# How to calibrate internal RC oscillators on STM32H5 MCUs

## Introduction

The STM32H5 series microcontrollers embed two internal RC oscillators that can be selected as the system clock source. These are known as HSI (high-speed internal) and CSI (low-power internal) oscillators.

The HSI oscillator provides a clock up to 64 MHz. The CSI oscillator is a low-power clock source.

There are two secondary internal clock sources:

- LSI: 32 kHz (low-speed internal)
- HSI48: 48 MHz (high-speed internal), which can drive the USB FS and the RNG (random number generator).

The operating temperature has an impact on the accuracy of the oscillators. At 30 °C, the HSI accuracy is ±0.4%, the MSI accuracy is ±1%, and the HSI48 accuracy is ±4%. In the temperature range of -40 °C to 125 °C, the accuracy decreases. To compensate for the influence of temperature on accuracy, STM32H5 devices include built-in features to calibrate the HSI, CSI, and HSI48 oscillators and to measure the LSI oscillator frequency.

This document describes how to calibrate the HSI, CSI, and HSI48 oscillators, with the following methods:

- Finding the frequency with the minimum error
- Finding the maximum allowed frequency error
- Implementing a table of premeasured values and then searching in it for the appropriate change

The measurement of the LSI oscillator is performed by connecting it to a timer input capture.

# 1 STM32H5 system clock

The STM32H5 devices have different sources that can be used to drive the system clock:
- HSI: high-speed internal up to 64 MHz RC oscillator clock
- HSE: 4 to 50 MHz high-speed external oscillator clock
- CSI: low power internal RC oscillator clock
- PLL: 1 MHz to 250 MHz phase-locked loop clocked by HSI, CSI, or HSE oscillators.

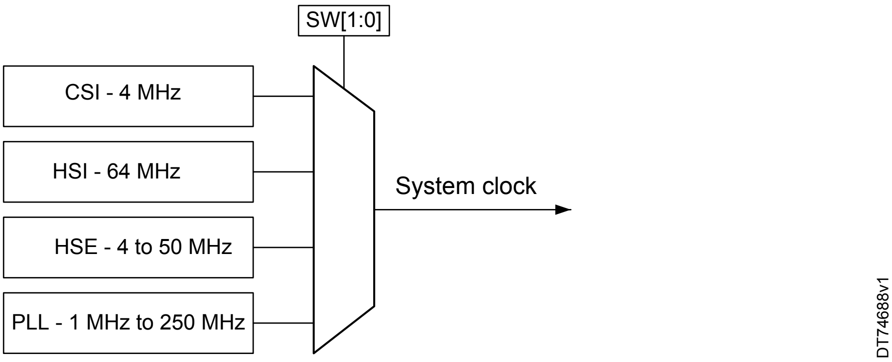
The HSI oscillator has a typical frequency of 64 MHz and consumes 300 µA.

The CSI is a low power RC oscillator that can serve as a system clock, peripheral clock, or PLL input. It provides a clock frequency of about 4 MHz. It offers advantages such as low cost, faster startup time compared to HSE, and very low power consumption.

The HSI48 clock signal is generated from an internal 48 MHz RC oscillator and can be used directly for USB, RNG.

The internal RC oscillators (HSI, CSI and HSI48) provide a low-cost clock source (no external components required). They also have a faster startup time and a lower power consumption than an external oscillator, and can be calibrated to improve their accuracy. However, even with calibration, their frequency is less accurate than the frequency of an external crystal oscillator or a ceramic resonator (tens of ppm).

**Figure 1. Simplified clock tree**




The STM32H5 devices also embed the following secondary clock sources (that cannot be used as system clock):
- LSI: 32 kHz low-speed internal RC that can be kept running in Stop and Standby modes for the IDWG (independent watchdog), the RTC and the LCD. The LSI oscillator cannot be calibrated, but it can be measured to evaluate any frequency deviations (due to temperature and voltage changes).
- LSE crystal: 32.768 kHz low-speed external crystal RC that optionally drives the RTC (real time clock)
- HSI48: 48 MHz high-speed internal RC that is designed to provide a high-precision clock to the USB peripheral by means of a special CRS (clock recovery system) circuitry. It can also drive RNG.

# 2 Internal RC oscillator calibration

The frequency of the internal RC oscillators may vary from one device to another due to manufacturing process variations. For this reason, the CSI and the HSI RC oscillators are factory-calibrated at $T_A$ = 30 °C. After reset, the factory calibration value is automatically loaded in the internal calibration bits.

The frequency can be fine-tuned to achieve better accuracy with wider temperature and supply voltage ranges. The trimming bits are used for this purpose.

For the HSI oscillator, the calibration value is loaded in HSICAL[11:0] after reset. Seven trimming bits in HSITRIM[6:0] are used for fine-tuning. The default trimming value is 64. An increase/decrease in this trimming value causes an increase/decrease in the HSI frequency. The HSI oscillator is fine-tuned by steps of 0.24%, as follows:

- a trimming value in the range of 65 to 127 increases the HSI frequency.
- a trimming value in the range of 0 to 63 decreases the HSI frequency.
- a trimming value equal to 64 does not change the default value.

The figure below shows an HSI oscillator behavior versus calibration value. The HSI oscillator frequency increases with the calibration value (calibration value = default HSICAL[11:0] + HSITRIM[6:0]).

For more details about the trimming step value, refer to the datasheet.

For the CSI oscillator, the calibration value is loaded in CSICAL[7:0] after reset. Five trimming bits in CSITRIM[5:0] are used for fine-tuning. The default trimming value is 32. An increase/decrease in this trimming value causes an increase/decrease in the CSI frequency. The CSI oscillator is fine-tuned by steps of 0.4%, as follows:

- a trimming value in the range of 17 to 31 increases the CSI frequency
- a trimming value in the range of 0 to 31 decreases the CSI frequency
- a trimming value equal to 32 does not change the default value.

The CSI oscillator frequency increases with the calibration value (calibration value = default CSICAL[7:0] + CSITRIM[5:0]).

For more details about the trimming step value, refer to the datasheet.

For the HSI48 oscillator, the calibration value is loaded in HSI48CAL[9:0] after reset. Six trimming bits TRIM[5:0] (in CRS_CR register) are used for fine-tuning. The default trimming value is 32. An increase/decrease in this trimming value causes an increase/decrease of the HSI48 frequency.

The HSI48 oscillator is fine-tuned in steps of 0.17%, as follows:

- a trimming value, in the range of 33 to 63, increases the HSI48 frequency.
- a trimming value, in the range of 0 to 31, decreases the HSI48 frequency.
- a trimming value equal to 32 does not change the default value.

The HSI48 oscillator frequency increases with the calibration value (calibration value = default HSI48CAL[9:0] + TRIM[5:0]).

## 2.1 Calibration principle

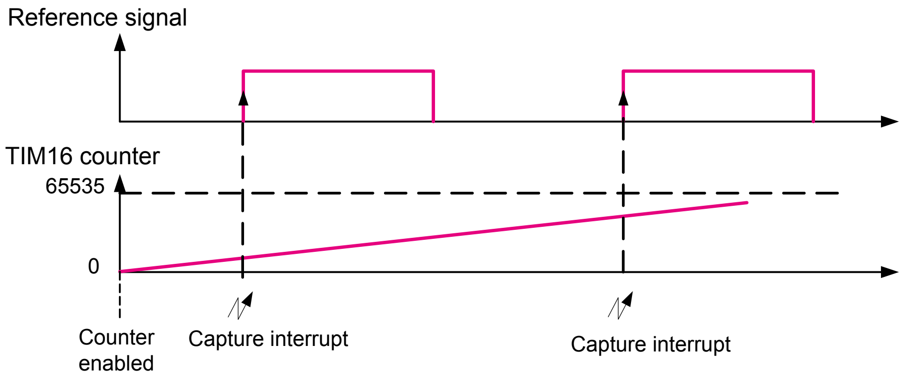
The calibration principle consists in the following steps:

1. Set the internal RC oscillator (that needs to be calibrated) as system clock.
2. Measure the internal RC oscillator (HSI or CSI) frequency for each trimming value.
3. Compute the frequency error for each trimming value.
4. Set the trimming bits with the optimum value (corresponding to the lowest frequency error).

The internal oscillator frequency is not measured directly but is computed from the number of clock pulses counted using a timer compared with the typical value. To do this, a very accurate reference frequency must be available, such as the LSE frequency provided by the external 32.768 kHz crystal or the 50 or 60 Hz of the mains (refer to Section 2.2.2: Case 2: another source used as reference frequency).

The figure below shows how the reference signal period is measured.

**Figure 2. Timing diagram of internal oscillator calibration**




After enabling the timer counter, when the first rising edge of the reference signal occurs, the timer counter value is captured and stored in IC1ReadValue1. At the second rising edge, the timer counter is captured again and stored in IC1ReadValue2. The elapsed time between two consecutive rising edges (IC1ReadValue2 - IC1ReadValue1) represents an entire period of the reference signal.

Since the timer counter is clocked by the system clock (HSI or CSI), the real frequency generated by the internal RC oscillator versus the reference signal is given by:

measuredfrequency = (IC1ReadValue2 – IC1ReadValue1) × REFERENCE_FREQUENCY

The error (in Hz) is computed as the absolute value of the difference between the measured frequency and the typical value.

Hence the internal oscillator frequency error is expressed as:

frequencyerror(Hz) = measuredfrequency – sysclockfrequency

## 2.2 Hardware implementation

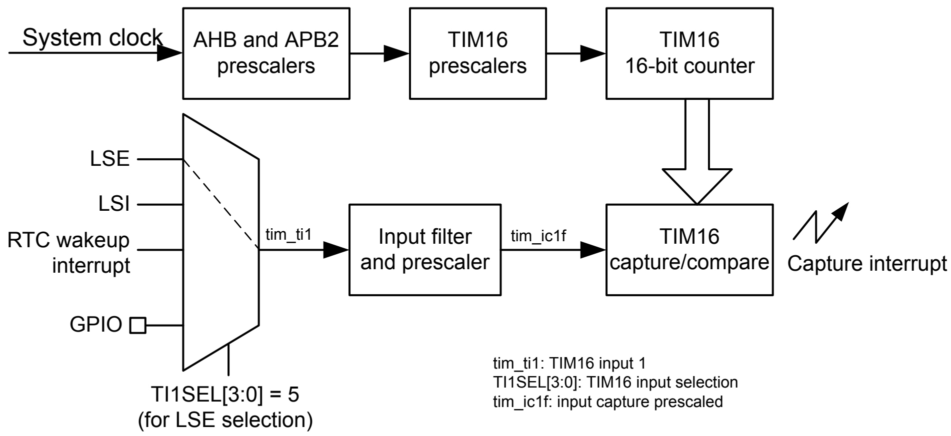
### 2.2.1 Case 1: LSE used as reference frequency

The STM32H5 devices offer the ability to connect internally the LSE to timer 16 channel 1. Thus, the LSE clock can be used as the reference signal for internal oscillator calibration, and no additional hardware connections are required. Only the LSE crystal/oscillator must be connected to OSC32_IN and OSC32_OUT.

*Note: TIM16 is not available in STM32H523/533 devices.*

The figure below shows the hardware connections needed for internal oscillators calibration, using the LSE as an accurate frequency source for calibration.

**Figure 3. Hardware connection using LSE as the reference frequency**

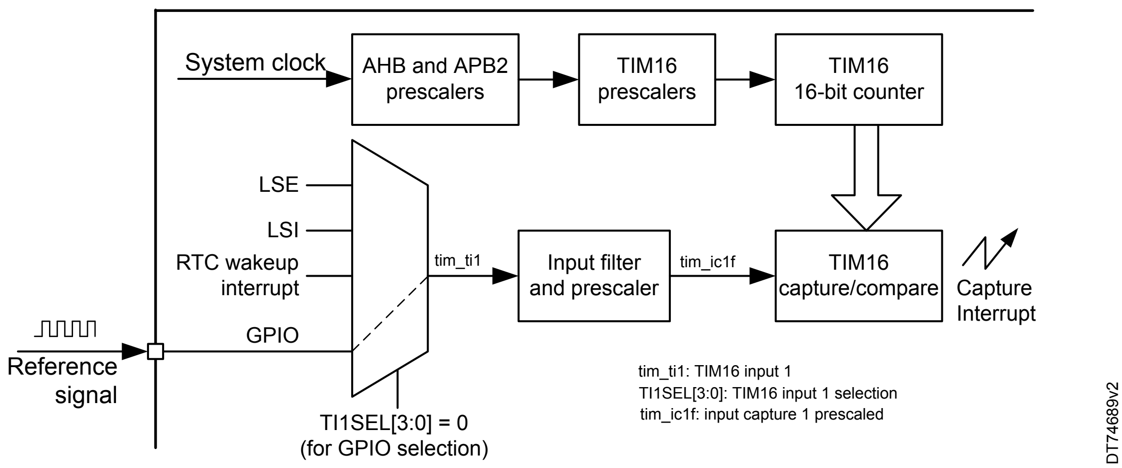



### 2.2.2 Case 2: another source used as reference frequency

Any signal with accurate frequency can be used for the internal oscillator calibration, and the main frequency signal is one of the possibilities.

As shown in the figure below, the reference signal must be connected to timer 16 channel 1.

**Figure 4. Hardware connection using external reference frequency**

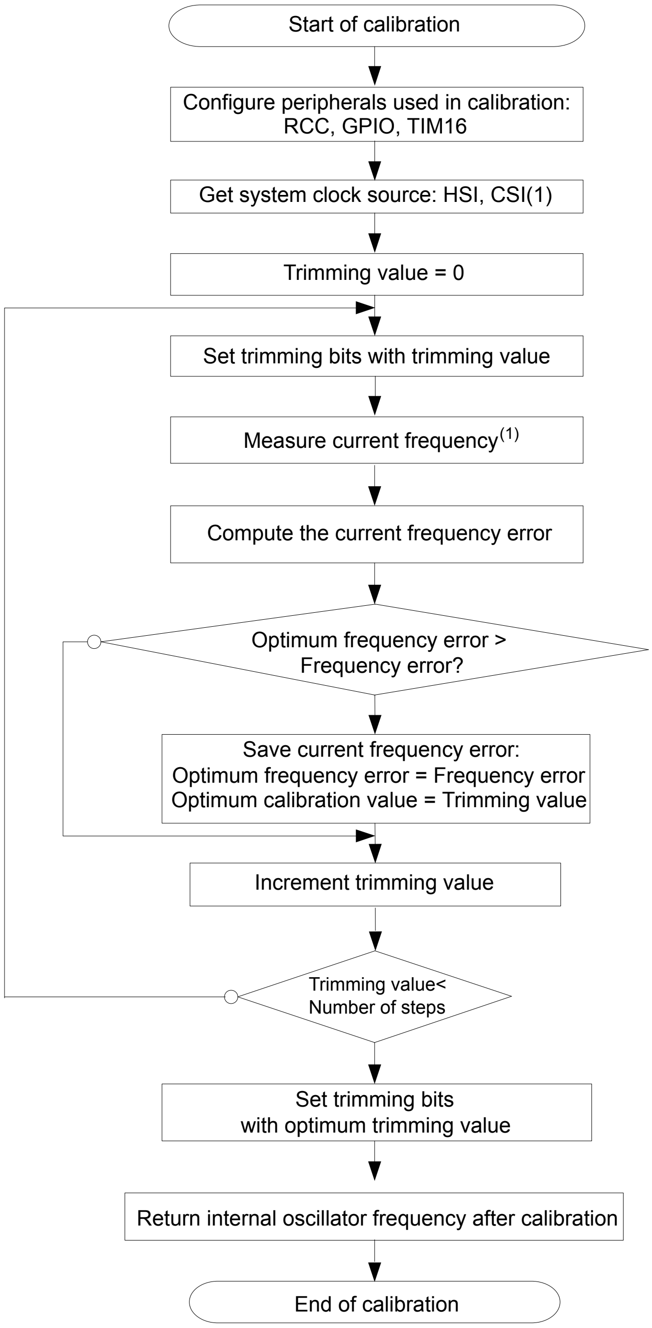



## 2.3 Description of the internal oscillator calibration

### 2.3.1 HSI/CSI calibration with minimum error

Figure 5 details the algorithm for finding the minimum frequency.

Figure 5. **Internal oscillator calibration: finding the minimum frequency**

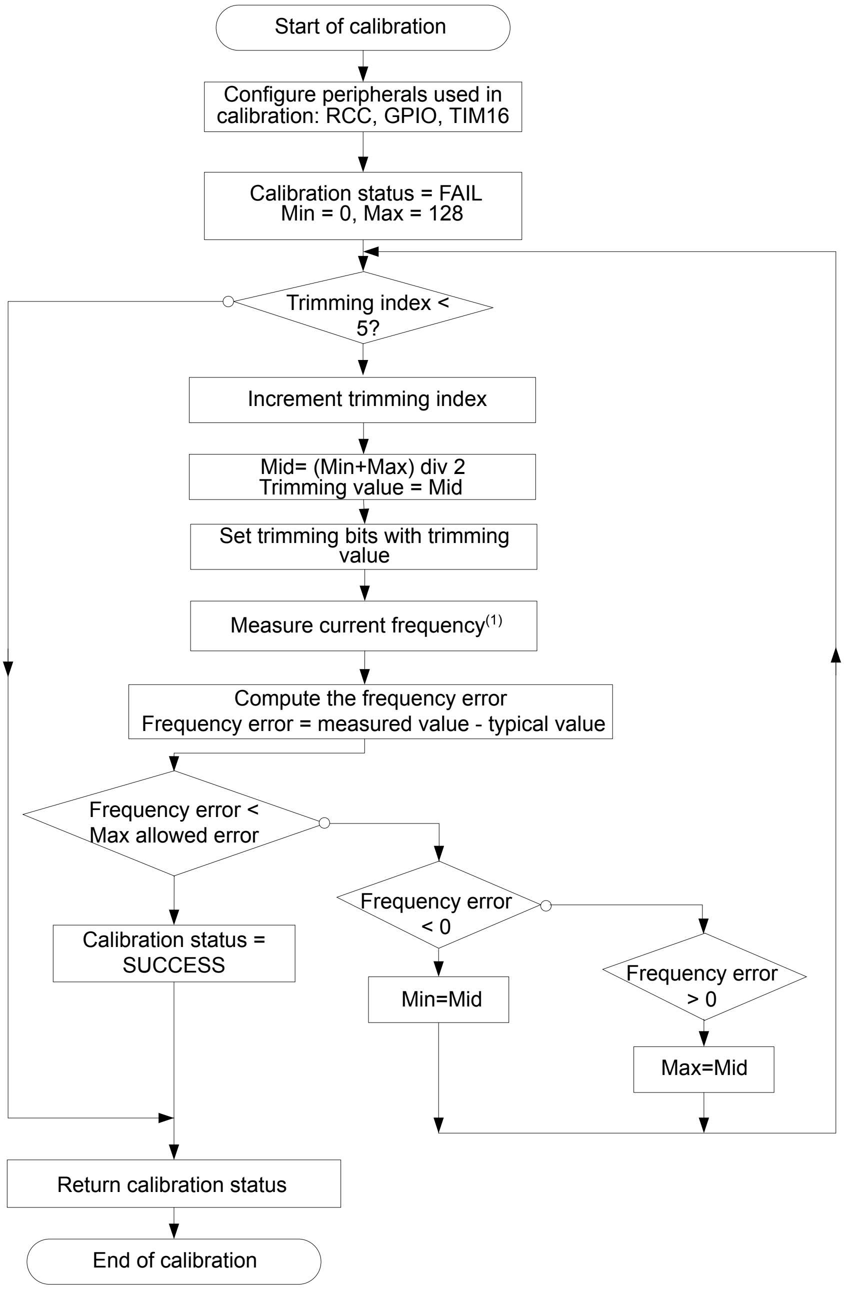



1. *Frequency measurement is detailed in Section 2.3.4: HSI/CSI frequency measurement.*

### 2.3.2 HSI calibration with fixed error

The figure below details the algorithm for the maximum allowed frequency error.

**Figure 6. HSI calibration flowchart: maximum allowed frequency error**




1. *Frequency measurement is detailed in Section 2.3.4: HSI/CSI frequency measurement.*

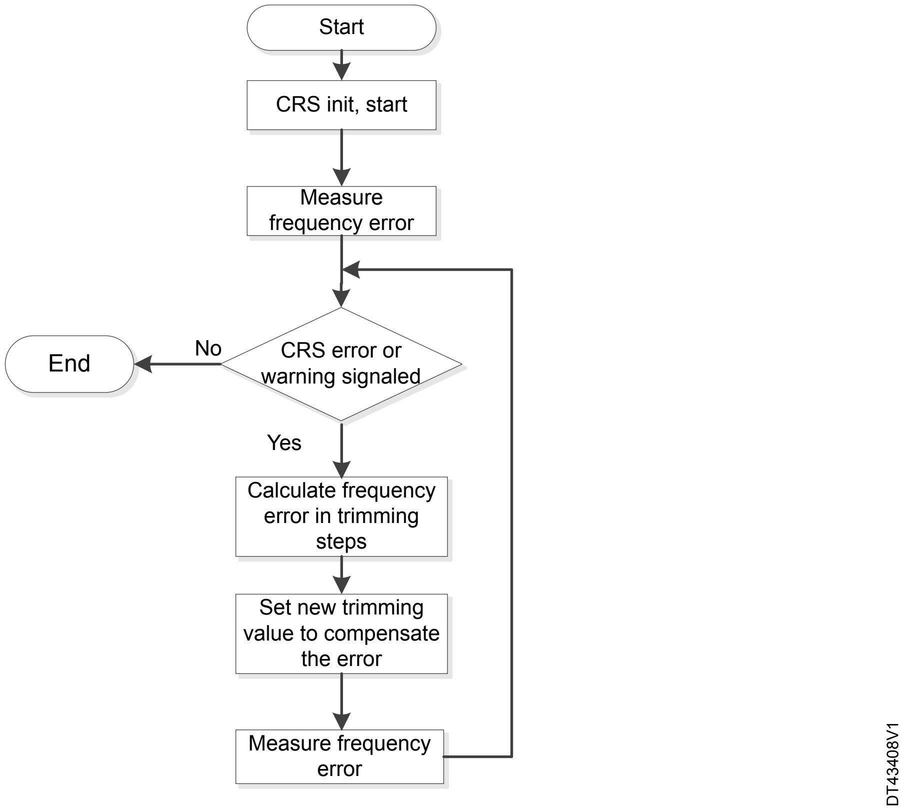
### 2.3.3 HSI48 calibration using CRS

The HSI48 can be measured similarly to the HSI or the CSI. The STM32H5 devices implement a CRS (clock recovery system) capable of doing an automatic adjustment of oscillator-trimming based on a comparison with a selectable synchronization signal.

Internally, the HSI48 implements a 16-bit down/up counter that increments or decrements step by step the trim value, until the expected frequency value is reached.

The HSI48 calibration using CRS can be run in a fully automatic way. To speed up the process, the CRS can be used to measure the actual error, and to set the trim value with a precalculated value. This process can be repeated once or twice as the curve may not be linear. When the requested frequency is reached, the automatic calibration can be activated for further smooth calibration (for example to compensate temperature changes).

**Figure 7. HSI48 trimming algorithm**



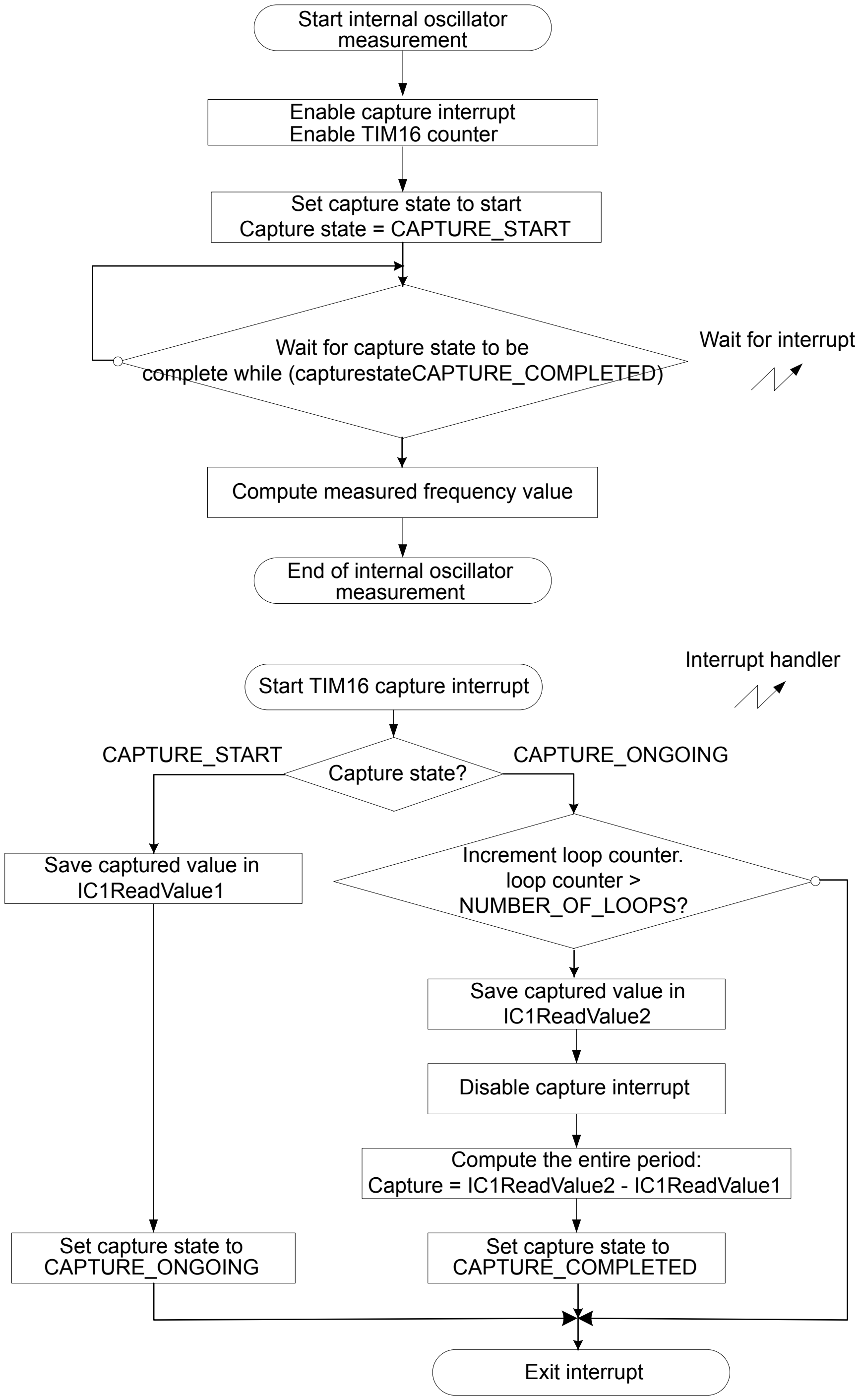

### 2.3.4 HSI/CSI frequency measurement

The internal oscillator frequency measurement is performed by TIM16 capture interrupt. In TIM16 ISR, an entire period of internal oscillator frequency is computed. The number of periods to be measured for each trimming value is configurable.

The computation of the frequency measurements does not depend on the duty cycle of the source reference signal. It depends on the source reference signal frequency, since the capture 1 interrupt is configured to occur on every rising edge of the reference signal (refer to Section 2.1).

The figure below details the frequency measurement algorithm.

**Figure 8. HSI/CSI oscillator frequency measurement flowchart**



# 3 Internal LSI oscillator measurement

The internal LSI RC oscillator is a low-power and low-cost clock source. In the STM32H5 devices, an internal connection is provided between the internal RC oscillator (LSI) and the embedded timer (TIM16) to facilitate the measurement procedure.

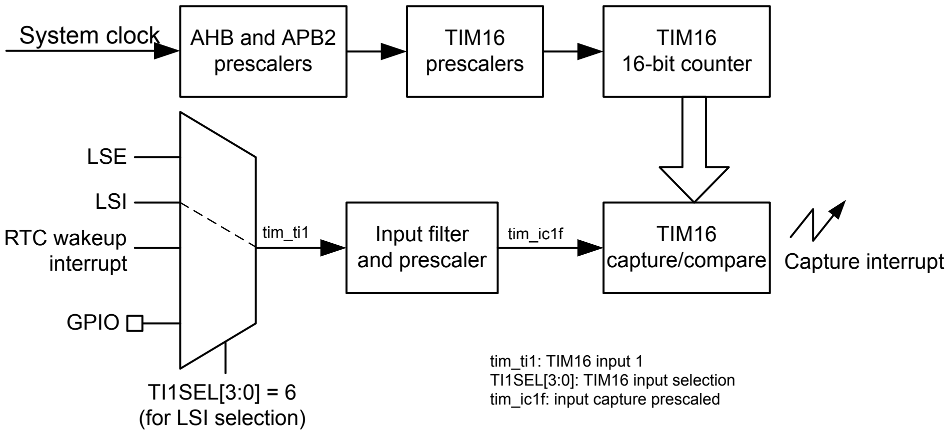
*Note: TIM16 is not available in STM32H523/533 devices.*

### Measurement principle

The internal LSI RC oscillator measurement procedure consists in running the timer counter using the HSI clock, configuring the timer in input-capture mode, and then connecting the internal LSI RC oscillator (that needs to be measured) to the timer.

The figure below shows the configuration used to perform the LSI measurement. The LSI can be connected internally to the TIM16 input 1 (TI1).

**Figure 9. LSI measurement configuration**




After enabling the timer counter, when the first rising edge of the internal oscillator signal to be measured occurs, the timer-counter value is captured and then stored in IC1ReadValue1. On the second rising edge, the timer-counter is captured again and stored in IC1ReadValue2. The elapsed time between two consecutive rising edges of the clock represents an entire period (see Section 2.1).

The internal oscillator frequency value is computed as HSI_Value / Capture, where:

- HSI_Value is the HSI frequency value (64 MHz typical).
- Capture represents an entire period of internal LSI RC oscillator: IC1ReadValue2 - IC1ReadValue1.

The frequency measurement accuracy depends on the HSI frequency accuracy. Consequently, if a reference signal is available, the internal RC oscillator calibration routine described in Section 2 can be run before performing the internal RC oscillator measurement procedure.

The input capture prescaler can be used for better measurement accuracy. The previous formula becomes:

LSI_Frequency = InputCapturePrescaler × HSI_Value / Capture_Value

The same algorithm shown in Section 2.3.4 is used to measure the LSI oscillator frequency.

*Note: TIM16 ISR is used for LSI measurement.*

# 4 Conclusion

Even if the internal RC oscillators are factory-calibrated, the user can recalibrate them in the operating environment if a high-accuracy clock is required in the application.

This application note describes routines for:

- CSI and high-speed internal oscillator calibration: how to fine-tune the oscillator to the typical value
- Low-speed internal oscillator measurement: how to get the exact LSI frequency value

Several frequency sources can be used to calibrate the (HSI, HSI48, and CSI oscillators) such as LSE crystal or AC line among others. Regardless of the reference frequency source, the calibration principle is the same: a reference signal must be provided to be measured by a timer. The higher the accuracy of the reference signal frequency, the better the accuracy of the internal oscillator frequency measurement.

The error is computed as the absolute value of the typical frequency value and the measured one for each trimming value. After this, the calibration value is calculated and then programmed in the trimming bits.

The second part of this document presents the measurement of the LSI oscillator. The internal connection between internal oscillators and embedded timers in the STM32H5 devices is used for this purpose. The timer is clocked using the system clock source and configured in input capture mode. The captured time between two consecutive rising edges of internal oscillator represents an entire period.

## Revision history

Table 1. Document revision history

| Date | Version | Changes |
|---|---|---|
| 12-Dec-2024 | 1 | Initial release. |

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