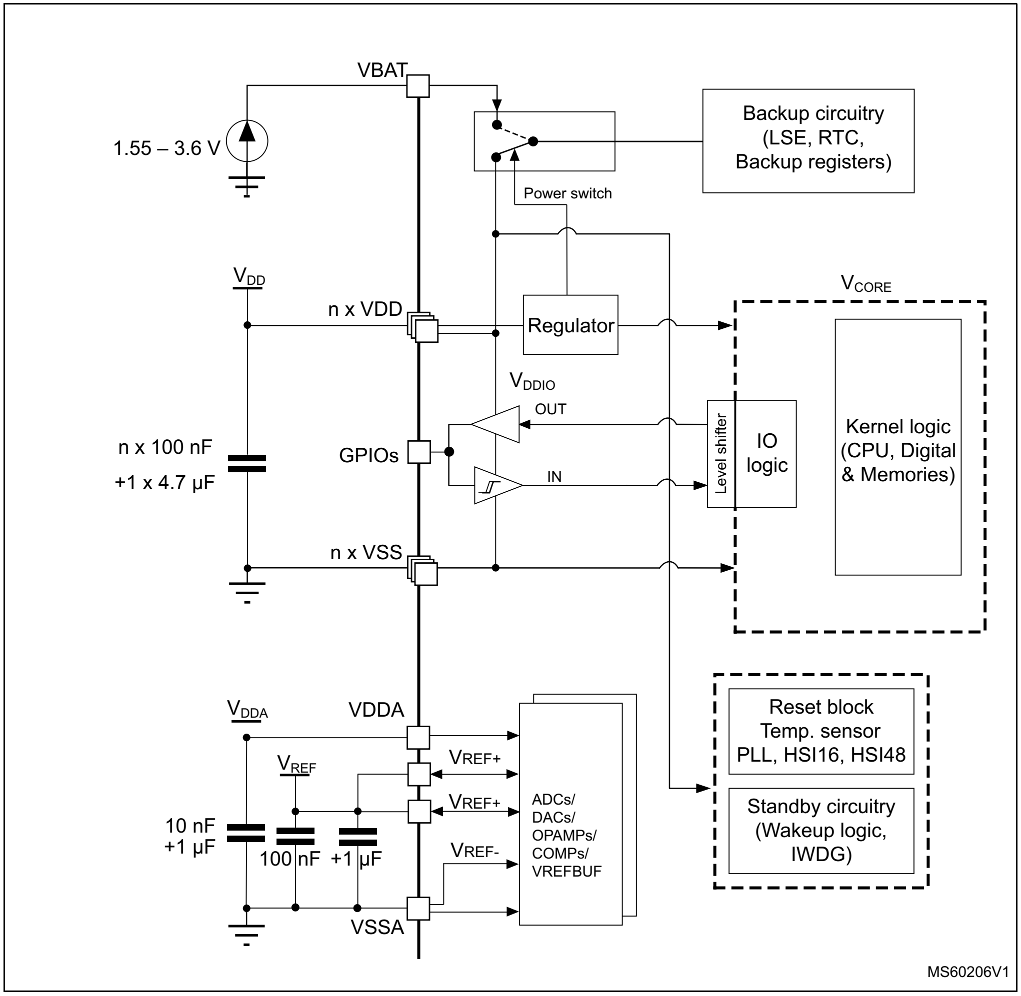


Figure 15. Pin input voltage



5.1.6 Power supply scheme

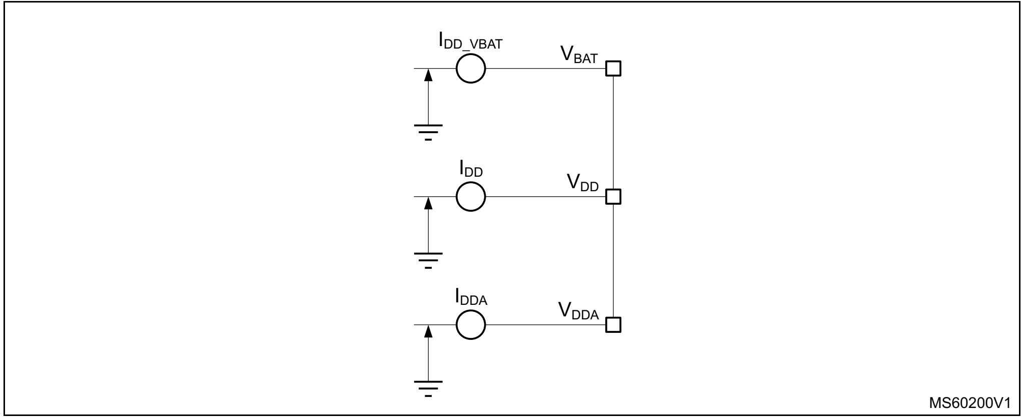
Figure 16. Power supply scheme



Caution: Each power supply pair (V_{DD}/V_{SS}, V_{DDA}/V_{SSA} etc.) must be decoupled with filtering ceramic capacitors as shown above. These capacitors must be placed as close as possible to, or below, the appropriate pins on the underside of the PCB to ensure the good functionality of the device.

5.1.7 Current consumption measurement

Figure 17. Current consumption measurement



The I_{DD_ALL} parameters given in *Table 21* to *Table 25* represent the total MCU consumption including the current supplying V_{DD}, V_{DDA} and V_{BAT}.

5.2 Absolute maximum ratings

Stresses above the absolute maximum ratings listed in *Table 14: Voltage characteristics*, *Table 15: Current characteristics* and *Table 16: Thermal characteristics* may cause permanent damage to the device. These are stress ratings only and functional operation of the device at these conditions is not implied. Exposure to maximum rating conditions for extended periods may affect device reliability. Exposure to maximum rating conditions for extended periods may affect device reliability. Device mission profile (application conditions) is compliant with JEDEC JESD47 qualification standard, extended mission profiles are available on demand.

Table 14. Voltage characteristics(1)

Symbol	Ratings	Min	Max	Unit
V_{DD} - V_{SS}	External main supply voltage (including V_{DD}, V_{DDA}, V_{BAT} and V_{REF+})	-0.3	4.0	V
V_{IN}(2)	Input voltage on FT_xxx pins except FT_c pins	V_{SS}-0.3	min (V_{DD}, V_{DDA}) + 4.0(3)(4)	
	Input voltage on FT_c pins	V_{SS}-0.3	5.5	
	Input voltage on TT_xx pins	V_{SS}-0.3	4.0	
	Input voltage on any other pins	V_{SS}-0.3	4.0	
$\|\Delta V_{DDx}\|$	Variations between different V_{DDX} power pins of the same domain	-	50	mV
$\|V_{SSx}-V_{SS}\|$	Variations between all the different ground pins(5)	-	50	
V_{REF+}-V_{DDA}	Allowed voltage difference for $V_{REF+} > V_{DDA}$	-	0.4	V

1. All main power (V_{DD}, V_{DDA}, V_{BAT}) and ground (V_{SS}, V_{SSA}) pins must always be connected to the external power supply, in the permitted range.

2. V_{IN} maximum must always be respected. Refer to *Table 15: Current characteristics* for the maximum allowed injected current values.
3. This formula has to be applied only on the power supplies related to the IO structure described in the pin definition table.
4. To sustain a voltage higher than 4 V the internal pull-up/pull-down resistors must be disabled.
5. Include VREF- pin.

Table 15. Current characteristics

Symbol	Ratings	Max	Unit
$\sum IV_{DD}$	Total current into sum of all V_{DD} power lines (source)(1)	150	mA
$\sum IV_{SS}$	Total current out of sum of all V_{SS} ground lines (sink)(1)	150	
$IV_{DD(PIN)}$	Maximum current into each V_{DD} power pin (source)(1)	100	
$IV_{SS(PIN)}$	Maximum current out of each V_{SS} ground pin (sink)(1)	100	
$I_{IO(PIN)}$	Output current sunk by any I/O and control pin except FT_f	20	
	Output current sunk by any FT_f pin	20	
	Output current sourced by any I/O and control pin	20	
$\sum I_{IO(PIN)}$	Total output current sunk by sum of all I/Os and control pins(2)	100	
	Total output current sourced by sum of all I/Os and control pins(2)	100	
$I_{INJ(PIN)}$(3)	Injected current on FT_xxx, TT_xx, NRST pins	-5/0(4)	
$\sum\lvert I_{INJ(PIN)}\rvert$	Total injected current (sum of all I/Os and control pins)(5)	±25	

1. All main power (V_{DD}, V_{DDA}, V_{BAT}) and ground (V_{SS}, V_{SSA}) pins must always be connected to the external power supplies, in the permitted range.
2. This current consumption must be correctly distributed over all I/Os and control pins. The total output current must not be sunk/sourced between two consecutive power supply pins referring to high pin count LQFP packages.
3. Positive injection (when $V_{IN} > V_{DD}$) is not possible on these I/Os and does not occur for input voltages lower than the specified maximum value.
4. A negative injection is induced by VIN < VSS. IINJ(PIN) must never be exceeded. Refer also to *Table 14: Voltage characteristics* for the minimum allowed input voltage values.
5. When several inputs are submitted to a current injection, the maximum $\sum\lvert I_{INJ(PIN)}\rvert$ is the absolute sum of the negative injected currents (instantaneous values).

Table 16. Thermal characteristics

Symbol	Ratings	Value	Unit
T_{STG}	Storage temperature range	–65 to +150	°C
T_J	Maximum junction temperature	150	°C

5.3 Operating conditions

5.3.1 General operating conditions

Table 17. General operating conditions

Symbol	Parameter	Conditions	Min	Max	Unit
f_{HCLK}	Internal AHB clock frequency	-	0	170	MHz
f_{PCLK1}	Internal APB1 clock frequency	-	0	170	
f_{PCLK2}	Internal APB2 clock frequency	-	0	170	
V_{DD}	Standard operating voltage	-	1.71[1]	3.6	V
V_{DDA}	Analog supply voltage	ADC or COMP used	1.62	3.6	V
		DAC 1 MSPS or DAC 15 MSPS	1.71		
		OPAMP used	2.0	3.6	
		VREFBUF used	2.4	3.6	
		ADC, DAC, OPAMP, COMP, VREFBUF not used	0		
V_{BAT}	Backup operating voltage	-	1.55	3.6	V
V_{IN}	I/O input voltage	TT_xx	-0.3	V_{DD}+0.3	V
		FT_c	-0.3	5	
		All I/O except TT_xx and FT_c	-0.3	MIN(MIN(V_{DD}, V_{DDA})+3.6 V, 5.5 V)[2][3]	
P_D	Power dissipation	See *Section 6.10: Thermal characteristics* for application appropriate thermal resistance and package. Power dissipation is then calculated according ambient temperature (T_A) and maximum junction temperature (T_J) and selected thermal resistance.			mW
T_A	Ambient temperature for the suffix 6 version	Maximum power dissipation	-40	85	°C
		Low-power dissipation[4]	-40	105	
	Ambient temperature for the suffix 3 version	Maximum power dissipation	-40	125	
		Low-power dissipation[4]	-40	130	
T_J	Junction temperature range	Suffix 6 version	-40	105	°C
		Suffix 3 version	-40	130	

1. When RESET is released functionality is guaranteed down to V_{BOR0} Min.
2. This formula has to be applied only on the power supplies related to the IO structure described by the pin definition table. Maximum I/O input voltage is the smallest value between MIN(V_{DD}, V_{DDA})+3.6 V and 5.5V.
3. For operation with voltage higher than Min (V_{DD}, V_{DDA}) +0.3 V, the internal Pull-up and Pull-Down resistors must be disabled.
4. In low-power dissipation state, T_A can be extended to this range as long as T_J does not exceed T_{Jmax} (see *Section 6.10: Thermal characteristics*).

5.3.2 Operating conditions at power-up / power-down

The parameters given in *Table 18* are derived from tests performed under the ambient temperature condition summarized in *Table 17*.

Table 18. Operating conditions at power-up / power-down

Symbol	Parameter	Conditions	Min	Max	Unit
t_{VDD}	V_{DD} rise time rate	-	0	∞	µs/V
	V_{DD} fall time rate		10	∞	
t_{VDDA}	V_{DDA} rise time rate	-	0	∞	µs/V
	V_{DDA} fall time rate		10	∞	

5.3.3 Embedded reset and power control block characteristics

The parameters given in *Table 19* are derived from tests performed under the ambient temperature conditions summarized in *Table 17: General operating conditions*.

Table 19. Embedded reset and power control block characteristics

Symbol	Parameter	Conditions(1)	Min	Typ	Max	Unit
$t_{RSTTEMPO}$(2)	Reset temporization after BOR0 is detected	V_{DD} rising	-	250	400	µs
V_{BOR0}(2)	Brown-out reset threshold 0	Rising edge	1.62	1.66	1.7	V
		Falling edge	1.6	1.64	1.69	
V_{BOR1}	Brown-out reset threshold 1	Rising edge	2.06	2.1	2.14	V
		Falling edge	1.96	2	2.04	
V_{BOR2}	Brown-out reset threshold 2	Rising edge	2.26	2.31	2.35	V
		Falling edge	2.16	2.20	2.24	
V_{BOR3}	Brown-out reset threshold 3	Rising edge	2.56	2.61	2.66	V
		Falling edge	2.47	2.52	2.57	
V_{BOR4}	Brown-out reset threshold 4	Rising edge	2.85	2.90	2.95	V
		Falling edge	2.76	2.81	2.86	
V_{PVD0}	Programmable voltage detector threshold 0	Rising edge	2.1	2.15	2.19	V
		Falling edge	2	2.05	2.1	
V_{PVD1}	PVD threshold 1	Rising edge	2.26	2.31	2.36	V
		Falling edge	2.15	2.20	2.25	
V_{PVD2}	PVD threshold 2	Rising edge	2.41	2.46	2.51	V
		Falling edge	2.31	2.36	2.41	
V_{PVD3}	PVD threshold 3	Rising edge	2.56	2.61	2.66	V
		Falling edge	2.47	2.52	2.57	

Table 19. Embedded reset and power control block characteristics (continued)

Symbol	Parameter	Conditions[1]	Min	Typ	Max	Unit
V_{PVD4}	PVD threshold 4	Rising edge	2.69	2.74	2.79	V
		Falling edge	2.59	2.64	2.69	
V_{PVD5}	PVD threshold 5	Rising edge	2.85	2.91	2.96	V
		Falling edge	2.75	2.81	2.86	
V_{PVD6}	PVD threshold 6	Rising edge	2.92	2.98	3.04	V
		Falling edge	2.84	2.90	2.96	
V_{hyst_BORH0}	Hysteresis voltage of BORH0	Hysteresis in continuous mode	-	20	-	mV
		Hysteresis in other mode	-	30	-	
$V_{hyst\_BOR\_PVD}$	Hysteresis voltage of BORH (except BORH0) and PVD	-	-	100	-	mV
I_{DD} (BOR_PVD)[2]	BOR[3] (except BOR0) and PVD consumption from V_{DD}	-	-	1.1	1.6	µA
V_{PVM1}	V_{DDA} peripheral voltage monitoring (COMP/ADC)	Rising edge	1.61	1.65	1.69	V
		Falling edge	1.6	1.64	1.68	
V_{PVM2}	V_{DDA} peripheral voltage monitoring (OPAMP/DAC)	Rising edge	1.78	1.82	1.86	V
		Falling edge	1.77	1.81	1.85	
V_{hyst_PVM1}	PVM1 hysteresis	-	-	10	-	mV
V_{hyst_PVM2}	PVM2 hysteresis	-	-	10	-	mV
I_{DD} (PVM1/PVM2)[2]	PVM1 and PVM2 consumption from V_{DD}	-	-	2	-	µA

1. Continuous mode means Run/Sleep modes, or temperature sensor enable in Low-power run/Low-power sleep modes.
2. Guaranteed by design.
3. BOR0 is enabled in all modes (except shutdown) and its consumption is therefore included in the supply current characteristics tables.

5.3.4 Embedded voltage reference

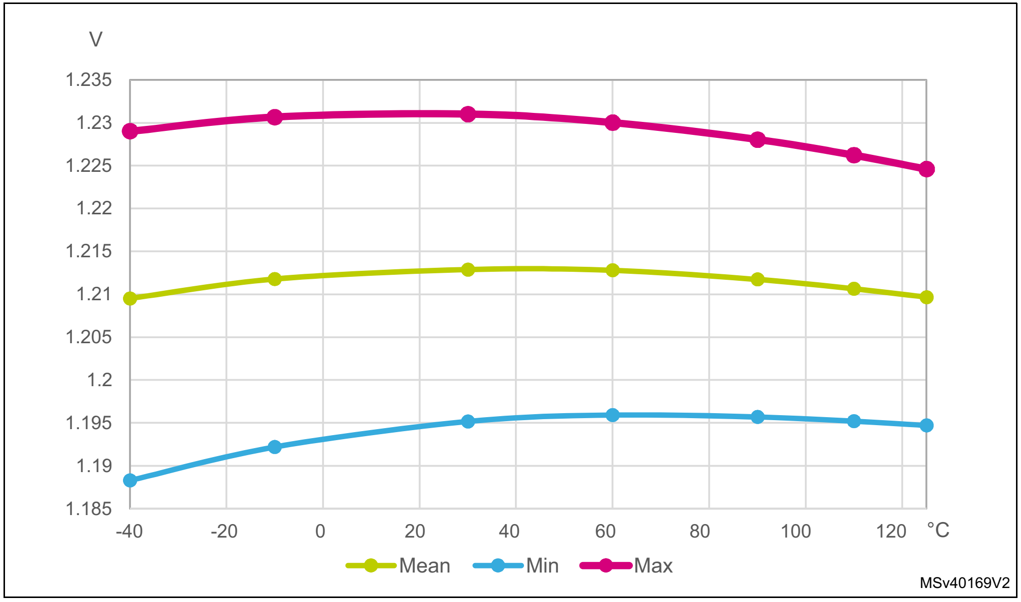
The parameters given in *Table 20* are derived from tests performed under the ambient temperature and supply voltage conditions summarized in *Table 17: General operating conditions*.

Table 20. Embedded internal voltage reference

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
V_{REFINT}	Internal reference voltage	–40 °C < T_A < +130 °C	1.182	1.212	1.232	V
$t_{S\_vrefint}$ (1)	ADC sampling time when reading the internal reference voltage	-	4(2)	-	-	µs
$t_{start\_vrefint}$	Start time of reference voltage buffer when ADC is enable	-	-	8	12(2)	µs
$I_{DD}(V_{REFINTBUF})$	V_{REFINT} buffer consumption from V_{DD} when converted by ADC	-	-	12.5	20(2)	µA
ΔV_{REFINT}	Internal reference voltage spread over the temperature range	V_{DD} = 3 V	-	5	7.5(2)	mV
T_{Coeff}	Average temperature coefficient	–40°C < T_A < +130°C	-	30	50(2)	ppm/°C
A_{Coeff}	Long term stability	1000 hours, T = 25°C	-	300	1000(2)	ppm
$V_{DDCoeff}$	Average voltage coefficient	3.0 V < V_{DD} < 3.6 V	-	250	1200(2)	ppm/V
V_{REFINT_DIV1}	1/4 reference voltage	-	24	25	26	% V_{REFINT}
V_{REFINT_DIV2}	1/2 reference voltage		49	50	51	
V_{REFINT_DIV3}	3/4 reference voltage		74	75	76	

1. The shortest sampling time is determined in the application by multiple iterations.
2. Guaranteed by design.

Figure 18. V_{REFINT} versus temperature



5.3.5 Supply current characteristics

The current consumption is a function of several parameters and factors such as the operating voltage, ambient temperature, I/O pin loading, device software configuration, operating frequencies, I/O pin switching rate, program location in memory and executed binary code

The current consumption is measured as described in *Figure 17: Current consumption measurement*.

Typical and maximum current consumption

The MCU is placed under the following conditions:

- All I/O pins are in analog input mode
- All peripherals are disabled except when explicitly mentioned
- The Flash memory access time is adjusted with the minimum wait states number, depending on the f_{HCLK} frequency (refer to the table “number of wait states according to CPU clock (HCLK) frequency” available in the reference manual RM0440 "STM32G4 Series advanced Arm®-based 32-bit MCUs").
- When the peripherals are enabled $f_{PCLK} = f_{HCLK}$
- The voltage scaling Range 1 is adjusted to f_{HCLK} frequency as follows:
  - Voltage Range 1 Boost mode for 150 MHz < f_{HCLK} ≤ 170 MHz
  - Voltage Range 1 Normal mode for 26 MHz < f_{HCLK} ≤ 150 MHz

The parameters given in *Table 21* to *Table 25* are derived from tests performed under ambient temperature and supply voltage conditions summarized in *Table 17: General operating conditions*.

Table 21. Current consumption in Run and Low-power run modes, code with data processing running from Flash in single Bank, ART enable (Cache ON Prefetch OFF)

Symbol	Parameter	Condition		f_{HCLK}	Typ					Max					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (Run)	Supply current in Run mode	$f_{HCLK} = f_{HSE}$ up to 48 MHz included, bypass mode PLL ON above 48 MHz all peripherals disable	Range 2	26 MHz	3.65	3.85	4.45	5.1	6.45	4.40	6.60	11.0	16.0	22.0	mA
				16 MHz	2.30	2.55	3.1	3.8	5.15	3.00	5.00	9.00	14.9	21.0	
				8 MHz	1.25	1.50	2.05	2.8	4.1	2.00	3.6	7.70	13.0	19.0	
				4 MHz	0.75	0.955	1.5	2.3	3.6	1.40	3.00	7.00	12.0	19.0	
				2 MHz	0.47	0.69	1.25	2	3.35	0.990	2.60	6.70	12.0	19.0	
				1 MHz	0.34	0.55	1.1	1.9	3.2	0.830	2.50	6.50	12.0	18.0	
				100 KHz	0.22	0.43	0.98	1.75	3.1	0.690	2.30	6.30	11.0	18.0	
			Range 1 Boost mode	170 MHz	29.50	29.5	31	32	34.5	31.0	35.0	42.0	48.0	56.0	
			Range 1	150 MHz	24.50	26	27	28	30	26.0	28.0	34.0	44.0	47.0	
				120 MHz	19.50	20	20.5	21.5	23.5	21.0	23.0	32.0	38.0	43.0	
				80 MHz	13.00	13.5	14	15.5	17	15.0	17.0	25.0	30.0	37.0	
				72 MHz	12.00	12	13	14	15.5	13.0	16.0	23.0	29.0	36.0	
				64 MHz	10.50	11	11.5	12.5	14.5	12.0	14.0	21.0	27.0	34.0	
				48 MHz	7.90	8.2	9	9.7	11.5	9.10	13.0	19.0	25.0	32.0	
				32 MHz	5.40	5.65	6.4	7.2	8.85	6.50	9.60	15.0	21.0	29.0	
				24 MHz	4.10	4.35	5.1	5.95	7.6	5.20	8.00	14.0	20.0	28.0	
				16 MHz	2.80	3.1	3.8	4.7	6.3	4.30	6.40	12.0	18.0	26.0	

Table 21. Current consumption in Run and Low-power run modes, code with data processing running from Flash in single Bank, ART enable (Cache ON Prefetch OFF) (continued)

Symbol	Parameter	Condition		f_{HCLK}	Typ					Max					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (LPRun)	Supply current in Low-power run mode	SYSCLK source is HSE in bypass mode all peripherals disable		2 MHz	455	725	1350	2250	3800	1200	3200	8100	14000	22000	µA
				1 MHz	280	545	1200	2100	3600	1100	3000	7900	14000	22000	
				250 KHz	160	435	1100	2000	3500	840	2800	7700	14000	22000	
				62.5 KHz	130	405	1050	1950	3500	810	2700	7600	14000	22000	
		SYSCLK source is HSI16 all peripherals disable		2 MHz	920	1200	1850	2750	4250	1900	3800	8700	15000	22000	
				1 MHz	780	1100	1700	2650	4150	1700	3700	8600	14000	22000	
				250 KHz	725	980	1600	2500	4050	1600	3600	8400	14000	22000	
				62.5 KHz	720	955	1600	2500	4000	1500	3500	8400	14000	22000	

Table 22. Current consumption in Run and Low-power run modes, code with data processing running from Flash in dual bank, ART enable (Cache ON Prefetch OFF)

Symbol	Parameter	Conditions		f_{HCLK}	Typ					Max[1]					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (Run)	Supply current in Run mode	$f_{HCLK} = f_{HSE}$ up to 48MHz included, bypass mode PLL ON above 48 MHz all peripherals disable	Range 2	26 MHz	3.70	3.9	4.45	5.15	6.45	4.40	6.60	11.0	16.0	22.0	mA
				16 MHz	2.35	2.55	3.1	3.85	5.15	3.00	5.00	9.00	14.0	21.0	
				8 MHz	1.25	1.5	2.05	2.8	4.15	2.00	3.60	7.70	13.0	19.0	
				4 MHz	0.75	0.97	1.5	2.3	3.6	1.40	3.00	7.00	12.0	19.0	
				2 MHz	0.47	0.7	1.25	2.05	3.35	0.990	2.60	6.70	12.0	19.0	
				1 MHz	0.34	0.56	1.1	1.9	3.2	0.830	2.50	6.50	12.0	18.0	
				100 KHz	0.22	0.44	0.975	1.8	3.1	0.690	2.30	6.30	11.0	18.0	
			Range 1 Boost mode	170 MHz	29.50	30	31	32	34.5	31.0	35.0	42.0	48.0	56.0	
			Range 1	150 MHz	24.50	24.5	25.5	26.5	28.5	26.0	28.0	34.0	44.0	47.0	
				120 MHz	19.50	20	20.5	22	23.5	21.0	23.0	32.0	38.0	43.0	
				80 MHz	13.00	13.5	14.5	15.5	17	15.0	17.0	25.0	30.0	37.0	
				72 MHz	12.00	12.5	13	14	15.5	13.0	16.0	23.0	29.0	36.0	
				64 MHz	10.50	11	11.5	13	14.5	12.0	14.0	21.0	27.0	34.0	
				48 MHz	7.95	8.3	9	10	11.5	9.10	13.0	19.0	25.0	32.0	
				32 MHz	5.40	5.7	6.45	7.25	8.9	6.50	9.60	15.0	21.0	29.0	
				24 MHz	4.10	4.4	5.1	6	7.65	5.20	8.00	14.0	20.0	28.0	
				16 MHz	2.85	3.15	3.8	4.75	6.35	4.30	6.40	12.0	18.0	26.0	

Table 22. Current consumption in Run and Low-power run modes, code with data processing running from Flash in dual bank, ART enable (Cache ON Prefetch OFF) (continued)

Symbol	Parameter	Conditions		f_{HCLK}	Typ					Max[(1)]					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (LPRun)	Supply current in Low-power run mode	SYSCLK source is HSE in bypass mode all peripherals disable		2 MHz	450	725	1350	2250	3800	1200	3200	8100	14000	22000	µA
				1 MHz	270	575	1200	2150	3650	1100	3000	7900	14000	22000	
				250 KHz	185	460	1050	2000	3550	840	2800	7700	14000	22000	
				62.5 KHz	130	430	1050	2000	3500	810	2700	7600	14000	22000	
		SYSCLK source is HSI16 all peripherals disable		2 MHz	970	1200	1850	2750	4300	1900	3800	8700	15000	22000	
				1 MHz	800	1100	1700	2650	4150	1700	3700	8600	14000	22000	
				250 KHz	680	990	1600	2550	4050	1600	3600	8400	14000	22000	
				62.5 KHz	695	965	1600	2500	4050	1500	3500	8400	14000	22000	

1. Guaranteed by characterization results, unless otherwise specified.

Table 23. Current consumption in Run and Low-power run modes, code with data processing running from SRAM1

Symbol	Parameter	Conditions		f_{HCLK}	Typ					Max[1]					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD(Run)	Supply current in Run mode	$f_{HCLK} = f_{HSE}$ up to 48MHz included, bypass mode PLL ON above 48 MHz all peripherals disable	Range 2	26 MHz	3.35	3.55	4.1	4.95	6.45	4.00	6.20	11.0	15.0	22.0	mA
				16 MHz	2.15	2.35	2.9	3.7	5.25	3.10	4.70	8.70	14.0	20.0	
				8 MHz	1.15	1.35	1.9	2.7	4.2	1.90	3.50	7.50	13.0	19.0	
				4 MHz	0.69	0.855	1.4	2.2	3.7	1.30	2.90	6.90	12.0	19.0	
				2 MHz	0.43	0.595	1.15	1.95	3.45	0.960	2.60	6.60	12.0	18.0	
				1 MHz	0.30	0.47	1	1.8	3.3	0.810	2.40	6.40	12.0	18.0	
				100 KHz	0.19	0.355	0.89	1.7	3.2	0.680	2.30	6.30	11.0	18.0	
			Range 1 Boost mode	170 MHz	26.00	26.5	27.5	28.5	30.5	28.0	32.0	39.0	45.0	53.0[2]	
			Range 1	150 MHz	21.50	22	22.5	23.5	25.5	23.0	25.0	31.0	41.0	46.0[2]	
				120 MHz	17.50	17.5	18.5	19.5	21.5	19.0	21.0	30.0	36.0	41.0	
				80 MHz	11.50	12	12.5	13.5	15.5	13.0	15.0	23.0	29.0	35.0	
				72 MHz	10.50	11	11.5	12.5	14.5	12.0	14.0	21.0	27.0	34.0	
				64 MHz	9.45	9.7	10.5	11.5	13.5	11.0	13.0	20.0	26.0	33.0	
				48 MHz	7.25	7.5	8.2	9.25	11	8.10	12.0	17.0	23.0	31.0	
				32 MHz	4.90	5.15	5.85	6.9	8.7	6.00	8.90	15.0	21.0	29.0	
				24 MHz	3.75	4	4.7	5.7	7.5	4.80	7.50	13.0	19.0	27.0	
				16 MHz	2.60	2.85	3.5	4.5	6.3	4.00	6.10	12.0	18.0	26.0	

Table 23. Current consumption in Run and Low-power run modes, code with data processing running from SRAM1 (continued)

Symbol	Parameter	Conditions		f_{HCLK}	Typ					Max[1]					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (LPRun)	Supply current in Low-power run mode	SYSCLK source is HSE in bypass mode all peripherals disable		2 MHz	365	570	1200	2150	3850	1200	3100	7900	14000	22000	µA
				1 MHz	240	425	1050	2000	3650	960	2900	7700	14000	22000	
				250 KHz	135	315	945	1850	3550	840	2800	7600	13000	22000	
				62.5 KHz	105	285	915	1850	3550	780	2700	7600	13000	22000	
		SYSCLK source is HSI16 all peripherals disable		2 MHz	835	1050	1650	2600	4300	1800	3700	8600	14000	22000	
				1 MHz	775	940	1550	2500	4150	1700	3600	8500	14000	22000	
				250 KHz	640	860	1450	2400	4100	1500	3500	8400	14000	22000	
				62.5 KHz	640	830	1450	2350	4050	1600	3500	8400	14000	22000	

1. Guaranteed by characterization results, unless otherwise specified.
2. Guaranteed by test in production.

Table 24. Typical current consumption in Run and Low-power run modes, with different codes running from Flash, ART enable (Cache ON Prefetch OFF)

Symbol	Parameter	Conditions		Code	Typ Single Bank Mode	Typ Dual Bank Mode	Unit	Typ Single Bank Mode	Typ Dual Bank Mode	Unit
		-	Voltage scaling		25°C	25°C		25°C	25°C	
IDD (Run)	Supply current in Run mode	$f_{HCLK}=f_{HSE}$ up to 48 MHZ included, bypass mode PLL ON above 48 MHz all peripherals disable	Range2 f_{HCLK}=26MHz	Reduced code(1)	3.65	3.7	mA	140	142	µA/MHz
				Coremark	3.65	3.7		140	142	
				Dhrystone2.1	3.65	3.7		140	142	
				Fibonacci	4.55	4.2		175	162	
				While(1)	2.90	3		112	115	
			Range 1 f_{HCLK}= 150 MHz	Reduced code(1)	24.5	24.5	mA	163	163	µA/MHz
				Coremark	24	24		160	160	
				Dhrystone2.1	24.5	24.5		163	163	
				Fibonacci	22.5	28		150	187	
				While(1)	19.5	20		130	133	
			Range 1 Boost mode f_{HCLK}= 170 MHz	Reduced code(1)	29.5	29.5	mA	174	174	µA/MHz
				Coremark	29	29		171	171	
				Dhrystone2.1	29.5	29.5		174	174	
				Fibonacci	38	35		224	206	
				While(1)	23.5	24		138	141	

Table 24. Typical current consumption in Run and Low-power run modes, with different codes running from Flash, ART enable (Cache ON Prefetch OFF) (continued)

Symbol	Parameter	Conditions		Code	Typ Single Bank Mode	Typ Dual Bank Mode	Unit	Typ Single Bank Mode	Typ Dual Bank Mode	Unit
		-	Voltage scaling		25°C	25°C		25°C	25°C	
I_{DD} (LPRun)	Supply current in Low-power run	SYSCLK source is HSI16 f_{HCLK} = 2 MHz all peripherals disable		Reduced code(1)	920	970	µA	460	485	µA/MHz
				Coremark	905	985		453	493	
				Dhrystone2.1	915	915		458	458	
				Fibonacci	1,050	950		525	475	
				While(1)	930	875		465	438	

1. Reduced code used for characterization results provided in *Table 21*, *Table 23*.

Table 25. Typical current consumption in Run and Low-power run modes, with different codes running from SRAM1

Symbol	Parameter	Conditions		Code	Typ	Unit	Typ	Unit
		-	Voltage scaling		25°C		25°C	
IDD (Run)	Supply current in Run mode	f_{HCLK} = f_{HSE} up to 48 MHZ included, bypass mode PLL ON above 48 MHz all peripherals disable	Range2 f_{HCLK}=26 MHz	Reduced code(1)	3.25	mA	125	µA/MHz
				Coremark	3.35		129	
				Dhrystone2.1	3.30		127	
				Fibonacci	3.30		127	
				While(1)	3.40		131	
			Range 1 f_{HCLK}= 150 MHz	Reduced code(1)	21.50	mA	143	µA/MHz
				Coremark	22.50		150	
				Dhrystone2.1	21.50		143	
				Fibonacci	22.50		150	
				While(1)	20.00		133	
			Range 1 Boost mode f_{HCLK}= 170 MHz	Reduced code(1)	26.00	mA	153	µA/MHz
				Coremark	27.00		159	
				Dhrystone2.1	26.00		153	
				Fibonacci	27.50		162	
				While(1)	24.50		144	
IDD (LPRun)	Supply current in Low-power run	f_{HCLK} = f_{HSE} = 2 MHz all peripherals disable		Reduced code(1)	955	µA	478	µA/MHz
				Coremark	890		445	
				Dhrystone2.1	915		458	
				Fibonacci	880		440	
				While(1)	905		453	

1. Reduced code used for characterization results provided in *Table 21*, *Table 23*.

Table 26. Typical current consumption in Run and Low-power run modes, with different codes running from SRAM2

Symbol	Parameter	Conditions		f_{HCLK}	Typ	Unit	Typ	Unit
		-	Voltage scaling		Single bank mode		Single bank mode	
IDD (Run)	Supply current in Run mode	f_{HCLK} = f_{HSE} up to 48 MHZ included, bypass mode PLL ON above 48 MHz all peripherals disable	Range2 f_{HCLK}=26 M Hz	Reduced code(1)	2.65	mA	102	µA/MHz
				Coremark	2.80		108	
				Dhrystone2.1	2.65		102	
				Fibonacci	2.60		100	
				While(1)	2.45		94	
			Range 1 f_{HCLK}= 150 MHz	Reduced code(1)	17.50	mA	117	µA/MHz
				Coremark	18.00		120	
				Dhrystone2.1	17.50		117	
				Fibonacci	17.00		113	
				While(1)	16		107	
			Range 1 Boost mode f_{HCLK}= 170 MHz	Reduced code(1)	21.00	mA	124	µA/MHz
				Coremark	22.00		129	
				Dhrystone2.1	21.00		124	
				Fibonacci	20.50		121	
				While(1)	19.50		115	
IDD (LPRun)	Supply current in Low-power run	SYSCLK source is HSI16 F_{HCLK} = 2MHz all peripherals disable		Reduced code(1)	890	µA	445	µA/MHz
				Coremark	830		415	
				Dhrystone2.1	825		413	
				Fibonacci	830		415	
				While(1)	815		408	

1. Reduced code used for characterization results provided in *Table 21*, *Table 23*.

Table 27. Typical current consumption in Run and Low-power run modes, with different codes running from CCMSRAM

Symbol	Parameter	Conditions		f_{HCLK}	Typ	Unit	Typ	Unit
		-	Voltage scaling		Single bank mode		Single bank mode	
IDD (Run)	Supply current in Run mode	$f_{HCLK} = f_{HSE}$ up to 48 MHZ included, bypass mode PLL ON above 48 MHz all peripherals disable	Range2 f_{HCLK}=26 M Hz	Reduced code(1)	2.75	mA	106	µA/MHz
				Coremark	2.85		110	
				Dhrystone2.1	2.75		106	
				Fibonacci	2.95		113	
				While(1)	2.60		100	
			Range 1 f_{HCLK}= 150 MHz	Reduced code(1)	18.00	mA	120	µA/MHz
				Coremark	18.50		123	
				Dhrystone2.1	18.00		120	
				Fibonacci	19.00		127	
				While(1)	17.00		113	
			Range 1 Boost mode f_{HCLK}= 170 MHz	Reduced code(1)	22.00	mA	129	µA/MHz
				Coremark	22.50		132	
				Dhrystone2.1	22.00		129	
				Fibonacci	23.50		138	
				While(1)	20.50		121	
IDD (LPRun)	Supply current in Low-power run	SYSCLK source is HSI16 F_{HCLK} = 2MHz all peripherals disable		Reduced code(1)	900	µA	450	µA/MHz
				Coremark	850		425	
				Dhrystone2.1	870		435	
				Fibonacci	850		425	
				While(1)	810		405	

1. Reduced code used for characterization results provided in *Table 21Table 23*.

Table 28. Current consumption in Sleep and Low-power sleep mode Flash ON

Symbol	Parameter	Condition		f_{HCLK}	Typ					Max					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (Sleep)	Supply current in sleep mode	$f_{HCLK} = f_{HSE}$ up to 48 MHz included, bypass mode PLL ON above 48 MHz all peripherals disable	Range 2	26 MHz	0.98	1.1	1.75	2.4	3.75	1.90	3.50	7.60	13.0	19.0	mA
				16 MHz	0.67	0.835	1.45	2.15	3.5	1.50	3.00	7.10	12.0	19.0	
				8 MHz	0.44	0.605	1.25	2	3.35	1.10	2.70	6.70	12.0	19.0	
				4 MHz	0.33	0.5	1.1	1.9	3.25	0.860	2.50	6.50	12.0	18.0	
				2 MHz	0.27	0.445	1.05	1.85	3.2	0.760	2.40	6.40	11.0	18.0	
				1 MHz	0.24	0.415	1.05	1.8	3.15	0.720	2.30	6.40	11.0	18.0	
				100 KHz	0.21	0.385	0.995	1.8	3.1	0.670	2.30	6.30	11.0	18.0	
			Range 1 Boost mode	170 MHz	6.60	6.95	7.8	8.9	10.5	8.00	12.0	18.0	24.0	33.0	
			Range 1	150 MHz	5.50	5.8	6.55	7.55	9.25	6.40	9.50	15.0	21.0	29.0	
				120 MHz	4.50	4.75	5.5	6.55	8.2	5.40	8.20	14.0	20.0	28.0	
				80 MHz	3.15	3.45	4.2	5.15	6.8	4.50	6.60	12.0	18.0	26.0	
				72 MHz	2.85	3.15	3.9	4.9	6.55	4.20	6.30	12.0	18.0	26.0	
				64 MHz	2.60	2.9	3.65	4.6	6.3	3.50	6.00	12.0	18.0	26.0	
				48 MHz	1.90	2.2	3	3.65	5.3	3.20	5.30	11.0	17.0	25.0	
				32 MHz	1.40	1.65	2.4	3.2	4.85	2.70	4.80	11.0	17.0	25.0	
				24 MHz	1.10	1.35	2.1	3	4.65	2.30	4.50	9.80	16.0	25.0	
				16 MHz	0.83	1.1	1.85	2.75	4.35	1.90	4.10	9.40	16.0	24.0	

Table 28. Current consumption in Sleep and Low-power sleep mode Flash ON (continued)

Symbol	Parameter	Condition		f_{HCLK}	Typ					Max					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (LPSleep)	Supply current in Low-power sleep mode	SYSCLK source is HSE in bypass mode all peripherals disable		2 MHz	205	430	1150	2050	3600	1600	2900	7800	14000	22000	μA
				1 MHz	165	400	1100	2000	3550	1100	2900	7700	14000	22000	
				250 KHz	145	370	1100	2000	3550	820	2800	7700	13000	22000	
				62.5 KHz	140	365	1050	2000	3550	810	2800	7700	13000	22000	
		SYSCLK source is HSI16 all peripherals disable		2 MHz	700	925	1650	2550	4100	1600	3600	8400	14000	22000	μA
				1 MHz	710	925	1600	2550	4100	1600	3600	8400	14000	22000	
				250 KHz	670	910	1600	2500	4050	1600	3600	8400	14000	22000	
				62.5 KHz	685	910	1600	2500	4050	1600	3600	8400	14000	22000	

Table 29. Current consumption in low-power sleep modes, Flash in power-down

Symbol	Parameter	Condition		f_{HCLK}	Typ					Max					Unit
		-	Voltage scaling		25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (LPSleep)	Supply current in low-power sleep mode	SYSCLK source is HSE in bypass mode all peripherals disable		2 MHz	210	385	1150	2050	3550	910	2900	7800	14000	22000	μA
				1 MHz	150	360	1100	2000	3550	860	2900	7700	14000	22000	
				250 KHz	120	330	1050	2000	3500	820	2700	7600	13000	21000	
				62.5 KHz	110	330	1050	1950	3500	810	2700	7600	13000	21000	
		SYSCLK source is HSI16 all peripherals disable		2 MHz	675	900	1600	2500	4050	1600	3600	8500	14000	22000	
				1 MHz	695	890	1600	2500	4050	1600	3600	8400	14000	22000	
				250 KHz	640	885	1600	2500	4050	1600	3600	8500	14000	22000	
				62.5 KHz	690	880	1600	2500	4050	1400	3000	7000	12000	19000	

Table 30. Current consumption in Stop 1 mode

Symbol	Parameter	Conditions		Typ					Max[1]					Unit
		-	V_{DD}	25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD (Stop 1)	Supply current in Stop 1 mode, RTC disabled	RTC disabled	1.8 V	80	250	830	1550	2850	630	2100	5900	11000	18000	µA
			2.4 V	80	250	835	1600	2850	640	2100	5900	11000	18000	
			3.0 V	80.5	255	840	1600	2900	640	2200	6000	11000	18000	
			3.6 V	81.5	255	845	1600	2900	640	2200	6000	11000	18000	
IDD (Stop 1 with RTC)	Supply current in Stop 1 mode, RTC enabled	RTC clocked by LSI	1.8 V	80.5	255	830	1550	2850	640	2100	5900	11000	18000	
			2.4 V	81	255	835	1600	2850	640	2200	5900	11000	18000	
			3.0 V	81.5	255	835	1600	2850	640	2200	6000	11000	18000	
			3.6 V	82	255	845	1600	2900	650	2200	6000	11000	18000	
		RTC clocked by LSE bypassed at 32768 Hz	1.8 V	80	255	830	1550	2850	-	-	-	-	-	
			2.4 V	80.5	255	830	1600	2850	-	-	-	-	-	
			3.0 V	81.5	255	835	1600	2900	-	-	-	-	-	
			3.6 V	83	260	845	1600	2900	-	-	-	-	-	
		RTC clocked by LSE quartz in low drive mode at 32768 Hz	1.8 V	83.5	220	655	1300	-	-	-	-	-	-	
			2.4 V	84	220	660	1300	-	-	-	-	-	-	
			3.0 V	84.5	220	660	1300	-	-	-	-	-	-	
			3.6 V	87	220	660	1300	-	-	-	-	-	-	
IDD (wakeup from Stop 1	Supply current during wakeup from Stop 1 mode	Wakeup clock is HSI6, voltage Range 1	3.0 V	1.73	-	-	-	-	-	-	-	-	-	mA
		Wakeup clock is HSI6 = 4 MHz, (HPRE = 4), voltage Range 2	3.0 V	1.29	-	-	-	-	-	-	-	-	-	

1. Guaranteed by characterization results, unless otherwise specified.

Table 31. Current consumption in Stop 0 mode

Symbol	Parameter	Conditions		Typ					Max[1]					Unit
		-	V_{DD}	25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
I_{DD}(Stop 0)	Supply current in Stop 0 mode, RTC disabled	-	1.8 V	190	380	980	1750	3100	790	2400	6500	11000	19000	µA
			2.4 V	190	380	985	1750	3100	790	2400	6400	11000	19000	
			3 V	190	380	985	1750	3100	800	2400	6500	12000	19000	
			3.6 V	190	380	985	1750	3100	800	2500	6500	12000	19000	

1. Guaranteed by characterization results, unless otherwise specified.

Table 32. Current consumption in Standby mode

Symbol	Parameter	Conditions		Typ					Max[1]					Unit
		-	V_{DD}	25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
I_{DD} (Standby)	Supply current in Standby mode (backup registers retained), RTC disabled	No independent watchdog	1.8 V	100	275	1350	3450	8450	200	1100	4100	9700	27000	nA
			2.4 V	110	325	1600	4100	10000	220	1200	4800	12000	31000	
			3 V	130	385	1900	4850	12000	240	1400	5500	13000	35000	
			3.6 V	180	530	2400	6050	14500	360	1700	6300	15000	40000	
		With independent watchdog	1.8 V	300	-	-	-	-	-	-	-	-	-	
			2.4 V	365	-	-	-	-	-	-	-	-	-	
			3 V	435	-	-	-	-	-	-	-	-	-	
			3.6 V	545	-	-	-	-	-	-	-	-	-	

Table 32. Current consumption in Standby mode (continued)

Symbol	Parameter	Conditions		Typ					Max[1]					Unit
		-	V_{DD}	25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
I_{DD} (Standby with RTC)	Supply current in Standby mode (backup registers retained), RTC enabled	RTC clocked by LSI, no independent watchdog	1.8 V	540	725	1800	3850	8850	660	1500	4600	11000	27000	nA
			2.4 V	700	920	2150	4650	10500	860	1900	5300	12000	31000	
			3 V	885	1150	2650	5550	12500	1100	2200	6300	14000	36000	
			3.6 V	1100	1450	3350	7000	15500	1400	2700	7400	16000	41000	
		RTC clocked by LSI, with independent watchdog	1.8 V	580	-	-	-	-	-	-	-	-	-	
			2.4 V	760	-	-	-	-	-	-	-	-	-	
			3 V	960	-	-	-	-	-	-	-	-	-	
			3.6 V	1200	-	-	-	-	-	-	-	-	-	
		RTC clocked by LSE bypassed at 32768 Hz	1.8 V	410	580	1600	3650	8600	-	-	-	-	-	nA
			2.4 V	545	750	1950	4450	10500	-	-	-	-	-	
			3 V	830	1150	2750	5800	13000	-	-	-	-	-	
			3.6 V	2200	3050	5550	9550	18000	-	-	-	-	-	
		RTC clocked by LSE quartz[2] in low drive mode	1.8 V	370	570	1350	3150	7100	-	-	-	-	-	
			2.4 V	495	715	1650	3800	8350	-	-	-	-	-	
			3 V	655	915	2100	4550	9850	-	-	-	-	-	
			3.6 V	875	1350	2800	5750	12000	-	-	-	-	-	
I_{DD} (SRAM2)[3]	Supply current to be added in Standby mode when SRAM2 is retained	-	1.8 V	300	825	2950	6300	12550	-	-	-	-	-	nA
			2.4 V	305	875	2900	6400	12500	-	-	-	-	-	
			3 V	305	865	2950	6150	12500	-	-	-	-	-	
			3.6 V	310	870	3000	6450	13000	-	-	-	-	-	

Table 32. Current consumption in Standby mode (continued)

Symbol	Parameter	Conditions		Typ					Max[1]					Unit
		-	V_{DD}	25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
I_{DD} (wakeup from Standby)	Supply current during wakeup from Standby mode	Wakeup clock is HSI16 = 16 MHz(4)	3 V	2.46	-	-	-	-	-	-	-	-	-	mA

1. Guaranteed by characterization results, unless otherwise specified.
2. Based on characterization done with a 32.768 kHz crystal (MC306-G-06Q-32.768, manufacturer JFVNY) with two 6.8 pF loading capacitors.
3. The supply current in Standby with SRAM2 mode is: I_{DD_ALL}(Standby) + I_{DD_ALL}(SRAM2). The supply current in Standby with RTC with SRAM2 mode is: II_{DD_ALL}(Standby + RTC) + I_{DD_ALL}(SRAM2).
4. Wakeup with code execution from Flash. Average value given for a typical wakeup time as specified in *Table 36: Low-power mode wakeup timings*.

Table 33. Current consumption in Shutdown mode

Symbol	Parameter	Conditions		Typ					Max[1]					Unit
		-	V_{DD}	25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
I_{DD} (Shutdown)	Supply current in Shutdown mode (backup registers retained) RTC disabled	-	1.8 V	19	140	885	2500	6600	78.0	490	3100	8100	24000	nA
			2.4 V	28	180	1050	2950	7800	94.0	570	3600	9300	27000	
			3 V	43	230	1300	3600	9300	130	680	4100	11000	31000	
			3.6 V	87	360	1750	4700	12000	190	870	4900	13000	35000	

Table 33. Current consumption in Shutdown mode (continued)

Symbol	Parameter	Conditions		Typ					Max[1]					Unit
		-	V_{DD}	25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
I_{DD} (Shutdown with RTC)	Supply current in Shutdown mode (backup registers retained) RTC enabled	RTC clocked by LSE bypassed at 32768 Hz	1.8 V	330	445	1150	2700	6800	-	-	-	-	-	nA
			2.4 V	460	605	1450	3350	8150	-	-	-	-	-	
			3 V	745	1000	2200	4550	10500	-	-	-	-	-	
			3.6 V	2100	2850	4900	8150	15500	-	-	-	-	-	
		RTC clocked by LSE quartz[2] in low drive mode	1.8 V	285	450	1050	2500	-	-	-	-	-	-	
			2.4 V	410	585	1300	3050	-	-	-	-	-	-	
			3 V	565	770	1750	3750	-	-	-	-	-	-	
			3.6 V	780	1200	2400	4850	-	-	-	-	-	-	
I_{DD}(wakeup from Shutdown)	Supply current during wakeup from Shutdown mode	Wakeup clock is HSI16 = 16 MHz[3]	3 V	1.6	-	-	-	-	-	-	-	-	-	mA

1. Guaranteed by characterization results, unless otherwise specified.
2. Based on characterization done with a 32.768 kHz crystal (MC306-G-06Q-32.768, manufacturer JFVNY) with two 6.8 pF loading capacitors.
3. Wakeup with code execution from Flash. Average value given for a typical wakeup time as specified in *Table 36: Low-power mode wakeup timings*.

Table 34. Current consumption in V_{BAT} mode

Symbol	Parameter	Conditions		Typ					Max[1]					Unit
		-	V_{BAT}	25°C	55°C	85°C	105°C	125°C	25°C	55°C	85°C	105°C	125°C	
IDD(V_{BAT})	Backup domain supply current	RTC disabled	1.8 V	4	17	92	245	600	-	-	-	-	-	nA
			2.4 V	5	20	105	280	690	-	-	-	-	-	
			3 V	6	24	125	330	805	-	-	-	-	-	
			3.6 V	16	54	260	675	1650	-	-	-	-	-	
		RTC enabled and clocked by LSE bypassed at 32768 Hz	1.8 V	310	315	350	470	-	-	-	-	-	-	
			2.4 V	435	440	500	665	-	-	-	-	-	-	
			3 V	720	815	1050	1350	-	-	-	-	-	-	
			3.6 V	2150	2600	3400	4050	-	-	-	-	-	-	
		RTC enabled and clocked by LSE quartz[2]	1.8 V	270	345	455	715	835	-	-	-	-	-	
			2.4 V	385	455	650	910	910	-	-	-	-	-	
			3 V	525	600	910	1150	1000	-	-	-	-	-	
			3.6 V	710	995	1250	1700	1900	-	-	-	-	-	

1. Guaranteed by characterization results, unless otherwise specified.
2. Based on characterization done with a 32.768 kHz crystal (MC306-G-06Q-32.768, manufacturer JFVNY) with two 6.8 pF loading capacitors.

IO system current consumption

The current consumption of the I/O system has two components: static and dynamic.

I/O static current consumption

All the I/Os used as inputs with pull-up generate current consumption when the pin is externally held low. The value of this current consumption can be simply computed by using the pull-up/pull-down resistors values given in *Table 54: I/O static characteristics*.

For the output pins, any external pull-down or external load must also be considered to estimate the current consumption.

Additional I/O current consumption is due to I/Os configured as inputs if an intermediate voltage level is externally applied. This current consumption is caused by the input Schmitt trigger circuits used to discriminate the input value. Unless this specific configuration is required by the application, this supply current consumption can be avoided by configuring these I/Os in analog mode. This is notably the case of ADC, OPAMP, COMP input pins which should be configured as analog inputs.

Caution: Any floating input pin can also settle to an intermediate voltage level or switch inadvertently, as a result of external electromagnetic noise. To avoid current consumption related to floating pins, they must either be configured in analog mode, or forced internally to a definite digital value. This is done either by using pull-up/down resistors or by configuring the pins in output mode.

I/O dynamic current consumption

In addition to the internal peripheral current consumption measured previously (see *Table 36: Low-power mode wakeup timings*), the I/Os used by an application also contribute to the current consumption. When an I/O pin switches, it uses the current from the I/O supply voltage to supply the I/O pin circuitry and to charge/discharge the capacitive load (internal or external) connected to the pin:

$$I_{SW} = V_{DDIOx} \times f_{SW} \times C$$

where

I_{SW} is the current sunk by a switching I/O to charge/discharge the capacitive load

V_{DD} is the I/O supply voltage

f_{SW} is the I/O switching frequency

C is the total capacitance seen by the I/O pin: $C = C_{INT} + C_{EXT} + C_S$

C_S is the PCB board capacitance including the pad pin.

The test pin is configured in push-pull output mode and is toggled by software at a fixed frequency.

On-chip peripheral current consumption

The current consumption of the on-chip peripherals is given in *Table 35*. The MCU is placed under the following conditions:

- All I/O pins are in Analog mode
- The given value is calculated by measuring the difference of the current consumptions:
  - when the peripheral is clocked on
  - when the peripheral is clocked off
- Ambient operating temperature and supply voltage conditions summarized in *Table 14: Voltage characteristics*
- The power consumption of the digital part of the on-chip peripherals is given in *Table 35*. The power consumption of the analog part of the peripherals (where applicable) is indicated in each related section of the datasheet.

Table 35. Peripheral current consumption

Bus	Peripheral	Range 1 Boost mode	Range 1 Normal mode	Range 2	Low-power run and sleep	Unit
-	Bus Matrix	6.12	5.69	4.70	6.11	µA/MHz
	AHB1 to APB1 bridge	0.26	0.25	0.22	0.03	
	AHB1 to APB2 bridge	0.39	0.37	0.32	0.03	
	FSMC	10.21	9.52	7.87	10.28	
	QUADSPI	3.51	3.27	2.69	3.51	
AHB1	CORDIC	1.28	1.19	0.98	0.78	µA/MHz
	CRC	0.74	0.68	0.57	0.63	
	DMA 1	2.83	2.64	2.17	2.75	
	DMA 2	3.11	2.90	2.39	2.43	
	DMAMUX	6.71	6.26	5.17	6.68	
	SRAM1	0.58	0.54	0.44	0.54	
	FLASH	6.46	6.01	4.95	6.15	
	FMAC	4.59	4.29	3.57	3.83	

Table 35. Peripheral current consumption (continued)

Bus	Peripheral	Range 1 Boost mode	Range 1 Normal mode	Range 2	Low-power run and sleep	Unit
AHB2	ADC1/ADC2	6.24	5.80	4.77	5.88	µA/MHz
	ADC3/ADC4/ADC5	8.21	7.64	6.29	8.14	
	DAC1	4.70	4.38	3.63	4.40	
	DAC2	2.51	2.34	1.93	2.14	
	DAC3	4.62	4.31	3.57	4.15	
	DAC4	4.31	4.01	3.32	3.90	
	GPIOA	0.09	0.08	0.07	0.14	
	GPIOB	0.10	0.09	0.07	0.03	
	GPIOC	0.10	0.09	0.08	0.03	
	GPIOD	0.06	0.06	0.03	0.05	
	GPIOE	0.23	0.22	0.18	0.10	
	GPIOF	0.07	0.07	0.05	0.02	
	GPIOG	0.25	0.24	0.20	0.24	
	SRAM2	0.39	0.37	0.29	0.28	
	CCM SRAM	0.29	0.27	0.23	0.22	
	RNG	2.09	1.95	NA	NA	

Table 35. Peripheral current consumption (continued)

Bus	Peripheral	Range 1 Boost mode	Range 1 Normal mode	Range 2	Low-power run and sleep	Unit
APB1	CRS	0.74	0.68	0.57	0.51	µA/MHz
	FDCAN1/FDCAN2/FDCAN3	22.20	20.68	17.10	21.15	
	I2C1	1.29	1.20	0.99	1.28	
	I2C2	1.29	1.20	0.99	1.28	
	I2C3	1.25	1.17	0.96	1.56	
	I2C4	1.25	1.16	0.96	1.97	
	LPTIM1	1.11	1.03	0.85	1.42	
	LPUART1	1.91	1.78	1.47	2.03	
	PWR	0.71	0.65	0.53	0.53	
	RTC	2.64	2.46	2.07	3.26	
	SPI2/I2S2	4.05	3.77	3.11	4.16	
	SPI3/I2S3	4.08	3.81	3.13	4.49	
	TIM2	7.97	7.42	6.16	8.29	
	TIM3	6.37	5.93	4.92	6.81	
	TIM4	6.43	5.98	4.97	6.50	
	TIM5	8.28	7.71	6.38	8.11	
	TIM6	1.22	1.13	0.94	1.45	
	TIM7	1.28	1.18	0.98	1.56	
	UART4	2.51	2.33	1.92	3.14	
	UART5	2.79	2.60	2.14	3.34	
	USART2	2.75	2.56	2.12	3.11	
	USART3	2.71	2.52	2.08	2.47	
	USB	0.46	0.43	NA	NA	
	UCPD	2.46	2.28	1.89	NA	
	WWDG	0.42	0.39	0.31	0.42	

Table 35. Peripheral current consumption (continued)

Bus	Peripheral	Range 1 Boost mode	Range 1 Normal mode	Range 2	Low-power run and sleep	Unit
APB2	HRTIM	69.98	65.11	53.68	60.95	µA/MHz
	SAI1	2.67	2.48	2.05	2.64	
	SPI1	1.99	1.86	1.54	2.02	
	SPI4	1.99	1.86	1.54	2.02	
	TIM1	10.85	10.13	8.40	9.93	
	TIM8	10.67	9.96	8.25	9.82	
	TIM15	4.81	4.48	3.71	4.57	
	TIM16	3.71	3.45	2.88	3.45	
	TIM17	3.66	3.41	2.83	3.81	
	TIM20	10.71	9.99	8.29	10.00	
	USART1	2.49	2.31	1.91	2.49	
	SYSCFG/COMP/OPAMP/VREFBUF	1.63	1.52	1.25	0.91	

Table 35. Peripheral current consumption (continued)

Bus	Peripheral		Range 1 Boost mode	Range 1 Normal mode	Range 2	Low-power run and sleep	Unit
Independent clock domain	ADC1/ ADC2	independent clock domain	0.72	0.67	0.53	0.63	µA/MHz
	ADC3/ ADC4/ ADC5	independent clock domain	0.67	0.62	0.50	0.22	
	FDCAN1/ FDCAN2/ FDCAN3	independent clock domain	11.62	10.84	8.95	10.24	
	I2C1	independent clock domain	4.03	3.76	3.12	4.15	
	I2C2	independent clock domain	3.78	3.52	2.93	3.23	
	I2C3	independent clock domain	2.72	2.55	2.11	2.65	
	I2C4	independent clock domain	3.95	3.67	3.04	2.81	
	I2S2	independent clock domain	1.49	1.40	1.15	1.63	
	I2S3	independent clock domain	1.52	1.43	1.16	2.15	
	LPTIM1	independent clock domain	4.00	3.71	3.08	3.57	
	LPUART1	independent clock domain	4.43	4.13	3.45	4.02	
	QUADSPI	independent clock domain	0.54	0.51	0.44	0.75	
	RNG	independent clock domain	0.83	0.87	NA	NA	
	USB	independent clock domain	1.10	1.17	NA	NA	
	SAI1	independent clock domain	3.36	3.14	2.58	3.25	
	UART4	independent clock domain	6.60	6.17	5.14	6.02	
	UART5	independent clock domain	6.60	6.16	5.12	6.12	
	USART1	independent clock domain	7.62	7.12	5.89	6.90	
	USART2	independent clock domain	7.37	6.86	5.70	6.72	
	USART3	independent clock domain	7.98	7.44	6.17	8.21	
All	-		369.00	316.04	266.18	325.00	µA/MHz

5.3.6 Wakeup time from low-power modes and voltage scaling transition times

The wakeup times given in *Table 36* are the latency between the event and the execution of the first user instruction.

The device goes in low-power mode after the WFE (Wait For Event) instruction.

Table 36. Low-power mode wakeup timings(1)

Symbol	Parameter	Conditions		Typ	Max	Unit
$t_{WUSLEEP}$	Wakeup time from Sleep mode to Run mode	-		11	12	Nb of CPU cycles
$t_{WULPSLEEP}$	Wakeup time from Low-power sleep mode to Low-power run mode	-		10	11	
$t_{WUSTOP0}$	Wake up time from Stop 0 mode to Run mode in Flash	Range 1	Wakeup clock HSI16 = 16 MHz	5.8	6	µs
		Range 2	Wakeup clock HSI16 = 16 MHz	18.4	19.1	
	Wake up time from Stop 0 mode to Run mode in SRAM1	Range 1	Wakeup clock HSI16 = 16 MHz	2.8	3	
		Range 2	Wakeup clock HSI16 = 16 MHz	2.9	3	
$t_{WUSTOP1}$	Wake up time from Stop 1 mode to Run in Flash	Range 1	Wakeup clock HSI16 = 16 MHz	9.5	9.8	
		Range 2	Wakeup clock HSI16 = 16 MHz	21.9	22.7	
	Wake up time from Stop 1 mode to Run mode in SRAM1	Range 1	Wakeup clock HSI16 = 16 MHz	6.6	6.9	
		Range 2	Wakeup clock HSI16 = 16 MHz	6.4	6.6	
	Wake up time from Stop 1 mode to Low-power run mode in Flash	Regulator in low-power mode (LPR=1 in PWR_CR1)	Wakeup clock HSI16 = 16 MHz, with HPRE = 8	26.1	27.1(2)	
	Wake up time from Stop 1 mode to Low-power run mode in SRAM1			14.4	15(2)	
t_{WUSTBY}	Wakeup time from Standby mode to Run mode	Range 1	Wakeup clock HSI16 = 16 MHz	29.7	33.8	
$t_{WUSTBY\ SRAM2}$	Wakeup time from Standby with SRAM2 to Run mode	Range 1	Wakeup clock HSI16 = 16 MHz	29.7	33.5	
t_{WUSHDN}	Wakeup time from Shutdown mode to Run mode	Range 1	Wakeup clock HSI16 = 16 MHz	267.9	274.6(2)	
$t_{WULPRUN}$	Wakeup time from Low-power run mode to Run mode(3)	Wakeup clock HSI16 = 16 MHz with HPRE = 8		5	7	

1. Guaranteed by characterization results.
2. Characterization results for temperature range from 0°C to 125°C.
3. Time until REGLPF flag is cleared in PWR_SR2.

Table 37. Regulator modes transition times(1)

Symbol	Parameter	Conditions	Typ	Max	Unit
t_{VOST}	Regulator transition time from Range 2 to Range 1 or Range 1 to Range 2(2)	Wakeup clock HSI16 = 16 MHz with HPRE = 8	20	40	µs

1. Guaranteed by characterization results.
2. Time until VOSF flag is cleared in PWR_SR2.

Table 38. Wakeup time using USART/LPUART(1)

Symbol	Parameter	Conditions	Typ	Max	Unit
$t_{WUUSART}$ $t_{WULPUART}$	Wakeup time needed to calculate the maximum USART/LPUART baudrate allowing to wakeup up from stop mode when USART/LPUART clock source is HSI16	Stop 0 mode	-	1.7	µs
		Stop 1 mode	-	8.5	

1. Guaranteed by design.

5.3.7 External clock source characteristics

High-speed external user clock generated from an external source

In bypass mode the HSE oscillator is switched off and the input pin is a standard GPIO.

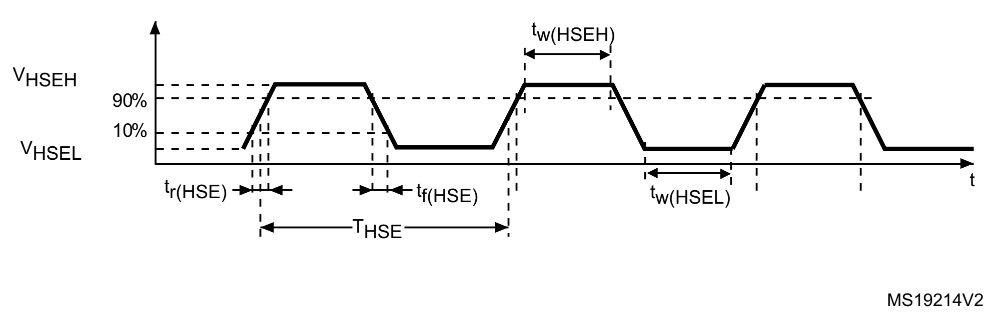
The external clock signal has to respect the I/O characteristics in *Section 5.3.14*. However, the recommended clock input waveform is shown in *Figure 19: High-speed external clock source AC timing diagram*.

Table 39. High-speed external user clock characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_{HSE_ext}	User external clock source frequency	Voltage scaling Range 1	-	8	48	MHz
		Voltage scaling Range 2	-	8	26	
V_{HSEH}	OSC_IN input pin high level voltage	-	0.7 V_{DD}	-	V_{DD}	V
V_{HSEL}	OSC_IN input pin low level voltage	-	V_{SS}	-	0.3 V_{DD}	
$t_{w(HSEH)}$ $t_{w(HSEL)}$	OSC_IN high or low time	Voltage scaling Range 1	7	-	-	ns
		Voltage scaling Range 2	18	-	-	

1. Guaranteed by design.

Figure 19. High-speed external clock source AC timing diagram



Low-speed external user clock generated from an external source

In bypass mode the LSE oscillator is switched off and the input pin is a standard GPIO.

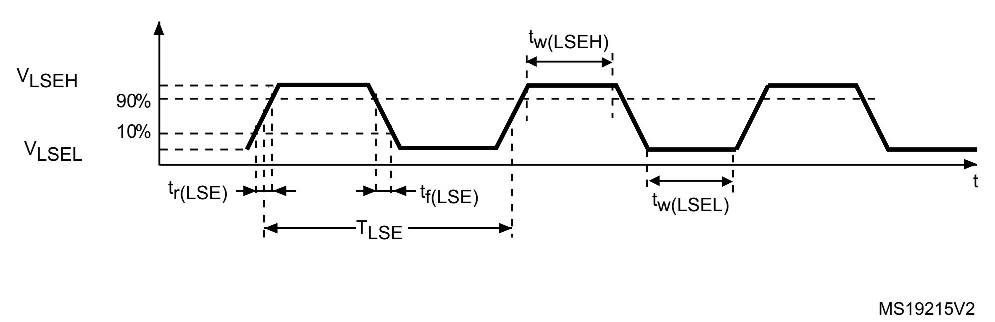
The external clock signal has to respect the I/O characteristics in *Section 5.3.14*. However, the recommended clock input waveform is shown in *Figure 20*.

Table 40. Low-speed external user clock characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_{LSE_ext}	User external clock source frequency	-	-	32.768	1000	kHz
V_{LSEH}	OSC32_IN input pin high level voltage	-	0.7 V_{DD}	-	V_{DD}	V
V_{LSEL}	OSC32_IN input pin low level voltage	-	V_{SS}	-	0.3 V_{DD}	
$t_{w(LSEH)}$ $t_{w(LSEL)}$	OSC32_IN high or low time	-	250	-	-	ns

1. Guaranteed by design.

Figure 20. Low-speed external clock source AC timing diagram



High-speed external clock generated from a crystal/ceramic resonator

The high-speed external (HSE) clock can be supplied with a 4 to 48 MHz crystal/ceramic resonator oscillator. All the information given in this paragraph are based on design simulation results obtained with typical external components specified in *Table 41*. In the application, the resonator and the load capacitors have to be placed as close as possible to the oscillator pins in order to minimize output distortion and startup stabilization time. Refer to the crystal resonator manufacturer for more details on the resonator characteristics (frequency, package, accuracy).

Table 41. HSE oscillator characteristics(1)

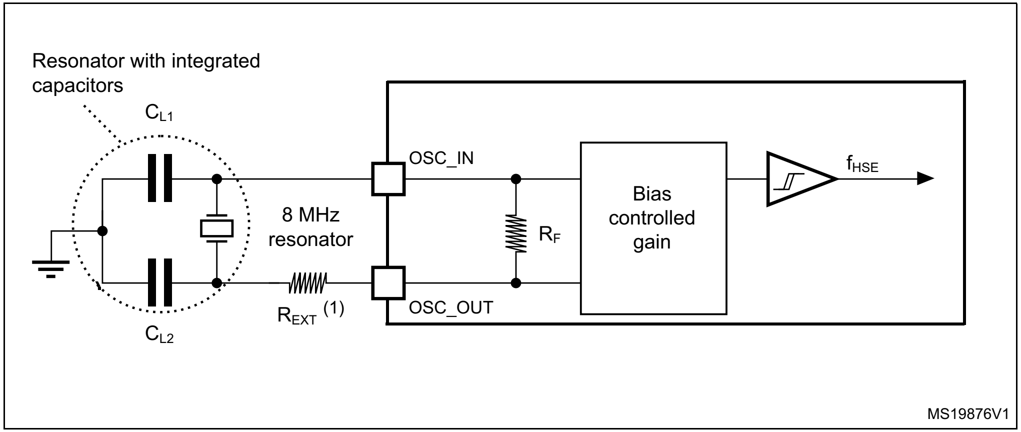
Symbol	Parameter	Conditions(2)	Min	Typ	Max	Unit
f_{OSC_IN}	Oscillator frequency	-	4	8	48	MHz
R_F	Feedback resistor	-	-	200	-	kΩ
$I_{DD(HSE)}$	HSE current consumption	During startup(3)	-	-	5.5	mA
		V_{DD} = 3 V, Rm = 30 Ω, CL = 10 pF@8 MHz	-	0.44	-	
		V_{DD} = 3 V, Rm = 45 Ω, CL = 10 pF@8 MHz	-	0.45	-	
		V_{DD} = 3 V, Rm = 30 Ω, CL = 5 pF@48 MHz	-	0.68	-	
		V_{DD} = 3 V, Rm = 30 Ω, CL = 10 pF@48 MHz	-	0.94	-	
		V_{DD} = 3 V, Rm = 30 Ω, CL = 20 pF@48 MHz	-	1.77	-	
G_m	Maximum critical crystal transconductance	Startup	-	-	1.5	mA/V
$t_{SU(HSE)}$(4)	Startup time	V_{DD} is stabilized	-	2	-	ms

1. Guaranteed by design.
2. Resonator characteristics given by the crystal/ceramic resonator manufacturer.
3. This consumption level occurs during the first 2/3 of the $t_{SU(HSE)}$ startup time
4. $t_{SU(HSE)}$ is the startup time measured from the moment it is enabled (by software) to a stabilized 8 MHz oscillation is reached. This value is measured for a standard crystal resonator and it can vary significantly with the crystal manufacturer

For C_{L1} and C_{L2}, it is recommended to use high-quality external ceramic capacitors in the 5 pF to 20 pF range (typ.), designed for high-frequency applications, and selected to match the requirements of the crystal or resonator (see *Figure 21*). C_{L1} and C_{L2} are usually the same size. The crystal manufacturer typically specifies a load capacitance which is the series combination of C_{L1} and C_{L2}. PCB and MCU pin capacitance must be included (10 pF can be used as a rough estimate of the combined pin and board capacitance) when sizing C_{L1} and C_{L2}.

Note: For information on selecting the crystal, refer to the application note AN2867 “Oscillator design guide for ST microcontrollers” available from the ST website www.st.com.

Figure 21. Typical application with an 8 MHz crystal



1. R_{EXT} value depends on the crystal characteristics.

Low-speed external clock generated from a crystal resonator

The low-speed external (LSE) clock can be supplied with a 32.768 kHz crystal resonator oscillator. All the information given in this paragraph are based on design simulation results obtained with typical external components specified in *Table 42*. In the application, the resonator and the load capacitors have to be placed as close as possible to the oscillator pins in order to minimize output distortion and startup stabilization time. Refer to the crystal resonator manufacturer for more details on the resonator characteristics (frequency, package, accuracy).

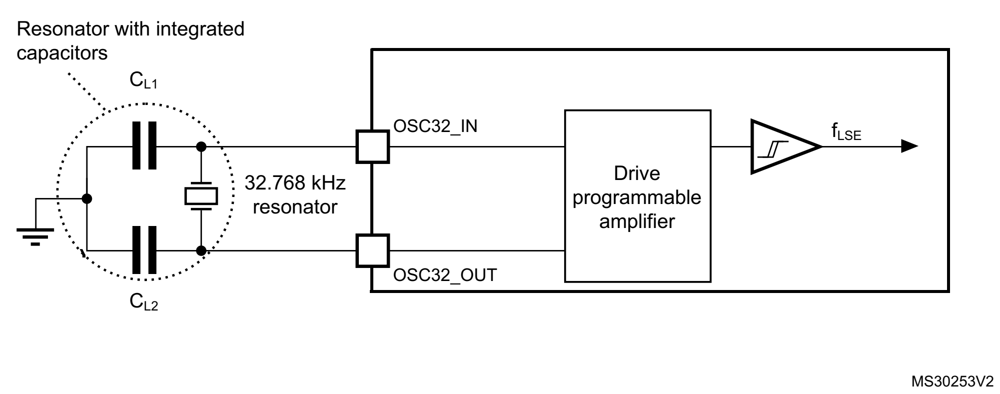
Table 42. LSE oscillator characteristics (f_{LSE} = 32.768 kHz)[1]

Symbol	Parameter	Conditions[2]	Min	Typ	Max	Unit
$I_{DD(LSE)}$	LSE current consumption	LSEDRV[1:0] = 00 Low drive capability	-	250	-	nA
		LSEDRV[1:0] = 01 Medium low drive capability	-	315	-	
		LSEDRV[1:0] = 10 Medium high drive capability	-	500	-	
		LSEDRV[1:0] = 11 High drive capability	-	630	-	
$Gm_{critmax}$	Maximum critical crystal gm	LSEDRV[1:0] = 00 Low drive capability	-	-	0.5	µA/V
		LSEDRV[1:0] = 01 Medium low drive capability	-	-	0.75	
		LSEDRV[1:0] = 10 Medium high drive capability	-	-	1.7	
		LSEDRV[1:0] = 11 High drive capability	-	-	2.7	
$t_{SU(LSE)}$[3]	Startup time	V_{DD} is stabilized	-	2	-	s

1. Guaranteed by design.
2. Refer to the note and caution paragraphs below the table, and to the application note AN2867 “Oscillator design guide for ST microcontrollers”.
3. $t_{SU(LSE)}$ is the startup time measured from the moment it is enabled (by software) to a stabilized 32.768 kHz oscillation is reached. This value is measured for a standard crystal and it can vary significantly with the crystal manufacturer

Note: For information on selecting the crystal, refer to the application note AN2867 “Oscillator design guide for ST microcontrollers” available from the ST website www.st.com.

Figure 22. Typical application with a 32.768 kHz crystal



Note: An external resistor is not required between OSC32_IN and OSC32_OUT and it is forbidden to add one.

5.3.8 Internal clock source characteristics

The parameters given in *Table 43* are derived from tests performed under ambient temperature and supply voltage conditions summarized in *Table 17: General operating conditions*. The provided curves are characterization results, not tested in production.

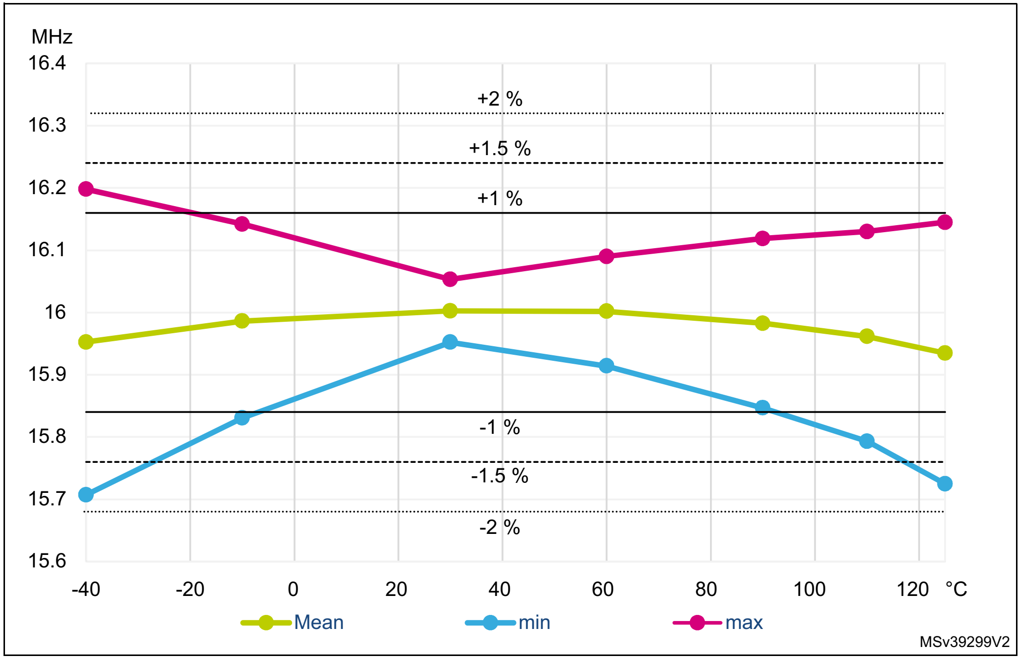
High-speed internal (HSI16) RC oscillator

Table 43. HSI16 oscillator characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_{HSI16}	HSI16 Frequency	V_{DD}=3.0 V, T_A=30 °C	15.88	-	16.08	MHz
TRIM	HSI16 user trimming step	Trimming code is not a multiple of 64	0.2	0.3	0.4	%
		Trimming code is a multiple of 64	-4	-6	-8	
DuCy(HSI16)(2)	Duty Cycle	-	45	-	55	%
Δ_{Temp}(HSI16)	HSI16 oscillator frequency drift over temperature	T_A= 0 to 85 °C	-1	-	1	%
		T_A= -40 to 125 °C	-2	-	1.5	%
Δ_{VDD}(HSI16)	HSI16 oscillator frequency drift over V_{DD}	V_{DD}=1.62 V to 3.6 V	-0.1	-	0.05	%
t_{su}(HSI16)(2)	HSI16 oscillator start-up time	-	-	0.8	1.2	µs
t_{stab}(HSI16)(2)	HSI16 oscillator stabilization time	-	-	3	5	µs
I_{DD}(HSI16)(2)	HSI16 oscillator power consumption	-	-	155	190	µA

1. Guaranteed by characterization results.
2. Guaranteed by design.

Figure 23. HSI16 frequency versus temperature



High-speed internal 48 MHz (HSI48) RC oscillator

Table 44. HSI48 oscillator characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_{HSI48}	HSI48 Frequency	V_{DD}=3.0V, T_A=30°C	-	48	-	MHz
TRIM	HSI48 user trimming step	-	-	0.11(2)	0.18(2)	%
USER TRIM COVERAGE	HSI48 user trimming coverage	±32 steps	±3(3)	±3.5(3)	-	%
DuCy(HSI48)	Duty Cycle	-	45(2)	-	55(2)	%
ACC_{HSI48_REL}	Accuracy of the HSI48 oscillator over temperature (factory calibrated)	V_{DD} = 3.0 V to 3.6 V, T_A = –15 to 85 °C	-	-	±3(3)	%
		V_{DD} = 1.65 V to 3.6 V, T_A = –40 to 125 °C	-	-	±4.5(3)	
D_{VDD}(HSI48)	HSI48 oscillator frequency drift with V_{DD}	V_{DD} = 3 V to 3.6 V	-	0.025(3)	0.05(3)	%
		V_{DD} = 1.65 V to 3.6 V	-	0.05(3)	0.1(3)	
t_{su}(HSI48)	HSI48 oscillator start-up time	-	-	2.5(2)	6(2)	µs
I_{DD}(HSI48)	HSI48 oscillator power consumption	-	-	340(2)	380(2)	µA

Table 44. HSI48 oscillator characteristics[1] (continued)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
N_T jitter	Next transition jitter Accumulated jitter on 28 cycles[4]	-	-	+/-0.15[2]	-	ns
P_T jitter	Paired transition jitter Accumulated jitter on 56 cycles[4]	-	-	+/-0.25[2]	-	ns

1. V_{DD} = 3 V, T_A = –40 to 125°C unless otherwise specified.
2. Guaranteed by design.
3. Guaranteed by characterization results.
4. Jitter measurement are performed without clock source activated in parallel.

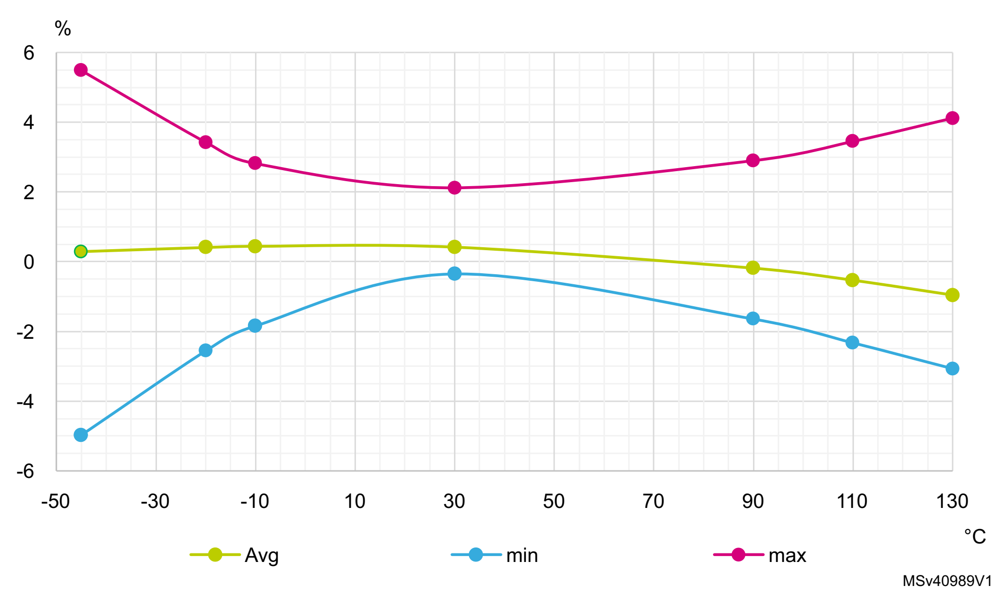


Figure 24. HSI48 frequency versus temperature

Low-speed internal (LSI) RC oscillator

Table 45. LSI oscillator characteristics[1]

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_{LSI}	LSI Frequency	V_{DD} = 3.0 V, T_A = 30 °C	31.04	-	32.96	kHz
		V_{DD} = 1.62 to 3.6 V, T_A = -40 to 125 °C	29.5	-	34	
$t_{SU}(LSI)$[2]	LSI oscillator start-up time	-	-	80	130	µs

Table 45. LSI oscillator characteristics(1) (continued)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
$t_{STAB}(LSI)^{(2)}$	LSI oscillator stabilization time	5% of final frequency	-	125	180	µs
$I_{DD}(LSI)^{(2)}$	LSI oscillator power consumption	-	-	110	180	nA

1. Guaranteed by characterization results.
2. Guaranteed by design.

5.3.9 PLL characteristics

The parameters given in *Table 46* are derived from tests performed under temperature and V_{DD} supply voltage conditions summarized in *Table 17: General operating conditions*.

Table 46. PLL characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_{PLL_IN}	PLL input clock(2)	-	2.66	-	16	MHz
	PLL input clock duty cycle	-	45	-	55	%
$f_{PLL\_P\_OUT}$	PLL multiplier output clock P	Voltage scaling Range 1 Boost mode	2.0645	-	170	MHz
		Voltage scaling Range 1	2.0645	-	150	
		Voltage scaling Range 2	2.0645	-	26	
$f_{PLL\_Q\_OUT}$	PLL multiplier output clock Q	Voltage scaling Range 1 Boost mode	8	-	170	
		Voltage scaling Range 1	8	-	150	
		Voltage scaling Range 2	8	-	26	
$f_{PLL\_R\_OUT}$	PLL multiplier output clock R	Voltage scaling Range 1 Boost mode	8	-	170	
		Voltage scaling Range 1	8	-	150	
		Voltage scaling Range 2	8	-	26	
f_{VCO_OUT}	PLL VCO output	Voltage scaling Range 1	96	-	344	
		Voltage scaling Range 2	96	-	128	
t_{LOCK}	PLL lock time	-	-	15	40	µs
Jitter	RMS cycle-to-cycle jitter	System clock 150 MHz	-	28.6	-	±ps
	RMS period jitter		-	21.4	-	
$I_{DD}(PLL)$	PLL power consumption on $V_{DD}^{(1)}$	VCO freq = 96 MHz	-	200	260	µA
		VCO freq = 192 MHz	-	300	380	
		VCO freq = 344 MHz	-	520	650	

1. Guaranteed by design.
2. Take care of using the appropriate division factor M to obtain the specified PLL input clock values.

5.3.10 Flash memory characteristics

Table 47. Flash memory characteristics[(1)]

Symbol	Parameter	Conditions	Typ	Max	Unit
t_{prog}	64-bit programming time	-	81.7	83.35	µs
t_{prog_row}	One row (32 double word) programming time	Normal programming	2.61	2.7	ms
		Fast programming	1.91	1.95	
t_{prog_page}	One page (2 Kbytes) programming time	Normal programming	20.91	21.34	
		Fast programming	15.29	15.6	
t_{ERASE}	Page (2 Kbytes) erase time	-	22.02	24.47	
t_{prog_bank}	One bank (256 Kbyte) programming time	Normal programming	2.68	2.73	s
		Fast programming	1.96	2	
t_{ME}	Mass erase time (one or two banks)	-	22.13	24.6	ms
I_{DD}	Average consumption from V_{DD}	Write mode	3.5	-	mA
		Erase mode	3.5	-	
	Maximum current (peak)	Write mode	7 (for 6 µs)	-	
		Erase mode	7 (for 67 µs)	-	

1. Guaranteed by design.

Table 48. Flash memory endurance and data retention

Symbol	Parameter	Conditions	Min(1)	Unit
N_{END}	Endurance	T_A = -40 to +105 °C	10	kcycles
t_{RET}	Data retention	1 kcycle(2) at T_A = 85 °C	30	Years
		1 kcycle(2) at T_A = 105 °C	15	
		1 kcycle(2) at T_A = 125 °C	7	
		10 kcycles(2) at T_A = 55 °C	30	
		10 kcycles(2) at T_A = 85 °C	15	
		10 kcycles(2) at T_A = 105 °C	10	

1. Guaranteed by characterization results.
2. Cycling performed over the whole temperature range.

5.3.11 EMC characteristics

Susceptibility tests are performed on a sample basis during device characterization.

Functional EMS (electromagnetic susceptibility)

While a simple application is executed on the device (toggling 2 LEDs through I/O ports). the device is stressed by two electromagnetic events until a failure occurs. The failure is indicated by the LEDs:

- **Electrostatic discharge (ESD)** (positive and negative) is applied to all device pins until a functional disturbance occurs. This test is compliant with the IEC 61000-4-2 standard.
- **FTB**: A Burst of Fast Transient voltage (positive and negative) is applied to V_{DD} and V_{SS} through a 100 pF capacitor, until a functional disturbance occurs. This test is compliant with the IEC 61000-4-4 standard.

A device reset allows normal operations to be resumed.

The test results are given in *Table 49*. They are based on the EMS levels and classes defined in application note AN1709.

Table 49. EMS characteristics

Symbol	Parameter	Conditions	Level/ Class
V_{FESD}	Voltage limits to be applied on any I/O pin to induce a functional disturbance	V_{DD} = 3.3 V, T_A = +25 °C, f_{HCLK} = 170 MHz, conforming to IEC 61000-4-2	3B
V_{EFTB}	Fast transient voltage burst limits to be applied through 100 pF on V_{DD} and V_{SS} pins to induce a functional disturbance	V_{DD} = 3.3 V, T_A = +25 °C, f_{HCLK} = 170 MHz, conforming to IEC 61000-4-4	5A

Designing hardened software to avoid noise problems

EMC characterization and optimization are performed at component level with a typical application environment and simplified MCU software. It should be noted that good EMC performance is highly dependent on the user application and the software in particular.

Therefore it is recommended that the user applies EMC software optimization and prequalification tests in relation with the EMC level requested for his application.

Software recommendations

The software flowchart must include the management of runaway conditions such as:

- Corrupted program counter
- Unexpected reset
- Critical Data corruption (control registers...)

Prequalification trials

Most of the common failures (unexpected reset and program counter corruption) can be reproduced by manually forcing a low state on the NRST pin or the Oscillator pins for 1 second.

To complete these trials, ESD stress can be applied directly on the device, over the range of specification values. When unexpected behavior is detected, the software can be hardened to prevent unrecoverable errors occurring (see application note AN1015).

Electromagnetic Interference (EMI)

The electromagnetic field emitted by the device are monitored while a simple application is executed (toggling 2 LEDs through the I/O ports). This emission test is compliant with IEC 61967-2 standard which specifies the test board and the pin loading.

Table 50. EMI characteristics

Symbol	Parameter	Conditions	Monitored frequency band	Max vs. [f_{HSE}/f_{HCLK}]	Unit
				8 MHz / 170 MHz	
S_{EMI}	Peak level	V_{DD} = 3.6 V, T_A = 25 °C, LQFP128 package compliant with IEC 61967-2	0.1 MHz to 30 MHz	4	dBµV
			30 MHz to 130 MHz	0	
			130 MHz to 1 GHz	16	
			1 GHz to 2 GHz	11	
			EMI Level	3.5	-

5.3.12 Electrical sensitivity characteristics

Based on three different tests (ESD, LU) using specific measurement methods, the device is stressed in order to determine its performance in terms of electrical sensitivity.

Electrostatic discharge (ESD)

Electrostatic discharges (a positive then a negative pulse separated by 1 second) are applied to the pins of each sample according to each pin combination. The sample size depends on the number of supply pins in the device (3 parts × (n+1) supply pins). This test conforms to the ANSI/JEDEC standard.

Table 51. ESD absolute maximum ratings

Symbol	Ratings	Conditions		Class	Maximum value[1]	Unit
$V_{ESD(HBM)}$	Electrostatic discharge voltage (human body model)	T_A = +25 °C, conforming to ANSI/ESDA/JEDEC JS-001		2	2000	V
$V_{ESD(CDM)}$	Electrostatic discharge voltage (charge device model)	T_A = +25 °C, conforming to ANSI/ESDA/JEDEC JS-002	LQFP100 and LQFP128	C1	250	V
			Other packages	C2a	500	

1. Guaranteed by characterization results.

Static latch-up

Two complementary static tests are required on three parts to assess the latch-up performance:

- A supply overvoltage is applied to each power supply pin.
- A current injection is applied to each input, output and configurable I/O pin.

These tests are compliant with EIA/JESD 78E IC latch-up standard.

Table 52. Electrical sensitivities

Symbol	Parameter	Conditions	Class
LU	Static latch-up class	TA = +125 °C conforming to JESD78E	Class II level A

5.3.13 I/O current injection characteristics

As a general rule, current injection to the I/O pins, due to external voltage below V_{SS} or above V_{DD} (for standard, 3.3 V-capable I/O pins) should be avoided during normal product operation. However, in order to give an indication of the robustness of the microcontroller in cases when abnormal injection accidentally happens, susceptibility tests are performed on a sample basis during device characterization.

Functional susceptibility to I/O current injection

While a simple application is executed on the device, the device is stressed by injecting current into the I/O pins programmed in floating input mode. While current is injected into the I/O pin, one at a time, the device is checked for functional failures.

The failure is indicated by an out of range parameter: ADC error above a certain limit (higher than 5 LSB TUE), out of conventional limits of induced leakage current on adjacent pins (out of the -5 µA/+0 µA range) or other functional failure (for example reset occurrence or oscillator frequency deviation).

The characterization results are given in *Table 53*.

Negative induced leakage current is caused by negative injection and positive induced leakage current is caused by positive injection.

Table 53. I/O current injection susceptibility

Symbol	Description		Functional susceptibility		Unit
			Negative injection	Positive injection	
I_{INJ}(1)	Injected current on pin	All except TT_a, PF10, PB8-BOOT0, PC10	-5	NA	mA
		PF10, PB8-BOOT0, PC10	-0	NA	
		TT_a pins	-5	0	

1. Guaranteed by characterization.

5.3.14 I/O port characteristics

General input/output characteristics

Unless otherwise specified, the parameters given in *Table 54* are derived from tests performed under the conditions summarized in *Table 17: General operating conditions*. All I/Os are designed as CMOS- and TTL-compliant.

Table 54. I/O static characteristics

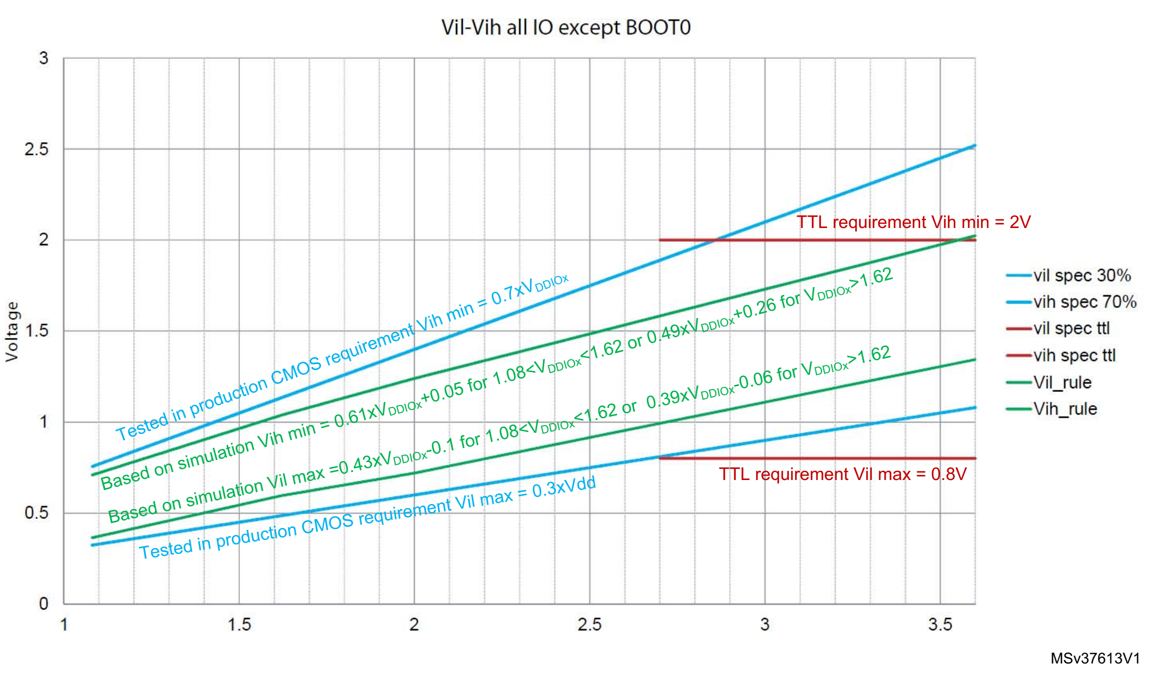
Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_{IL}(1)(2)	I/O input low level voltage	All except FT_c	1.62 V<V_{DD}<3.6 V	-	-	0.3xV_{DD}	V
						0.39xV_{DD}-0.06(3)	
		FT_c	1.62 V<V_{DD}<3.6 V	-	-	0.3xV_{DD}	
						0.25xV_{DD}	
V_{IH}(1)(2)	I/O input high level voltage	All except FT_c	1.62 V<V_{DD}<3.6 V	0.7xV_{DD}	-	-	V
				0.49xV_{DD} +0.26(3)	-	-	
		FT_c	1.62 V<V_{DD}<3.6 V	0.7xV_{DD}	-	-	
V_{HYS}(3)	Input hysteresis	TT_xx, FT_xxx, NRST	1.62 V<V_{DD}<3.6 V	-	200	-	mV
I_{leak}	Input leakage current(3)	FT_xx except FT_c	$0 < V_{IN} \leq V_{DD}$	-	-	±100	nA
			$V_{DD} \leq V_{IN} \leq V_{DD}$+1 V	-	-	650(4)	
			V_{DD}+1 V < $V_{IN} \leq$ 5.5 V	-	-	200(4)	
		FT_c	$0 \leq V_{IN} \leq V_{DDMAX}$	-	-	2000	
			$V_{DD} \leq V_{IN}$ <0.5 V	-	-	3000	
		FT_u, PC3	$0 \leq V_{IN} \leq V_{DD}$	-	-	±150	
			$V_{DD} \leq V_{IN} \leq V_{DD}$+ 1 V	-	-	±2500	
			$V_{DD} \leq V_{IN} \leq$ 5.5 V	-	-	±250	
		FT_d	$0 \leq V_{IN} \leq V_{DD}$	-	-	±4500	
			V_{DD} + 1V $\leq V_{IN} \leq$ 5.5 V	-	-	±9000	
		TT_xx	$0 \leq V_{IN} \leq V_{DD}$	-	-	±150	
			$V_{DD} \leq V_{IN} \leq$ 3.6 V	-	-	2000	
R_{PU}	Weak pull-up equivalent resistor(5)	$V_{IN} = V_{SS}$		25	40	55	kΩ
R_{PD}	Weak pull-down equivalent resistor(5)	$V_{IN} = V_{DD}$		25	40	55	
C_{IO}	I/O pin capacitance	I/O pin capacitance	-	-	5	-	pF

1. Refer to *Figure 25: I/O input characteristics*

2. Data based on characterization results, not tested in production
3. Guaranteed by design.
4. This value represents the pad leakage of the I/O itself. The total product pad leakage is provided by this formula: $I_{Total\_Ileak\_max}$ = 10 µA + [number of I/Os where VIN is applied on the pad] x I_{lkg}(Max).
5. Pull-up and pull-down resistors are designed with a true resistance in series with a switchable PMOS/NMOS. This PMOS/NMOS contribution to the series resistance is minimal (~10% order).

All I/Os are CMOS- and TTL-compliant (no software configuration required). Their characteristics cover more than the strict CMOS-technology or TTL parameters. The coverage of these requirements is shown in *Figure 25* for standard I/Os, and 5 V tolerant I/Os (except FT_c).

Figure 25. I/O input characteristics



Output driving current

The GPIOs (general purpose input/outputs) can sink or source up to ±8 mA, and sink or source up to ± 20 mA (with a relaxed V_{OL}/V_{OH}).

In the user application, the number of I/O pins which can drive current must be limited to respect the absolute maximum rating specified in *Section 5.2*:

- The sum of the currents sourced by all the I/Os on $V_{DD,}$ plus the maximum consumption of the MCU sourced on $V_{DD,}$ cannot exceed the absolute maximum rating ΣI_{VDD} (see *Table 14: Voltage characteristics*).
- The sum of the currents sunk by all the I/Os on V_{SS}, plus the maximum consumption of the MCU sunk on V_{SS}, cannot exceed the absolute maximum rating ΣI_{VSS} (see *Table 14: Voltage characteristics*).

Output voltage levels

Unless otherwise specified, the parameters given in the table below are derived from tests performed under the ambient temperature and supply voltage conditions summarized in *Table 17: General operating conditions*. All I/Os are CMOS- and TTL-compliant (FT OR TT unless otherwise specified).

Table 55. Output voltage characteristics(1)(2)

Symbol	Parameter	Conditions	Min	Max	Unit
V_{OL}(3)	Output low level voltage for an I/O pin	CMOS port $\lvert I_{IO}\rvert$ = 2 mA for FT_c I/Os = 8 mA for other I/Os $V_{DD} \geq 2.7$ V	-	0.4	V
V_{OH}(3)	Output high level voltage for an I/O pin		V_{DD}-0.4	-	
V_{OL}(3)	Output low level voltage for an I/O pin	TTL port $\lvert I_{IO}\rvert$ = 2 mA for FT_c I/Os = 8 mA for other I/Os $V_{DD} \geq 2.7$ V	-	0.4	
V_{OH}(3)	Output high level voltage for an I/O pin		2.4	-	
V_{OL}(3)	Output low level voltage for an I/O pin	All I/Os except FT_c $\lvert I_{IO}\rvert$ = 20 mA $V_{DD} \geq 2.7$ V	-	1.3	
V_{OH}(3)	Output high level voltage for an I/O pin		V_{DD}-1.3	-	
V_{OL}(3)	Output low level voltage for an I/O pin	$\lvert I_{IO}\rvert$ = 1 mA for FT_c I/Os = 4 mA for other I/Os $V_{DD} \geq 1.62$ V	-	0.4	
V_{OH}(3)	Output high level voltage for an I/O pin		V_{DD}-0.45	-	
V_{OLFM+}(3)	Output low level voltage for an FT I/O pin in FM+ mode (FT I/O with “f” option)	$\lvert I_{IO}\rvert$ = 20 mA $V_{DD} \geq 2.7$ V	-	0.4	
		$\lvert I_{IO}\rvert$ = 10 mA $V_{DD} \geq 1.62$ V	-	0.4	

1. The I_{IO} current sourced or sunk by the device must always respect the absolute maximum rating specified in *Table 14: Voltage characteristics*, and the sum of the currents sourced or sunk by all the I/Os (I/O ports and control pins) must always respect the absolute maximum ratings ΣI_{IO}.
2. TTL and CMOS outputs are compatible with JEDEC standards JESD36 and JESD52.
3. Guaranteed by design.

Input/output AC characteristics

The definition and values of input/output AC characteristics are given in *Figure 26* and *Table 56*, respectively.

Unless otherwise specified, the parameters given are derived from tests performed under the ambient temperature and supply voltage conditions summarized in *Table 17: General operating conditions*.

Table 56. I/O (except FT_c) AC characteristics(1) (2)

Speed	Symbol	Parameter	Conditions	Min	Max	Unit
00	Fmax	Maximum frequency	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	5	MHz
			C=50 pF, 1.62 V≤V_{DD}≤2.7 V	-	1	
			C=10 pF, 2.7 V≤V_{DD}≤3.6 V	-	10	
			C=10 pF, 1.62 V≤V_{DD}≤2.7 V	-	1.5	
	Tr/Tf	Output rise and fall time	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	25	ns
			C=50 pF, 1.62 V≤V_{DD}≤2.7 V	-	52	
			C=10 pF, 2.7 V≤V_{DD}≤3.6 V	-	17	
			C=10 pF, 1.62 V≤V_{DD}≤2.7 V	-	37	
01	Fmax	Maximum frequency	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	25	MHz
			C=50 pF, 1.62 V≤V_{DD}≤2.7 V	-	10	
			C=10 pF, 2.7 V≤V_{DD}≤3.6 V	-	50	
			C=10 pF, 1.62 V≤V_{DD}≤2.7 V	-	15	
	Tr/Tf	Output rise and fall time	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	9	ns
			C=50 pF, 1.62 V≤V_{DD}≤2.7 V	-	16	
			C=10 pF, 2.7 V≤V_{DD}≤3.6 V	-	4.5	
			C=10 pF, 1.62 V≤V_{DD}≤2.7 V	-	9	
10	Fmax	Maximum frequency	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	50	MHz
			C=50 pF, 1.62 V≤V_{DD}≤2.7 V	-	25	
			C=10 pF, 2.7 V≤V_{DD}≤3.6 V	-	100(3)	
			C=10 pF, 1.62 V≤V_{DD}≤2.7 V	-	37.5	
	Tr/Tf	Output rise and fall time	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	5.8	ns
			C=50 pF, 1.62 V≤V_{DD}≤2.7 V	-	11	
			C=10 pF, 2.7 V≤V_{DD}≤3.6 V	-	2.5	
			C=10 pF, 1.62 V≤V_{DD}≤2.7 V	-	5	
11	Fmax	Maximum frequency	C=30 pF, 2.7 V≤V_{DD}≤3.6 V	-	120(3)	MHz
			C=30 pF, 1.62 V≤V_{DD}≤2.7 V	-	50	
			C=10 pF, 2.7 V≤V_{DD}≤3.6 V	-	180(3)	
			C=10 pF, 1.62 V≤V_{DD}≤2.7 V	-	75	
	Tr/Tf	Output rise and fall time(4)	C=30 pF, 2.7 V≤V_{DD}≤3.6 V	-	3.3	ns
			C=30 pF, 1.62 V≤V_{DD}≤2.7 V	-	6	
			C=10 pF, 2.7 V≤V_{DD}≤3.6 V	-	1.7	
			C=10 pF, 1.62 V≤V_{DD}≤2.7 V	-	3.3	

Table 56. I/O (except FT_c) AC characteristics(1) (2) (continued)

Speed	Symbol	Parameter	Conditions	Min	Max	Unit
FM+	Fmax(5)	Maximum frequency	C=50 pF, 1.6 V≤V_{DD}≤3.6 V	-	1	MHz
	Tr/TF(4)	Output high to low level fall time		-	5	ns

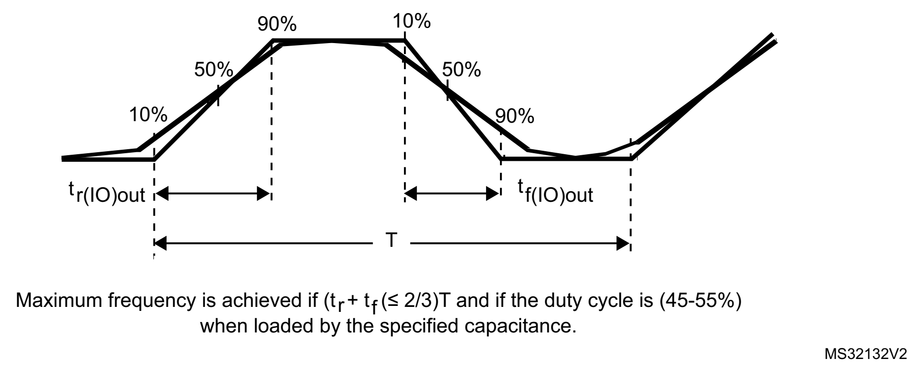
1. The I/O speed is configured using the OSPEEDRy[1:0] bits. The Fm+ mode is configured in the SYSCFG_CFGR1 register. Refer to the reference manual RM0440 "STM32G4 Series advanced Arm®-based 32-bit MCUs" for a description of GPIO Port configuration register.
2. Guaranteed by design.
3. This value represented the I/O capability but maximum system frequency is 170 MHz.
4. The fall time is defined between 70% and 30% of the output waveform accordingly to I2C specification.
5. The maximum frequency is defined with the following conditions:
   - (Tr+ Tf) ≤ 2/3 T.
   - 45%<Duty cycle<55%

Table 57. I/O FT_c AC characteristics(1) (2)

Speed	Symbol	Parameter	Conditions	Min	Max	Unit
0	Fmax	Maximum frequency	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	2	MHz
			C=50 pF, 1.6 V≤V_{DD}≤2.7 V	-	1	
	Tr/Tf	Output H/L to L/H level fall time	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	170	ns
			C=50 pF, 1.6 V≤V_{DD}≤2.7 V	-	330	
1	Fmax	Maximum frequency	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	10	MHz
			C=50 pF, 1.6 V≤V_{DD}≤2.7 V	-	5	
	Tr/Tf	Output H/L to L/H level fall time	C=50 pF, 2.7 V≤V_{DD}≤3.6 V	-	35	ns
			C=50 pF, 1.6 V≤V_{DD}≤2.7 V	-	65	

1. The I/O speed is configured using the OSPEEDRy[1:0] bits. The Fm+ mode is configured in the SYSCFG_CFGR1 register. Refer to the reference manual RM0440 "STM32G4 Series advanced Arm®-based 32-bit MCUs" for a description of GPIO Port configuration register.
2. Guaranteed by design.

Figure 26. I/O AC characteristics definition[1]



1. Refer to *Table 56: I/O (except FT_c) AC characteristics*.

5.3.15 NRST pin characteristics

The NRST pin input driver uses the CMOS technology. It is connected to a permanent pull-up resistor, R_{PU}.

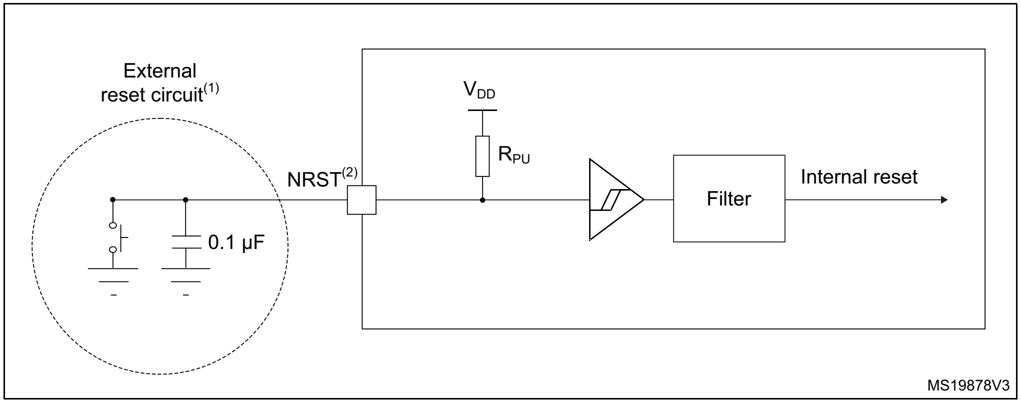
Unless otherwise specified, the parameters given in the table below are derived from tests performed under the ambient temperature and supply voltage conditions summarized in *Table 17: General operating conditions*.

Table 58. NRST pin characteristics[1]

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
$V_{IL(NRST)}$	NRST input low level voltage	-	-	-	0.3_xV_{DD}	V
$V_{IH(NRST)}$	NRST input high level voltage	-	0.7_xV_{DD}	-	-	
$V_{hys(NRST)}$	NRST Schmitt trigger voltage hysteresis	-	-	200	-	mV
R_{PU}	Weak pull-up equivalent resistor[2]	$V_{IN} = V_{SS}$	25	40	55	kΩ
$V_{F(NRST)}$	NRST input filtered pulse	-	-	-	70	ns
$V_{NF(NRST)}$	NRST input not filtered pulse	1.71 V ≤ V_{DD} ≤ 3.6 V	350	-	-	ns

1. Guaranteed by design.
2. The pull-up is designed with a true resistance in series with a switchable PMOS. This PMOS contribution to the series resistance is minimal (~10% order).

Figure 27. Recommended NRST pin protection



1. The reset network protects the device against parasitic resets.
2. The user must ensure that the level on the NRST pin can go below the $V_{IL(NRST)}$ max level specified in *Table 58: NRST pin characteristics*. Otherwise the reset is not taken into account by the device.
3. The external capacitor on NRST must be placed as close as possible to the device.

5.3.16 High-resolution timer (HRTIM)

The parameters given in *Table 59* are derived from tests performed under ambient temperature and supply voltage conditions summarized in *Table 17*.

Table 59. HRTIM characteristics(1)

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
T_A	Timer ambient temperature range	f_{HRTIM}=170 MHz	-40	-	125	°C
f_{HRTIM}	HRTIM input clock for DLL calibration	As per T_A conditions	-	-	170	MHz
t_{HRTIM}			5.88	-	-	ns
$t_{RES(HRTIM)}$	high-resolution step size	f_{HRTIM}=170 MHz, T_A from -40 to 105°C	-	184	-	ps
Res_{HRTIM}	Timer resolution	-	-	-	16	bit
t_{DTG}	Dead time generator clock period	-	0.125	-	16	t_{HRTIM}
		f_{HRTIM}=170 MHz	0.735	-	94.1	ns
$\|t_{DTR}\| / \|t_{DTF}\|$ max	Dead time range (absolute value)	-	-	-	511	t_{DTG}
		f_{HRTIM}=170 MHz	-	-	48.09	µs
f_{CHPFRQ}	Chopper stage clock frequency	-	1/256	-	1/16	f_{HRTIM}
		f_{HRTIM}=170 MHz	0.664	-	10.625	MHz
t_{1STPW}	Chopper first pulse length	-	16	-	256	t_{HRTIM}
		f_{HRTIM}=170 MHz	0.094	-	1.506	µs

1. Data based on characterization results, not tested in production.

Table 60. HRTIM output response to fault protection[1]

Symbol	Parameter	Conditions	Min.	Typ.	Max.[2]	Unit
$t_{LAT(DF)}$	Digital fault response latency	Propagation delay from HRTIM1_FLTx digital input to HRTIM_CHxy output pin	-	9	20	ns
$t_{W(FLT)}$	Minimum Fault pulse width	-	7	-	-	
$t_{LAT(AF)}$	Analog fault response latency	Propagation delay from comparator COMPx_INP input pin to HRTIM_CHxy output pin	-	16	31	

1. Refer to Fault paragraph in HRTIM section of RM0440.
2. Data based on characterization results, not tested in production.

Table 61. HRTIM output response to external events 1 to 5 (Low-Latency mode[1])

Symbol	Parameter	Conditions	Min	Typ[2]	Max[2]	Unit
$t_{LAT(DEEV)}$	Digital external event response latency	Propagation delay from HRTIM1_EEVx digital input to HRTIM_CHxy output pin (30pF load)	-	12	23	ns
$t_{W(EEV)}$	Minimum external event pulse width	-	7	-	-	
$t_{LAT(AEEV)}$	Analog external event response latency	Propagation delay from comparator COMPx_INP input pin to HRTIM_CHxy output pin (30pF load)	-	19	31	

1. EExFAST bit in HRTIM_EECR1 register is set (Low Latency mode). This functionality is available on external events channels 1 to 5. Refer to Latency to external events paragraph in HRTIM section of RM0440.
2. Data based on characterization results, not tested in production.

Table 62. HRTIM output response to external events 1 to 10 (Synchronous mode (1))

Symbol	Parameter	Conditions	Min.	Typ.	Max.(2)	Unit
$t_{LAT(DEEV)}$	Digital external event response latency	Propagation delay from HRTIM1_EEVx digital input to HRTIM_CHxy output pin (30pF load) (3)	-	56	66	ns
$t_{LAT(AEEV)}$	Analog external event response latency	Propagation delay from COMPx_INP input pin to HRTIM_CHxy output pin (30pF load) (3)	-	62	76	ns
$t_{W(EEV)}$	Minimum external event pulse width	-	7	-	-	ns
$T_{JIT(EEV)}$	External event response jitter	Jitter of the delay from HRTIM1_EEVx digital input or COMPx_INP to HRTIM_CHxy output pin	-	-	1	t_{HRTIM} (4)

1. EExFAST bit in HRTIM_EECR1 or HRTIM_EECR2 register is cleared (synchronous mode). External event filtering is disabled, i.e. EExF[3:0]=0000 in HRTIM_EECR2 register. Refer to Latency to external events paragraph in HRTIM section of RM0440.
2. Data based on characterization results, not tested in production.
3. This parameter is given for f_{HRTIM} = 170 MHz.
4. $T_{HRTIM} = 1 / f_{HRTIM}$ with f_{HRTIM}= 170 MHz.

Table 63. HRTIM synchronization input / output(1)

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
$t_{W(SYNCIN)}$	Minimum pulse width on SYNCIN inputs, including HRTIM_SCIN	-	2	-	-	t_{HRTIM}
$t_{RES(ESR)}$	Response time to external synchronization request	-	-	-	3	t_{HRTIM}
$t_{W(SYNCOUT)}$	Pulse width on HRTIM_SCOUT output	-	-	16	-	t_{HRTIM}
		f_{HRTIM}=170 MHz	-	94.1	-	ns

1. Guaranteed by design, not tested in production.

5.3.17 Extended interrupt and event controller input (EXTI) characteristics

The pulse on the interrupt input must have a minimal length in order to guarantee that it is detected by the event controller.

Table 64. EXTI input characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
PLEC	Pulse length to event controller	-	20	-	-	ns

1. Guaranteed by design.

5.3.18 Analog switches booster

Table 65. Analog switches booster characteristics[1]

Symbol	Parameter	Min	Typ	Max	Unit
V_{DD}	Supply voltage	1.62	-	3.6	V
$t_{SU(BOOST)}$	Booster startup time	-	-	240	µs
$I_{DD(BOOST)}$	Booster consumption for $1.62\ V \leq V_{DD} \leq 2.0\ V$	-	-	250	µA
	Booster consumption for $2.0\ V \leq V_{DD} \leq 2.7\ V$	-	-	500	
	Booster consumption for $2.7\ V \leq V_{DD} \leq 3.6\ V$	-	-	900	

1. Guaranteed by design.

5.3.19 Analog-to-digital converter characteristics

Unless otherwise specified, the parameters given in Table 66 are preliminary values derived from tests performed under ambient temperature, f_{PCLK} frequency and V_{DDA} supply voltage conditions summarized in Table 17: General operating conditions.

Note: It is recommended to perform a calibration after each power-up.

Table 66. ADC characteristics(1) (2)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
V_{DDA}	Analog supply voltage	-	1.62	-	3.6	V
V_{REF+}	Positive reference voltage	$V_{DDA} \geq 2$ V	2	-	V_{DDA}	V
		$V_{DDA} < 2$ V	V_{DDA}			V
V_{REF-}	Negative reference voltage	-	V_{SSA}			V
V_{CMIN}	Input common mode	Differential	$(V_{REF+}+V_{REF-})/2 - 0.18$	$(V_{REF+} + V_{REF-})/2$	$(V_{REF+} + V_{REF-})/2 + 0.18$	V
f_{ADC}	ADC clock frequency	Range 1, single ADC operation	0.14	-	60	MHz
		Range 2	-	-	26	
		Range 1, all ADCs operation, single ended mode $V_{DDA} \geq 2.7$ V	0.14	-	52	
		Range 1, all ADCs operation, single ended mode $V_{DDA} \geq 1.62$ V	0.14	-	42	
		Range 1, all ADCs operation, differential mode $V_{DDA} \geq 1.62$ V	0.14	-	56	
f_s	Sampling rate, continuous mode	For given resolution and sampling time cycles (t_s)	0.001	f_{ADC} / (sampling time [cycles] + resolution [bits] + 0.5)		Msps
T_{TRIG}	External trigger period	Considering trigger conversion latency time (t_{LATR} or $t_{LATRINJ}$)	-	-	1ms	-
		Resolution = 12 bits, $f_{ADC=60\ MHz}$	tconv + [t_{LATR} or $t_{LATRINJ}$]	-		
V_{AIN} (3)	Conversion voltage range	-	0	-	V_{REF+}	V

Table 66. ADC characteristics(1) (2) (continued)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
R_{AIN}(4)	External input impedance	-	-	-	50	kΩ
C_{ADC}	Internal sample and hold capacitor	-	-	5	-	pF
t_{STAB}	Power-up time	-	1			conversion cycle
t_{CAL}	Calibration time	f_{ADC} = 60 MHz	1.93			µs
		-	116			$1/f_{ADC}$
t_{LATR}	Trigger conversion latency Regular and injected channels without conversion abort	CKMODE = 00	1.5	2	2.5	$1/f_{ADC}$
		CKMODE = 01	-	-	2.0	
		CKMODE = 10	-	-	2.25	
		CKMODE = 11	-	-	2.125	
$t_{LATRINJ}$	Trigger conversion latency Injected channels aborting a regular conversion	CKMODE = 00	2.5	3	3.5	$1/f_{ADC}$
		CKMODE = 01	-	-	3.0	
		CKMODE = 10	-	-	3.25	
		CKMODE = 11	-	-	3.125	
t_s	Sampling time	f_{ADC} = 60 MHz	0.0416	-	10.675	µs
		-	2.5	-	640.5	$1/f_{ADC}$
$t_{ADCVREG\_STUP}$	ADC voltage regulator start-up time	-	-	-	20	µs
t_{CONV}	Total conversion time (including sampling time)	f_{ADC} = 60 MHz Resolution = 12 bits	0.25	-	10.883	µs
		-	t_s[cycles] + resolution [bits] +0.5 = 15 to 653			$1/f_{ADC}$
I_{DDA}(ADC)	ADC consumption from the V_{DDA} supply	fs = 4 Msps	-	590	730	µA
		fs = 1 Msps	-	160	220	
		fs = 10 ksps	-	16	50	
I_{DDV_S}(ADC)	ADC consumption from the V_{REF+} single ended mode	fs = 4 Msps	-	110	140	µA
		fs = 1 Msps	-	30	40	
		fs = 10 ksps	-	0.6	2	
I_{DDV_D}(ADC)	ADC consumption from the V_{REF+} differential mode	fs = 4 Msps	-	220	270	µA
		fs = 1 Msps	-	60	70	
		fs = 10 ksps	-	1.3	3	

1. Guaranteed by design.

2. The I/O analog switch voltage booster is enabled when V_{DDA} < 2.4 V (BOOSTEN = 1 in the SYSCFG_CFGR1 when V_{DDA} < 2.4V). It is disabled when $V_{DDA} \geq 2.4$ V.
3. V_{REF+} can be internally connected to V_{DDA}, depending on the package. Refer to *Section 4: Pinouts and pin description* for further details.
4. The maximum value of RAIN can be found in *Table 67: Maximum ADC RAIN*.

The maximum value of R_{AIN} can be found in *Table 67: Maximum ADC RAIN*.

Table 67. Maximum ADC R_{AIN}(1)(2)

Resolution	Sampling cycle @60 MHz	Sampling time [ns]	R_{AIN} max (Ω)	
			Fast channels(3)	Slow channels(4)
12 bits	2.5	41.67	100	N/A
	6.5	108.33	330	100
	12.5	208.33	680	470
	24.5	408.33	1500	1200
	47.5	791.67	2200	1800
	92.5	1541.67	4700	3900
	247.5	4125	12000	10000
	640.5	10675	39000	33000
10 bits	2.5	41.67	120	N/A
	6.5	108.33	390	180
	12.5	208.33	820	560
	24.5	408.33	1500	1200
	47.5	791.67	2200	1800
	92.5	1541.67	5600	4700
	247.5	4125	12000	10000
	640.5	10675	47000	39000
8 bits	2.5	41.67	180	N/A
	6.5	108.33	470	270
	12.5	208.33	1000	680
	24.5	408.33	1800	1500
	47.5	791.67	2700	2200
	92.5	1541.67	6800	5600
	247.5	4125	15000	12000
	640.5	10675	50000	50000
6 bits	2.5	41.67	220	N/A
	6.5	108.33	560	330
	12.5	208.33	1200	1000
	24.5	408.33	2700	2200
	47.5	791.67	3900	3300
	92.5	1541.67	8200	6800
	247.5	4125	18000	15000
	640.5	10675	50000	50000

1. Guaranteed by design.
2. The I/O analog switch voltage booster is enabled when V_{DDA} < 2.4 V (BOOSTEN = 1 in the SYSCFG_CFGR1 when V_{DDA} < 2.4V). It is disabled when $V_{DDA} \geq 2.4$ V.
3. Fast channels are: ADCx_IN1 to ADCx_IN5.
4. Slow channels are: all ADC inputs except the fast channels.

Table 68. ADC accuracy - limited test conditions 1(1)(2)(3)

Symbol	Parameter	Conditions(4)			Min	Typ	Max	Unit
ET	Total unadjusted error	Single ADC operation ADC clock frequency ≤ 60 MHz, V_{DDA} = VREF+ = 3 V, TA = 25 °C Continuous mode, sampling rate: Fast channels@4Msps Slow channels@2Msps	Single ended	Fast channel (max speed)	-	5.9	6.9	LSB
				Slow channel (max speed)	-	5.5	6.9	
			Differential	Fast channel (max speed)	-	4.6	5.6	
				Slow channel (max speed)	-	4	5.6	
EO	Offset error		Single ended	Fast channel (max speed)	-	2.5	4	
				Slow channel (max speed)	-	1.9	4	
			Differential	Fast channel (max speed)	-	1.8	2.8	
				Slow channel (max speed)	-	1.1	2.8	
EG	Gain error		Single ended	Fast channel (max speed)	-	4.6	6.6	
				Slow channel (max speed)	-	4.5	6.6	
			Differential	Fast channel (max speed)	-	3.6	4.6	
				Slow channel (max speed)	-	3.3	4.6	
ED	Differential linearity error		Single ended	Fast channel (max speed)	-	1.1	1.9	
				Slow channel (max speed)	-	1.3	1.9	
			Differential	Fast channel (max speed)	-	1.3	1.6	
				Slow channel (max speed)	-	1.4	1.6	
EL	Integral linearity error		Single ended	Fast channel (max speed)	-	2.3	3.4	
				Slow channel (max speed)	-	2.4	3.4	
			Differential	Fast channel (max speed)	-	2.1	3.2	
				Slow channel (max speed)	-	2.2	3.2	
ENOB	Effective number of bits		Single ended	Fast channel (max speed)	10.4	10.6	-	bits
				Slow channel (max speed)	10.4	10.6	-	
			Differential	Fast channel (max speed)	10.8	10.9	-	
				Slow channel (max speed)	10.8	10.9	-	
SINAD	Signal-to-noise and distortion ratio		Single ended	Fast channel (max speed)	64.4	65.6	-	dB
				Slow channel (max speed)	64.4	65.6	-	
			Differential	Fast channel (max speed)	66.8	67.5	-	
				Slow channel (max speed)	66.8	67.5	-	
SNR	Signal-to-noise ratio		Single ended	Fast channel (max speed)	65	66.9	-	
				Slow channel (max speed)	65	66.9	-	
			Differential	Fast channel (max speed)	67	69	-	
				Slow channel (max speed)	67	69	-	

Table 68. ADC accuracy - limited test conditions 1(1)(2)(3) (continued)

Symbol	Parameter	Conditions(4)			Min	Typ	Max	Unit
THD	Total harmonic distortion	Single ADC operation ADC clock frequency ≤ 60 MHz, V_{DDA} = VREF+ = 3 V, TA = 25 °C Continuous mode, sampling rate: Fast channels@4Msps Slow channels@2Msps	Single ended	Fast channel (max speed)	-	-73	-72	dB
				Slow channel (max speed)	-	-73	-72	
			Differential	Fast channel (max speed)	-	-73	-72	
				Slow channel (max speed)	-	-73	-72	

1. Evaluated by characterization – Not tested in production.
2. ADC DC accuracy values are measured after internal calibration.
3. ADC accuracy vs. negative Injection Current: Injecting negative current on any analog input pins should be avoided as this significantly reduces the accuracy of the conversion being performed on another analog input. It is recommended to add a Schottky diode (pin to ground) to analog pins which may potentially inject negative current.
4. The I/O analog switch voltage booster is enabled when V_{DDA} < 2.4 V (BOOSTEN = 1 in the SYSCFG_CFGR1 when V_{DDA} < 2.4 V). It is disabled when V_{DDA} ≥ 2.4 V. No oversampling.

Table 69. ADC accuracy - limited test conditions 2(1)(2)(3)

Sym-bol	Parameter	Conditions(4)			Min	Typ	Max	Unit
ET	Total unadjusted error	Single ADC operation ADC clock frequency ≤ 60 MHz, 2 V ≤ V_{DDA} Continuous mode, sampling rate: Fast channels@4Msps Slow channels@2Msps	Single ended	Fast channel (max speed)	-	5.9	8.4	LSB
				Slow channel (max speed)	-	5.5	8	
			Differential	Fast channel (max speed)	-	4.6	6.6	
				Slow channel (max speed)	-	4	6	
EO	Offset error		Single ended	Fast channel (max speed)	-	2.5	6	
				Slow channel (max speed)	-	1.9	6.9	
			Differential	Fast channel (max speed)	-	1.8	3.3	
				Slow channel (max speed)	-	1.1	3.3	
EG	Gain error		Single ended	Fast channel (max speed)	-	4.6	8.1	
				Slow channel (max speed)	-	4.5	8.1	
			Differential	Fast channel (max speed)	-	3.6	4.6	
				Slow channel (max speed)	-	3.3	4.6	
ED	Differential linearity error		Single ended	Fast channel (max speed)	-	1.1	1.8	
				Slow channel (max speed)	-	1.3	1.8	
			Differential	Fast channel (max speed)	-	1.3	1.6	
				Slow channel (max speed)	-	1.4	1.6	
EL	Integral linearity error		Single ended	Fast channel (max speed)	-	2.3	4.4	
				Slow channel (max speed)	-	2.4	4.4	
			Differential	Fast channel (max speed)	-	2.1	4.1	
				Slow channel (max speed)	-	2.2	3.7	
ENOB	Effective number of bits		Single ended	Fast channel (max speed)	10	10.6	-	bits
				Slow channel (max speed)	10	10.6	-	
			Differential	Fast channel (max speed)	10.7	10.9	-	
				Slow channel (max speed)	10.7	10.9	-	
SINAD	Signal-to-noise and distortion ratio		Single ended	Fast channel (max speed)	62	65.6	-	dB
				Slow channel (max speed)	62	65.6	-	
			Differential	Fast channel (max speed)	65	67.5	-	
				Slow channel (max speed)	65	67.5	-	
SNR	Signal-to-noise ratio		Single ended	Fast channel (max speed)	64	66.9	-	
				Slow channel (max speed)	64	66.9	-	
			Differential	Fast channel (max speed)	66.5	69	-	
				Slow channel (max speed)	66.5	69	-	

Table 69. ADC accuracy - limited test conditions 2(1)(2)(3) (continued)

Sym-bol	Parameter	Conditions(4)			Min	Typ	Max	Unit
THD	Total harmonic distortion	Single ADC operation ADC clock frequency ≤ 60 MHz, 2 V ≤ V_{DDA} Continuous mode, sampling rate: Fast channels@4Msps Slow channels@2Msps	Single ended	Fast channel (max speed)	-	-73	-65	dB
				Slow channel (max speed)	-	-73	-67	
			Differential	Fast channel (max speed)	-	-73	-70	
				Slow channel (max speed)	-	-73	-71	

1. Evaluated by characterization – Not tested in production.
2. ADC DC accuracy values are measured after internal calibration.
3. ADC accuracy vs. negative Injection Current: Injecting negative current on any analog input pins should be avoided as this significantly reduces the accuracy of the conversion being performed on another analog input. It is recommended to add a Schottky diode (pin to ground) to analog pins which may potentially inject negative current.
4. The I/O analog switch voltage booster is enabled when V_{DDA} < 2.4 V (BOOSTEN = 1 in the SYSCFG_CFGR1 when V_{DDA} < 2.4 V). It is disabled when V_{DDA} ≥ 2.4 V. No oversampling.

Table 70. ADC accuracy - limited test conditions 3[(1)(2)(3)]

Sym-bol	Parameter	Conditions[(4)]			Min	Typ	Max	Unit
ET	Total unadjusted error	Single ADC operation ADC clock frequency ≤ 60 MHz, 1.62 V ≤ V_{DDA} = V_{REF+} ≤ 3.6 V, Continuous mode, sampling rate: Fast channels@4Msps Slow channels@2Msps	Single ended	Fast channel (max speed)	-	5.9	7.9	LSB
				Slow channel (max speed)	-	5.5	7.5	
			Differential	Fast channel (max speed)	-	4.6	7.6	
				Slow channel (max speed)	-	4	5.5	
EO	Offset error		Single ended	Fast channel (max speed)	-	2.5	5.5	
				Slow channel (max speed)	-	1.9	5.5	
			Differential	Fast channel (max speed)	-	1.8	3.5	
				Slow channel (max speed)	-	1.1	3	
EG	Gain error		Single ended	Fast channel (max speed)	-	4.6	7.1	
				Slow channel (max speed)	-	4.5	7	
			Differential	Fast channel (max speed)	-	3.6	4.1	
				Slow channel (max speed)	-	3.3	4.8	
ED	Differential linearity error		Single ended	Fast channel (max speed)	-	1.1	1.9	
				Slow channel (max speed)	-	1.3	1.9	
			Differential	Fast channel (max speed)	-	1.3	1.6	
				Slow channel (max speed)	-	1.4	1.6	
EL	Integral linearity error		Single ended	Fast channel (max speed)	-	2.3	4.4	
				Slow channel (max speed)	-	2.4	4.4	
			Differential	Fast channel (max speed)	-	2.1	3.7	
				Slow channel (max speed)	-	2.2	3.7	
ENOB	Effective number of bits		Single ended	Fast channel (max speed)	10	10.6	-	bits
				Slow channel (max speed)	10	10.6	-	
			Differential	Fast channel (max speed)	10.6	10.9	-	
				Slow channel (max speed)	10.6	10.9	-	
SINAD	Signal-to-noise and distortion ratio		Single ended	Fast channel (max speed)	62	65.6	-	dB
				Slow channel (max speed)	62	65.6	-	
			Differential	Fast channel (max speed)	65	67.5	-	
				Slow channel (max speed)	65	67.5	-	
SNR	Signal-to-noise ratio		Single ended	Fast channel (max speed)	63	66.9	-	
				Slow channel (max speed)	63	66.9	-	
			Differential	Fast channel (max speed)	66	69	-	
				Slow channel (max speed)	66	69	-	

Table 70. ADC accuracy - limited test conditions 3[1][2][3] (continued)

Sym-bol	Parameter	Conditions[4]			Min	Typ	Max	Unit
THD	Total harmonic distortion	Single ADC operation ADC clock frequency ≤ 60 MHz, $1.62\ V \leq V_{DDA} = V_{REF+} \leq 3.6\ V$, Continuous mode, sampling rate: Fast channels@4Msps Slow channels@2Msps	Single ended	Fast channel (max speed)	-	-73	-67	dB
				Slow channel (max speed)	-	-73	-67	
			Differential	Fast channel (max speed)	-	-73	-71	
				Slow channel (max speed)	-	-73	-71	

1. Evaluated by characterization – Not tested in production.
2. ADC DC accuracy values are measured after internal calibration.
3. ADC accuracy vs. negative Injection Current: Injecting negative current on any analog input pins should be avoided as this significantly reduces the accuracy of the conversion being performed on another analog input. It is recommended to add a Schottky diode (pin to ground) to analog pins which may potentially inject negative current.
4. The I/O analog switch voltage booster is enabled when $V_{DDA} < 2.4$ V (BOOSTEN = 1 in the SYSCFG_CFGR1 when $V_{DDA} < 2.4$ V). It is disabled when $V_{DDA} \geq 2.4$ V. No oversampling.

Table 71. ADC accuracy (Multiple ADCs operation) - limited test conditions 1(1)(2)(3)

Symbol	Parameter	Conditions(4)		Min	Typ	Max	Unit
ET	Total unadjusted error	Multiple ADC operation ADC clock frequency: single ended ≤ 52 MHz, differential ≤ 56 MHz, $V_{DDA} = V_{REF} = 3.3$ V, 25°C, Continuous mode, sampling time: Fast channels: 2.5 cycles Slow channels: 6.5 cycles LQFP100 package	Single ended	-	4.5	-	LSB
			Differential	-	4.1	-	
EO	Offset error		Single ended	-	1.3	-	
			Differential	-	0.4	-	
EG	Gain error		Single ended	-	3.9	-	
			Differential	-	3.4	-	
ED	Differential linearity error		Single ended	-	1.5	-	
			Differential	-	1.2	-	
EL	Integral linearity error		Single ended	-	1.7	-	
			Differential	-	2.1	-	
ENOB	Effective number of bits		Single ended	-	10.7	-	bits
			Differential	-	10.9	-	
SINAD	Signal-to-noise and distortion ratio		Single ended	-	66.3	-	dB
			Differential	-	67.2	-	
SNR	Signal-to-noise ratio		Single ended	-	67.3	-	
			Differential	-	68.6	-	
THD	Total harmonic distortion		Single ended	-	-73.5	-	dB
			Differential	-	-73	-	

1. Data based on characterization result, not tested in production.
2. ADC DC accuracy values are measured after internal calibration.
3. ADC accuracy vs. negative Injection Current: Injecting negative current on any analog input pins should be avoided as this significantly reduces the accuracy of the conversion being performed on another analog input. It is recommended to add a Schottky diode (pin to ground) to analog pins which may potentially inject negative current.
4. The I/O analog switch voltage booster is enabled when $V_{DDA} < 2.4$ V (BOOSTEN = 1 in the SYSCFG_CFGR1 when $V_{DDA} < 2.4$ V). It is disabled when $V_{DDA} \geq 2.4$ V. No oversampling.

Table 72. ADC accuracy (Multiple ADCs operation) - limited test conditions 2(1)(2)(3)

Symbol	Parameter	Conditions(4)		Min	Typ	Max	Unit
ET	Total unadjusted error	Multiple ADC operation ADC clock frequency: single ended ≤ 52 MHz, differential ≤ 56 MHz, V_{DDA} ≥ 2.7 V, V_{REF}≥ 1.62 V, -40 to 125°C, Continuous mode, sampling time: Fast channels: 2.5 cycles Slow channels: 6.5 cycles LQFP100 package	Single ended	-	7.1	-	LSB
			Differential	-	4.6	-	
EO	Offset error		Single ended	-	4.2	-	
			Differential	-	2.8	-	
EG	Gain error		Single ended	-	6.8	-	
			Differential	-	4.3	-	
ED	Differential linearity error		Single ended	-	1.5	-	
			Differential	-	1.7	-	
EL	Integral linearity error		Single ended	-	3.1	-	
			Differential	-	2.4	-	
ENOB	Effective number of bits		Single ended	-	10.2	-	bits
			Differential	-	10.6	-	
SINAD	Signal-to-noise and distortion ratio		Single ended	-	62.9	-	dB
			Differential	-	65.3	-	
SNR	Signal-to-noise ratio		Single ended	-	63.6	-	
			Differential	-	66.3	-	
THD	Total harmonic distortion		Single ended	-	-70.9	-	dB
			Differential	-	-71.8	-	

1. Data based on characterization result, not tested in production.
2. ADC DC accuracy values are measured after internal calibration.
3. ADC accuracy vs. negative Injection Current: Injecting negative current on any analog input pins should be avoided as this significantly reduces the accuracy of the conversion being performed on another analog input. It is recommended to add a Schottky diode (pin to ground) to analog pins which may potentially inject negative current.
4. The I/O analog switch voltage booster is enabled when V_{DDA} < 2.4 V (BOOSTEN = 1 in the SYSCFG_CFGR1 when V_{DDA} < 2.4 V). It is disabled when V_{DDA} ≥ 2.4 V. No oversampling.

Table 73. ADC accuracy (Multiple ADCs operation) - limited test conditions 3[(1)(2)(3)]

Symbol	Parameter	Conditions[(4)]		Min	Typ	Max	Unit
ET	Total unadjusted error	Multiple ADC operation ADC clock frequency: single ended ≤ 42 MHz, differential ≤ 56 MHz, $V_{DDA}= V_{REF}\geq 1.62$ V, -40 to 125°C, Continuous mode, sampling time: Fast channels: 2.5 cycles Slow channels: 6.5 cycles LQFP100 package	Single ended	-	7.4	-	LSB
			Differential	-	4.6	-	
EO	Offset error		Single ended	-	4	-	
			Differential	-	2.8	-	
EG	Gain error		Single ended	-	7.2	-	
			Differential	-	4.3	-	
ED	Differential linearity error		Single ended	-	1.8	-	
			Differential	-	1.7	-	
EL	Integral linearity error		Single ended	-	3.1	-	
			Differential	-	2.4	-	
ENOB	Effective number of bits		Single ended	-	10.1	-	bits
			Differential	-	10.6	-	
SINAD	Signal-to-noise and distortion ratio		Single ended	-	62.6	-	dB
			Differential	-	65.3	-	
SNR	Signal-to-noise ratio		Single ended	-	63.2	-	
			Differential	-	66.3	-	
THD	Total harmonic distortion		Single ended	-	-70.6	-	dB
			Differential	-	-71.8	-	

1. Data based on characterization result, not tested in production.
2. ADC DC accuracy values are measured after internal calibration.
3. ADC accuracy vs. negative Injection Current: Injecting negative current on any analog input pins should be avoided as this significantly reduces the accuracy of the conversion being performed on another analog input. It is recommended to add a Schottky diode (pin to ground) to analog pins which may potentially inject negative current.
4. The I/O analog switch voltage booster is enabled when $V_{DDA} < 2.4$ V (BOOSTEN = 1 in the SYSCFG_CFGR1 when $V_{DDA} < 2.4$ V). It is disabled when $V_{DDA} \geq 2.4$ V. No oversampling.

Figure 28. ADC accuracy characteristics

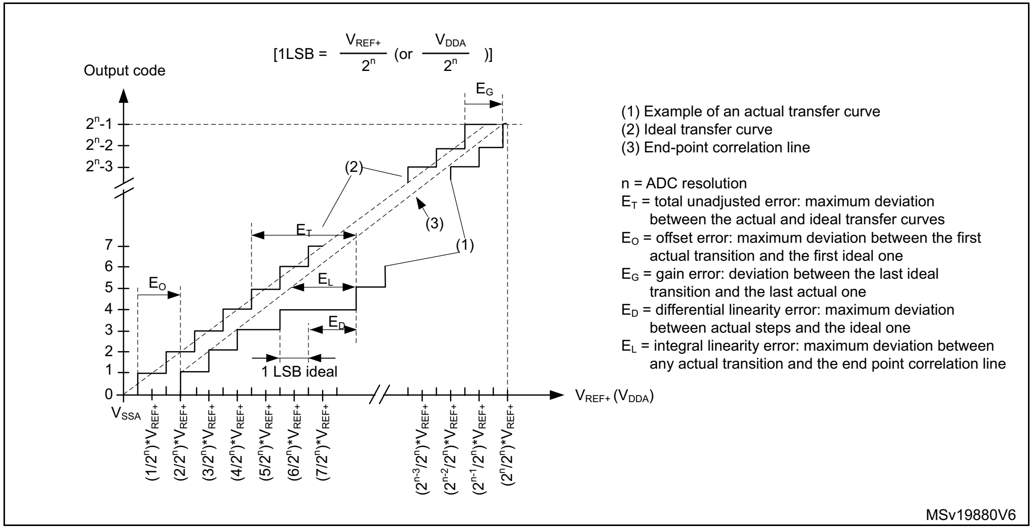
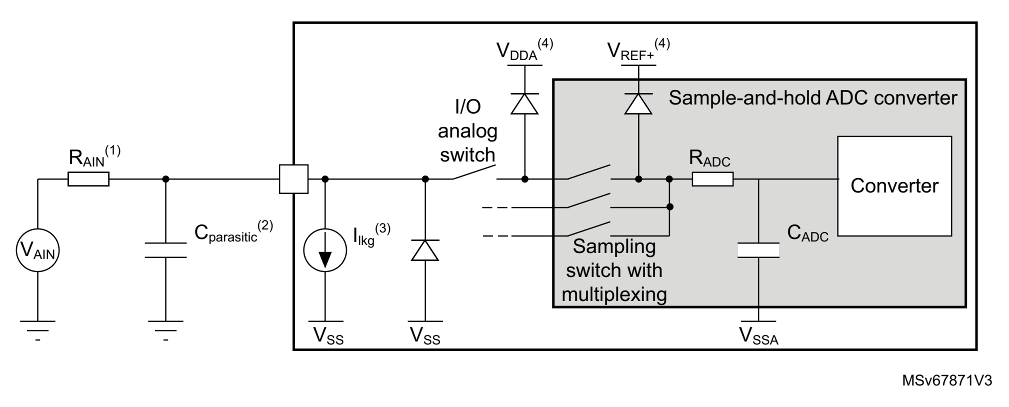


Figure 29. Typical connection diagram when using the ADC with FT/TT pins featuring analog switch function



1. Refer to *Table 66: ADC characteristics* for the values of R_{AIN} and C_{ADC}.
2. $C_{parasitic}$ represents the capacitance of the PCB (dependent on soldering and PCB layout quality) plus the pad capacitance (refer to *Table 54: I/O static characteristics* for the value of the pad capacitance). A high $C_{parasitic}$ value downgrades conversion accuracy. To remedy this, f_{ADC} should be reduced.
3. Refer to *Table 54: I/O static characteristics* for the values of I_{lkg}.
4. Refer to *Figure 16: Power supply scheme*.

General PCB design guidelines

Power supply decoupling must be performed as shown in *Figure 16: Power supply scheme*. The decoupling capacitor on V_{DDA} must be ceramic (good quality) and it must be placed as close as possible to the chip.

5.3.20 Digital-to-Analog converter characteristics

Table 74. DAC 1MSPS characteristics(1)

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_{DDA}	Analog supply voltage for DAC ON	DAC output buffer OFF, DAC_OUT pin not connected (internal connection only)		1.71	-	3.6	V
		Other modes		1.80	-		
V_{REF+}	Positive reference voltage	DAC output buffer OFF, DAC_OUT pin not connected (internal connection only)		1.71	-	V_{DDA}	
		Other modes		1.80	-		
V_{REF-}	Negative reference voltage	-		V_{SSA}			
R_L	Resistive load	DAC output buffer ON	connected to V_{SSA}	5	-	-	kΩ
			connected to V_{DDA}	25	-	-	
R_O	Output Impedance	DAC output buffer OFF		9.6	11.7	13.8	kΩ
R_{BON}	Output impedance sample and hold mode, output buffer ON	V_{DD} = 2.7 V		-	-	2	kΩ
		V_{DD} = 2.0 V		-	-	3.5	
R_{BOFF}	Output impedance sample and hold mode, output buffer OFF	V_{DD} = 2.7 V		-	-	16.5	kΩ
		V_{DD} = 2.0 V		-	-	18.0	
C_L	Capacitive load	DAC output buffer ON		-	-	50	pF
C_{SH}		Sample and hold mode		-	0.1	1	µF
V_{DAC_OUT}	Voltage on DAC_OUT output	DAC output buffer ON		0.2	-	V_{REF+} – 0.2	V
		DAC output buffer OFF		0	-	V_{REF+}	
$t_{SETTLING}$	Settling time (full scale: for a 12-bit code transition between the lowest and the highest input codes when DAC_OUT reaches final value)	Normal mode DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ	±0.5 LSB	-	1.7	3	µs
			±1 LSB	-	1.6	2.9	
			±2 LSB	-	1.55	2.85	
			±4 LSB	-	1.48	2.8	
			±8 LSB	-	1.4	2.75	
		Normal mode DAC output buffer OFF, ±1LSB, CL = 10 pF		-	2	2.5	
t_{WAKEUP}(2)	Wakeup time from off state (setting the ENx bit in the DAC Control register) until final value ±1 LSB	Normal mode DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ		-	4.2	7.5	µs
		Normal mode DAC output buffer OFF, CL ≤ 10 pF		-	2	5	
PSRR	V_{DDA} supply rejection ratio	Normal mode DAC output buffer ON CL ≤ 50 pF, RL = 5 kΩ, DC		-	-80	-28	dB

Table 74. DAC 1MSPS characteristics[1] (continued)

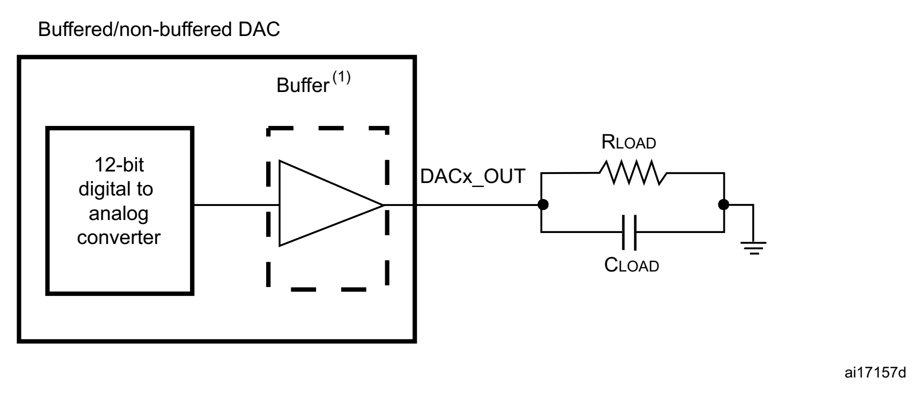
Symbol	Parameter	Conditions		Min	Typ	Max	Unit
$T_{W\_to\_W}$	Minimal time between two consecutive writes into the DAC_DORx register to guarantee a correct DAC_OUT for a small variation of the input code (1 LSB)				-	-	µs
	DAC_MCR:MODEx[2:0] = 000 or 001	CL ≤ 50 pF, RL ≥ 5 kΩ		1			
	DAC_MCR:MODEx[2:0] = 010 or 011	CL ≤ 10 pF		1.4			
t_{SAMP}	Sampling time in sample and hold mode (code transition between the lowest input code and the highest input code when DACOUT reaches final value ±1LSB)	DAC_OUT pin connected	DAC output buffer ON, C_{SH} = 100 nF	-	0.7	3.5	ms
			DAC output buffer OFF, C_{SH} = 100 nF	-	10.5	18	
		DAC_OUT pin not connected (internal connection only)	DAC output buffer OFF	-	2	3.5	µs
I_{leak}	Output leakage current	Sample and hold mode, DAC_OUT pin connected		-	-	-[3]	nA
Cl_{int}	Internal sample and hold capacitor	-		5.2	7	8.8	pF
t_{TRIM}	Middle code offset trim time	DAC output buffer ON		50	-	-	µs
V_{offset}	Middle code offset for 1 trim code step	V_{REF+} = 3.6 V		-	1500	-	µV
		V_{REF+} = 1.8 V		-	750	-	
I_{DDA}(DAC)	DAC consumption from V_{DDA}	DAC output buffer ON	No load, middle code (0x800)	-	315	500	µA
			No load, worst code (0xF1C)	-	450	670	
		DAC output buffer OFF	No load, middle code (0x800)	-	-	0.2	
		Sample and hold mode, C_{SH} = 100 nF		-	315 x Ton/(Ton +Toff)[4]	670 x Ton/(Ton +Toff)[4]	

Table 74. DAC 1MSPS characteristics[1] (continued)

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
I_{DDV}(DAC)	DAC consumption from V_{REF+}	DAC output buffer ON	No load, middle code (0x800)	-	185	240	µA
			No load, worst code (0xF1C)	-	340	400	
		DAC output buffer OFF	No load, middle code (0x800)	-	155	205	
		Sample and hold mode, buffer ON, C_{SH} = 100 nF, worst case		-	185 x Ton/(Ton +Toff)[4]	400 x Ton/(Ton +Toff)[4]	
		Sample and hold mode, buffer OFF, C_{SH} = 100 nF, worst case		-	155 x Ton/(Ton +Toff)[4]	205 x Ton/(Ton +Toff)[4]	

1. Guaranteed by design.
2. In buffered mode, the output can overshoot above the final value for low input code (starting from min value).
3. Refer to *Table 54: I/O static characteristics*.
4. Ton is the Refresh phase duration. Toff is the Hold phase duration. Refer to the reference manual RM0440 "STM32G4 Series advanced Arm®-based 32-bit MCUs" for more details.

Figure 30. 12-bit buffered / non-buffered DAC



1. The DAC integrates an output buffer to reduce the output impedance and to drive external loads directly without the use of an external operational amplifier. The buffer can be bypassed by configuring the BOFFx bit in the DAC_CR register.

Table 75. DAC 1MSPS accuracy(1)

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
DNL	Differential non linearity (2)	DAC output buffer ON		-	-	±2	LSB
		DAC output buffer OFF		-	-	±2	
-	monotonicity	10 bits		Guaranteed			
INL	Integral non linearity(3)	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ		-	-	±4	
		DAC output buffer OFF CL ≤ 50 pF, no RL		-	-	±4	
Offset	Offset error at code 0x800(3)	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ	V_{REF+} = 3.6 V	-	-	±12	
			V_{REF+} = 1.8 V	-	-	±25	
		DAC output buffer OFF CL ≤ 50 pF, no RL		-	-	±8	
Offset1	Offset error at code 0x001(4)	DAC output buffer OFF CL ≤ 50 pF, no RL		-	-	±5	
OffsetCal	Offset Error at code 0x800 after calibration	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ	V_{REF+} = 3.6 V	-	-	±5	
			V_{REF+} = 1.8 V	-	-	±7	
Gain	Gain error(5)	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ		-	-	±0.5	%
		DAC output buffer OFF CL ≤ 50 pF, no RL		-	-	±0.5	
TUE	Total unadjusted error	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ		-	-	±30	LSB
		DAC output buffer OFF CL ≤ 50 pF, no RL		-	-	±12	
TUECal	Total unadjusted error after calibration	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ		-	-	±23	LSB
SNR	Signal-to-noise ratio	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ 1 kHz, BW 500 kHz		-	71.2	-	dB
		DAC output buffer OFF CL ≤ 50 pF, no RL, 1 kHz BW 500 kHz		-	71.6	-	
THD	Total harmonic distortion	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ, 1 kHz		-	-78	-	dB
		DAC output buffer OFF CL ≤ 50 pF, no RL, 1 kHz		-	-79	-	

Table 75. DAC 1MSPS accuracy(1) (continued)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
SINAD	Signal-to-noise and distortion ratio	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ, 1 kHz	-	70.4	-	dB
		DAC output buffer OFF CL ≤ 50 pF, no RL, 1 kHz	-	71	-	
ENOB	Effective number of bits	DAC output buffer ON CL ≤ 50 pF, RL ≥ 5 kΩ, 1 kHz	-	11.4	-	bits
		DAC output buffer OFF CL ≤ 50 pF, no RL, 1 kHz	-	11.5	-	

1. Guaranteed by design.
2. Difference between two consecutive codes - 1 LSB.
3. Difference between measured value at Code i and the value at Code i on a line drawn between Code 0 and last Code 4095.
4. Difference between the value measured at Code (0x001) and the ideal value.
5. Difference between ideal slope of the transfer function and measured slope computed from code 0x000 and 0xFFF when buffer is OFF, and from code giving 0.2 V and (V_{REF+} – 0.2) V when buffer is ON.

Table 76. DAC 15MSPS characteristics(1)

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_{DDA}	Analog supply voltage for DAC ON	-		1.71	-	3.6	V
V_{REF+}	Positive reference voltage	-		1.71	-	V_{DDA}	
V_{REF-}	Negative reference voltage	-		V_{SSA}			
V_{DAC_OUT}	Voltage on DAC_OUT output	-		0	-	V_{REF+}	V
$t_{SETTLING}$	Settling time (full scale: for a 12-bit code transition between the lowest and the highest input codes when DAC_OUT reaches final value)	V_{DDA}>2,7V With One comparator on DAC output	10%-90%	-	16	22	ns
			5%-95%	-	21	29	
			1%-99%	-	33	46	
			32lsb	-	40	53	
			1lsb	-	64	87	
		V_{DDA}>2,7V With One comparator and OPAMP on DAC output	10%-90%	-	24	32	
			5%-95%	-	32	43	
			1%-99%	-	49	67	
			32lsb	-	57	75	
			1lsb	-	93	125	

Table 76. DAC 15MSPS characteristics(1) (continued)

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
$t_{SETTLING}$	Settling time (full scale: for a 12-bit code transition between the lowest and the highest input codes when DAC_OUT reaches final value)	V_{DDA}<2,7V With One comparator on DAC output	10%-90%	-	16	88	ns
			5%-95%	-	21	116	
			1%-99%	-	33	181	
			32lsb	-	40	196	
			1lsb	-	64	332	
		V_{DDA}<2,7V With One comparator and OPAMP on DAC output	10%-90%	-	24	128	
			5%-95%	-	32	170	
			1%-99%	-	49	265	
			32lsb	-	57	284	
			1lsb	-	93	483	
t_{WAKEUP}(2)	Wakeup time from off state (setting the ENx bit in the DAC Control register) until final value ±1 LSB	Normal mode CL ≤ 10 pF		-	1.4	3.5	µs
PSRR	V_{DDA} supply rejection ratio	V_{DD} > 2.7 V		65	85	-	dB
		V_{DD} <2.7 V		40	85	-	
t_{SAMP}	Sampling time in sample and hold mode (code transition between the lowest input code and the highest input code when DACOUT reaches final value ±1LSB)	-		-	0.7	-	µs
CI_{int}	Internal sample and hold capacitor	-		-	4	5	pF
dV/dt (hold phase)	Voltage decay rate in Sample and hold mode, during hold phase	CSH = 4 pF T = 55°C		-	50	-	mV/ms
I_{DDA}(DAC)	DAC consumption from V_{DDA}	No load, middle code (0x800)		-	-	0.2	µA
I_{DDV}(DAC)	DAC consumption from V_{REF+}	No load, middle code (0x800)(3)		-	720	955	

1. Guaranteed by design.
2. In buffered mode, the output can overshoot above the final value for low input code (starting from min value).
3. Worst case consumption is at code 0x800.

Table 77. DAC 15MSPS accuracy(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
DNL	Differential non linearity (2)	-	-2	-	2	LSB
INL	Integral non linearity(3)	CL ≤ 50 pF, no RL	-5	-	5	
TUE	Total unadjusted error	CL ≤ 50 pF, no RL	-5	-	5	
DCS	Dynamic code spike	Spike amplitude on DAC voltage when DAC output value is decreasing	-	0	4	

1. Guaranteed by design.
2. Difference between two consecutive codes - 1 LSB.
3. Difference between measured value at code i and the value at code i on a line drawn between code 0 and last code 4095. Offset error is included.

5.3.21 Voltage reference buffer characteristics

Table 78. VREFBUF characteristics(1)

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_{DDA}	Analog supply voltage	Normal mode	VRS = 00	2.4	-	3.6	V
			VRS = 01	2.8	-	3.6	
			VRS = 10	3.135	-	3.6	
		Degraded mode(2)	VRS= 00	1.65	-	2.4	
			VRS = 01	1.65	-	2.8	
			VRS= 10	1.65	-	3.135	
V_{REFBUF_OUT}	Voltage reference output	Normal mode(3)	VRS= 00	2.044	2.048	2.052	
			VRS= 01	2.496	2.5	2.504	
			VRS = 10	2.896	2.9	2.904	
		Degraded mode(2)	VRS= 00	V_{DDA} -250 mV	-	V_{DDA}	
			VRS = 01	V_{DDA} -250 mV	-	V_{DDA}	
			VRS = 10	V_{DDA} -250 mV	-	V_{DDA}	
V_{REFOUT_TEMP}(3)	Voltage reference output spread over the temperature range	V_{DDA} = 3V		-	-	See *Figure 31*, *Figure 32*, *Figure 33*	mV
TRIM	Trim step resolution	-		-	±0.05	±0.1	%
CL	Load capacitor	-		0.5	1	1.5	µF
esr	Equivalent Serial Resistor of Cload	-		-	-	2	Ω
I_{load}	Static load current	-		-	-	6.5	mA
I_{line_reg}(4)	Line regulation	-		-	1000	2000	ppm/V
I_{load_reg}	Load regulation	500 µA ≤ I_{load} ≤4 mA	Normal mode	-	50	500	ppm/mA
T_{Coeff}	Temperature coefficient	-40 °C < TJ < +125 °C		-	-	Tcoeff_vrefint + 50(5)	ppm/ °C
		0 °C < TJ < +50 °C		-	-		
PSRR	Power supply rejection	DC		40	55	-	dB
		100 kHz		25	40	-	
t_{START}	Start-up time	CL = 0.5 µF(6)		-	300	350	µs
		CL = 1.1 µF(6)		-	500	650	
		CL = 1.5 µF(6)		-	650	800	

Table 78. VREFBUF characteristics[1] (continued)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
I_{INRUSH}	Control of maximum DC current drive on VREFBUF_ OUT during start-up phase [7]	-	-	8	-	mA
I_{DDA}(VREF BUF)	VREFBUF consumption from V_{DDA}	I_{load} = 0 µA	-	16	25	µA
		I_{load} = 500 µA	-	18	30	
		I_{load} = 4 mA	-	35	50	
		I_{load} = 6.5 mA	-	45	80	

1. Guaranteed by design, unless otherwise specified.
2. In degraded mode, the voltage reference buffer can not maintain accurately the output voltage which follows (V_{DDA} - drop voltage).
3. Guaranteed by characterization results.
4. Line regulation is given for overall supply variation, in normal mode.
5. Tcoeff_vrefint refer to Tcoeff parameter in the embedded voltage reference section.
6. The capacitive load must include a 100 nF low ESR capacitor in order to cut-off the high frequency noise.
7. To correctly control the VREFBUF inrush current during start-up phase and scaling change, the V_{DDA} voltage should be in the range [2.4 V to 3.6 V], [2.8 V to 3.6 V] and [3.135 V to 3.6 V] respectively for VRS=0,1 and 2.

Figure 31. V_{REFOUT_TEMP} in case VRS = 00

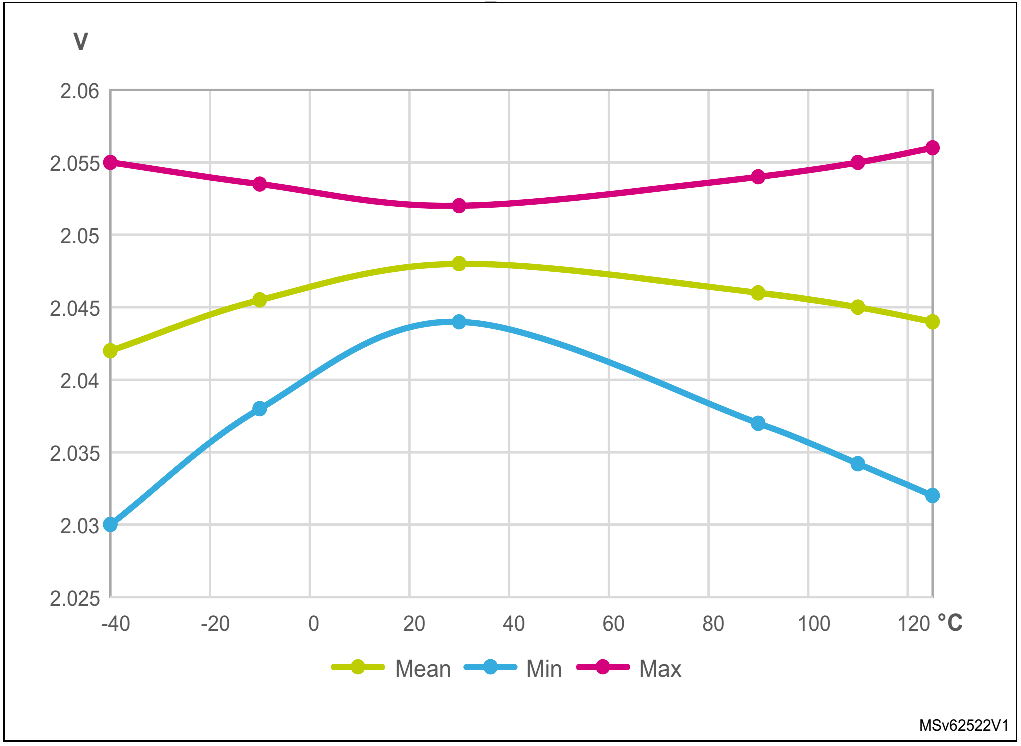


Figure 32. V_{REFOUT_TEMP} in case VRS = 01

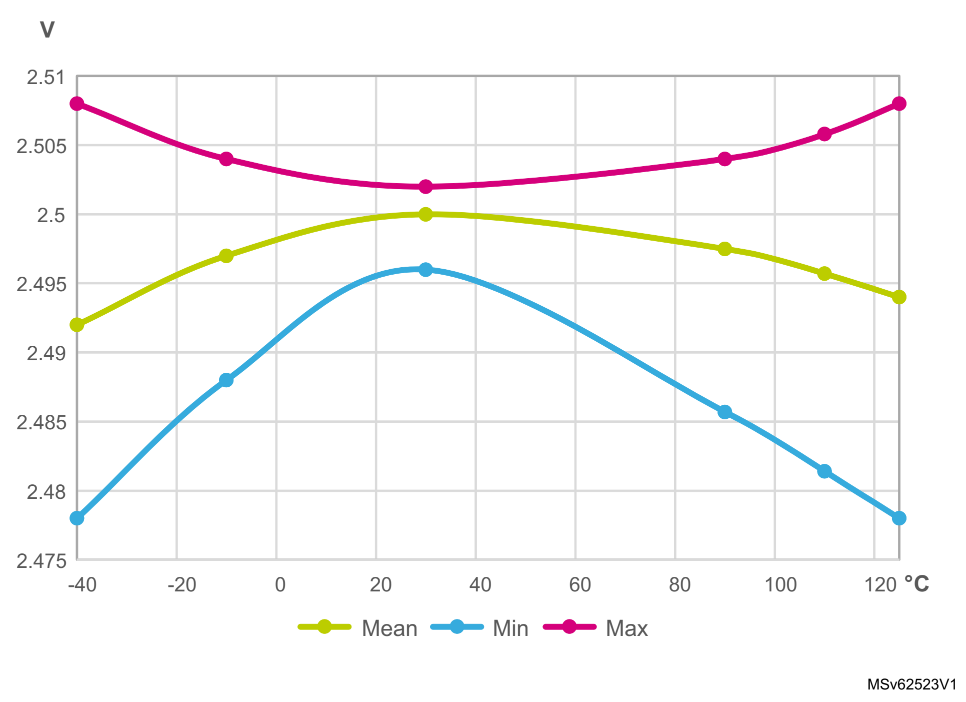
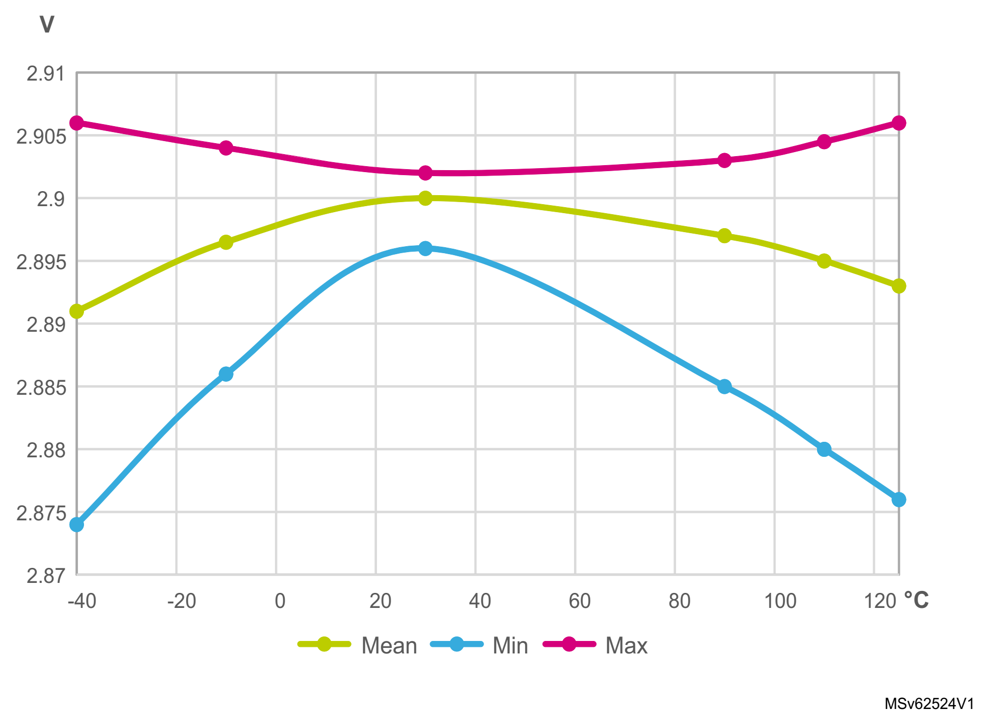


Figure 33. V_{REFOUT_TEMP} in case VRS = 10



5.3.22 Comparator characteristics

Table 79. COMP characteristics(1)

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
V_{DDA}	Analog supply voltage	-		1.62	-	3.6	V
V_{IN}	Comparator input voltage range	-		0	-	V_{DDA}	
V_{BG}(2)	Scaler input voltage	-		VREFINT			
V_{SC}(3)	Scaler offset voltage	-		-	±5	±10	mV
I_{DDA}(SCALER)	Scaler static consumption from V_{DDA}	BRG_EN=0 (bridge disable)		-	200	300	nA
		BRG_EN=1 (bridge enable)		-	0.8	1	µA
t_{START_SCALER}	Scaler startup time	-		-	100	200	µs
t_{START}	Comparator startup time to reach propagation delay specification	-		-	-	5	µs
t_D(4)	Propagation delay (From COMP input pin to COMP output pin) for 200 mV step with 100 mV overdrive	50pF load on output	V_{DDA} < 2.7 V	-	-	35	ns
			V_{DDA} ≥2.7 V	-	16.7	31	ns
V_{offset}(3)	Comparator offset error	Full V_{DDA} voltage range, full temperature range		-9	-6/+2	3	mV
V_{hys}	Comparator hysteresis	HYST[2:0] = 0		-	0	-	mV
		HYST[2:0] =1		4	9	16	
		HYST[2:0] = 2		7	18	32	
		HYST[2:0] = 3		11	27	47	
		HYST[2:0] = 4		15	36	63	
		HYST[2:0] = 5		19	45	79	
		HYST[2:0] = 6		23	54	95	
		HYST[2:0] = 7		26	63	110	
I_{DDA}(COMP)	Comparator consumption from V_{DDA}	Static		-	450	720	µA
		With 50 kHz ±100 mV overdrive square signal		-	450	-	

1. Guaranteed by design, unless otherwise specified.
2. Refer to *Table 20: Embedded internal voltage reference*.
3. Guaranteed by characterization results.
4. Typical value (3V) is an average for all comparators propagation delay.

5.3.23 Operational amplifiers characteristics

Table 80. OPAMP characteristics(1) (2)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
V_{DDA}	Analog supply voltage	-	2	3.3	3.6	V
CMIR	Common mode input range	-	0	-	V_{DDA}	V
VI_{OFFSET}(3)	Input offset voltage	25 °C, No Load on output.	-	-	±1.5	mV
		All voltage/temperature.	-	-	±3	
ΔVI_{OFFSET}	Input offset voltage drift	-	-	±10	-	µV/°C
TRIMOFFSETP	Offset trim step at low common input voltage (0.1 x V_{DDA})	-	-	1.1	1.2	mV
TRIMOFFSETN	Offset trim step at high common input voltage (0.9 x V_{DDA})	-	-	1.3	1.65	
I_{LOAD}	Drive current	-	-	-	500	µA
I_{LOAD_PGA}	Drive current in PGA mode	-	-	-	270	
C_{LOAD}	Capacitive load	-	-	-	50	pF
CMRR	Common mode rejection ratio	-	-	60	-	dB
PSRR	Power supply rejection ratio	$C_{LOAD} \leq 50$ pf, $R_{LOAD} \geq 4$ kΩ DC Vcom=$V_{DDA}/2$	-	80	-	dB
GBW	Gain Bandwidth Product	100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV	7	13	-	MHz
SR(3)	Slew rate (from 10 and 90% of output voltage)	Normal mode	2.5	6.5	-	V/µs
		High-speed mode	18	45	-	
AO	Open loop gain	100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV	65	95	-	dB
		200mV ≤ Output dynamic range ≤ V_{DDA} - 200mV	75	95	-	
V_{OHSAT}(3)	High saturation voltage	I_{load} = max or R_{load} = min Input at V_{DDA}. Follower mode	V_{DDA} - 100	-	-	mV
V_{OLSAT}(3)	Low saturation voltage	I_{load} = max or R_{load} = min Input at 0. Follower mode	-	-	100	
φ_m	Phase margin	Follower mode, Vcom=$V_{DDA}/2$	-	65	-	°
GM	Gain margin	Follower mode, Vcom=$V_{DDA}/2$	-	10	-	dB

Table 80. OPAMP characteristics(1) (2) (continued)

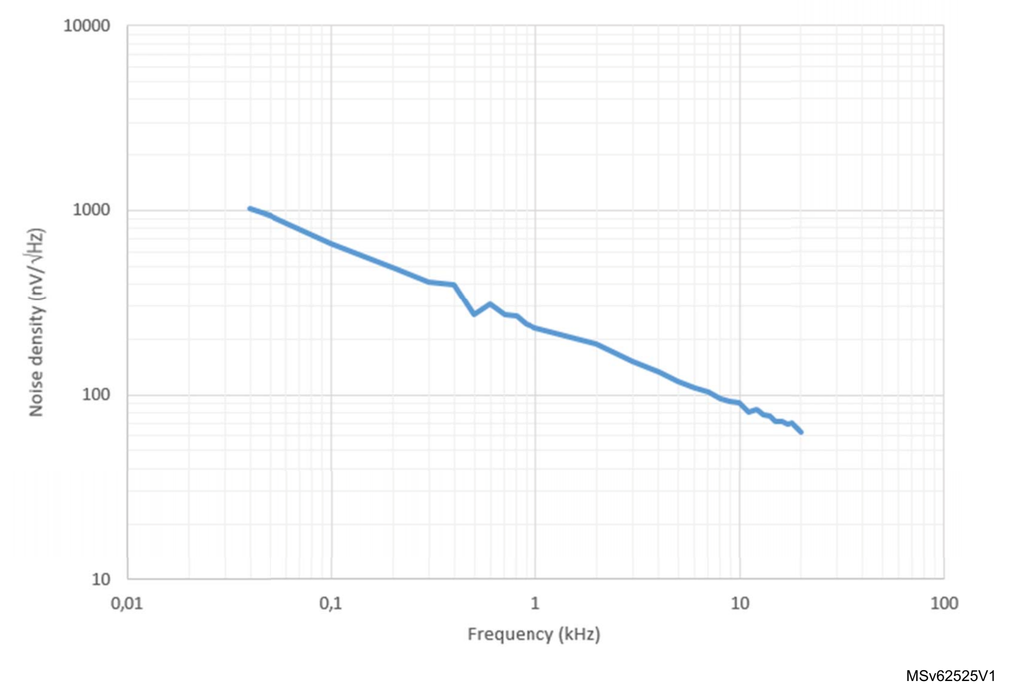
Symbol	Parameter	Conditions		Min	Typ	Max	Unit
t_{WAKEUP}(3)	Wake up time from OFF state.	Normal mode	C_{LOAD} ≤ 50 pf, R_{LOAD} ≥ 4 kΩ follower configuration	-	3	6	µs
		High-speed mode	C_{LOAD} ≤ 50 pf, R_{LOAD} ≥ 20 kΩ follower configuration	-	3	6	
I_{bias}	OPAMP input bias current	See I_{leak} parameter in *Table 54: I/O static characteristics* for given pin.					
PGA gain	Non inverting gain value(4)	PGA Gain = 2 0.1 ≤ Out dynamic range ≤ V_{DDA} - 0.1	V_{DDA} < 2.2	-2	-	2	%
			V_{DDA} ≥ 2.2	-1	-	1	
		PGA Gain=4, 100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV		-1	-	1	
		PGA Gain=8 100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV		-1	-	1	
		PGA Gain=16, 100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV		-1	-	1	
		PGA Gain=32 200mV ≤ Output ≤ V_{DDA} - 200mV		-2	-	2	
		PGA Gain=64 200mV ≤ Output dynamic range ≤ V_{DDA} - 200mV		-2	-	2	
	Inverting gain value	PGA Gain = -1 100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV	V_{DDA} < 2.2	-2	-	2	%
			V_{DDA} ≥ 2.2	-1	-	1	
		PGA Gain=-3, 100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV		-1	-	1	
		PGA Gain=-7 100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV		-1	-	1	
		PGA Gain=-15, 100mV ≤ Output dynamic range ≤ V_{DDA} - 100mV		-1	-	1	
		PGA Gain=-31 200mV ≤ Output ≤ V_{DDA} - 200mV		-2	-	2	
		PGA Gain=-63 200mV ≤ Output dynamic range ≤ V_{DDA} - 200mV		-5	-	2	

Table 80. OPAMP characteristics[1] [2] (continued)

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
$R_{network}$	R2/R1 internal resistance values in non-inverting PGA mode[5]	PGA Gain = 2		-	10/10	-	kΩ/kΩ
		PGA Gain = 4		-	30/10	-	
		PGA Gain = 8		-	70/10	-	
		PGA Gain = 16		-	150/10	-	
		PGA Gain = 32		-	310/10	-	
		PGA Gain = 64		-	630/10	-	
	R2/R1 internal resistance values in inverting PGA mode[5]	PGA Gain = -1		-	10/10	-	
		PGA Gain = -3		-	30/10	-	
		PGA Gain = -7		-	70/10	-	
		PGA Gain = -15		-	150/10	-	
		PGA Gain = -31		-	310/10	-	
		PGA Gain = -63		-	630/10	-	
Delta R	Resistance variation (R1 or R2)	-		-15	-	+15	%
PGA BW	PGA bandwidth for different non inverting gain	Gain = 2		-	GBW/2	-	MHz
		Gain = 4		-	GBW/4	-	
		Gain = 8		-	GBW/8	-	
		Gain = 16		-	GBW/16	-	
		Gain = 32		-	GBW/32	-	
		Gain = 64		-	GBW/64	-	
	PGA bandwidth for different inverting gain	Gain = -1		-	GBW/2	-	MHz
		Gain = -3		-	GBW/4	-	
		Gain = -7		-	GBW/8	-	
		Gain = -15		-	GBW/16	-	
		Gain = -31		-	GBW/32	-	
		Gain = -63		-	GBW/64	-	
eN	Voltage noise density	at 1 kHz, Output loaded with 4 kΩ		-	250	-	nV/√Hz
		at 10 kHz, Output loaded with 4 kΩ		-	90	-	
I_{DDA}(OPAMP)	OPAMP consumption from V_{DDA}	Normal mode	No load, follower mode	-	1.3	2.2	mA
		High-speed mode		-	1.4	2.6	
$T_{S\_OPAMP\_VOUT}$	ADC sampling time when reading the OPAMP output. OPAINTOEN=1	V_{DDA} < 2V		300	-	-	ns
		V_{DDA} ≥ 2V		200	-	-	
I_{DDA}(OPAMPINT)	OPAMP consumption from V_{DDA}. OPAINTOEN=1	Normal mode	no load, follower mode	-	0.45	0.7	mA
		High-speed mode		-	0.5	0.8	

1. Guaranteed by design, unless otherwise specified.
2. Data guaranteed on normal and high speed mode unless otherwise specified.
3. Guaranteed by characterization results.
4. Valid also for inverting gain configuration with external bias.
5. R2 is the internal resistance between OPAMP output and OPAMP inverting input. R1 is the internal resistance between OPAMP inverting input and ground. The PGA gain =1+R2/R1

Figure 34. OPAMP noise density @ 25°C



5.3.24 Temperature sensor characteristics

Table 81. TS characteristics

Symbol	Parameter	Min	Typ	Max	Unit
T_L(1)	V_{TS} linearity with temperature	-	±1	±2	°C
Avg_Slope(1)	Average slope	2.3	2.5	2.7	mV/°C
V_{30}	Voltage at 30°C (±5 °C)(2)	0.742	0.76	0.785	V
$t_{START-RUN}$(1)	Start-up time in Run mode (start-up of buffer)	-	8	15	µs
t_{START_CONT}(3)	Start-up time when entering in continuous mode	-	70	120	µs
t_{S_temp}(1)	ADC sampling time when reading the temperature	5	-	-	µs
$I_{DD}(TS)$(1)	Temperature sensor consumption from VDD, when selected by ADC	-	4.7	7	µA

1. Guaranteed by design.
2. Measured at V_{DDA} = 3.0 V ±10 mV. The V_{30} ADC conversion result is stored in the TS_CAL1 byte. Refer to *Table 5: Temperature sensor calibration values*.
3. Continuous mode means RUN mode or Temperature Sensor ON.

5.3.25 V_{BAT} monitoring characteristics

Table 82. V_{BAT} monitoring characteristics(1)

Symbol	Parameter	Min	Typ	Max	Unit
R	Resistor bridge for V_{BAT}	-	3x39	-	kΩ
Q	Ratio on V_{BAT} measurement	-	3	-	-
Er(2)	Error on Q	-10	-	10	%
t_{S_vbat}(2)	ADC sampling time when reading the V_{BAT}	12	-	-	µs

1. 1.55 V < V_{BAT} < 3.6 V.
2. Guaranteed by design.

Table 83. V_{BAT} charging characteristics

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
R_{BC}	Battery charging resistor	VBRS = 0	-	5	-	kΩ
		VBRS = 1	-	1.5	-	

5.3.26 Timer characteristics

The parameters given in the following tables are guaranteed by design.

Refer to *Section 5.3.14: I/O port characteristics* for details on the input/output alternate function characteristics (output compare, input capture, external clock, PWM output).

Table 84. TIMx(1) characteristics(2)

Symbol	Parameter	Conditions	Min	Max	Unit
$t_{res(TIM)}$	Timer resolution time	-	1	-	$t_{TIMxCLK}$
		$f_{TIMxCLK}$ = 170 MHz	5.88	-	ns
f_{EXT}	Timer external clock frequency on CH1 to CH4	-	0	$f_{TIMxCLK}/2$	MHz
		$f_{TIMxCLK}$ = 170 MHz	0	85	MHz
Res_{TIM}	Timer resolution	TIMx (except TIM2 and TIM5)	-	16	bit
		TIM2 and TIM5	-	32	
$t_{COUNTER}$	16-bit counter clock period	-	1	65536	$t_{TIMxCLK}$
		$f_{TIMxCLK}$ = 170 MHz	0.00588	385.5	µs
t_{MAX_COUNT}	Maximum possible count with 32-bit counter	-	-	65536 × 65536	$t_{TIMxCLK}$
		$f_{TIMxCLK}$ = 170 MHz	-	25.26	s
f_{ENC}	Encoder frequency on TI1 and TI2 input pins	-	0	$f_{TIMxCLK}/4$	MHz
		$f_{TIMxCLK}$ = 170MHz	0	42.5	MHz
$t_{W(INDEX)}$	Index pulsewidth on ETR input	-	2	-	Tck
$t_{W(TI1, TI2)}$	Min pulsewidth on TI1 and TI2 inputs in all encoder modes except directional clock x1	-	2	-	Tck
	Min pulsewidth on TI1 and TI2 inputs in directional clock x1	-	3	-	Tck

1. TIMx, is used as a general term in which x stands for 1,2,3,4,5,6,7,8,15,16, 17 or 20.
2. Guaranteed by design.

Table 85. IWDG min/max timeout period at 32 kHz (LSI)(1)(2)

Prescaler divider	PR[2:0] bits	Min timeout RL[11:0]= 0x000	Max timeout RL[11:0]= 0xFFF	Unit
/4	0	0.125	512	ms
/8	1	0.250	1024	
/16	2	0.500	2048	
/32	3	1.0	4096	
/64	4	2.0	8192	
/128	5	4.0	16384	
/256	6 or 7	8.0	32768	

1. Guaranteed by design.
2. The exact timings still depend on the phasing of the APB interface clock versus the LSI clock so that there is always a full RC period of uncertainty.

Table 86. WWDG min/max timeout value at 170 MHz (PCLK)(1)

Prescaler	WDGTB	Min timeout value	Max timeout value	Unit
1	0	0.0241	1.542	ms
2	1	0.0482	3.084	
4	2	0.0964	6.168	
8	3	0.1928	12.336	

1. Guaranteed by design.

5.3.27 Communication interfaces characteristics

I^{2}C interface characteristics

The I2C interface meets the timings requirements of the I^{2}C-bus specification and user manual rev. 03 for:

- Standard-mode (Sm): with a bit rate up to 100 kbit/s
- Fast-mode (Fm): with a bit rate up to 400 kbit/s
- Fast-mode Plus (Fm+): with a bit rate up to 1 Mbit/s.

The I2C timings requirements are guaranteed by design when the I2C peripheral is properly configured (refer to reference manual RM0440 "STM32G4 Series advanced Arm®-based 32-bit MCUs") and when the I2CCLK frequency is greater than the minimum shown in the table below.

Table 87. Minimum I2CCLK frequency in all I2C modes

Symbol	Parameter	Condition		Min	Unit
f(I2CCLK)	I2CCLK frequency	Standard mode		2	MHz
		Fast-mode	Analog Filtre ON DNF=0	8	
			Analog Filtre OFF DNF=1	9	
		Fast-mode Plus	Analog Filtre ON DNF=0	17	
			Analog Filtre OFF DNF=1	16	

The SDA and SCL I/O requirements are met with the following restrictions:

- The SDA and SCL I/O pins are not “true” open-drain. When configured as open-drain, the PMOS connected between the I/O pin and V_{DDIOx} is disabled, but is still present.
- The 20mA output drive requirement in Fast-mode Plus is supported partially. This limits the maximum load Cload supported in Fm+, which is given by these formulas:
  - t_r(SDA/SCL)=0.8473 x R_p x C_{load}
  - R_p(min)= (V_{DD} - V_{OL}(max)) / I_{OL}(max)

Where Rp is the I2C lines pull-up. Refer to *Section 5.3.14: I/O port characteristics* for the I2C I/Os characteristics.

All I2C SDA and SCL I/Os embed an analog filter. Refer to *Table 88* below for the analog filter characteristics:

Table 88. I2C analog filter characteristics(1)

Symbol	Parameter	Min	Max	Unit
t_{AF}	Maximum pulse width of spikes that are suppressed by the analog filter	50(2)	90(3)	ns

1. Guaranteed by design.
2. Spikes with widths below $t_{AF(min)}$ are filtered.
3. Spikes with widths above $t_{AF(max)}$ are not filtered

SPI characteristics

Unless otherwise specified, the parameters given in *Table 89* for SPI are derived from tests performed under the ambient temperature, f_{PCLKx} frequency and supply voltage conditions summarized in *Table 17: General operating conditions*.

- Output speed is set to OSPEEDRy[1:0] = 11
- Capacitive load C = 30 pF
- Measurement points are done at CMOS levels: 0.5 x V_{DD}

Refer to *Section 5.3.14: I/O port characteristics* for more details on the input/output alternate function characteristics (NSS, SCK, MOSI, MISO for SPI).

Table 89. SPI characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max(2)	Unit
f_{SCK} $1/t_{c(SCK)}$	SPI clock frequency	Master mode 2.7 V < V_{DD} < 3.6 V Voltage Range V1	-	-	75	MHz
		Master mode 1.71 V < V_{DD} < 3.6 V Voltage Range V1			50	
		Master transmitter mode 1.71 V < V_{DD} < 3.6 V Voltage Range V1			50	
		Slave receiver mode 1.71 V < V_{DD} < 3.6 V Voltage Range V1			50	
		Slave mode transmitter/full duplex 2.7 V < V_{DD} < 3.6 V Voltage Range V1			41	
		Slave mode transmitter/full duplex 1.71 V < V_{DD} < 3.6 V Voltage Range V1			27	
		1.71 V < V_{DD} < 3.6 V Voltage Range V2			13	
$t_{su(NSS)}$	NSS setup time	Slave mode	4*T_{pclk}	-	-	-
$t_{h(NSS)}$	NSS hold time	Slave mode	2*T_{pclk}	-	-	-
$t_{w(SCKH)}$ $t_{w(SCKL)}$	SCK high and low time	Master mode, SPI prescaler = 2	T_{pclk}-1	T_{pclk}	T_{pclk}+1	ns
$t_{su(MI)}$	Data input setup time	Master mode	4	-	-	ns
$t_{su(SI)}$		Slave mode	3	-	-	
$t_{h(MI)}$	Data input hold time	Master mode	4	-	-	ns
$t_{h(SI)}$		Slave mode	1	-	-	
$t_{a(SO)}$	Data output access time	Slave mode	9	-	34	ns
$t_{dis(SO)}$	Data output disable time	Slave mode	9	-	16	ns

Table 89. SPI characteristics(1) (continued)

Symbol	Parameter	Conditions	Min	Typ	Max(2)	Unit
$t_{v(SO)}$	Data output valid time	Slave mode 2.7 V < V_{DD} < 3.6 V Voltage Range V1	-	9	12	ns
		Slave mode 1.71 V < V_{DD} < 3.6 V Voltage Range V1	-	9	18	
		Slave mode 1.71 V < V_{DD} < 3.6 V Voltage Range V2	-	13	22	
$t_{v(MO)}$		Master mode	-	3.5	4.5	
$t_{h(SO)}$	Data output hold time	Slave mode 1.71 V < V_{DD} < 3.6 V	6	-	-	
		Slave mode Range V2	9	-	-	
$t_{h(MO)}$		Master mode	2	-	-	

1. Guaranteed by characterization results.
2. The maximum frequency in Slave transmitter mode is determined by the sum of tv(SO) and tsu(MI) which has to fit into SCK low or high-phase preceding the SCK sampling edge. This value can be achieved when the SPI communicates with a master having tsu(MI) = 0 while Duty(SCK) = 50%.

Figure 35. SPI timing diagram - slave mode and CPHA = 0

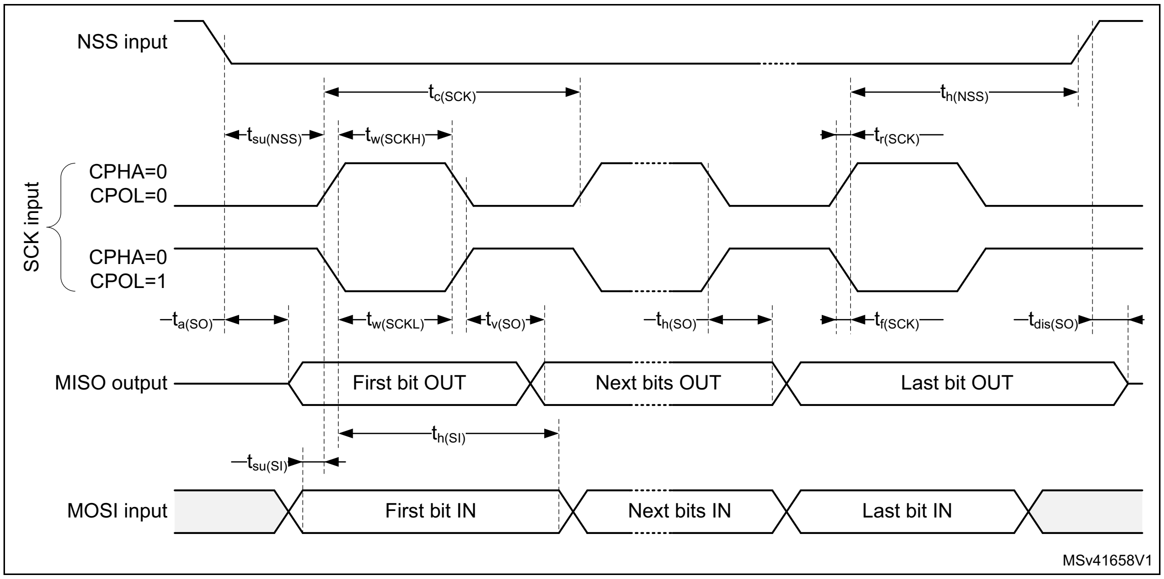
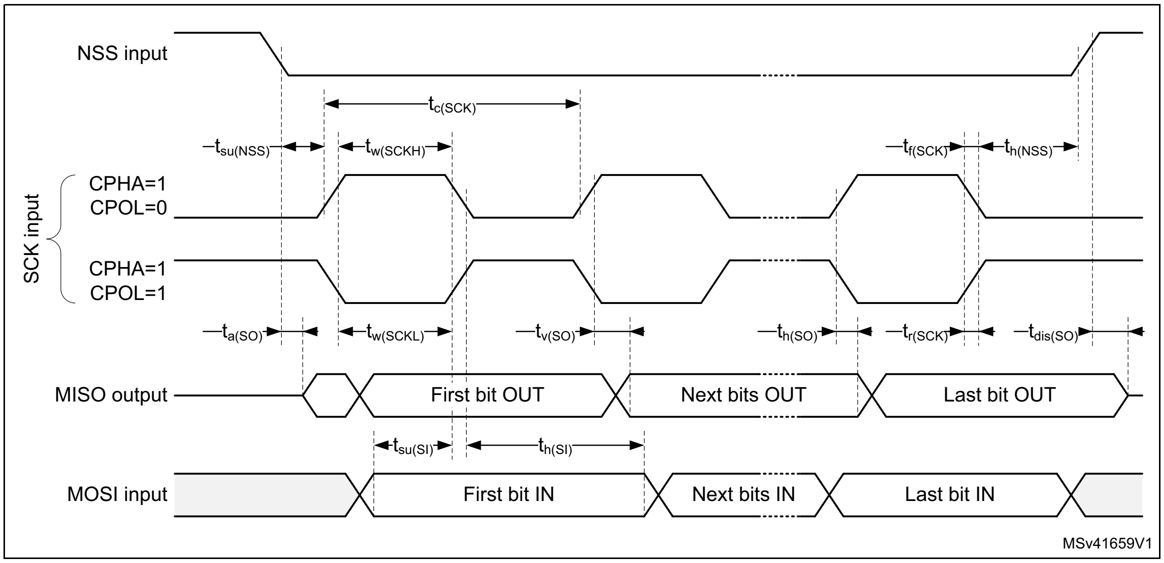
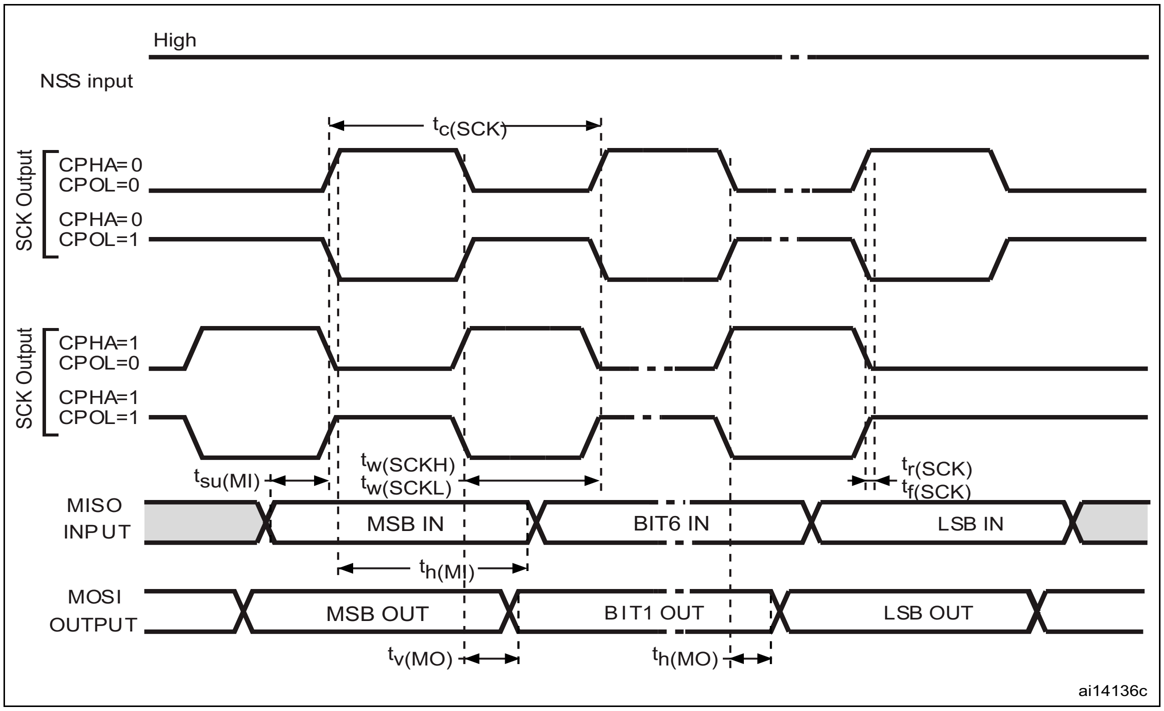


Figure 36. SPI timing diagram - slave mode and CPHA = 1



1. Measurement points are done at CMOS levels: 0.3 V_{DD} and 0.7 V_{DD}.

Figure 37. SPI timing diagram - master mode



1. Measurement points are done at CMOS levels: 0.3 V_{DD} and 0.7 V_{DD}.

I2S characteristics

Unless otherwise specified, the parameters given in *Table 90* for I2S are derived from tests performed under the ambient temperature, f_{PCLKx} frequency and V_{DD} supply voltage conditions summarized in *Table 17: General operating conditions*, with the following configuration:

- Output speed is set to OSPEEDRy[1:0] = 10
- Capacitive load C=30pF
- Measurement points are done at CMOS levels: 0.5 V_{DD}

Refer to *Section 5.3.14: I/O port characteristics* for more details on the input/output alternate function characteristics (CK,SD,WS).

Table 90. I2S characteristics(1)

Symbol	Parameter	Conditions		Min	Max	Unit
f_{MCLK}	I2S Main clock output	-		256x8 K	256 *Fs(2)	MHz
f_{CK}	I2S clock frequency	Master data		-	64xFs	MHz
		Slave data		-	64xFs	
D_{CK}	I2S clock frequency duty cycle	Slave receiver		30	70	%
$t_{v(WS)}$	WS valid time	Master mode		-	6	ns
$t_{h(WS)}$	WS hold time	Master mode		3	-	
		Slave mode		2	-	
$t_{su(WS)}$	WS setup time	Slave mode		4	-	
$t_{su(SD\_MR)}$	Data input setup time	Master receiver		3	-	
$t_{su(SD\_SR)}$		Slave receiver		4	-	
$t_{h(SD\_MR)}$	Data input hold time	Master receiver		4	-	
$t_{h(SD\_SR)}$		Slave receiver		2	-	
$t_{v(SD\_ST)}$	Data output valid time	Slave transmitter (after enable edge)	$2.7\text{ V} \leq V_{DD} \leq 3.6\text{ V}$	-	15	
			$1.65\text{ V} \leq V_{DD} \leq 3.6\text{ V}$	-	22	
$t_{v(SD\_MT)}$		Master transmitter (after enable edge)		-	3	
$t_{h(SD\_ST)}$	Data output hold time	Slave transmitter (after enable edge)		7	-	
$t_{h(SD\_MT)}$		Master transmitter (after enable edge)		1	-	

1. Guaranteed by characterization results, not tested in production.
2. 256xFs maximum is 49.152 MHz.

*Note: Refer to the reference manual RM0440 "STM32G4 Series advanced Arm®-based 32-bit MCUs" I2S section for more details about the sampling frequency (Fs), f_{MCK}, f_{CK}, D_{CK} values reflect only the digital peripheral behavior, source clock precision might slightly change the values D_{CK} depends mainly on ODD bit value. Digital contribution leads to a min of (I2SDIV/(2*I2SDIV+ODD) and a max (I2SDIV+ODD)/(2*I2SDIV+ODD) and Fs max supported for each mode/condition.*

SAI characteristics

Unless otherwise specified, the parameters given in *Table 91* for SAI are derived from tests performed under the ambient temperature, f_{PCLKx} frequency and V_{DD} supply voltage conditions summarized in*Table 17: General operating conditions*, with the following configuration:

- Output speed is set to OSPEEDRy[1:0] = 10
- Capacitive load C = 30 pF
- Measurement points are done at CMOS levels: 0.5 x V_{DD}

Refer to *Section 5.3.14: I/O port characteristics* for more details on the input/output alternate function characteristics (CK,SD,FS).

Table 91. SAI characteristics[1]

Symbol	Parameter	Conditions	Min	Max	Unit
f_{MCLK}	SAI Main clock output	-	-	50	MHz
f_{CK}	SAI clock frequency[2]	Master transmitter 2.7 V ≤ V_{DD} ≤ 3.6 V Voltage Range 1	-	33	MHz
		Master transmitter 1.71 V ≤ V_{DD} ≤ 3.6 V Voltage Range 1	-	22	
		Master receiver Voltage Range 1	-	22	
		Slave transmitter 2.7 V ≤ V_{DD} ≤ 3.6 V Voltage Range 1	-	45	
		Slave transmitter 1.71 V ≤ V_{DD} ≤ 3.6 V Voltage Range 1	-	29	
		Slave receiver Voltage Range 1	-	50	
		Slave transmitter Voltage Range 2	-	13	
$t_{v(FS)}$	FS valid time	Master mode 2.7 V ≤ V_{DD} ≤ 3.6 V	-	15	ns
		Master mode 1.71 V ≤ V_{DD} ≤ 3.6 V	-	22	
$t_{h(FS)}$	FS hold time	Master mode	10	-	ns
$t_{su(FS)}$	FS setup time	Slave mode	2	-	ns
$t_{h(FS)}$	FS hold time	Slave mode	1	-	ns
$t_{su(SD\_A\_MR)}$	Data input setup time	Master receiver	2.5	-	ns
$t_{su(SD\_B\_SR)}$		Slave receiver	1	-	
$t_{h(SD\_A\_MR)}$	Data input hold time	Master receiver	5	-	ns
$t_{h(SD\_B\_SR)}$		Slave receiver	1	-	
$t_{v(SD\_B\_ST)}$	Data output valid time	Slave transmitter (after enable edge) 2.7 V ≤ V_{DD} ≤ 3.6 V	-	11	ns
		Slave transmitter (after enable edge) 1.71 V ≤ V_{DD} ≤ 3.6 V	-	17	
		Slave transmitter (after enable edge) voltage range V2	-	20	
$t_{h(SD\_B\_ST)}$	Data output hold time	Slave transmitter (after enable edge)	10	-	ns

Table 91. SAI characteristics(1) (continued)

Symbol	Parameter	Conditions	Min	Max	Unit
$t_{v(SD\_A\_MT)}$	Data output valid time	Master transmitter (after enable edge) $2.7\ V \leq V_{DD} \leq 3.6\ V$	-	14	ns
		Master transmitter (after enable edge) $1.71\ V \leq V_{DD} \leq 3.6\ V$	-	21	
$t_{h(SD\_A\_MT)}$	Data output hold time	Master transmitter (after enable edge)	10	-	ns

1. Guaranteed by characterization results.
2. APB clock frequency must be at least twice SAI clock frequency.

Figure 38. SAI master timing waveforms

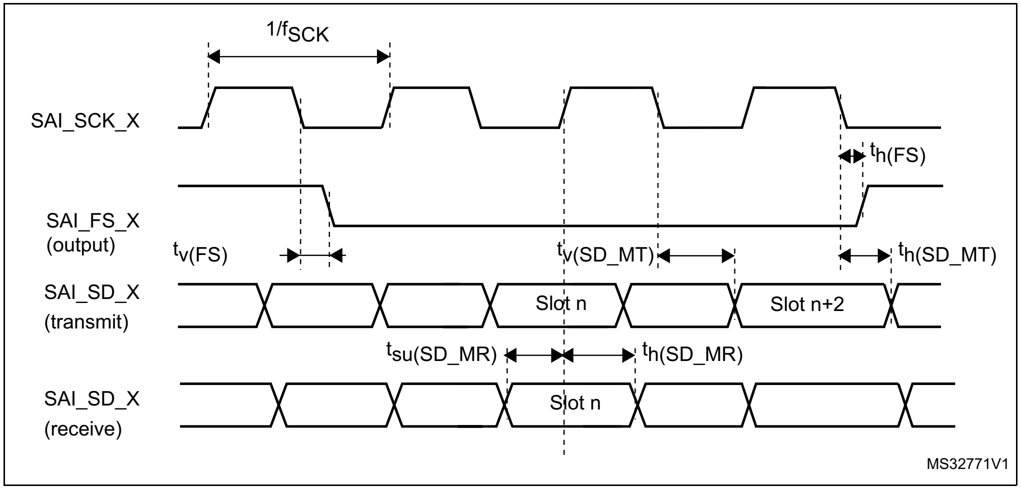
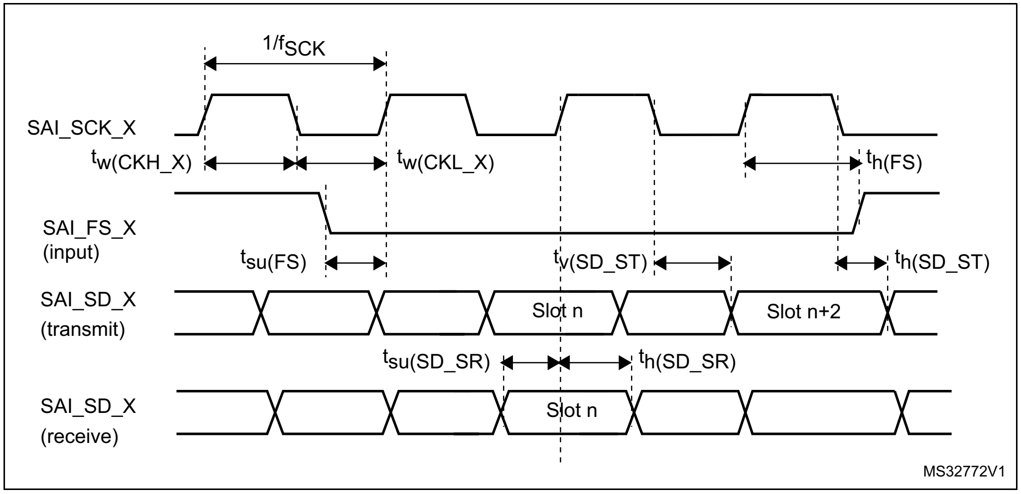


Figure 39. SAI slave timing waveforms



CAN (controller area network) interface

Refer to *Section 5.3.14: I/O port characteristics* for more details on the input/output alternate function characteristics (FDCANx_TX and FDCANx_RX).

USB characteristics

The device USB interface is fully compliant with the USB specification version 2.0 and is USB-IF certified (for Full-speed device operation).

Table 92. USB electrical characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
V_{DD}	USB transceiver operating voltage		3.0(2)	-	3.6	V
$t_{Crystal\_less}$	USB crystal less operation temperature		-15	-	85	°C
R_{PUI}	Embedded USB_DP pull-up value during idle		900	1250	1500	Ω
R_{PUR}	Embedded USB_PD pull-up value during reception		1400	2300	3200	
Z_{sDRV}(3)	Output driver impedance(4)	Driving high and low	28	36	44	Ω

1. TA = -40 to 125 °C unless otherwise specified.
2. The device USB functionality is ensured down to 2.7 V but not the full USB electrical characteristics, which are degraded in the 2.7-to-3.0 V voltage range.
3. Guarantee by design.
4. No external termination series resistors are required on USB_PD (D+) and USB_DM (D-); the matching impedance is already included in the embedded driver.

USART interface characteristics

Unless otherwise specified, the parameters given in *Table 93* for USART are derived from tests performed under the ambient temperature, f_{PCLKx} frequency and V_{DD} supply voltage conditions summarized in *Table 93*, with the following configuration:

- Output speed is set to OSPEEDRy[1:0] = 10
- Capacitive load C=30 pF
- Measurement points are done at CMOS levels: 0.5 V_{DD}

Refer to *Section 5.3.14: I/O port characteristics* for more details on the input/output alternate function characteristics (NSS, CK, TX, RX for USART).

Table 93. USART electrical characteristics(1)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_{CK}	USART clock frequency	Master mode	-	-	21	MHz
		Slave mode	-	-	22	
$t_{su}(NSS)$	NSS setup time	Slave mode	t_{ker} + 2	-	-	ns
$t_h(NSS)$	NSS hold time	Slave mode	2	-	-	
$t_w(CKH)$ $t_w(CKL)$	CK high and low time	Master mode	$1/f_{ck}/2-1$	$1/f_{ck}/2$	$1/f_{ck}/2+1$	ns
$t_{su}(RX)$	Data input setup time	Master mode	t_{ker} + 2	-	-	ns
		Slave mode	2	-	-	
$t_h(RX)$	Data input hold time	Master mode	1	-	-	
		Slave mode	0.5	-	-	

Table 93. USART electrical characteristics[1] (continued)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
t_v(TX)	Data output valid time	Master mode	-	0.5	1.5	ns
		Slave mode	-	10	22	
t_h(RX)	Data output hold time	Master mode	0	-	-	
		Slave mode	7	-	-	

1. Based on characterization, not tested in production.

5.3.28 FSMC characteristics

Unless otherwise specified, the parameters given in *Table 94* to *Table 107* for the FMC interface are derived from tests performed under the ambient temperature, f_{HCLK} frequency and V_{DD} supply voltage conditions summarized in *Table 17*, with the following configuration:

- Output speed is set to OSPEEDRy[1:0] = 11
- Capacitive load C = 30 pF
- Measurement points are done at CMOS levels: 0.5 x V_{DD}

Refer to *Section 5.3.14: I/O port characteristics* for more details on the input/output characteristics.

Asynchronous waveforms and timings

Figure 40 through *Figure 43* represent asynchronous waveforms and *Table 94* through *Table 101* provide the corresponding timings. The results shown in these tables are obtained with the following FMC configuration:

- AddressSetupTime = 0x1
- AddressHoldTime = 0x1
- DataHoldTime = 0x1
- ByteLaneSetup = 0x1
- DataSetupTime = 0x1 (except for asynchronous NWAIT mode, DataSetupTime = 0x5)
- BusTurnAroundDuration = 0x0

In all timing tables, the THCLK is the HCLK clock period.

Figure 40. Asynchronous non-multiplexed SRAM/PSRAM/NOR read waveforms

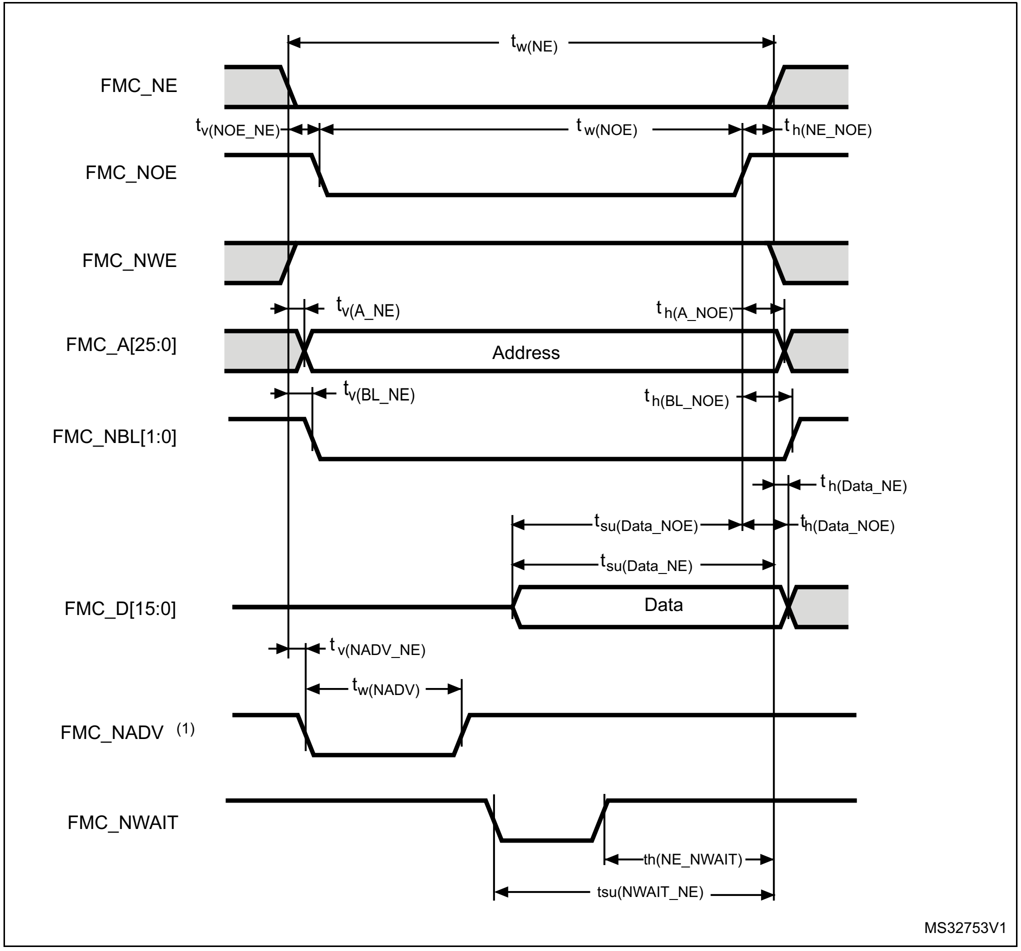


Table 94. Asynchronous non-multiplexed SRAM/PSRAM/NOR read timings(1)(2)

Symbol	Parameter	Min	Max	Unit
$t_{w(NE)}$	FMC_NE low time	$3\ T_{HCLK} – 0.5$	$3T_{HCLK} + 1$	ns
$t_{v(NOE\_NE)}$	FMC_NEx low to FMC_NOE low	0	1	
$t_{w(NOE)}$	FMC_NOE low time	$2\ T_{HCLK} – 0.5$	$2\ T_{HCLK} + 1$	
$t_{h(NE\_NOE)}$	FMC_NOE high to FMC_NE high hold time	T_{HCLK}	-	
$t_{v(A\_NE)}$	FMC_NEx low to FMC_A valid	-	2	
$t_{h(A\_NOE)}$	Address hold time after FMC_NOE high	$2\ T_{HCLK} – 1$	-	
$t_{su(Data\_NE)}$	Data to FMC_NEx high setup time	$T_{HCLK} + 20$	-	
$t_{su(Data\_NOE)}$	Data to FMC_NOEx high setup time	20	-	
$t_{h(Data\_NOE)}$	Data hold time after FMC_NOE high	0	-	
$t_{h(Data\_NE)}$	Data hold time after FMC_NEx high	0	-	
$t_{v(NADV\_NE)}$	FMC_NEx low to FMC_NADV low	-	1.5	
$t_{w(NADV)}$	FMC_NADV low time	-	$T_{HCLK} + 8$	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Table 95. Asynchronous non-multiplexed SRAM/PSRAM/NOR read-NWAIT timings(1)(2)

Symbol	Parameter	Min	Max	Unit
$t_{w(NE)}$	FMC_NE low time	-	$8\ T_{HCLK} + 1$	ns
$t_{w(NOE)}$	FMC_NWE low time	$7\ T_{HCLK} - 1$	$7\ T_{HCLK} + 0.5$	
$t_{w(NWAIT)}$	FMC_NWAIT low time	T_{HCLK}	-	
$t_{su(NWAIT\_NE)}$	FMC_NWAIT valid before FMC_NEx high	$5\ T_{HCLK} + 17$	-	
$t_{h(NE\_NWAIT)}$	FMC_NEx hold time after FMC_NWAIT invalid	$4\ T_{HCLK} + 17$	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Figure 41. Asynchronous non-multiplexed SRAM/PSRAM/NOR write waveforms

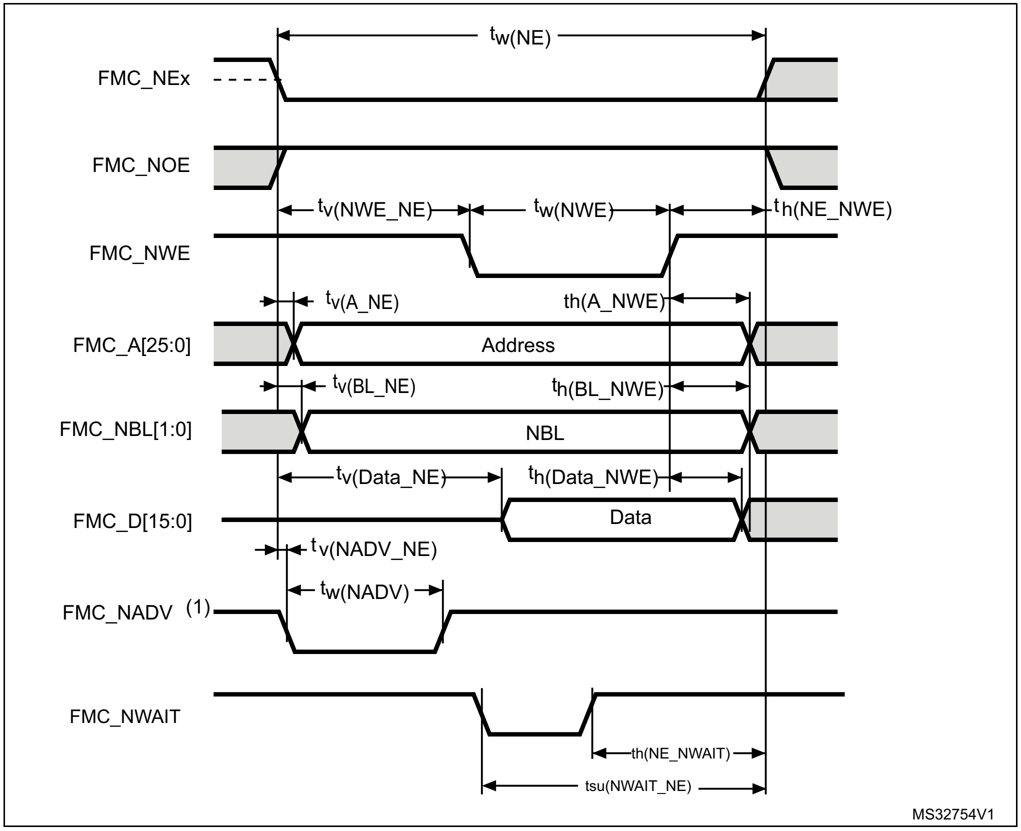


Table 96. Asynchronous non-multiplexed SRAM/PSRAM/NOR write timings(1)(2)

Symbol	Parameter	Min	Max	Unit
$t_{w(NE)}$	FMC_NE low time	$3\ T_{HCLK} - 0.5$	$3\ T_{HCLK} + 1$	ns
$t_{v(NWE\_NE)}$	FMC_NEx low to FMC_NWE low	$T_{HCLK} - 0.5$	$T_{HCLK} + 1$	
$t_{w(NWE)}$	FMC_NWE low time	$T_{HCLK} -2$	$T_{HCLK} + 1$	
$t_{h(NE\_NWE)}$	FMC_NWE high to FMC_NE high hold time	$T_{HCLK} - 0.5$	-	
$t_{v(A\_NE)}$	FMC_NEx low to FMC_A valid	-	0	
$t_{h(A\_NWE)}$	Address hold time after FMC_NWE high	$T_{HCLK} - 1$	-	
$t_{v(BL\_NE)}$	FMC_NEx low to FMC_BL valid	-	0	
$t_{h(BL\_NWE)}$	FMC_BL hold time after FMC_NWE high	$T_{HCLK} + 0.5$	-	
$t_{v(Data\_NE)}$	Data to FMC_NEx low to Data valid	-	$T_{HCLK} + 2$	
$t_{h(Data\_NWE)}$	Data hold time after FMC_NWE high	$T_{HCLK} + 6$	-	
$t_{v(NADV\_NE)}$	FMC_NEx low to FMC_NADV low	-	1.5	
$t_{w(NADV)}$	FMC_NADV low time	-	$T_{HCLK} + 0.5$	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Table 97. Asynchronous non-multiplexed SRAM/PSRAM/NOR write-NWAIT timings(1)(2)

Symbol	Parameter	Min	Max	Unit
$t_{w(NE)}$	FMC_NE low time	9 T_{HCLK} - 1	9 T_{HCLK} + 1	ns
$t_{w(NWE)}$	FMC_NWE low time	6 T_{HCLK} - 1	6 T_{HCLK} + 1	
$t_{su(NWAIT\_NE)}$	FMC_NWAIT valid before FMC_NEx high	7 T_{HCLK} + 17	-	
$t_{h(NE\_NWAIT)}$	FMC_NEx hold time after FMC_NWAIT invalid	7 T_{HCLK} + 17	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Figure 42. Asynchronous multiplexed PSRAM/NOR read waveforms

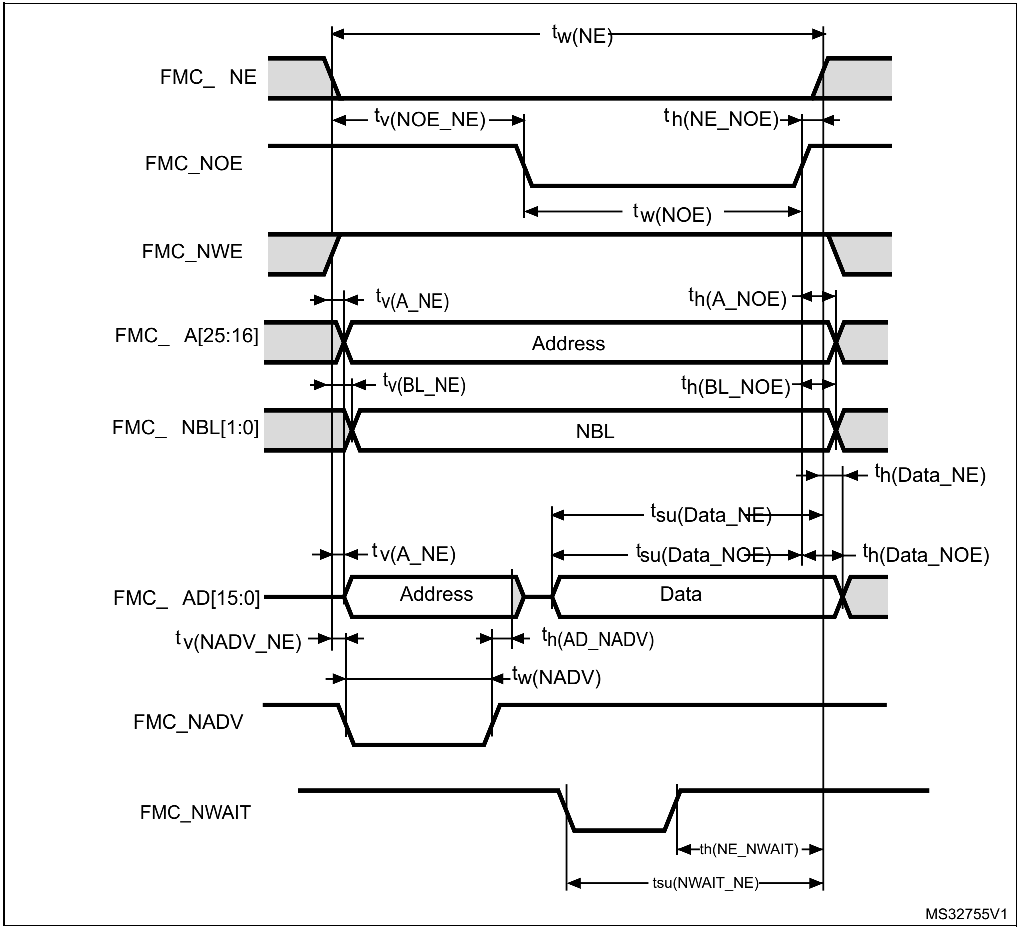


Table 98. Asynchronous multiplexed PSRAM/NOR read timings(1)(2)

Symbol	Parameter	Min	Max	Unit
$t_{w(NE)}$	FMC_NE low time	3 T_{HCLK} - 0.5	3 T_{HCLK} + 1	ns
$t_{v(NOE\_NE)}$	FMC_NEx low to FMC_NOE low	0	1	
$t_{w(NOE)}$	FMC_NOE low time	2 T_{HCLK} - 0.5	2 T_{HCLK} + 0.5	
$t_{h(NE\_NOE)}$	FMC_NOE high to FMC_NE high hold time	T_{HCLK}	-	
$t_{v(A\_NE)}$	FMC_NEx low to FMC_A valid	-	2	
$t_{v(NADV\_NE)}$	FMC_NEx low to FMC_NADV low	0.5	1.5	
$t_{w(NADV)}$	FMC_NADV low time	T_{HCLK}	T_{HCLK} + 1.5	
$t_{h(AD\_NADV)}$	FMC_AD(address) valid hold time after FMC_NADV high	T_{HCLK} - 0.3	-	
$t_{h(A\_NOE)}$	Address hold time after FMC_NOE high	Address hold until next read operation	-	
$t_{su(Data\_NE)}$	Data to FMC_NEx high setup time	T_{HCLK} + 20	-	
$t_{su(Data\_NOE)}$	Data to FMC_NOE high setup time	20	-	
$t_{h(Data\_NE)}$	Data hold time after FMC_NEx high	0	-	
$t_{h(Data\_NOE)}$	Data hold time after FMC_NOE high	0	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Table 99. Asynchronous multiplexed PSRAM/NOR read-NWAIT timings(1)(2)

Symbol	Parameter	Min	Max	Unit
$t_{w(NE)}$	FMC_NE low time	8 T_{HCLK} - 1	8 T_{HCLK} + 1	ns
$t_{w(NOE)}$	FMC_NWE low time	7 T_{HCLK} - 1	7 T_{HCLK} + 0.5	
$t_{su(NWAIT\_NE)}$	FMC_NWAIT valid before FMC_NEx high	5 T_{HCLK} + 17	-	
$t_{h(NE\_NWAIT)}$	FMC_NEx hold time after FMC_NWAIT invalid	4 T_{HCLK} + 17	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Figure 43. Asynchronous multiplexed PSRAM/NOR write waveforms

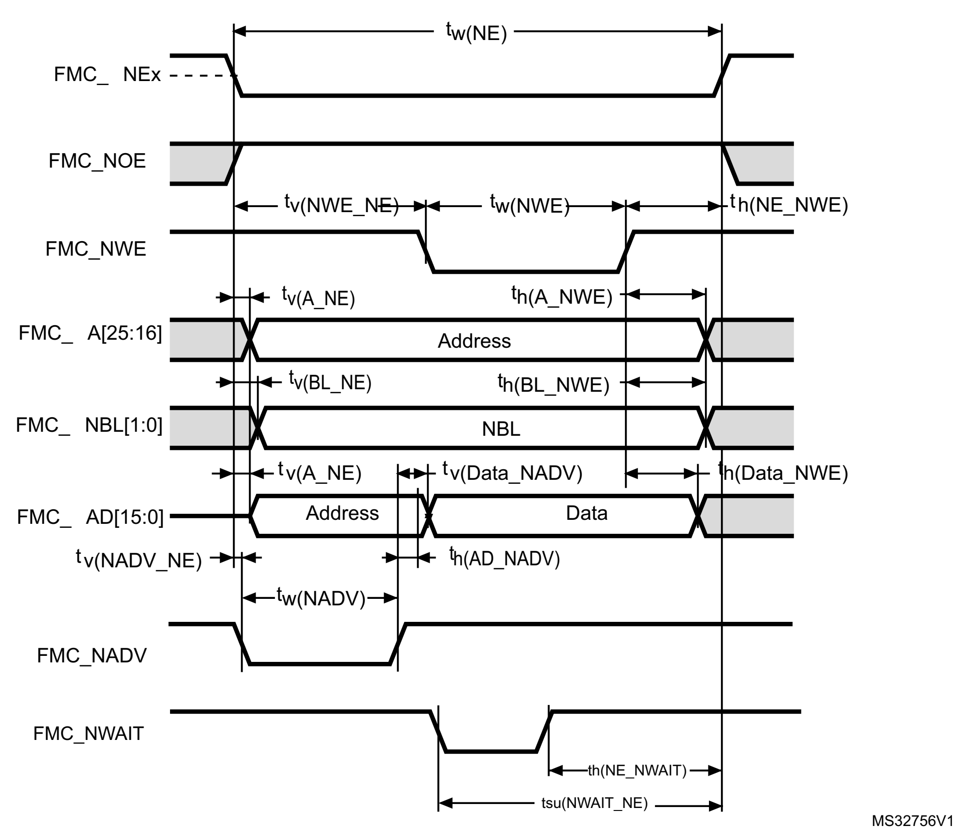


Table 100. Asynchronous multiplexed PSRAM/NOR write timings[1][2]

Symbol	Parameter	Min	Max	Unit
$t_{w(NE)}$	FMC_NE low time	3 T_{HCLK} - 0.5	3 T_{HCLK} + 1	ns
$t_{v(NWE\_NE)}$	FMC_NEx low to FMC_NWE low	T_{HCLK} - 0.5	T_{HCLK} + 1	
$t_{w(NWE)}$	FMC_NWE low time	T_{HCLK} - 2	T_{HCLK} + 1	
$t_{h(NE\_NWE)}$	FMC_NWE high to FMC_NE high hold time	T_{HCLK} - 0.5	-	
$t_{v(A\_NE)}$	FMC_NEx low to FMC_A valid	-	0	
$t_{v(NADV\_NE)}$	FMC_NEx low to FMC_NADV low	0	1.5	
$t_{w(NADV)}$	FMC_NADV low time	T_{HCLK} + 0.5	T_{HCLK} + 1.5	
$t_{h(AD\_NADV)}$	FMC_AD(address) valid hold time after FMC_NADV high	T_{HCLK} - 3	-	
$t_{h(A\_NWE)}$	Address hold time after FMC_NWE high	Address hold until next write operation	-	
$t_{h(BL\_NWE)}$	FMC_BL hold time after FMC_NWE high	T_{HCLK} - 0.5	-	
$t_{v(BL\_NE)}$	FMC_NEx low to FMC_BL valid	-	0	
$t_{v(Data\_NADV)}$	FMC_NADV high to Data valid	-	T_{HCLK} + 2	
$t_{h(Data\_NWE)}$	Data hold time after FMC_NWE high	T_{HCLK} + 6	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Table 101. Asynchronous multiplexed PSRAM/NOR write-NWAIT timings[1][2]

Symbol	Parameter	Min	Max	Unit
$t_{w(NE)}$	FMC_NE low time	9 T_{HCLK} - 1	9 T_{HCLK} + 1	ns
$t_{w(NWE)}$	FMC_NWE low time	6 T_{HCLK} - 1	6 T_{HCLK} + 0.5	
$t_{su(NWAIT\_NE)}$	FMC_NWAIT valid before FMC_NEx high	7 T_{HCLK} + 17	-	
$t_{h(NE\_NWAIT)}$	FMC_NEx hold time after FMC_NWAIT invalid	5 T_{HCLK} + 17	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Synchronous waveforms and timings

Figure 44 through *Figure 47* represent synchronous waveforms and *Table 102* through *Table 105* provide the corresponding timings. The results shown in these tables are obtained with the following FMC configuration:

- BurstAccessMode = FMC_BurstAccessMode_Enable
- MemoryType = FMC_MemoryType_CRAM
- WriteBurst = FMC_WriteBurst_Enable
- CLKDivision = 1
- DataLatency = 1 for NOR Flash; DataLatency = 0 for PSRAM

In all timing tables, the T_{HCLK} is the HCLK clock period.

- For 2.7 V ≤ V_{DD} ≤ 3.6 V, maximum FMC_CLK = 60 MHz for CLKDIV = 0x1 and 54 MHz for CLKDIV = 0x0 at CL = 30 pF (on FMC_CLK).
- For 1.71 V ≤ V_{DD} ≤ 2.7 V, maximum FMC_CLK = 60 MHz for CLKDIV = 0x1 and 32 MHz for CLKDIV = 0x0 at CL= 20 pF (on FMC_CLK).

Figure 44. Synchronous multiplexed NOR/PSRAM read timings

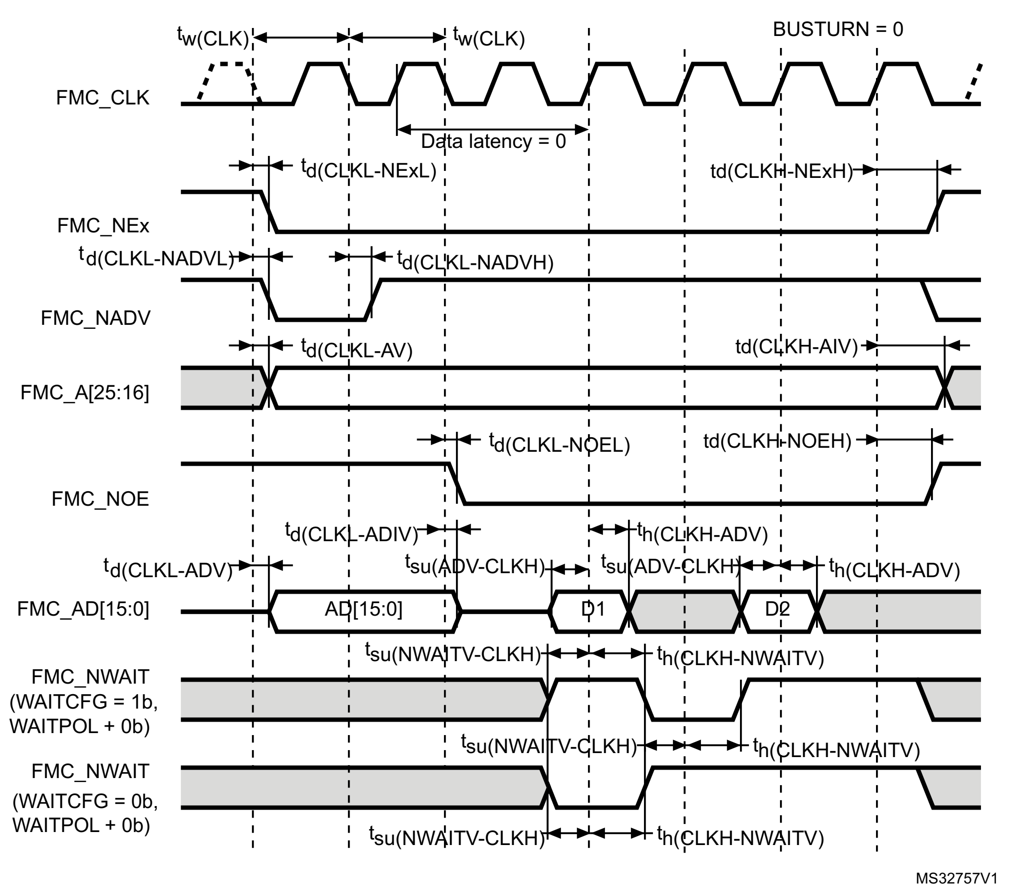


Table 102. Synchronous multiplexed NOR/PSRAM read timings(1)(2)(3)

Symbol	Parameter	Min	Max	Unit
$t_{w(CLK)}$	FMC_CLK period	R*T_{HCLK} - 0.5	-	ns
$t_{d(CLKL\text{-}NExL)}$	FMC_CLK low to FMC_NEx low (x=0..2)	-	1.5	
$t_{d(CLKH\_NExH)}$	FMC_CLK high to FMC_NEx high (x= 0…2)	R*T_{HCLK}/2 + 1	-	
$t_{d(CLKL\text{-}NADVL)}$	FMC_CLK low to FMC_NADV low	-	2.5	
$t_{d(CLKL\text{-}NADVH)}$	FMC_CLK low to FMC_NADV high	3.5	-	
$t_{d(CLKL\text{-}AV)}$	FMC_CLK low to FMC_Ax valid (x=16…25)	-	4	
$t_{d(CLKH\text{-}AIV)}$	FMC_CLK high to FMC_Ax invalid (x=16…25)	R*T_{HCLK}/2 + 1	-	
$t_{d(CLKL\text{-}NOEL)}$	FMC_CLK low to FMC_NOE low	-	2	
$t_{d(CLKH\text{-}NOEH)}$	FMC_CLK high to FMC_NOE high	R*T_{HCLK}/2 + 1	-	
$t_{d(CLKL\text{-}ADV)}$	FMC_CLK low to FMC_AD[15:0] valid	-	3	
$t_{d(CLKL\text{-}ADIV)}$	FMC_CLK low to FMC_AD[15:0] invalid	0	-	
$t_{su(ADV\text{-}CLKH)}$	FMC_A/D[15:0] valid data before FMC_CLK high	2	-	
$t_{h(CLKH\text{-}ADV)}$	FMC_A/D[15:0] valid data after FMC_CLK high	4	-	
$t_{su(NWAIT\text{-}CLKH)}$	FMC_NWAIT valid before FMC_CLK high	1.5	-	
$t_{h(CLKH\text{-}NWAIT)}$	FMC_NWAIT valid after FMC_CLK high	4	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.
3. Clock ratio R = (HCLK period /FMC_CLK period).

Figure 45. Synchronous multiplexed PSRAM write timings

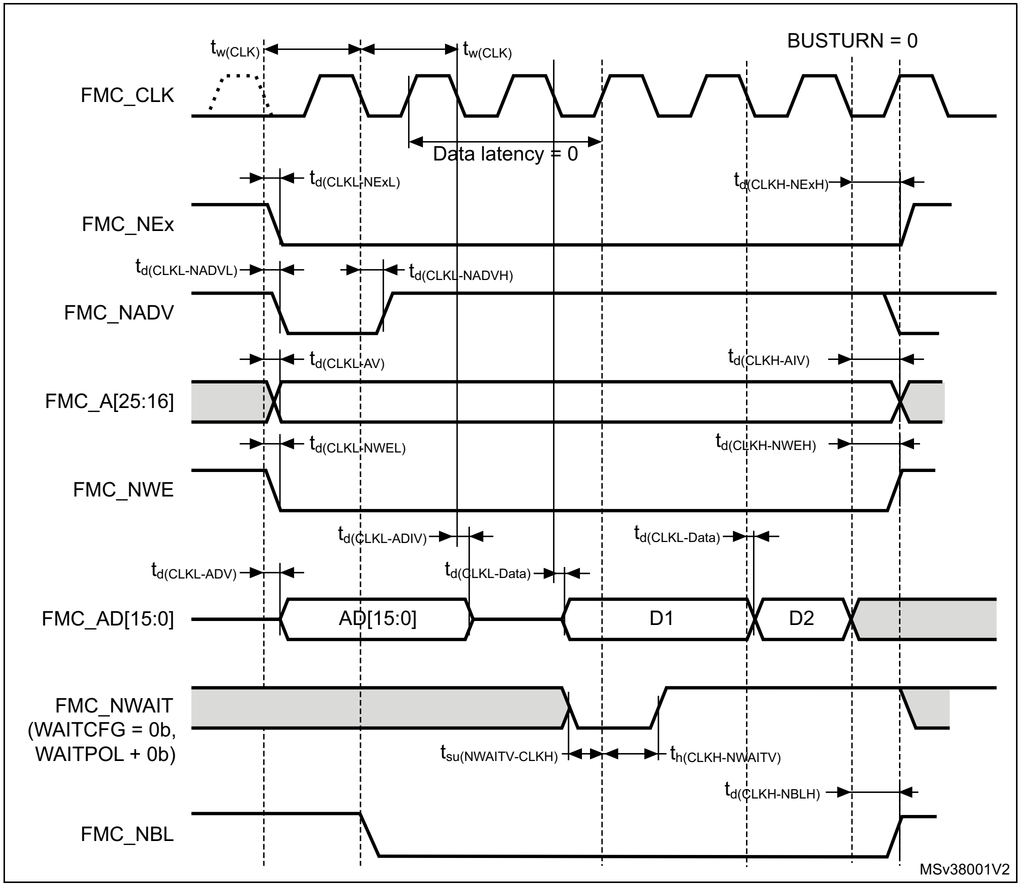


Table 103. Synchronous multiplexed PSRAM write timings(1)(2)(3)

Symbol	Parameter	Min	Max	Unit
$t_{w(CLK)}$	FMC_CLK period	$R*T_{HCLK}$ - 0.5	-	ns
$t_{d(CLKL-NExL)}$	FMC_CLK low to FMC_NEx low (x=0..2)	-	1.5	
$t_{d(CLKH-NExH)}$	FMC_CLK high to FMC_NEx high (x= 0…2)	$R*T_{HCLK}/2$ + 1	-	
$t_{d(CLKL-NADVL)}$	FMC_CLK low to FMC_NADV low	-	2.5	
$t_{d(CLKL-NADVH)}$	FMC_CLK low to FMC_NADV high	3.5	-	
$t_{d(CLKL-AV)}$	FMC_CLK low to FMC_Ax valid (x=16…25)	-	4	
$t_{d(CLKH-AIV)}$	FMC_CLK high to FMC_Ax invalid (x=16…25)	$R*T_{HCLK}/2$ + 1	-	
$t_{d(CLKL-NWEL)}$	FMC_CLK low to FMC_NWE low	-	2	
$t_{d(CLKH-NWEH)}$	FMC_CLK high to FMC_NWE high	$R*T_{HCLK}/2$ + 1	-	
$t_{d(CLKL-ADV)}$	FMC_CLK low to FMC_AD[15:0] valid	-	3	
$t_{d(CLKL-ADIV)}$	FMC_CLK low to FMC_AD[15:0] invalid	0	-	
$t_{d(CLKL-DATA)}$	FMC_A/D[15:0] valid data after FMC_CLK low	-	3	
$t_{d(CLKL-NBLL)}$	FMC_CLK low to FMC_NBL low	1	-	
$t_{d(CLKH-NBLH)}$	FMC_CLK high to FMC_NBL high	$R*T_{HCLK}/2$ + 1.5	-	
$t_{su(NWAIT-CLKH)}$	FMC_NWAIT valid before FMC_CLK high	1.5	-	
$t_{h(CLKH-NWAIT)}$	FMC_NWAIT valid after FMC_CLK high	4	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.
3. Clock ratio R = (HCLK period /FMC_CLK period).

Figure 46. Synchronous non-multiplexed NOR/PSRAM read timings

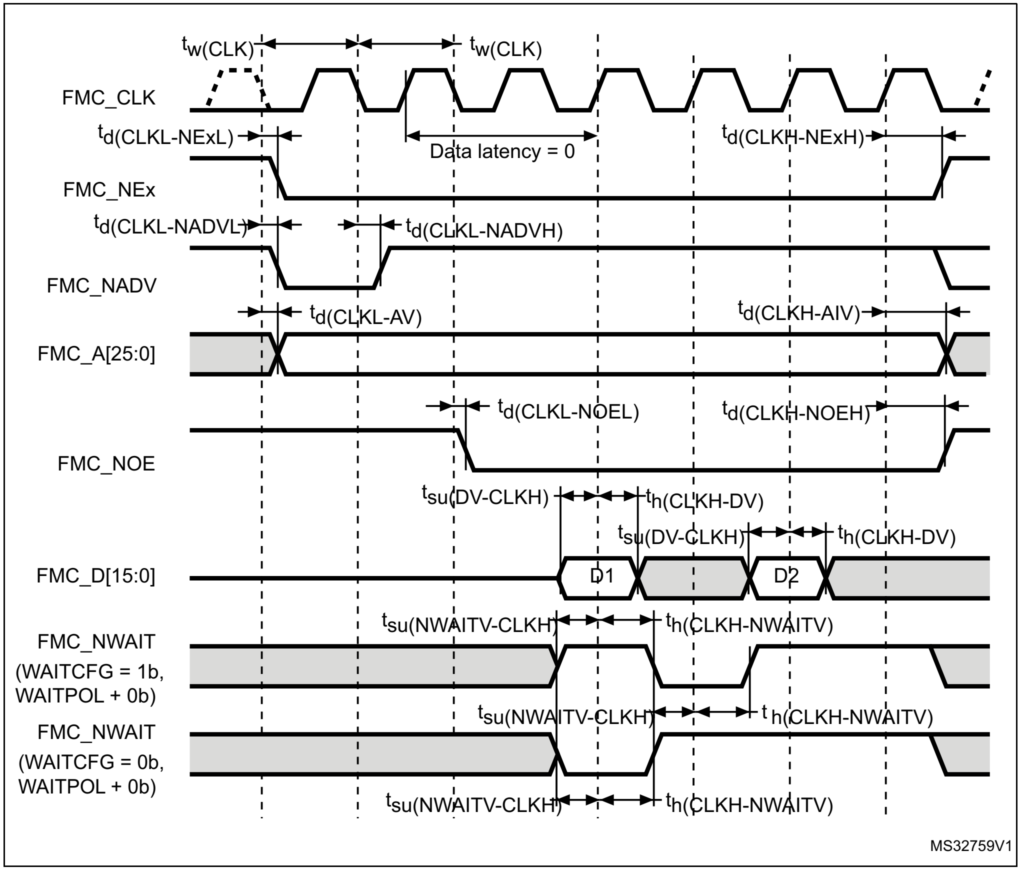


Table 104. Synchronous non-multiplexed NOR/PSRAM read timings(1)(2)(3)

Symbol	Parameter	Min	Max	Unit
$t_{w(CLK)}$	FMC_CLK period	$R*T_{HCLK}$ - 0.5	-	ns
$t_{d(CLKL-NExL)}$	FMC_CLK low to FMC_NEx low (x=0..2)	-	1.5	
$t_{d(CLKH-NExH)}$	FMC_CLK high to FMC_NEx high (x= 0…2)	$R*T_{HCLK}/2$ + 1	-	
$t_{d(CLKL-NADVL)}$	FMC_CLK low to FMC_NADV low	-	2.5	
$t_{d(CLKL-NADVH)}$	FMC_CLK low to FMC_NADV high	3.5	-	
$t_{d(CLKL-AV)}$	FMC_CLK low to FMC_Ax valid (x=16…25)	-	4	
$t_{d(CLKH-AIV)}$	FMC_CLK high to FMC_Ax invalid (x=16…25)	$R*T_{HCLK}/2$+- 1	-	
$t_{d(CLKL-NOEL)}$	FMC_CLK low to FMC_NOE low	-	2	
$t_{d(CLKH-NOEH)}$	FMC_CLK high to FMC_NOE high	$R*T_{HCLK}/2$ + 1	-	
$t_{su(DV-CLKH)}$	FMC_D[15:0] valid data before FMC_CLK high	2	-	
$t_{h(CLKH-DV)}$	FMC_D[15:0] valid data after FMC_CLK high	4	-	
$t_{su(NWAIT-CLKH)}$	FMC_NWAIT valid before FMC_CLK high	1.5	-	ns
$t_{h(CLKH-NWAIT)}$	FMC_NWAIT valid after FMC_CLK high	4	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.
3. Clock ratio R = (HCLK period /FMC_CLK period).

Figure 47. Synchronous non-multiplexed PSRAM write timings

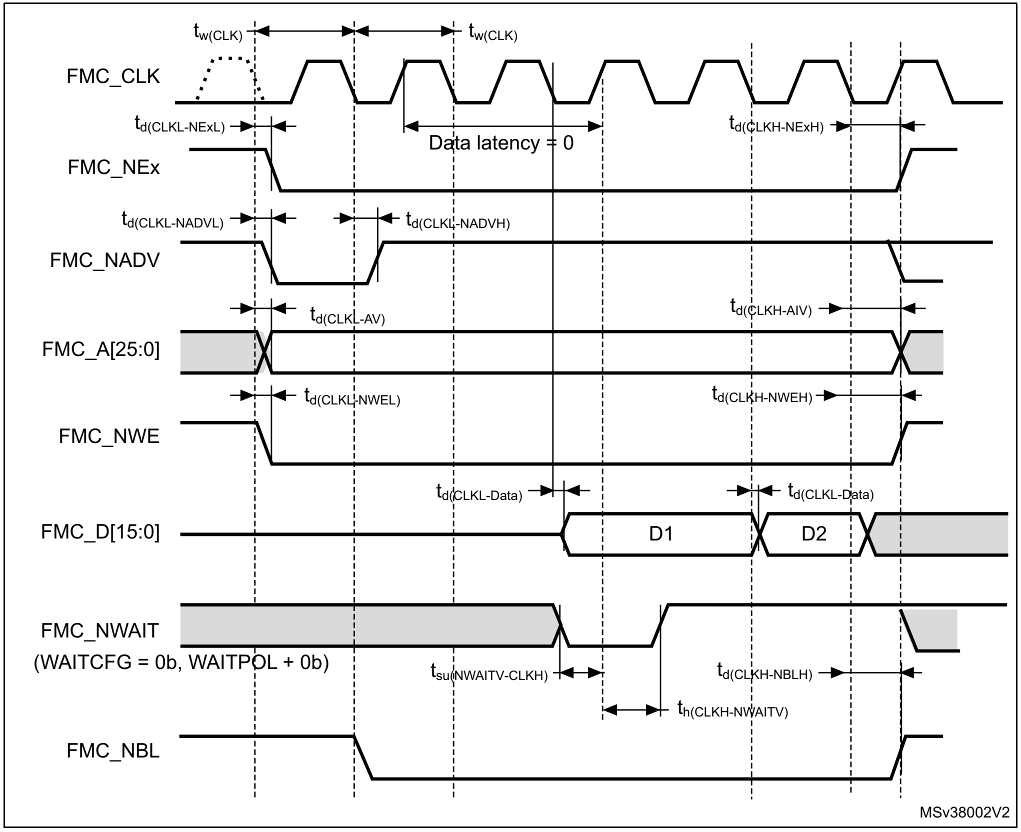


Table 105. Synchronous non-multiplexed PSRAM write timings(1)(2)(3)

Symbol	Parameter	Min	Max	Unit
$t_{w(CLK)}$	FMC_CLK period	R*T_{HCLK} - 0.5	-	ns
$t_{d(CLKL\text{-}NExL)}$	FMC_CLK low to FMC_NEx low (x=0..2)	-	1.5	
$t_{d(CLKH\text{-}NExH)}$	FMC_CLK high to FMC_NEx high (x= 0…2)	R*T_{HCLK}/2 + 1	-	
$t_{d(CLKL\text{-}NADVL)}$	FMC_CLK low to FMC_NADV low	-	2.5	
$t_{d(CLKL\text{-}NADVH)}$	FMC_CLK low to FMC_NADV high	3.5	-	
$t_{d(CLKL\text{-}AV)}$	FMC_CLK low to FMC_Ax valid (x=16…25)	-	4	
$t_{d(CLKH\text{-}AIV)}$	FMC_CLK high to FMC_Ax invalid (x=16…25)	R*T_{HCLK}/2 + 1	-	
$t_{d(CLKL\text{-}NWEL)}$	FMC_CLK low to FMC_NWE low	-	2	
$t_{d(CLKH\text{-}NWEH)}$	FMC_CLK high to FMC_NWE high	R*T_{HCLK}/2 + 1	-	
$t_{d(CLKL\text{-}Data)}$	FMC_D[15:0] valid data after FMC_CLK low	-	3	
$t_{d(CLKL\text{-}NBLL)}$	FMC_CLK low to FMC_NBL low	1	-	
$t_{d(CLKH\text{-}NBLH)}$	FMC_CLK high to FMC_NBL high	R*T_{HCLK}/2 + 1.5	-	
$t_{su(NWAIT\text{-}CLKH)}$	FMC_NWAIT valid before FMC_CLK high	1.5	-	
$t_{h(CLKH\text{-}NWAIT)}$	FMC_NWAIT valid after FMC_CLK high	4	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.
3. Clock ratio R = (HCLK period /FMC_CLK period).

NAND controller waveforms and timings

Figure 48 through *Figure 51* represent synchronous waveforms, and *Table 106* and *Table 107* provide the corresponding timings. The results shown in these tables are obtained with the following FMC configuration:

- COM.FMC_SetupTime = 0x01
- COM.FMC_WaitSetupTime = 0x03
- COM.FMC_HoldSetupTime = 0x02
- COM.FMC_HiZSetupTime = 0x01
- ATT.FMC_SetupTime = 0x01
- ATT.FMC_WaitSetupTime = 0x03
- ATT.FMC_HoldSetupTime = 0x02
- ATT.FMC_HiZSetupTime = 0x01
- Bank = FMC_Bank_NAND
- MemoryDataWidth = FMC_MemoryDataWidth_16b
- ECC = FMC_ECC_Enable
- ECCPageSize = FMC_ECCPageSize_512Bytes
- TCLRSetupTime = 0
- TARSetupTime = 0

In all timing tables, the T_{HCLK} is the HCLK clock period.

Figure 48. NAND controller waveforms for read access

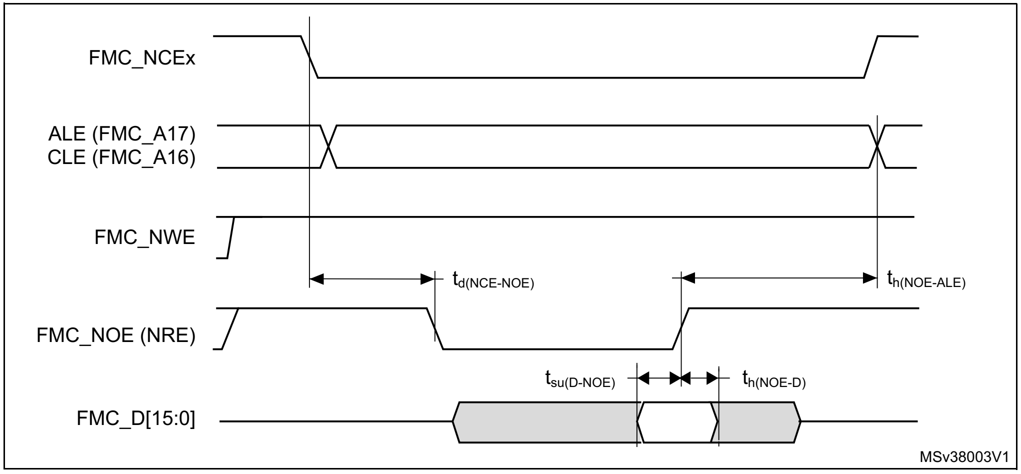


Figure 49. NAND controller waveforms for write access

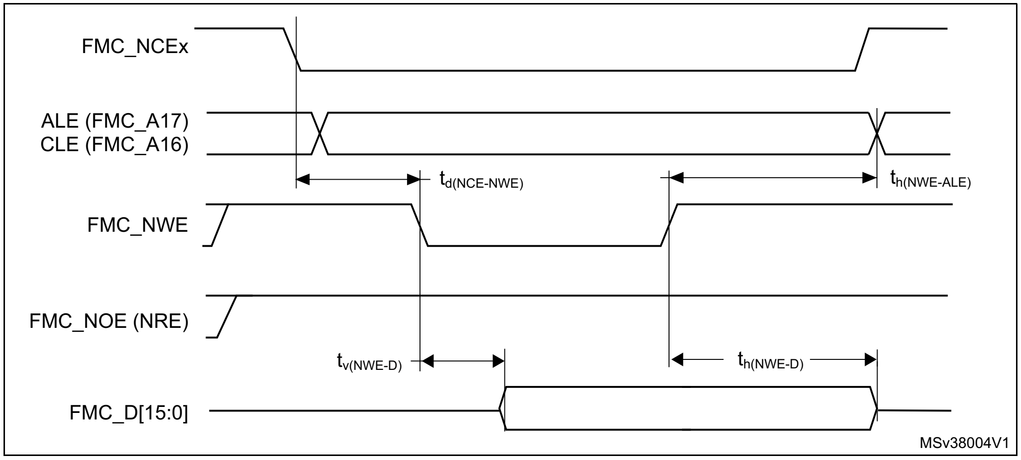


Figure 50. NAND controller waveforms for common memory read access

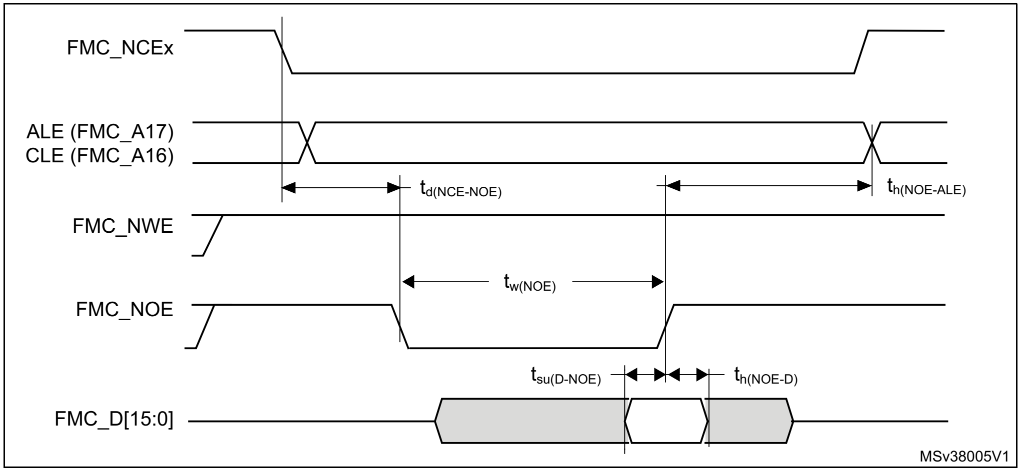


Figure 51. NAND controller waveforms for common memory write access

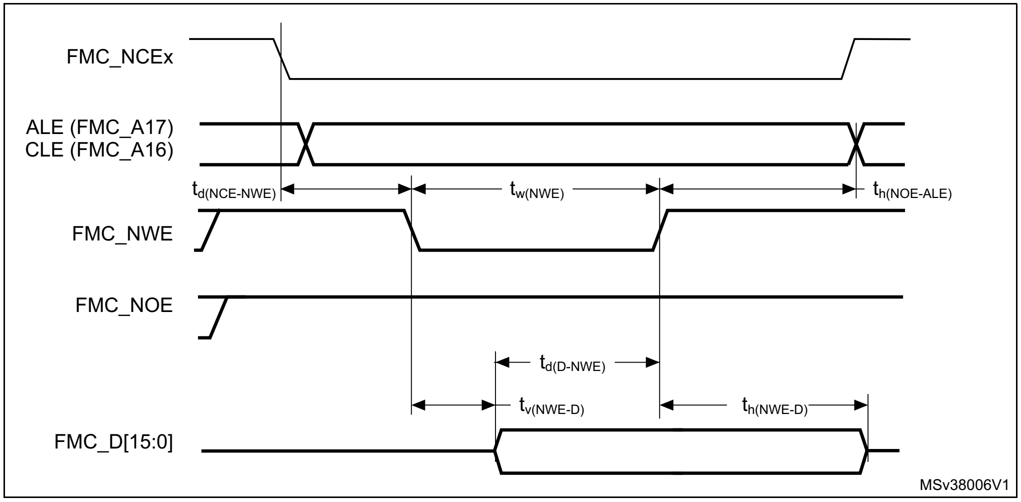


Table 106. Switching characteristics for NAND Flash read cycles(1)(2)

Symbol	Parameter	Min	Max	Unit
$T_{w(N0E)}$	FMC_NOE low width	4 T_{HCLK} - 1	4 T_{HCLK}	ns
$T_{su(D-NOE)}$	FMC_D[15-0] valid data before FMC_NOE high	19	-	
$T_{h(NOE-D)}$	FMC_D[15-0] valid data after FMC_NOE high	0	-	
$T_{d(NCE-NOE)}$	FMC_NCE valid before FMC_NOE low	-	3 T_{HCLK}	
$T_{h(NOE-ALE)}$	FMC_NOE high to FMC_ALE invalid	3 T_{HCLK}	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.

Table 107. Switching characteristics for NAND Flash write cycles(1)(2)

Symbol	Parameter	Min	Max	Unit
$T_{w(NWE)}$	FMC_NWE low width	4 T_{HCLK} -1	4 T_{HCLK}	ns
$T_{v(NWE-D)}$	FMC_NWE low to FMC_D[15-0] valid	0	-	
$T_{h(NWE-D)}$	FMC_NWE high to FMC_D[15-0] invalid	3 T_{HCLK} - 1	-	
$T_{d(D-NWE)}$	FMC_D[15-0] valid before FMC_NWE high	5 T_{HCLK}	-	
$T_{d(NCE\_NWE)}$	FMC_NCE valid before FMC_NWE low	-	3 T_{HCLK}	
$T_{h(NWE-ALE)}$	FMC_NWE high to FMC_ALE invalid	3 T_{HCLK}	-	

1. CL = 30 pF.
2. Guaranteed by characterization results.

5.3.29 QUADSPI characteristics

Unless otherwise specified, the parameters given in *Table 108* and *Table 109* for Quad SPI are derived from tests performed under the ambient temperature, f_{AHB} frequency and V_{DD} supply voltage conditions summarized in *Table 17: General operating conditions*, with the following configuration:

- Output speed is set to OSPEEDRy[1:0] = 11
- Capacitive load C = 15 or 20 pF
- Measurement points are done at CMOS levels: 0.5 x V_{DD}

Refer to *Section 5.3.14: I/O port characteristics* for more details on the input/output alternate function characteristics.

Table 108. Quad SPI characteristics in SDR mode[(1)]

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
F(QCK)	Quad SPI clock frequency	1.71 < V_{DD}< 3.6 V, C_{LOAD} = 15 pF Voltage Range 1	-	-	50	MHz
		1.71 < V_{DD}< 3.6 V, C_{LOAD} = 20 pF Voltage Range 2	-	-	110	
$t_{w(CKH)}$	Quad SPI clock high and low time Even division	PRESCALER [7:0] n =0,1, 3, 5...	$t_{(CK)}$/2-0.5	-	$t_{(CK)}$/2+1	ns
$t_{w(CKL)}$			$t_{(CK)}$/2-1	-	$t_{(CK)}$/2+0.5	
$t_{w(CKH)}$	Quad SPI clock high and low time Odd division	PRESCALER [7:0] n =2,4, 6, 8...	(n/2)*$t_{(CK)}$/(n+1) - 0.5	-	(n/2)*$t_{(CK)}$/(n+1) + 1	
$t_{w(CKL)}$			(n/2+1)*$t_{(CK)}$/(n+1) - 1	-	(n/2+1)*$t_{(CK)}$/(n+1) +0.5	
$t_{s(IN)}$	Data input setup time	1.71 < V_{DD}< 3.6 V	1	-	-	
$t_{h(IN)}$	Data input hold time	1.71 < V_{DD}< 3.6 V	5	-	-	
$t_{v(OUT)}$	Data output valid time	1.71 < V_{DD}< 3.6 V	-	1	1.5	
$t_{h(OUT)}$	Data output hold time	1.71 < V_{DD}< 3.6 V	0.5	-	-	

1. Guaranteed by characterization results.

Table 109. QUADSPI characteristics in DDR mode[(1)]

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
F(QCK)	Quad SPI clock frequency	1.71 < V_{DD}< 3.6 V, C_{LOAD} = 15 pF Voltage Range 1	-	-	50	MHz
		1.71 < V_{DD}< 3.6 V, C_{LOAD} = 20 pF Voltage Range 2	-	-	70	

Table 109. QUADSPI characteristics in DDR mode(1) (continued)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
$t_{w(CKH)}$	Quad SPI clock high and low time Even division	PRESCALER [7:0] n =0,1, 3, 5 ...	$t_{(CK)}/2$	-	$t_{(CK)}/2+1$	ns
$t_{w(CKL)}$			$t_{(CK)}/2-1$	-	$t_{(CK)}/2$	
$t_{w(CKH)}$	Quad SPI clock high and low time Odd division	PRESCALER [7:0] n =2,4, 6, 8...	$(n/2)*t_{(CK)}/(n+1)$	-	$(n/2)*t_{(CK)}/(n+1) + 1$	
$t_{w(CKL)}$			$(n/2+1)*t_{(CK)}/(n+1) - 1$	-	$(n/2+1)*t_{(CK)}/(n+1)$	
$t_{sr(IN)}$	Data input setup time on rising edge	$1.71 < V_{DD} < 3.6$ V	1	-	-	
$t_{sf(IN)}$	Data input setup time on falling edge	$1.71 < V_{DD} < 3.6$ V	1	-	-	
$t_{hr(IN)}$	Data input hold time on rising edge	$1.71 < V_{DD} < 3.6$ V	6	-	-	
$t_{hf(IN)}$	Data input hold time on falling edge	$1.71 < V_{DD} < 3.6$ V	5	-	-	
$t_{vr(OUT)}$	Data output valid time on rising edge	$1.71 < V_{DD} < 3.6$ V DHHC = 0	-	7.5	8	
		$1.71 < V_{DD} < 3.6$ V DHHC = 1		Thclk/2 +1	Thclk/2+1.5	
$t_{vf(OUT)}$	Data output valid time	$1.71 < V_{DD} < 3.6$ V DHHC = 0	-	7	10	
		$1.71 < V_{DD} < 3.6$ V DHHC = 1		Thclk/2 +1	Thclk/2+2	
$t_{hr(OUT)}$	Data output hold time on rising edge	$1.71 < V_{DD} < 3.6$ V DHHC = 0	2	-	-	
		$1.71 < V_{DD} < 3.6$ V DHHC = 1	Thclk/2+ 0.5	-	-	
$t_{hf(OUT)}$	Data output hold time on falling edge	$1.71 < V_{DD} < 3.6$ V DHHC = 0	3	-	-	
		$1.71 < V_{DD} < 3.6$ V DHHC = 1	Thclk/2+0.5	-	-	

1. Guaranteed by characterization results.

Figure 52. Quad SPI timing diagram - SDR mode

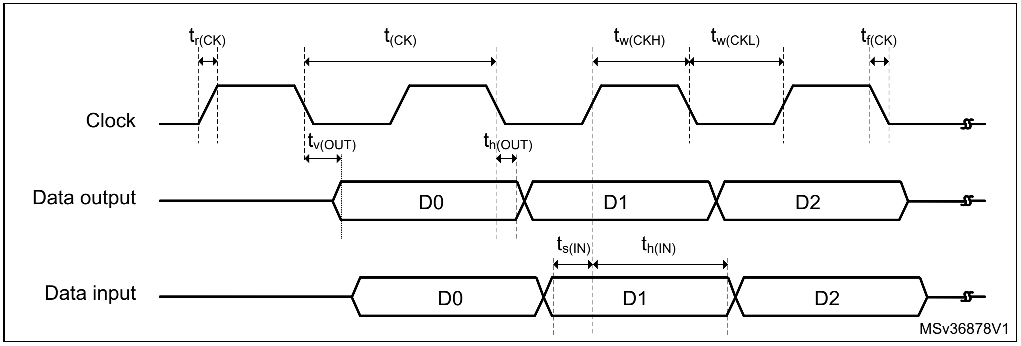
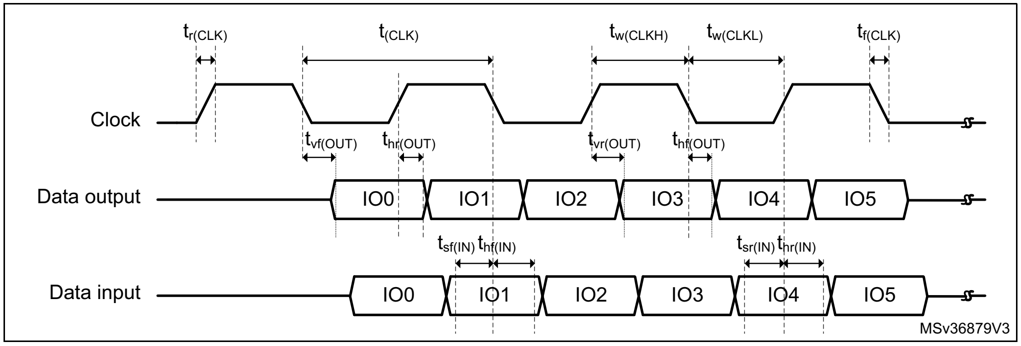


Figure 53. Quad SPI timing diagram - DDR mode



5.3.30 UCPD characteristics

UCPD1 controller complies with USB Type-C Rev.1.2 and USB Power Delivery Rev. 3.0 specifications.

Table 110. UCPD characteristics

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
V_{DD}	UCPD operating supply voltage	Sink mode only	3.0	3.3	3.6	V
		Sink and source mode	3.135	3.3	3.465	V

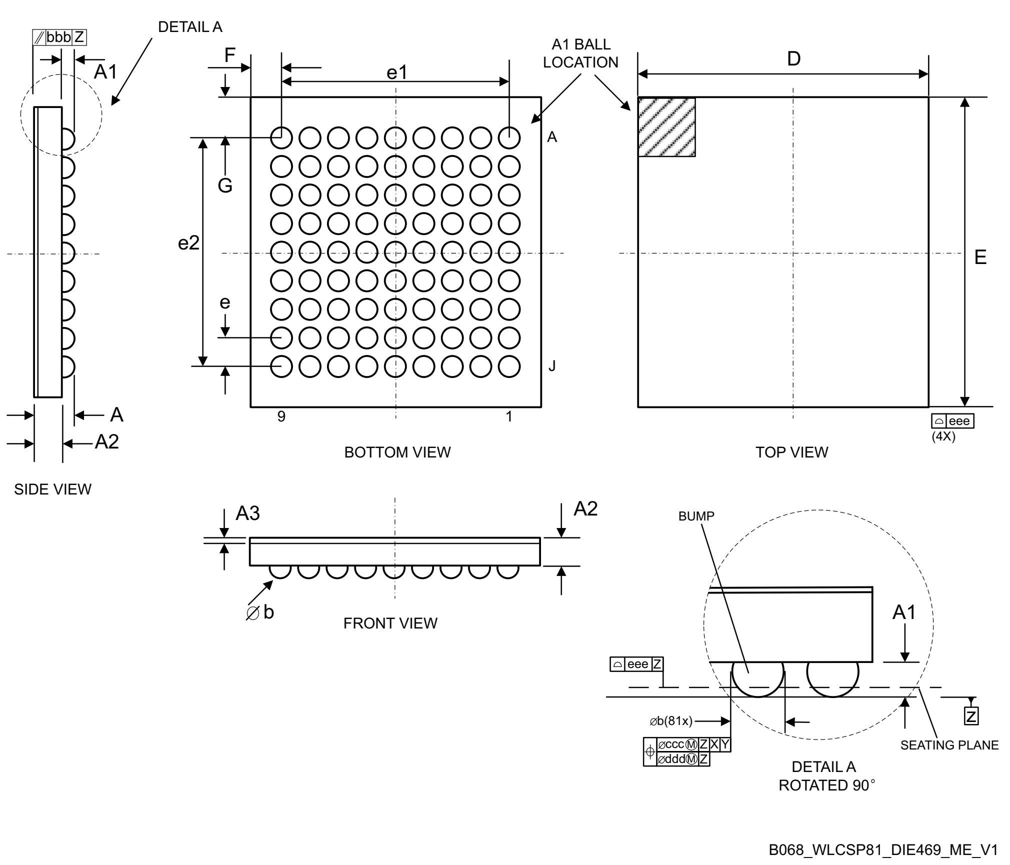
6 Package information

In order to meet environmental requirements, ST offers these devices in different grades of ECOPACK packages, depending on their level of environmental compliance. ECOPACK specifications, grade definitions and product status are available at: *www.st.com*. ECOPACK is an ST trademark.

6.1 WLCSP81 package information

This WLCSP is a 81-ball, 4.02 x 4.27 mm, 0.4 mm pitch wafer level chip scale package.

Figure 54. WLCSP81 - Outline



1. Drawing is not to scale.
2. Dimension is measured at the maximum bump diameter parallel to primary datum Z.
3. Primary datum Z and seating plane are defined by the spherical crowns of the bump.
4. Bump position designation per JESD 95-1, SPP-010.

Table 111. WLCSP81 - Mechanical data

Symbol	millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
A[2]	-	-	0.59	-	-	0.023
A1	-	0.18	-	-	0.007	-
A2	-	0.38	-	-	0.015	-
A3	-	0.025	-	-	0.001	-
b	0.22	0.25	0.28	0.009	0.010	0.011
D	4.00	4.02	4.04	0.157	0.158	0.159
E	4.25	4.27	4.29	0.167	0.168	0.169
e	-	0.40	-	-	0.016	-
e1	-	3.20	-	-	0.126	-
e2	-	3.20	-	-	0.126	-
F[3]	-	0.410	-	-	0.016	-
G[3]	-	0.535	-	-	0.021	-
aaa	-	-	0.10	-	-	0.004
bbb	-	-	0.10	-	-	0.004
ccc	-	-	0.10	-	-	0.004
ddd	-	-	0.05	-	-	0.002
eee	-	-	0.05	-	-	0.002

1. Values in inches are converted from mm and rounded to 3 decimal digits.
2. The maximum total package height is calculated by the RSS method (Root Sum Square) using nominal and tolerances values of A1 and A2.
3. Calculated dimensions are rounded to the 3rd decimal place

Figure 55. WLCSP81 - Recommended footprint

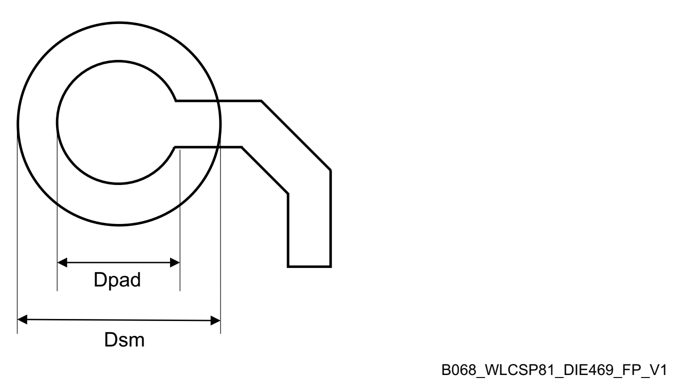


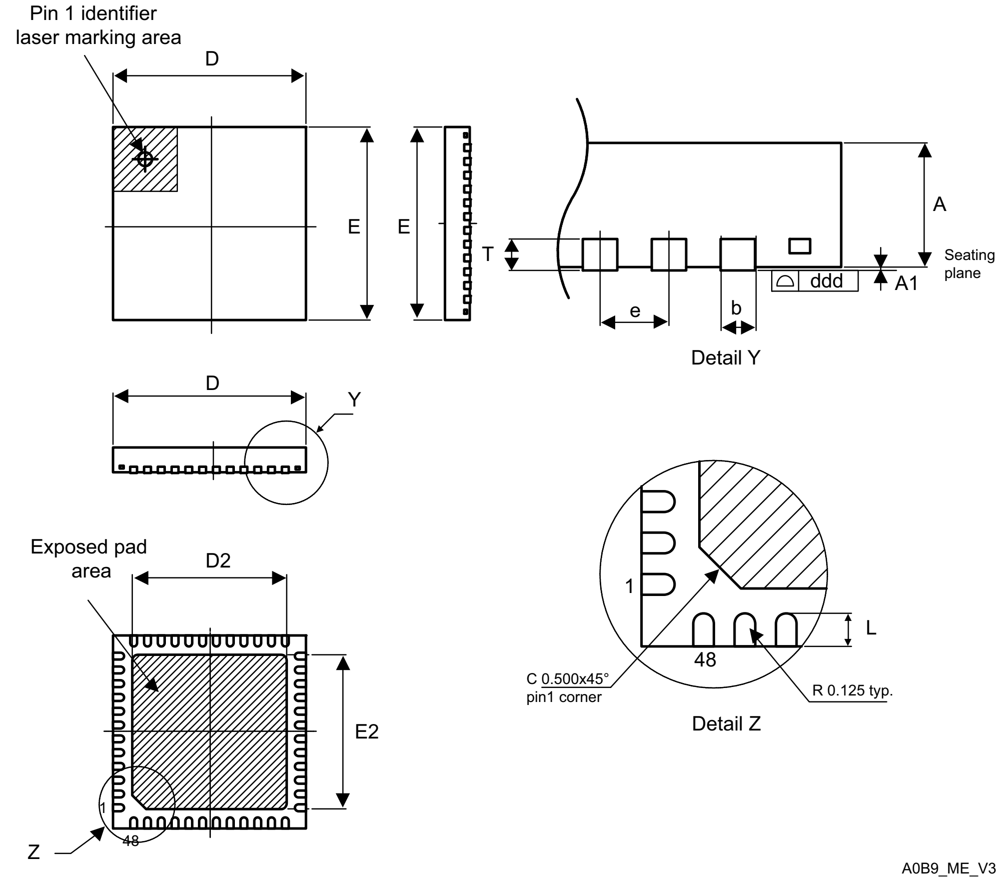
Table 112. WLCSP81 - Recommended PCB design rules

Dimension	Recommended values
Pitch	0.4 mm
Dpad	0,225 mm
Dsm	0.290 mm typ. (depends on soldermask registration tolerance)
Stencil opening	0.250 mm
Stencil thickness	0.100 mm

6.2 UFQFPN48 package information

This UFQFPN is a 48-lead, 7x7 mm, 0.5 mm pitch, ultra thin fine pitch quad flat package.

Figure 56. UFQFPN48 - Outline



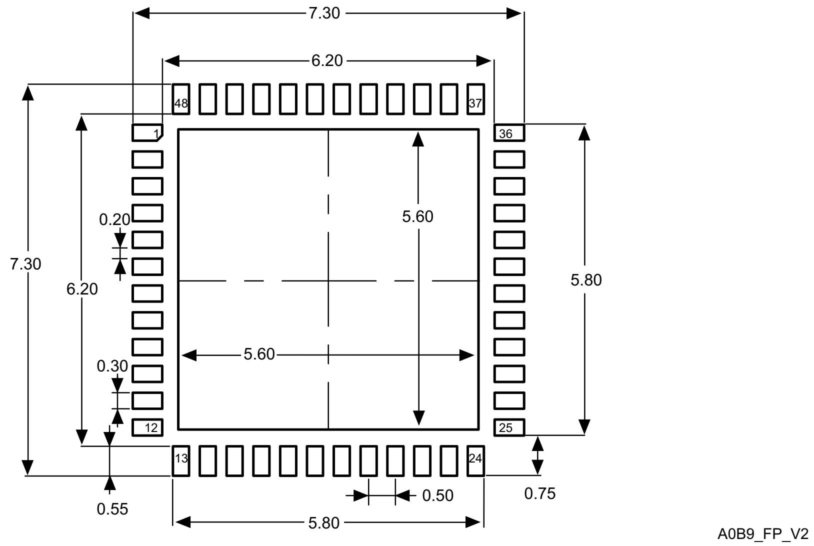
1. Drawing is not to scale.
2. All leads/pads should also be soldered to the PCB to improve the lead/pad solder joint life.
3. There is an exposed die pad on the underside of the UFQFPN48 package. It is recommended to connect and solder this back-side pad to PCB ground.

Table 113. UFQFPN48 - Mechanical data

Symbol	millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
A	0.500	0.550	0.600	0.0197	0.0217	0.0236
A1	0.000	0.020	0.050	0.0000	0.0008	0.0020
D	6.900	7.000	7.100	0.2717	0.2756	0.2795
E	6.900	7.000	7.100	0.2717	0.2756	0.2795
D2	5.500	5.600	5.700	0.2165	0.2205	0.2244
E2	5.500	5.600	5.700	0.2165	0.2205	0.2244
L	0.300	0.400	0.500	0.0118	0.0157	0.0197
T	-	0.152	-	-	0.0060	-
b	0.200	0.250	0.300	0.0079	0.0098	0.0118
e	-	0.500	-	-	0.0197	-
ddd	-	-	0.080	-	-	0.0031

1. Values in inches are converted from mm and rounded to 4 decimal digits.

Figure 57. UFQFPN48 - Recommended footprint



1. Dimensions are expressed in millimeters.

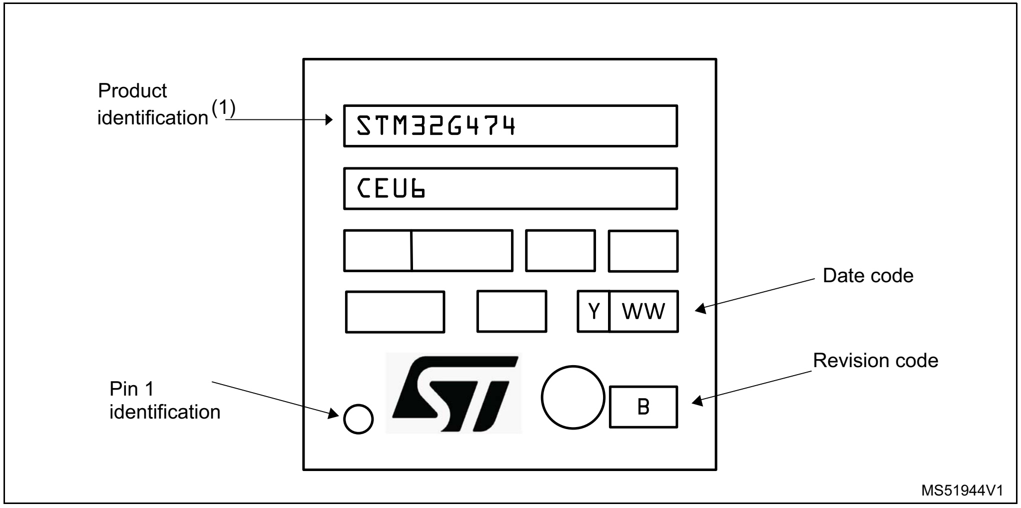
UFQFPN48 device marking

The following figure gives an example of topside marking orientation versus pin 1 identifier location.

The printed markings may differ depending on the supply chain.

Other optional marking or inset/upset marks, which identify the parts throughout supply chain operations, are not indicated below.

Figure 58. UFQFPN48 top view example

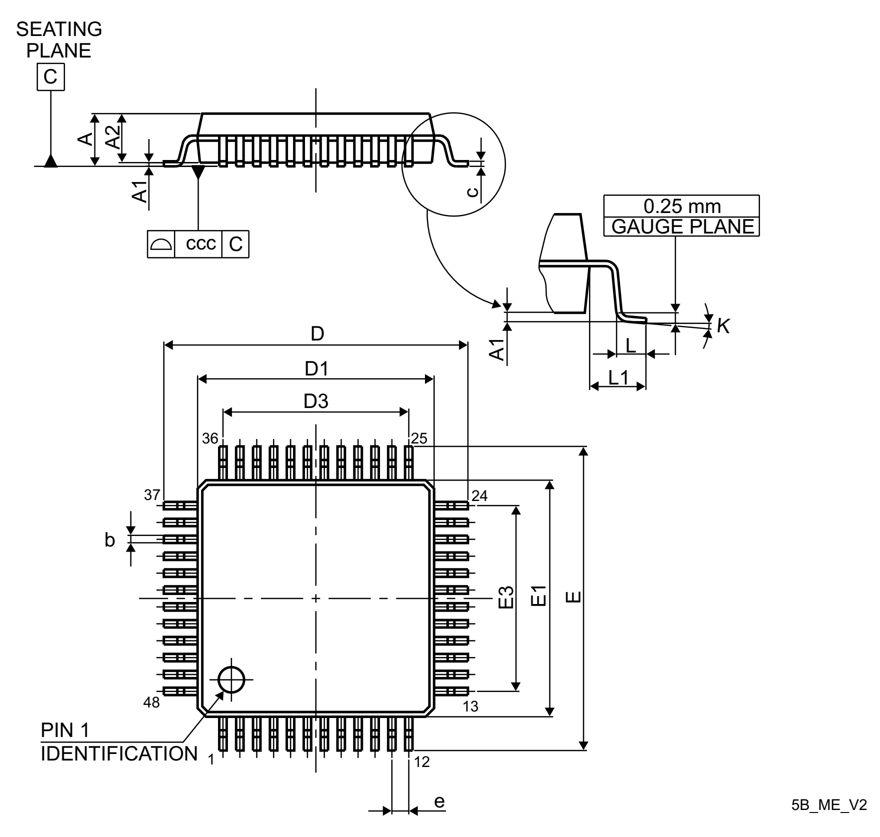


1. Parts marked as ES or E or accompanied by an engineering sample notification letter are not yet qualified and therefore not approved for use in production. ST is not responsible for any consequences resulting from such use. In no event will ST be liable for the customer using any of these engineering samples in production. ST's Quality department must be contacted prior to any decision to use these engineering samples to run a qualification activity.

6.3 LQFP48 package information

This LQFP is a 48-pin, 7 x 7 mm low-profile quad flat package.

Figure 59. LQFP48 - Outline



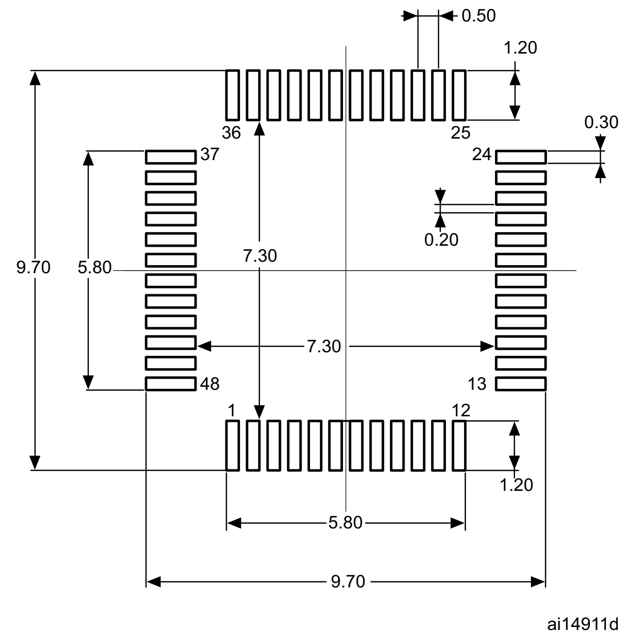
1. Drawing is not to scale.

Table 114. LQFP48 - Mechanical data

Symbol	millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
A	-	-	1.600	-	-	0.0630
A1	0.050	-	0.150	0.0020	-	0.0059
A2	1.350	1.400	1.450	0.0531	0.0551	0.0571
b	0.170	0.220	0.270	0.0067	0.0087	0.0106
c	0.090	-	0.200	0.0035	-	0.0079
D	8.800	9.000	9.200	0.3465	0.3543	0.3622
D1	6.800	7.000	7.200	0.2677	0.2756	0.2835
D3	-	5.500	-	-	0.2165	-
E	8.800	9.000	9.200	0.3465	0.3543	0.3622
E1	6.800	7.000	7.200	0.2677	0.2756	0.2835
E3	-	5.500	-	-	0.2165	-
e	-	0.500	-	-	0.0197	-
L	0.450	0.600	0.750	0.0177	0.0236	0.0295
L1	-	1.000	-	-	0.0394	-
k	0°	3.5°	7°	0°	3.5°	7°
ccc	-	-	0.080	-	-	0.0031

1. Values in inches are converted from mm and rounded to 4 decimal digits.

Figure 60. LQFP48 - Recommended footprint



1. Dimensions are expressed in millimeters.

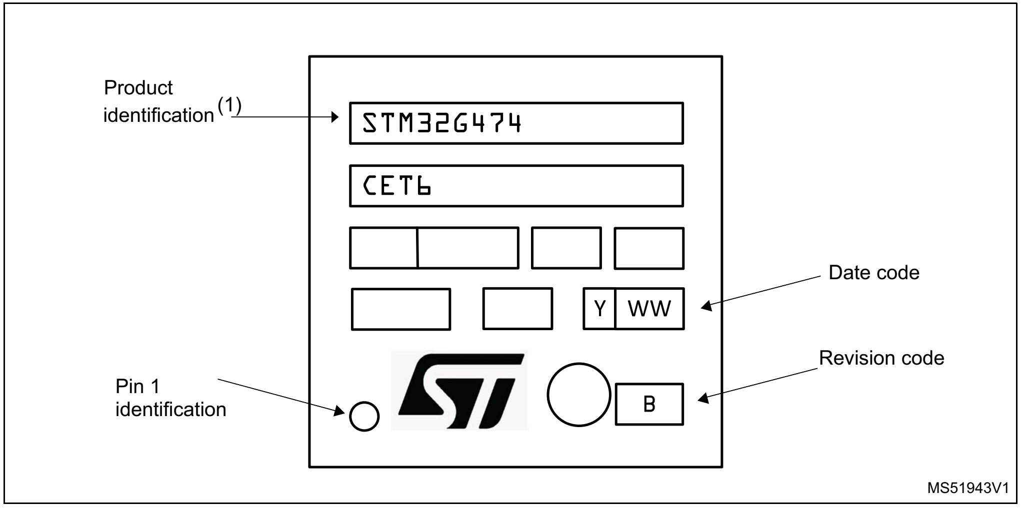
LQFP48 device marking

The following figure gives an example of topside marking orientation versus pin 1 identifier location.

The printed markings may differ depending on the supply chain.

Other optional marking or inset/upset marks, which identify the parts throughout supply chain operations, are not indicated below.

Figure 61. LQFP48 top view example

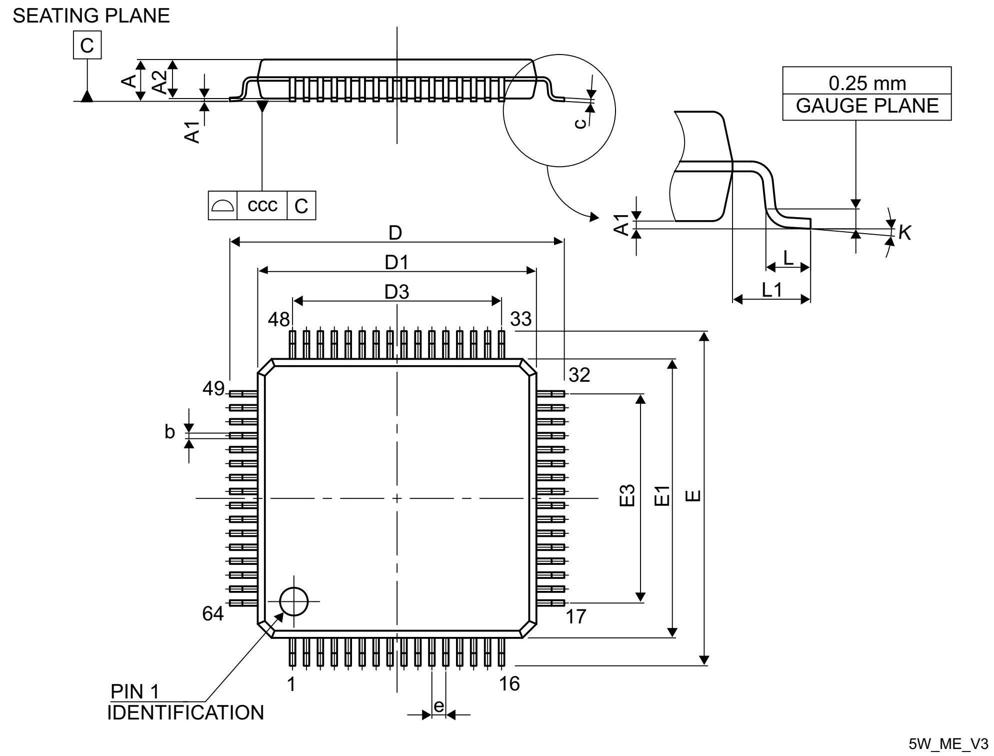


1. Parts marked as ES or E or accompanied by an engineering sample notification letter are not yet qualified and therefore not approved for use in production. ST is not responsible for any consequences resulting from such use. In no event will ST be liable for the customer using any of these engineering samples in production. ST’s Quality department must be contacted prior to any decision to use these engineering samples to run a qualification activity.

6.4 LQFP64 package information

This LQFP is a 64-pin, 10 x 10 mm low-profile quad flat package.

Figure 62. LQFP64 - Outline



1. Drawing is not to scale.

Table 115. LQFP64 - Mechanical data

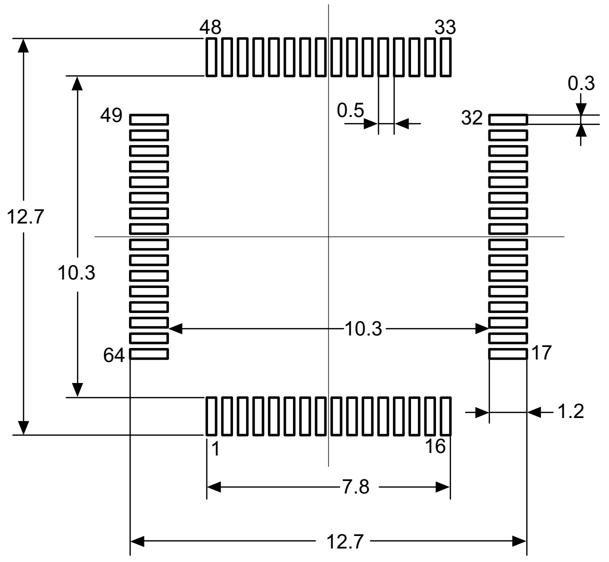
Symbol	millimeters			inches(1)		
	Min	Typ	Max	Min	Typ	Max
A	-	-	1.600	-	-	0.0630
A1	0.050	-	0.150	0.0020	-	0.0059
A2	1.350	1.400	1.450	0.0531	0.0551	0.0571
b	0.170	0.220	0.270	0.0067	0.0087	0.0106
c	0.090	-	0.200	0.0035	-	0.0079
D	-	12.000	-	-	0.4724	-
D1	-	10.000	-	-	0.3937	-
D3	-	7.500	-	-	0.2953	-
E	-	12.000	-	-	0.4724	-
E1	-	10.000	-	-	0.3937	-

Table 115. LQFP64 - Mechanical data (continued)

Symbol	millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
E3	-	7.500	-	-	0.2953	-
e	-	0.500	-	-	0.0197	-
K	0°	3.5°	7°	0°	3.5°	7°
L	0.450	0.600	0.750	0.0177	0.0236	0.0295
L1	-	1.000	-	-	0.0394	-
ccc	-	-	0.080	-	-	0.0031

1. Values in inches are converted from mm and rounded to 4 decimal digits.

Figure 63. LQFP64 - Recommended footprint



1. Dimensions are expressed in millimeters.

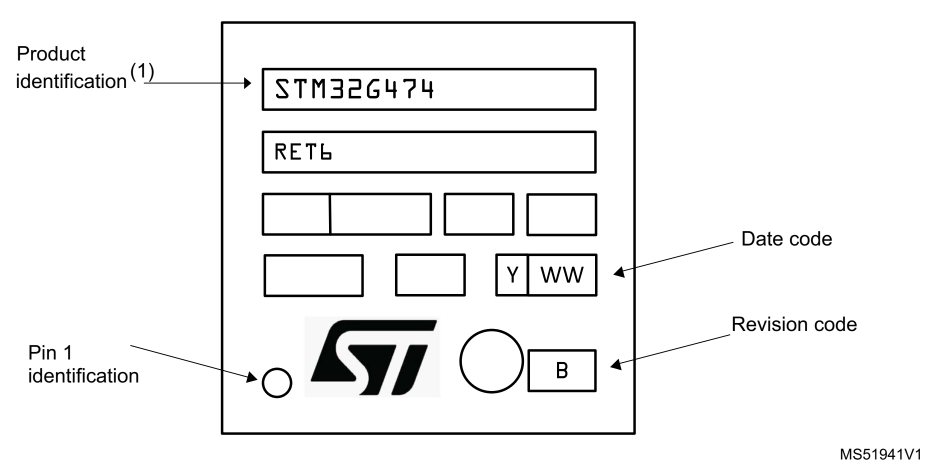
LQFP64 device marking

The following figure gives an example of topside marking orientation versus pin 1 identifier location.

The printed markings may differ depending on the supply chain.

Other optional marking or inset/upset marks, which identify the parts throughout supply chain operations, are not indicated below.

Figure 64. LQFP64 top view example

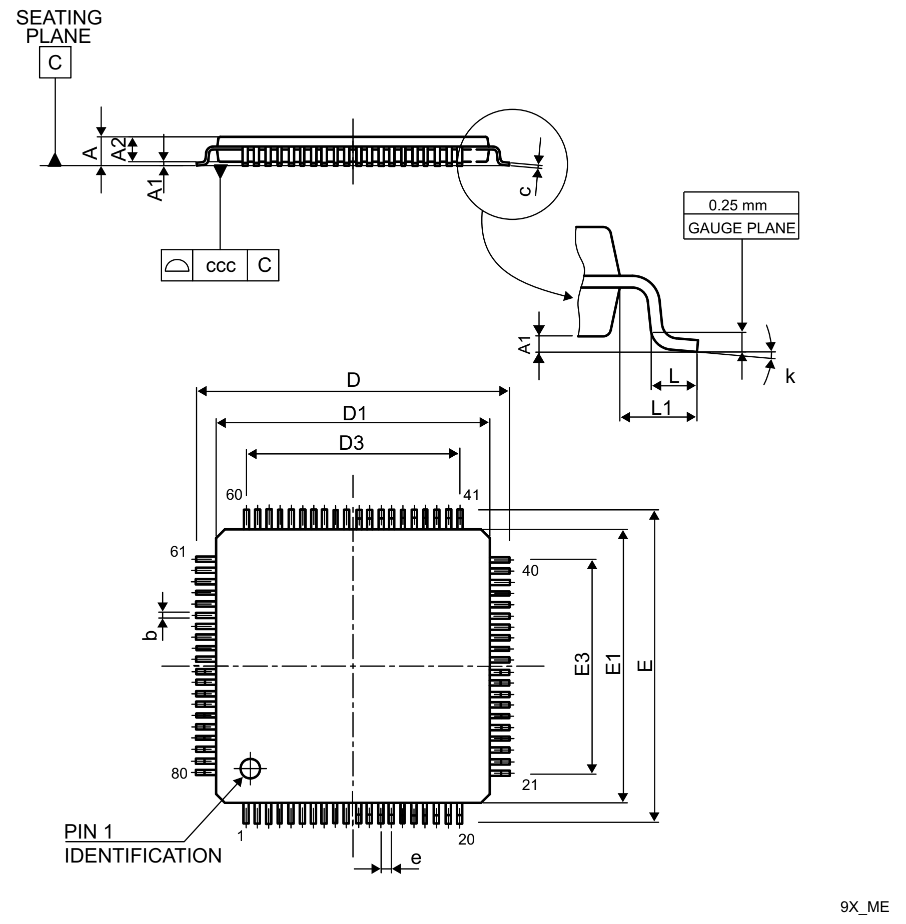


1. Parts marked as ES or E or accompanied by an engineering sample notification letter are not yet qualified and therefore not approved for use in production. ST is not responsible for any consequences resulting from such use. In no event will ST be liable for the customer using any of these engineering samples in production. ST's Quality department must be contacted prior to any decision to use these engineering samples to run a qualification activity.

6.5 LQFP80 package information

This LQFP is a 80-pin, 12 x 12 mm low-profile quad flat package.

Figure 65. LQFP80 - Outline



1. Drawing is not to scale.

Table 116. LQFP80 - Mechanical data

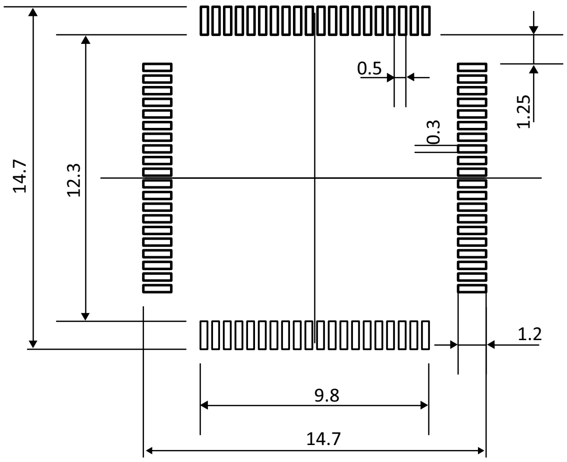
Symbol	Millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
A	-	-	1.600	-	-	0.0630
A1	0.050	-	0.150	0.0020	-	0.0059
A2	1.350	1.400	1.450	0.0531	0.0551	0.0571
b	0.170	0.220	0.270	0.0067	0.0087	0.0106
c	0.090	-	0.200	0.0035	-	0.0079
D	-	14.000	-	-	0.5512	-
D1	-	12.000	-	-	0.4724	-

Table 116. LQFP80 - Mechanical data (continued)

Symbol	Millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
D2	-	9.500	-	-	0.3740	-
E	-	14.000	-	-	0.5512	-
E1	-	12.000	-	-	0.4724	-
E3	-	9.500	-	-	0.3740	-
e	-	0.500	-	-	0.0197	-
L	0.450	0.600	0.750	0.0177	0.0236	0.0295
L1	-	1.000	-	-	0.0394	-
ccc	-	-	0.080	-	-	0.0031
k	0.0°	-	7.0°	0.0°	-	7.0°

1. Values in inches are converted from mm and rounded to 4 decimal digits.

Figure 66. LQFP80 - Recommended footprint



1. Dimensions are expressed in millimeters.

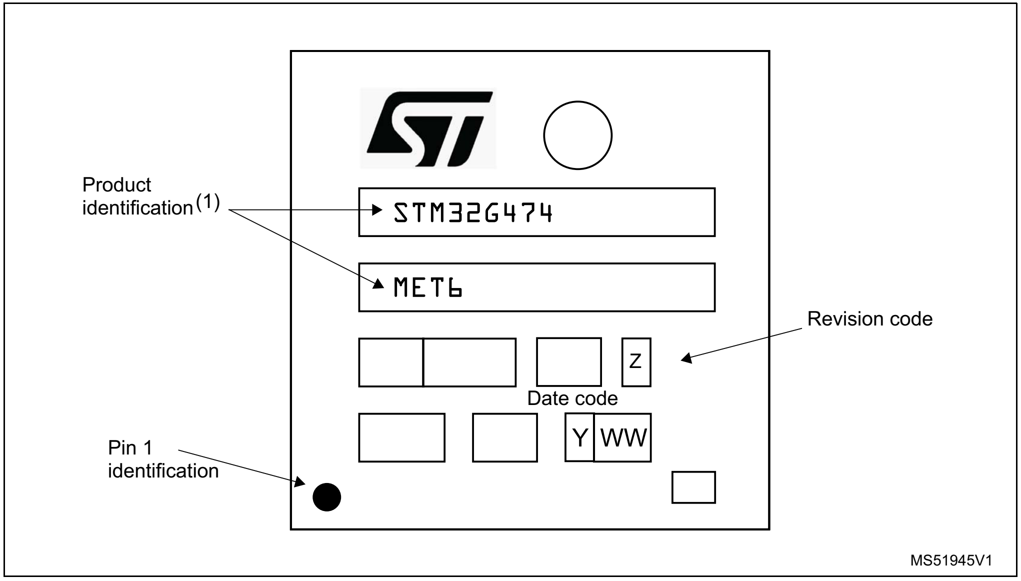
LQFP80 device marking

The following figure gives an example of topside marking orientation versus pin 1 identifier location.

The printed markings may differ depending on the supply chain.

Other optional marking or inset/upset marks, which identify the parts throughout supply chain operations, are not indicated below.

Figure 67. LQFP80 top view example



1. Parts marked as ES or E or accompanied by an engineering sample notification letter are not yet qualified and therefore not approved for use in production. ST is not responsible for any consequences resulting from such use. In no event will ST be liable for the customer using any of these engineering samples in production. ST's Quality department must be contacted prior to any decision to use these engineering samples to run a qualification activity.

6.6 TFBGA100 package information

This TFBGA is a 100-ball, 8 x 8 mm, 0.8 mm pitch fine pitch ball grid array package.

Figure 68. TFBGA100 - Outline

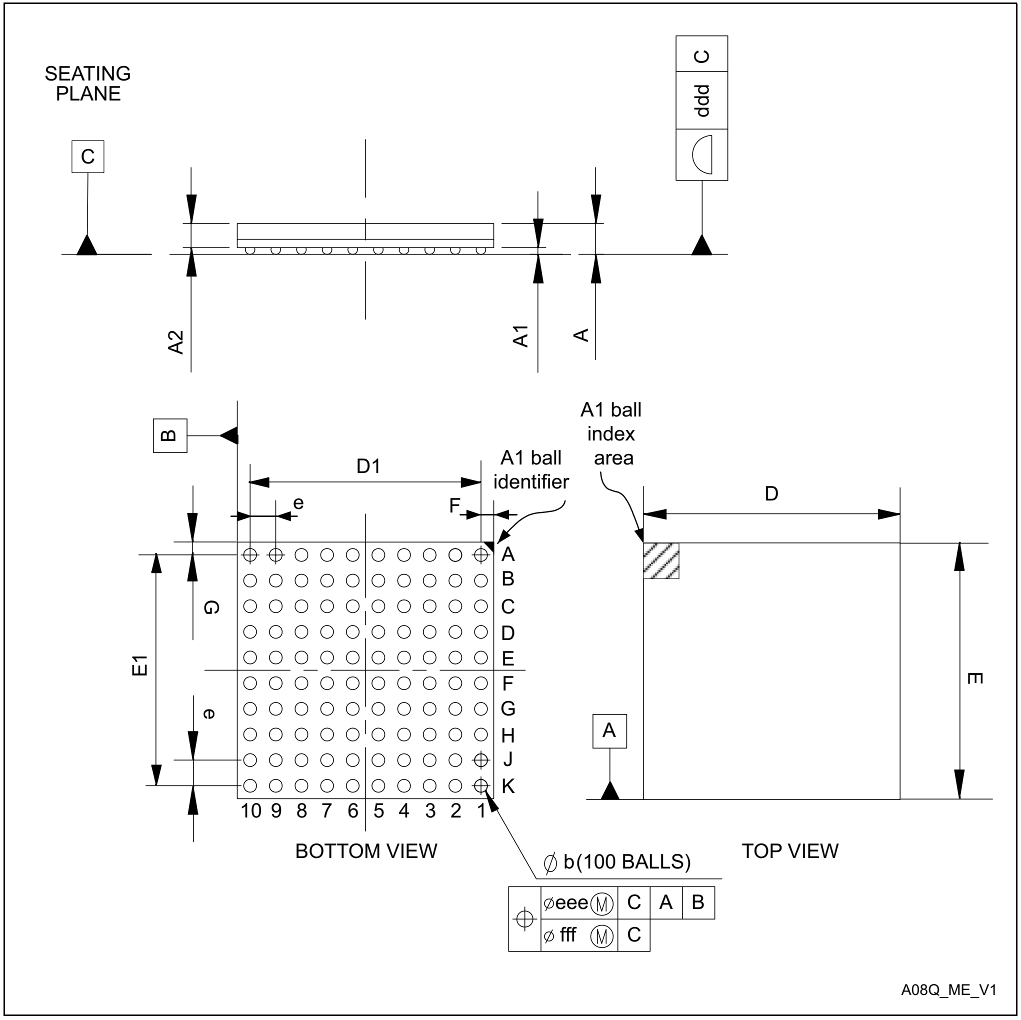


Table 117. TFBGA100 - Mechanical data

Symbol	millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
A	-	-	1.100	-	-	0.0433
A1	0.150	-	-	0.0059	-	-
A2	-	0.760	-	-	0.0299	-
b	0.350	0.400	0.450	0.0138	0.0157	0.0177
D	7.850	8.000	8.150	0.3091	0.3150	0.3209
D1	-	7.200	-	-	0.2835	-
E	7.850	8.000	8.150	0.3091	0.3150	0.3209
E1	-	7.200	-	-	0.2835	-
e	-	0.800	-	-	0.0315	-
F	-	0.400	-	-	0.0157	-
G	-	0.400	-	-	0.0157	-
ddd	-	-	0.100	-	-	0.0039
eee	-	-	0.150	-	-	0.0059
fff	-	-	0.080	-	-	0.0031

1. Values in inches are converted from mm and rounded to 4 decimal digits.

Figure 69. TFBGA100 - recommended footprint

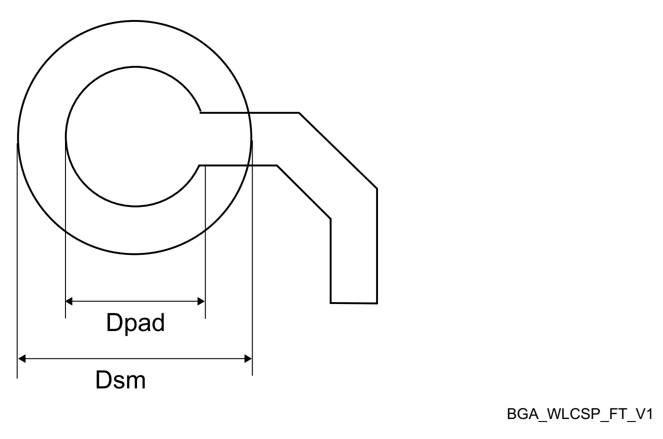


Table 118. TFBGA100 - Recommended PCB design rules

Dimension	Recommended values
Pitch	0.8
Dpad	0.400 mm
Dsm	0.470 mm typ. (depends on the soldermask registration tolerance)

Table 118. TFBGA100 - Recommended PCB design rules (continued)

Dimension	Recommended values
Stencil opening	0.400 mm
Stencil thickness	Between 0.100 mm and 0.125 mm
Pad trace width	0.120 mm

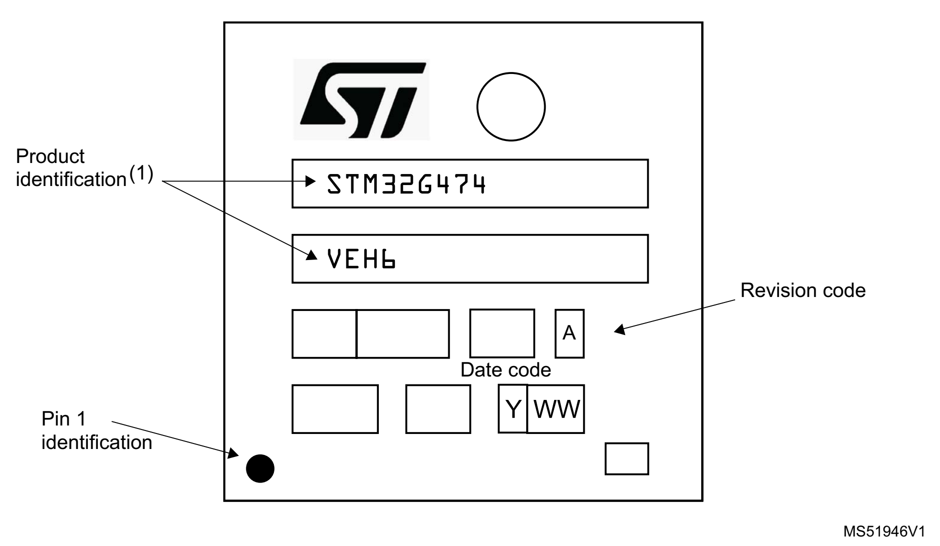
TFBGA100 device marking

The following figure gives an example of topside marking orientation versus pin 1 identifier location.

The printed markings may differ depending on the supply chain.

Other optional marking or inset/upset marks, which identify the parts throughout supply chain operations, are not indicated below.

Figure 70. TFBGA100 - Top view example

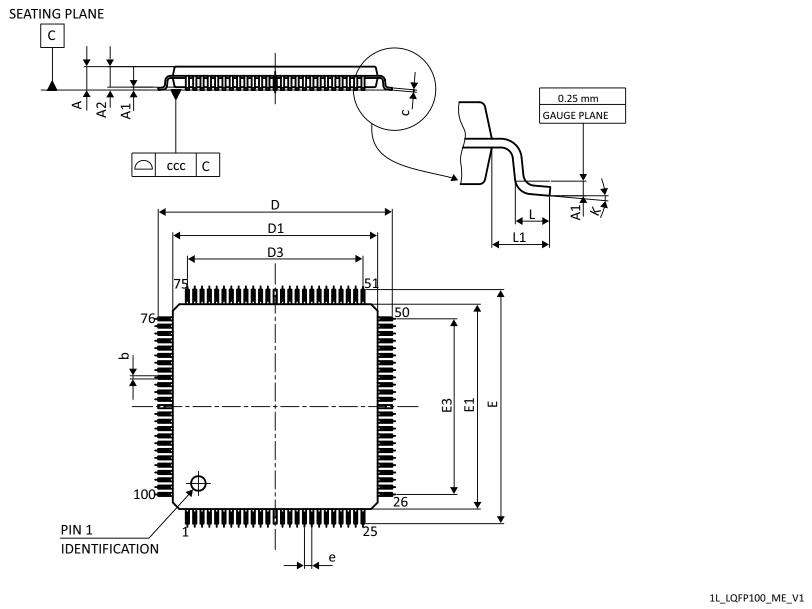


1. Parts marked as ES or E or accompanied by an engineering sample notification letter are not yet qualified and therefore not approved for use in production. ST is not responsible for any consequences resulting from such use. In no event will ST be liable for the customer using any of these engineering samples in production. ST's Quality department must be contacted prior to any decision to use these engineering samples to run a qualification activity.

6.7 LQFP100 package information

This LQFP is a 100-pin, 14 x 14 mm low-profile quad flat package.

Figure 71. LQFP100 - Outline



1. Drawing is not to scale.

Table 119. LQPF100 - Mechanical data

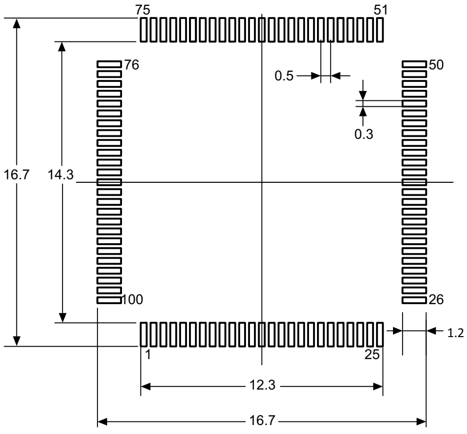
Symbol	millimeters			inches(1)		
	Min	Typ	Max	Min	Typ	Max
A	-	-	1.600	-	-	0.0630
A1	0.050	-	0.150	0.0020	-	0.0059
A2	1.350	1.400	1.450	0.0531	0.0551	0.0571
b	0.170	0.220	0.270	0.0067	0.0087	0.0106
c	0.090	-	0.200	0.0035	-	0.0079
D	15.800	16.000	16.200	0.6220	0.6299	0.6378
D1	13.800	14.000	14.200	0.5433	0.5512	0.5591
D3	-	12.000	-	-	0.4724	-
E	15.800	16.000	16.200	0.6220	0.6299	0.6378
E1	13.800	14.000	14.200	0.5433	0.5512	0.5591
E3	-	12.000	-	-	0.4724	-
e	-	0.500	-	-	0.0197	-
L	0.450	0.600	0.750	0.0177	0.0236	0.0295
L1	-	1.000	-	-	0.0394	-

Table 119. LQPF100 - Mechanical data (continued)

Symbol	millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
k	0.0°	3.5°	7.0°	0.0°	3.5°	7.0°
ccc	-	-	0.080	-	-	0.0031

1. Values in inches are converted from mm and rounded to 4 decimal digits.

Figure 72. LQFP100 - Recommended footprint



1L_LQFP100_FP_V1

1. Dimensions are expressed in millimeters.

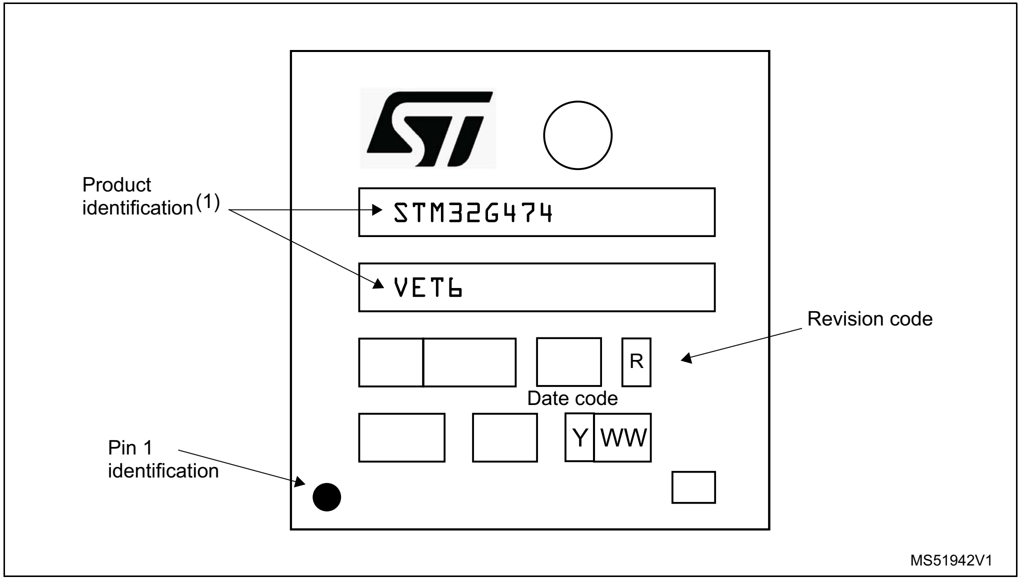
LQFP100 device marking

The following figure gives an example of topside marking orientation versus pin 1 identifier location.

The printed markings may differ depending on the supply chain.

Other optional marking or inset/upset marks, which identify the parts throughout supply chain operations, are not indicated below.

Figure 73. LQFP100 top view example

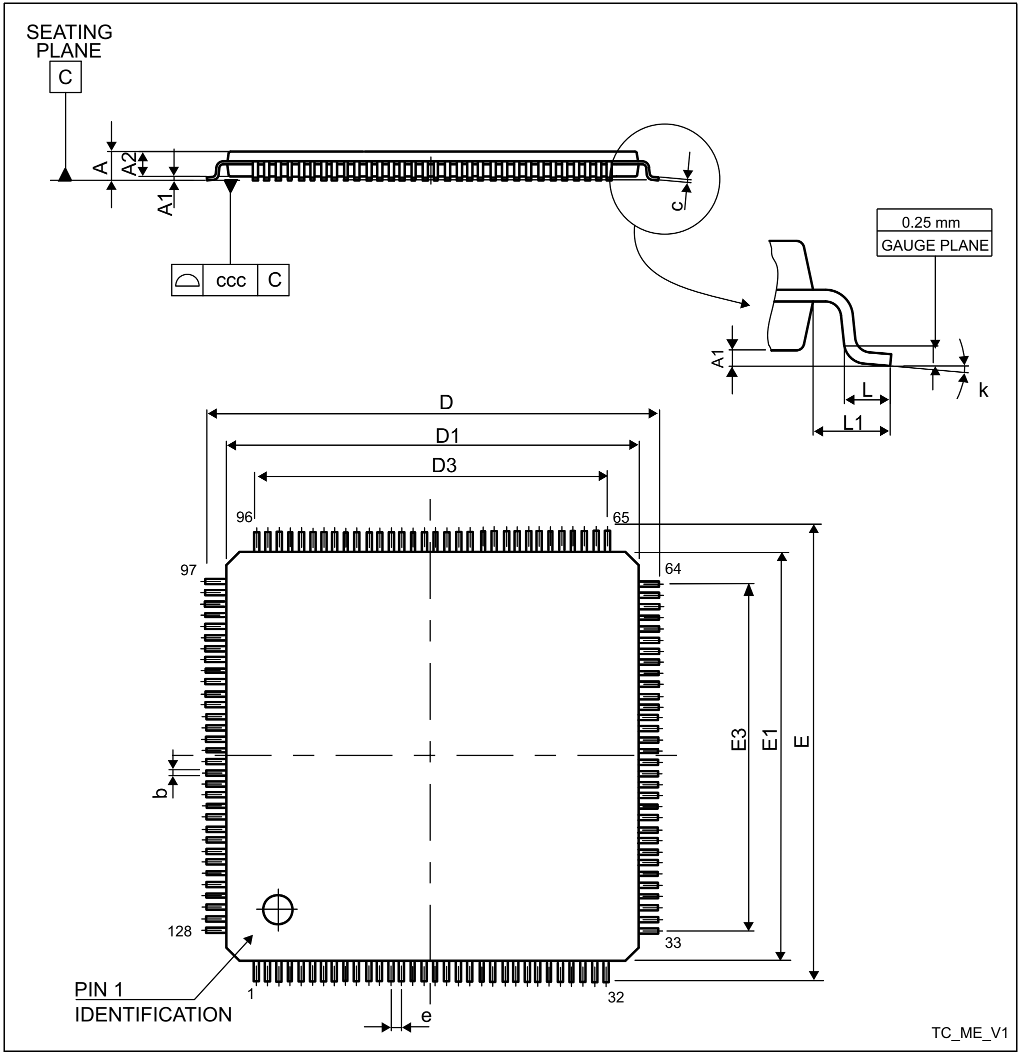


1. Parts marked as ES or E or accompanied by an engineering sample notification letter are not yet qualified and therefore not approved for use in production. ST is not responsible for any consequences resulting from such use. In no event will ST be liable for the customer using any of these engineering samples in production. ST’s Quality department must be contacted prior to any decision to use these engineering samples to run a qualification activity.

6.8 LQFP128 package information

This LQFP is a 128-pin, 14 x 14 mm low-profile quad flat package.

Figure 74. LQFP128 - Outline



1. Drawing is not to scale.

Table 120. LQFP128 - Mechanical data

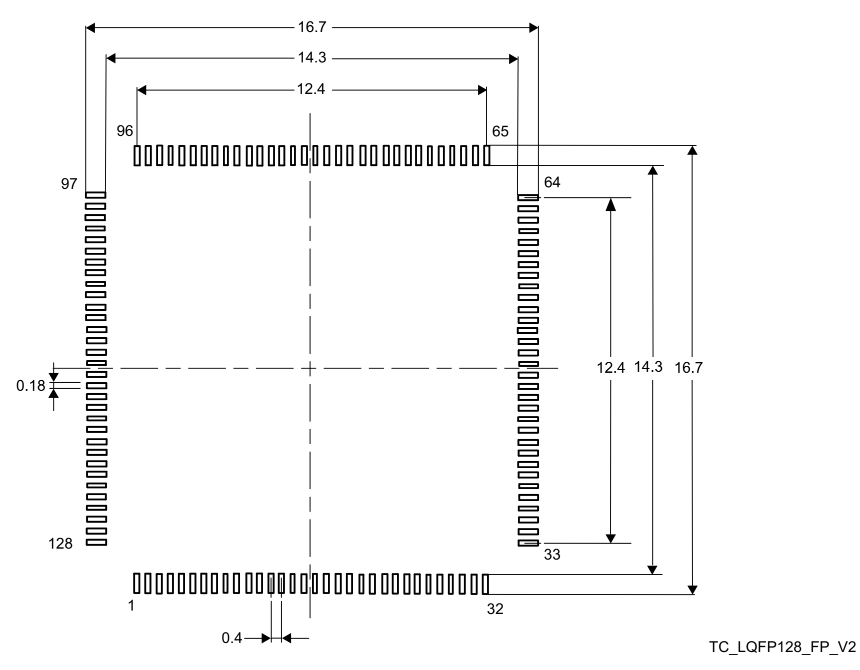
Symbol	Millimeters			Inches[1]		
	Min.	Typ.	Max.	Min.	Typ.	Max.
A	-	-	1.600	-	-	0.0630
A1	0.050	-	0.150	0.0020	-	0.0059
A2	1.350	1.400	1.450	0.0531	0.0551	0.0571
b	0.130	0.180	0.230	0.0051	0.0071	0.0091

Table 120. LQFP128 - Mechanical data (continued)

Symbol	Millimeters			Inches[1]		
	Min.	Typ.	Max.	Min.	Typ.	Max.
c	0.090	-	0.200	0.0035	-	0.0079
D	15.800	16.000	16.200	0.6220	0.6299	0.6378
D1	13.800	14.000	14.200	0.5433	0.5512	0.5591
D3	-	12.400	-	-	0.4882	-
E	15.800	16.000	16.200	0.6220	0.6299	0.6378
E1	13.800	14.000	14.200	0.5433	0.5512	0.5591
E3	-	12.400	-	-	0.4882	-
e	-	0.400	-	-	0.0157	-
L	0.450	0.600	0.750	0.0177	0.0236	0.0295
L1	-	1.000	-	-	0.0394	-
k	0°	3.5°	7°	0°	3.5°	7°
ccc	-	-	0.080	-	-	0.0031

1. Values in inches are converted from mm and rounded to 4 decimal digits.

Figure 75. LQFP128 - Recommended footprint



1. Dimensions are expressed in millimeters.

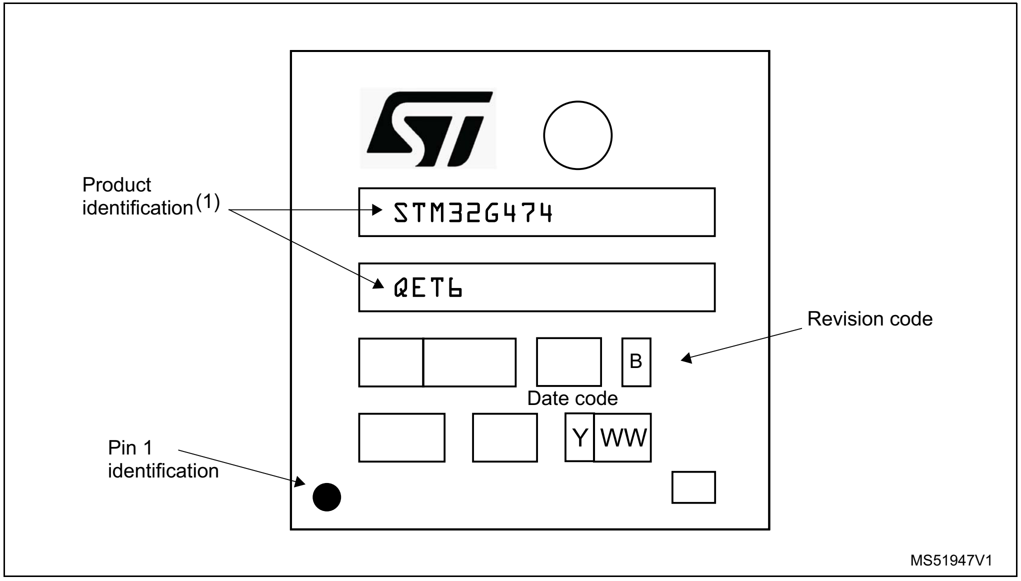
LQFP128 device marking

The following figure gives an example of topside marking orientation versus pin 1 identifier location.

The printed markings may differ depending on the supply chain.

Other optional marking or inset/upset marks, which identify the parts throughout supply chain operations, are not indicated below.

Figure 76. LQFP128 top view example

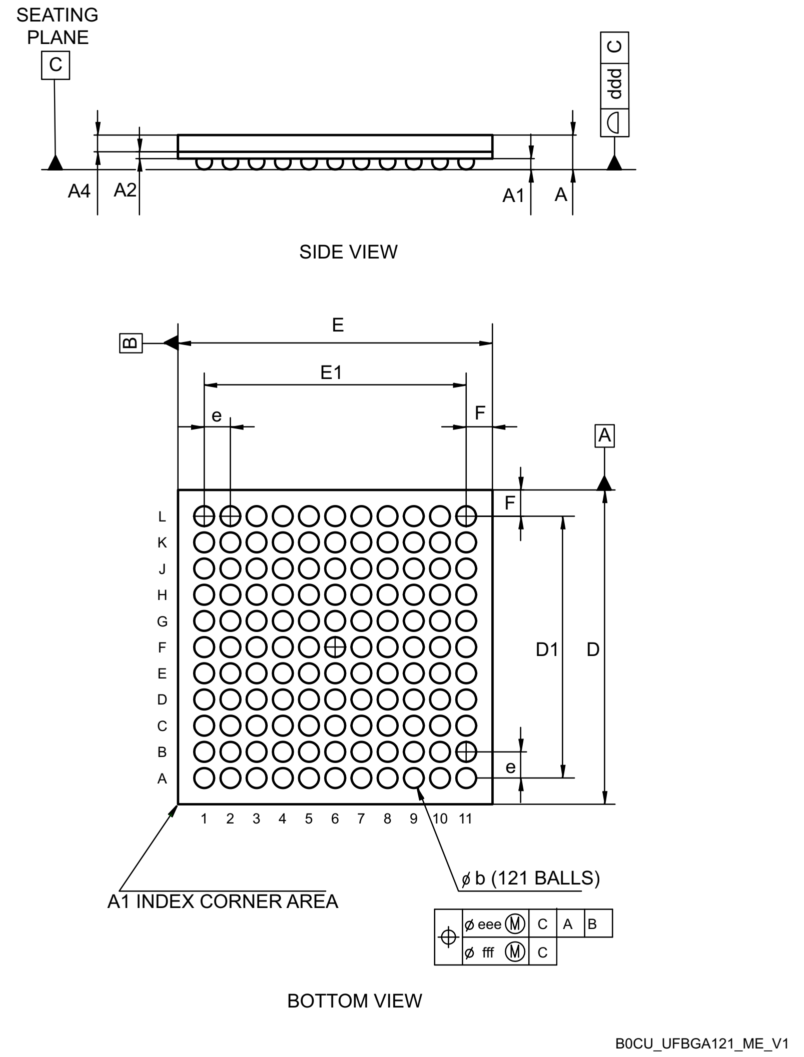


1. Parts marked as ES or E or accompanied by an engineering sample notification letter are not yet qualified and therefore not approved for use in production. ST is not responsible for any consequences resulting from such use. In no event will ST be liable for the customer using any of these engineering samples in production. ST's Quality department must be contacted prior to any decision to use these engineering samples to run a qualification activity.

6.9 UFBGA121 package information

This UFBGA is a 121 balls, 6 x 6 mm, 0.5 mm pitch, fine pitch, square ball grid array package.

Figure 77. UFBGA121 - Outline



1. Drawing is not to scale.
2. The terminal A1 corner must be identified on the top surface by using a corner chamfer, ink or metalized markings, or other feature of package body or integral heat slug.
A distinguishing feature is allowable on the bottom surface of the package to identify the terminal A1 corner. Exact shape of each corner is optional.

Table 121. UFBGA121 - Mechanical data

Symbol	millimeters			inches[1]		
	Min	Typ	Max	Min	Typ	Max
A[2]	-	-	0.60	-	-	0.0236
A1	-	-	0.11	-	-	0.0043
A2	-	0.13	-	-	0.0051	-
A4	-	0.32	-	-	0.0126	-
b[3]	0.24	0.29	0.34	0.0094	0.0114	0.0134
D	5.85	6.00	6.15	0.2303	0.2362	0.2421
D1	-	5.00	-	-	0.1969	-
E	5.85	6.00	6.15	0.2303	0.2362	0.2421
E1	-	5.00	-	-	0.1969	-
e	-	0.50	-	-	0.0197	-
F	-	0.50	-	-	0.0197	-
ddd	-	-	0.08	-	-	0.0031
eee[4]	-	-	0.15	-	-	0.0059
fff[5]	-	-	0.05	-	-	0.0020

1. Values in inches are converted from mm and rounded to 4 decimal digits.
2. - UFBGA stands for Ultra-Thin Profile Fine Pitch Ball Grid Array.
   - Ultra Thin profile: $0.50 < A \leq 0.65$mm / Fine pitch: $e < 1.00$mm pitch.
   - The total profile height (Dim A) is measured from the seating plane to the top of the component
   - The maximum total package height is calculated by the following methodology:
   A Max = A1 Typ + A2 Typ + A4 Typ + $\sqrt{}$ ($A1^2+A2^2+A4^2$ tolerance values)
3. The typical balls diameters before mounting is 0.20 mm
4. The tolerance of position that controls the location of the pattern of balls with respect to datum A and B. For each ball there is a cylindrical tolerance zone eee perpendicular to datum C and located on true position with respect
   to datum A and B as defined by e. The axis perpendicular to datum C of each ball must lie within this tolerance zone.
5. The tolerance of position that controls the location of the balls within the matrix with respect to each other. For each ball there is a cylindrical tolerance zone fff perpendicular to datum C and located on true position as defined by e. The axis perpendicular to datumC of each ball must lie within this tolerance zone.
   Each tolerance zone fff in the array is contained entirely in the respective zone eee above. The axis of each ball must lie simultaneously in both tolerance zones.

Figure 78. UFBGA121 - Recommended footprint

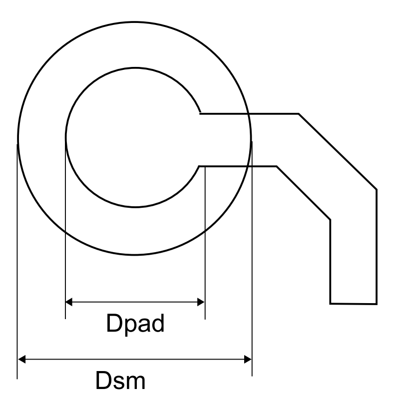


Table 122. UFBGA121 - Recommended PCB design rules

Dimension	Recommended values
Pitch	0.5 mm
Dpad	0,225 mm
Dsm	0.290 mm typ. (depends on soldermask registration tolerance)
Stencil opening	0.250 mm
Stencil thickness	0.100 mm

6.10 Thermal characteristics

The maximum chip-junction temperature, T_J max, in degrees Celsius, may be calculated using the following equation:

T_J max = T_A max + (P_D max x Θ_{JA})

Where:

- T_A max is the maximum ambient temperature in °C,
- Θ_{JA} is the package junction-to-ambient thermal resistance, in °C/W,
- P_D max is the sum of P_{INT} max and $P_{I/O}$ max (P_D max = P_{INT} max + $P_{I/O}$max),
- P_{INT} max is the product of I_{DD} and V_{DD}, expressed in Watts. This is the maximum chip internal power.

$P_{I/O}$ max represents the maximum power dissipation on output pins where:

$P_{I/O}$ max = $\Sigma (V_{OL} \times I_{OL}) + \Sigma ((V_{DDIOx} - V_{OH}) \times I_{OH})$,

taking into account the actual V_{OL} / I_{OL} and V_{OH} / I_{OH} of the I/Os at low and high level in the application.

Table 123. Package thermal characteristics

Symbol	Parameter	Value	Unit
Θ_{JA}	**Thermal resistance junction-ambient** LQFP128 - 14 × 14 mm	43.0	°C/W
	Thermal resistance junction-ambient LQFP100 - 14 × 14 mm	46.2	
	Thermal resistance junction-ambient LQFP80 - 12 × 12 mm	46.8	
	Thermal resistance junction-ambient LQFP64 - 10 × 10 mm	47.9	
	Thermal resistance junction-ambient LQFP48 - 7 × 7 mm	55.2	
	Thermal resistance junction-ambient TFBGA100 - 8 × 8 mm	30.8	
	Thermal resistance junction-ambient UFBGA121 - 6 × 6 mm	TBD	
	Thermal resistance junction-ambient UFQFPN48 - 7 × 7 mm	26.8	
	Thermal resistance junction-ambient WLCSP81 - 4.02 X 4.27 mm	45	

Table 123. Package thermal characteristics (continued)

Symbol	Parameter	Value	Unit
Θ_{JC}	**Thermal resistance junction-case** LQFP128 - 14 × 14 mm	7.0	°C/W
	Thermal resistance junction-case LQFP100 - 14 × 14 mm	8.3	
	Thermal resistance junction-case LQFP80 - 12 × 12 mm	8.2	
	Thermal resistance junction-case LQFP64 - 10 × 10 mm	8.0	
	Thermal resistance junction-case LQFP48 - 7 × 7 mm	9.6	
	Thermal resistance junction-case TFBGA100 - 8 × 8 mm	13	
	Thermal resistance junction-ambient UFBGA121 - 6 × 6 mm	TBD	
	Thermal resistance junction-case UFQFPN48 - 7 × 7 mm	2(1) 7.5	
	Thermal resistance junction-case WLCSP81 - 4.02 X 4.27 mm	1.46	
Θ_{JB}	**Thermal resistance junction-board** LQFP128 - 14 × 14 mm	19.9	°C/W
	Thermal resistance junction-board LQFP100 - 14 × 14 mm	22.9	
	Thermal resistance junction-board LQFP80 - 12 × 12 mm	22.3	
	Thermal resistance junction-board LQFP64 - 10 × 10 mm	21.8	
	Thermal resistance junction-board LQFP48 - 7 × 7 mm	24.3	
	Thermal resistance junction-board TFBGA100 - 8 × 8 mm	13.42	
	Thermal resistance junction-ambient UFBGA121 - 6 × 6 mm	TBD	
	Thermal resistance junction-board UFQFPN48 - 7 × 7 mm	11	
	Thermal resistance junction-board WLCSP81 - 4.02 X 4.27 mm	27.45	

1. Thermal resistance junction-case where the case is the bottom thermal pad on the UFQFPN package.

6.10.1 Reference document

JESD51-2 Integrated Circuits Thermal Test Method Environment Conditions - Natural Convection (Still Air). Available from www.jedec.org

6.10.2 Selecting the product temperature range

When ordering the microcontroller, the temperature range is specified in the ordering information scheme shown in *Section 7: Ordering information*.

Each temperature range suffix corresponds to a specific guaranteed ambient temperature at maximum dissipation and, to a specific maximum junction temperature.

As applications do not commonly use the STM32G474xE at maximum dissipation, it is useful to calculate the exact power consumption and junction temperature to determine which temperature range is best suited to the application.

The following examples show how to calculate the temperature range needed for a given application.

Example 1: High-performance application

Assuming the following application conditions:

Maximum ambient temperature T_{Amax} = 82 °C (measured according to JESD51-2), I_{DDmax} = 50 mA, V_{DD} = 3.5 V, maximum 20 I/Os used at the same time in output at low level with I_{OL} = 8 mA, V_{OL}= 0.4 V and maximum 8 I/Os used at the same time in output at low level with I_{OL} = 20 mA, V_{OL}= 1.3 V

$P_{INTmax} =$ 50 mA × 3.5 V= 175 mW

$P_{IOmax} =$ 20 × 8 mA × 0.4 V + 8 × 20 mA × 1.3 V = 272 mW

This gives: P_{INTmax} = 175 mW and P_{IOmax} = 272 mW:

$P_{Dmax} =$ 175 + 272 = 447 mW

Using the values obtained in T_{Jmax} is calculated as follows:

– For LQFP100, 42 °C/W

T_{Jmax} = 82 °C + (42 °C/W × 447 mW) = 82 °C + 18.774 °C = 100.774 °C

This is within the range of the suffix 6 version parts (–40 < T_J < 105 °C) see *Section 7: Ordering information*.

In this case, parts must be ordered at least with the temperature range suffix 6 (see *Section 7: Ordering information*).

Note: *With this given P_{Dmax} we can find the TAmax allowed for a given device temperature range (order code suffix 6 or 7).*

Suffix 6: T_{Amax} = T_{Jmax} - (42°C/W × 447 mW) = 105-18.774 = 86.226 °C

Suffix 3: T_{Amax} = T_{Jmax} - (42°C/W × 447 mW) = 130-18.774 = 111.226 °C

Example 2: High-temperature application

Using the same rules, it is possible to address applications that run at high ambient temperatures with a low dissipation, as long as junction temperature T_J remains within the specified range.

Assuming the following application conditions:

Maximum ambient temperature T_{Amax} = 100 °C (measured according to JESD51-2), I_{DDmax} = 20 mA, V_{DD} = 3.5 V, maximum 20 I/Os used at the same time in output at low level with I_{OL} = 8 mA, V_{OL}= 0.4 V

$P_{INTmax\ =}$ 20 mA × 3.5 V= 70 mW

$P_{IOmax\ =\ 20}$ × 8 mA × 0.4 V = 64 mW

This gives: P_{INTmax} = 70 mW and P_{IOmax} = 64 mW:

$P_{Dmax\ =}$ 70 $_{+}$ 64 = 134 mW

Thus: P_{Dmax} = 134 mW

Using the values obtained in T_{Jmax} is calculated as follows:

- For LQFP100, 42 °C/W

T_{Jmax} = 100 °C + (42 °C/W × 134 mW) = 100 °C + 5.628 °C = 105.628 °C

This is above the range of the suffix 6 version parts (–40 < T_J < 105 °C).

In this case, parts must be ordered at least with the temperature range suffix 3 (see *Section 7: Ordering information*) unless we reduce the power dissipation in order to be able to use suffix 6 parts.

7 Ordering information

Table 124. Ordering information

Example: STM32 G 474 V E T 6 x

Device family

STM32 = Arm-based 32-bit microcontroller

Product type

G = General-purpose

Sub-family

474 = STM32G474xB/xC/xE

Pin count

C = 48 pins
R = 64 pins
M = 80 pins, 81 pins
V = 100 pins
P = 121 pins
Q = 128 pins

Code size

B = 128 Kbytes
C = 256 Kbytes
E = 512 Kbytes

Package

H = TFBGA
I = UFBGA
T = LQFP
U = UFQFPN
Y = WLCSP

Temperature range

6 = Industrial temperature range, - 40 to 85 °C (105 °C junction)
3 = Industrial temperature range, - 40 to 125 °C (130 °C junction)

Options

xxx = programmed parts
TR = tape and reel

For a list of available options (memory, package, and so on) or for further information on any aspect of this device, contact the nearest ST sales office.

8 Revision history

Table 125. Document revision history

Date	Revision	Changes
15-May-2019	1	Initial release.
01-Oct-2019	2	Updated: – *Section 2: Description*, *Section 3.5: Embedded SRAM*, – *Table 2: STM32G474xB/xC/xE features and peripheral counts*, *Table 17: General operating conditions*, *Table 35: Peripheral current consumption*, *Table 66: ADC characteristics*, *Table 67: Maximum ADC RAIN*, *Table 89: SPI characteristics*, *Table 123: Package thermal characteristics*, *Table 124: Ordering information* Added: *Table 71: ADC accuracy (Multiple ADCs operation) - limited test conditions 1*, *Table 73: ADC accuracy (Multiple ADCs operation) - limited test conditions 3*, *Table 73: ADC accuracy (Multiple ADCs operation) - limited test conditions 3*
24-Apr-2020	3	Updated: – *Section 2: Description*, – *Table 2: STM32G474xB/xC/xE features and peripheral counts*, – *Table 12: STM32G474xB/xC/xE pin definition* – *Table 124: Ordering information* – Added: – *Section 4.9: UFBGA121 pinout description*, – *Section 6.9: UFBGA121 package information*:
03-Jun-2020	4	Updated: – *Table 2: STM32G474xB/xC/xE features and peripheral counts*, – *Table 36: Low-power mode wakeup timings* – *Section 3.5: Embedded SRAM* Deleted: – Table 23: Current consumption in Run and Low-power run modes, code with data processing running from Flash in single bank, ART disable – Table 24: Current consumption in Run and Low-power run modes, code with data processing running from Flash in dual bank, ART disable – Table 27: Typical current consumption in Run and Low-power run modes, with different codes running from Flash, ART disable

Table 125. Document revision history (continued)

Date	Revision	Changes
23-Oct-2020	5	Updated: – *Table 1: Device summary* – *Section 3.18: Analog-to-digital converter (ADC)* – *Table 2: STM32G474xB/xC/xE features and peripheral counts* – *Table 21: Current consumption in Run and Low-power run modes, code with data processing running from Flash in single Bank, ART enable (Cache ON Prefetch OFF)* – *Table 22: Current consumption in Run and Low-power run modes, code with data processing running from Flash in dual bank, ART enable (Cache ON Prefetch OFF)* – *Table 23: Current consumption in Run and Low-power run modes, code with data processing running from SRAM1* – *Table 28: Current consumption in Sleep and Low-power sleep mode Flash ON* – *Table 29: Current consumption in low-power sleep modes, Flash in power-down* – *Table 30: Current consumption in Stop 1 mode* – *Table 31: Current consumption in Stop 0 mode* – *Table 32: Current consumption in Standby mode* – *Table 51: ESD absolute maximum ratings* – *Table 76: DAC 15MSPS characteristics* – *Table 79: COMP characteristics* – *Table 80: OPAMP characteristics* – *Table 84: TIMx characteristics* – *Table 89: SPI characteristics* – *Table 90: I2S characteristics* – *Table 109: QUADSPI characteristics in DDR mode* – *Table 121: UFBGA121 - Mechanical data* – *Table 122: UFBGA121 - Recommended PCB design rules* – *Table 123: Package thermal characteristics* – *Table 124: Ordering information* – *Figure 77: UFBGA121 - Outline* – *Figure 78: UFBGA121 - Recommended footprint* Added: – *Figure 75: LQFP128 - Recommended footprint*

Table 125. Document revision history (continued)

Date	Revision	Changes
16-Nov-2021	6	Updated: – *Features* – *Section 2: Description* – *Section 3.4: Embedded Flash memory* – *Section 3.11.1: Power supply schemes* – *Table 5: Temperature sensor calibration values* – *Table 12: STM32G474xB/xC/xE pin definition* – *Figure 28: ADC accuracy characteristics* – *Figure 29: Typical connection diagram when using the ADC with FT/TT pins featuring analog switch function* – *Table 17: General operating conditions* – *Table 30: Current consumption in Stop 1 mode* – *Table 31: Current consumption in Stop 0 mode* – *Table 32: Current consumption in Standby mode* – *Section 5.3.14: I/O port characteristics* – *Table 68: ADC accuracy - limited test conditions 1* – *Table 69: ADC accuracy - limited test conditions 2* – *Table 70: ADC accuracy - limited test conditions 3* – *Figure 75: LQFP128 - Recommended footprint*

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