AN4067
Application note

How to calibrate STM32F0xx internal RC oscillators

Introduction

The STM32F0xx microcontrollers have an internal RC oscillator that can be selected as the system clock source, and a High speed internal RC oscillator dedicated to ADC. These are known as the HSI (High-speed Internal 8 MHz) and HSI14 (High-speed Internal 14 MHz) oscillators.

The operating temperature has an impact on the accuracy of the RC oscillators. At 25 °C, the HSI and HSI14 oscillators have an accuracy of ±1% typically, but in the temperature range of -40 to 105 °C, the accuracy decreases.

To compensate for the influence of temperature on internal RC oscillators accuracy, the STM32F0xx microcontrollers have built-in features to allow you to calibrate the HSI and HSI14 oscillators and measure the LSI (Low-speed internal) oscillator frequency.

This application note focuses on how to calibrate internal RC oscillators: HSI and HSI14. Two methods are presented:

- Method 1 consists in finding the frequency with the minimum error.
- Method 2 consists in finding the maximum allowed frequency error.

Both are implemented by providing an accurate reference signal.

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

Note: STM32F0xx devices are:
- STM32F050xx microcontrollers where the Flash memory density can go up to 32 Kbytes.
- STM32F051xx microcontrollers where the Flash memory density can go up to 64 Kbytes.

Table 1 lists the microcontrollers and development tools concerned by this application note.

Table 1. Applicable products and tools

Type	Applicable products
Microcontrollers	STM32 F0 series entry-level Cortex™-M0 microcontrollers
Development tools	STM320518-EVAL evaluation board

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1 STM32F0xx system clock

The STM32F0xx microcontroller family has various clock sources that can be used to drive the system clock:

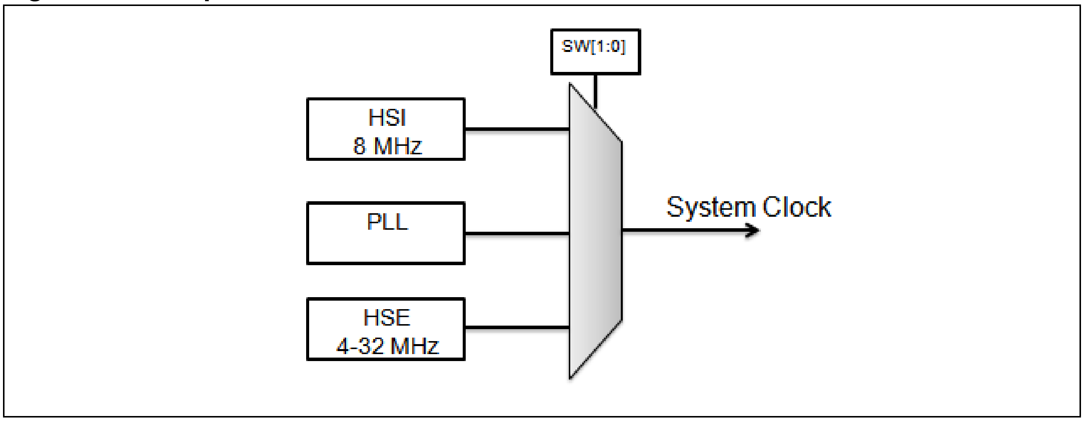
- An 8 MHz High-speed internal (HSI) RC oscillator clock
- A 4 to 32 MHz High-speed external (HSE) oscillator clock
- A Phase-locked loop (PLL) that is clocked by HSI or HSE oscillators

Typically, the High-speed internal (HSI) RC oscillator has a frequency of 8 MHz and consumes 80 µA.

The internal RC oscillator (HSI) has the advantage of providing a low-cost clock source (no external components required). It also has a faster startup time and a lower power consumption than the external oscillator. The HSI oscillator can be calibrated to improve its accuracy. But even with calibration, the internal RC oscillator frequency is less accurate than the frequency of an external crystal oscillator or a ceramic resonator (tens of ppm).

Note: The internal RC oscillator (HSI) can also be used as a backup clock source (auxiliary clock) if the external oscillator fails.

Figure 1. Simplified clock tree



The STM32F0xx devices also have three secondary clock sources (that cannot be used as system clock sources):

- A 40 kHz Low-Speed Internal (LSI) RC which is designed to drive the independent watchdog and optionally the Real time clock (RTC). The LSI oscillator cannot be calibrated, but can be measured to evaluate frequency deviations (due to temperature and voltage changes).
- A 32.768 kHz Low-speed external crystal (LSE crystal) which optionally drives the Real time clock (RTC)
- A 14 MHz high speed internal RC (HSI14) dedicated to ADC.

2 Internal RC oscillator calibration

The frequency of the internal RC oscillators may vary from one chip to another due to manufacturing process variations. For this reason, HSI and HSI14 RC oscillators are factory-calibrated by STMicroelectronics to have a 1% accuracy at T_A = 25 °C. After reset, the factory calibration value is automatically loaded in the internal calibration bits.

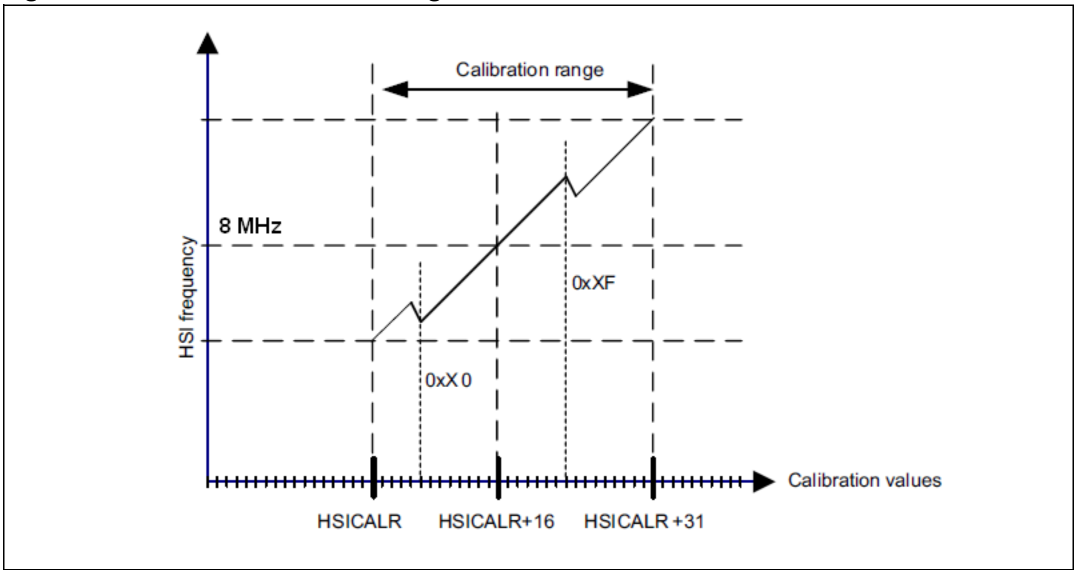
The frequency of the internal RC oscillators can be fine-tuned to achieve a better accuracy with wider temperature and supply voltage ranges. The trimming bits are used for this purpose.

For the HSI oscillator, the calibration value is loaded in HSICAL[7:0] bits after reset. Five trimming bits HSITRIM[4:0] are used for fine-tuning. The default trimming value is 16. An increase/decrease in this trimming value causes an increase/decrease in HSI frequency. The HSI oscillator is fine-tuned in steps of 1% (around 40 kHz).

- Writing a trimming value, in the range of 17 to 31, increases the HSI frequency.
- Writing a trimming value, in the range of 0 to 15, decreases the HSI frequency.
- Writing a trimming value, equal to 16, causes the HSI frequency to keep its default value.

Figure 2 shows the HSI oscillator behavior versus the calibration value. The HSI oscillator frequency increases with the calibration value (calibration value = default HSICAL[7:0] + HSITRIM[4:0]), except at modulo 16. At these calibration values, the negative steps can reach three times the positive steps.

Figure 2. HSI oscillator trimming characteristics

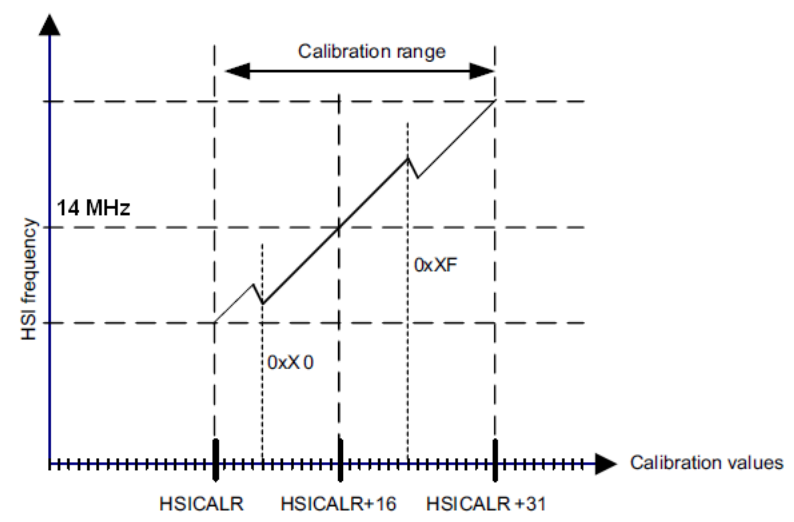


For the **HSI14** (14 MHz) oscillator, The calibration value is loaded in HSI14CAL[7:0] bits after reset. Five trimming bits HSI14TRIM[4:0] are used for fine-tuning. The default trimming value is 16. An increase/decrease in this trimming value causes an increase/decrease in the HSI14 frequency. The HSI14 oscillator is fine-tuned in steps of 1% (around 50 kHz).

- Writing a trimming value, in the range of 17 to 31, increases the HSI14 frequency.
- Writing a trimming value, in the range of 0 to 15, decreases the HSI14 frequency.
- Writing a trimming value, equal to 16, causes the HSI14 frequency to keep its default value.

Figure 3 shows the HSI14 oscillator behavior versus the calibration value. The HSI14 oscillator frequency increases with the calibration value (calibration value = default HSI14CAL[7:0] + HSI14TRIM[4:0]), except at modulo 16. At these calibration values, the negative steps can reach three times the positive steps.

Figure 3. HSI14 oscillator trimming characteristics



2.1 Calibration principle

2.1.1 HSI calibration

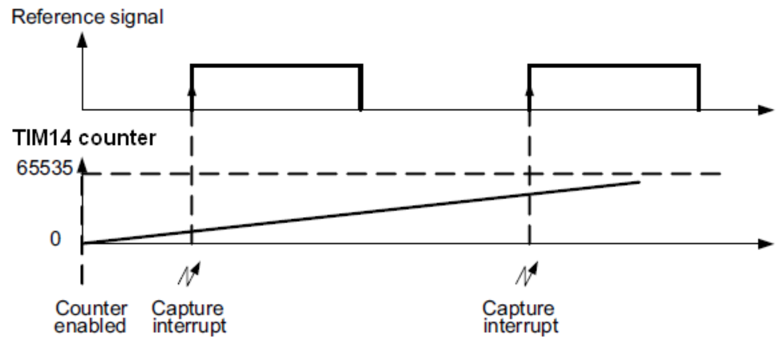
The calibration principle consists in:

1. Setting the HSI as the system clock source
2. Measuring the internal RC oscillator (HSI) frequency for each trimming value
3. Computing the frequency error for each trimming value
4. Setting 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 Hz/60 Hz of the mains (refer to *Section 2.2.1* and *Section 2.2.2*).

Figure 4 shows how the reference signal period is measured in number of timer counts.

Figure 4. 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 (internal RC oscillator HSI), the real frequency generated by the internal RC oscillator versus the reference signal is given by:

$$\mathrm{Measuredfrequency} = (\mathrm{IC1ReadValue2} - \mathrm{IC1ReadValue1}) \times \mathrm{referencefrequency}$$

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:

$$\mathrm{Error(Hz)} = |\mathrm{Measuredfrequency} - \mathrm{typicalvalue}|$$

After calculating the error for each trimming value, the algorithm determines the optimum trimming value (that corresponds to the nearest frequency to typical value) to be programmed in the trimming bits (refer to *Section 2.3: Description of the internal oscillator calibration firmware* for more details).

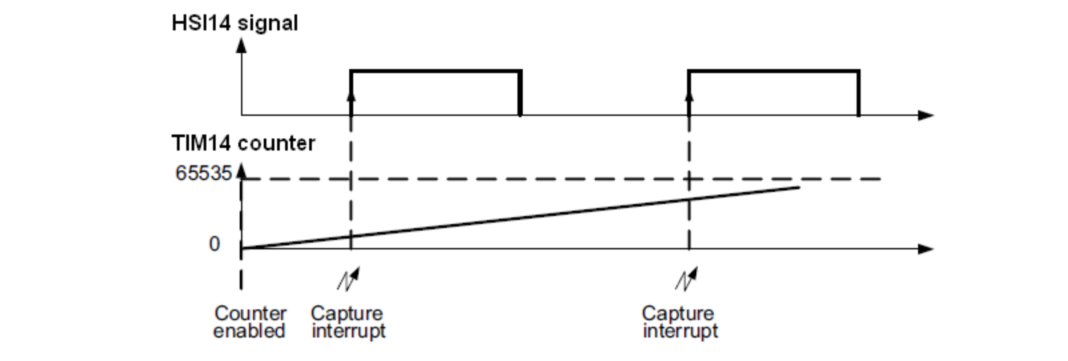
2.1.2 HSI14 calibration

The calibration principle consists in:

1. Setting the PLL, clocked by the HSI (after calibrating the HSI), as the system clock source.
2. Measuring the internal RC oscillator (HSI14) frequency for each trimming value.
3. Computing the frequency error for each trimming value.
4. Finally, setting the trimming bits with the optimum value (corresponding to the lowest frequency error).

Figure 5 shows how the reference signal period is measured in number of timer counts.

Figure 5. Timing diagram of internal oscillator calibration HSI14



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.

The real frequency generated by the internal RC oscillator HSI14 is given by:

$$\text{Measuredfrequency} = ((\text{SystemClock}) / (\text{IC1ReadValue2} - \text{IC1ReadValue1}))$$

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:

$$\text{Error(Hz)} = |\text{Measuredfrequency} - \text{typicalvalue}|$$

After calculating the error for each trimming value, the algorithm determines the optimum trimming value (that corresponds to the nearest frequency to the typical value) to be programmed in the trimming bits (refer to *Section 2.3: Description of the internal oscillator calibration firmware* for more details).

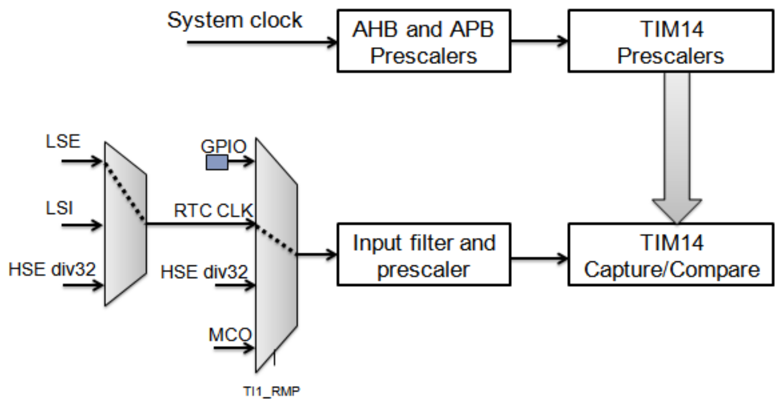
2.2 Hardware implementation

2.2.1 Case where LSE is used as the reference frequency to measure HSI

The STM32F0xx offers a useful feature, that is the ability to connect internally and indirectly the Low-speed external (LSE) oscillator to Timer 14 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 oscillator should be connected to OSC32_IN and OSC32_OUT.

Figure 6 shows the hardware connections needed for internal oscillators calibration, using LSE as an accurate frequency source for calibration.

Figure 6. Hardware connection using LSE as the reference frequency



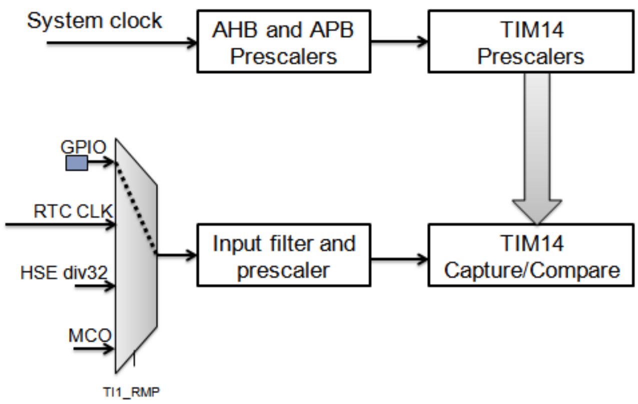
1. TI1_RPM: TIM14 input 1 remapping
2. TI1_RPM: Timer input 1
3. IC1PS: Input capture 1 prescaled

2.2.2 Case where another source is used as the reference frequency to measure HSI

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

As shown in *Figure 7* below, the reference signal should be connected to Timer 14 channel 1.

Figure 7. Hardware connection using external reference frequency



1. TI1_RPM: TIM14 input 1 remapping
2. TI1: Timer input 1
3. IC1PS: Input capture 1 prescaled

Note: When using an external signal as a reference, another timer can be used instead of TIM14. The firmware provided with this application note uses TIM14.

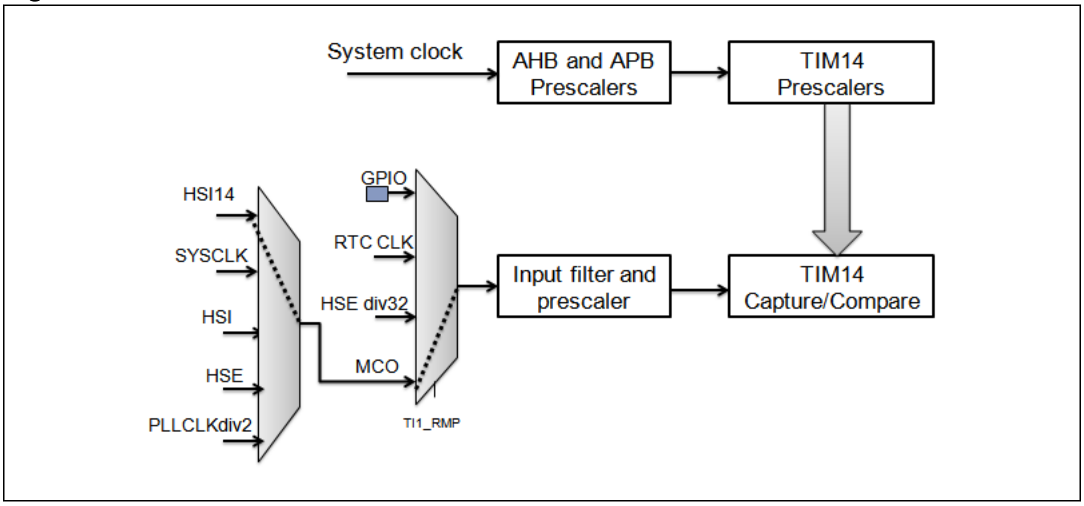
Refer to application note AN2868 “Internal RC oscillator (HSI) calibration” for more details about using mains frequency for calibration.

2.2.3 Measure the HSI14 frequency

The STM32F0xx offers a useful feature, that is the ability to connect internally and indirectly the High-speed internal (HSI14) oscillator to Timer 14 channel 1.

Figure 6 shows the hardware connections needed for internal oscillators calibration.

Figure 8. Hardware connection For HSI14



1. TI1_RPM: TIM14 input 1 remapping
2. TI1: Timer input 1
3. IC1PS: Input capture 1 prescaled

2.3 Description of the internal oscillator calibration firmware

The internal RC oscillator calibration firmware provided with this application note includes 4 major functions:

- `uint32_t HSI_CalibrateMinError(void)`
- `ErrorStatus HSI_CalibrateFixedError(uint32_t MaxAllowedError, uint32_t* Freq)`
- `uint32_t HSI14_CalibrateMinError(void)`
- `ErrorStatus HSI14_CalibrateFixedError(uint32_t MaxAllowedError, uint32_t* Freq)`

2.3.1 Internal oscillator calibration with minimum error

The `HSI_CalibrateMinError`() function calibrates the internal oscillator (HSI) to have the frequency nearest to the typical value. It measures all frequencies for different trimming values and provides the trimming value that corresponds to the frequency with the minimum error. The trimming value thus obtained is programmed in the trimming bits.

After calibration, the `HSI_CalibrateMinError()` function returns the internal oscillator frequency value as an unsigned 32-bit integer (uint32_t).

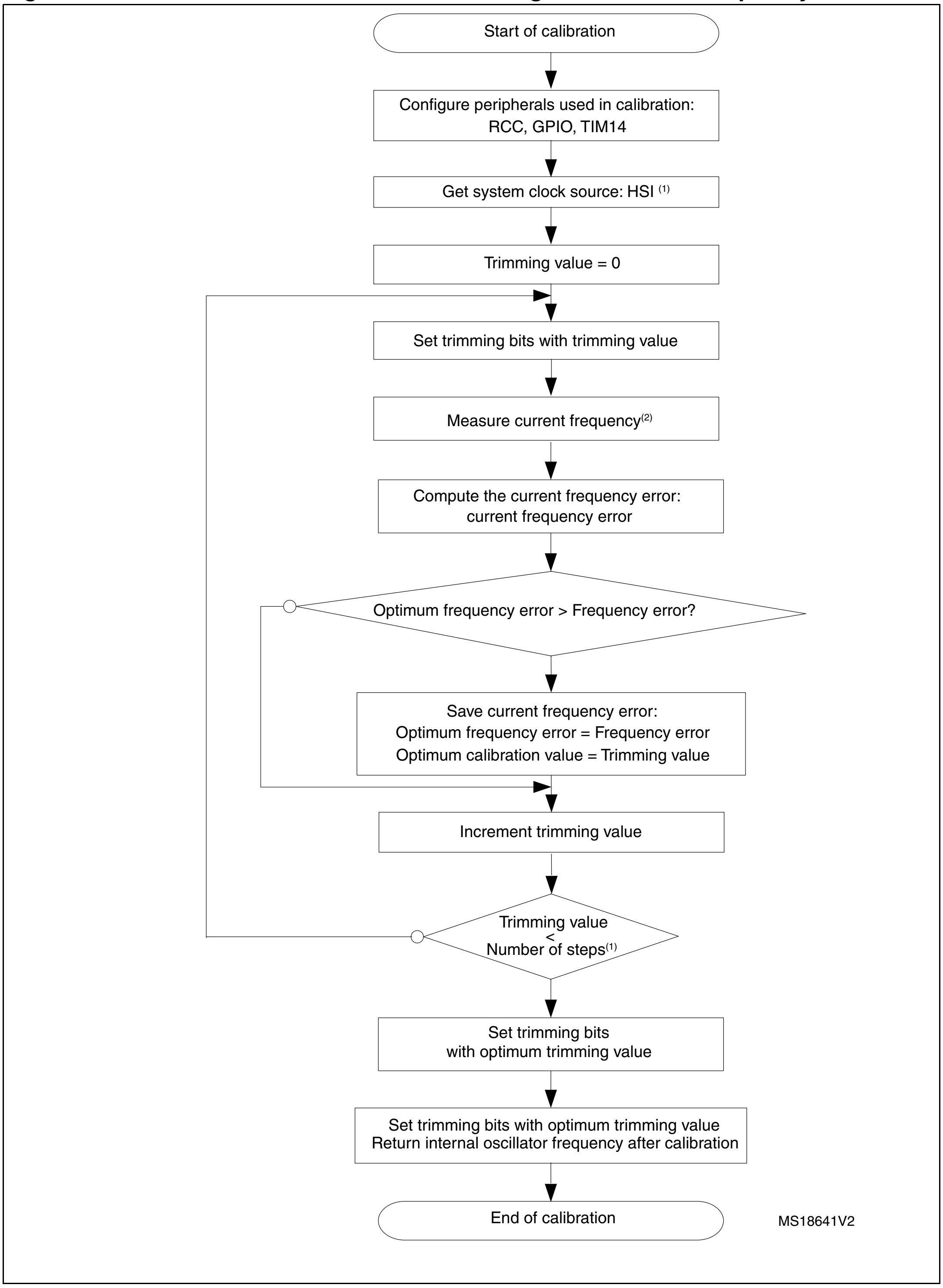
The flowchart in *Figure 9* provides the algorithm for this function.

Example

```
uint32_t InternOscAfterCalib = 0;
{
......
/* Get the internal oscillator (HSI) value after calibration */
  InternOscAfterCalib = HSI_CalibrateMinError();
}
```

In case of an HSI14 calibration, the **HSI14_CalibrateMinError()** function should be used instead of **`HSI_CalibrateMinError()`.**

Figure 9. Internal oscillator calibration: finding the minimum frequency error



1. If the system clock source is HSI, the trimming bits have a 5-bit length and the number of steps is 32.
2. The frequency measurement is detailed in *Section 2.3.3*.

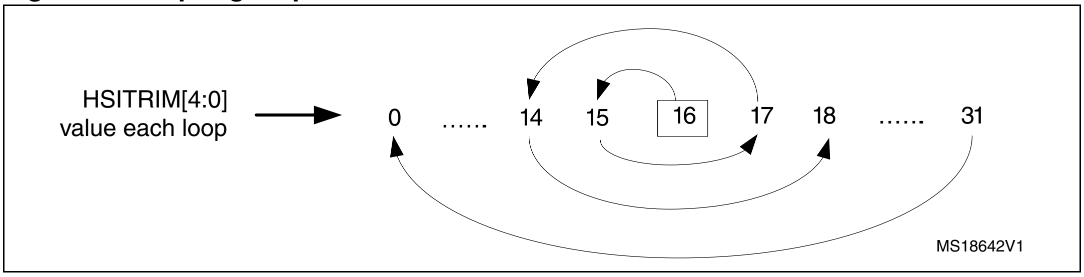
2.3.2 HSI calibration with fixed error

The HSI_CalibrateFixedError() function is provided to calibrate the HSI oscillator with a maximum allowed frequency error. It is configured by the user as an absolute value given in Hertz (the first parameter: ***MaxAllowedError***). This function is the same as `HSI_CalibrateMinError()` (refer to *ErrorStatus HSI14_CalibrateFixedError(uint32_t MaxAllowedError, uint32_t* Freq)*), but it searches for the frequency that has an error (in absolute value) lower than or equal to ***MaxAllowedError***.

- If it finds this frequency, it stops searching and configures the trimming bits HSITRIM[4:0] according to this frequency and returns SUCCESS, meaning that the calibration operation has succeeded.
- Otherwise, it continues searching for it until the HSITRIM bits = 31 (32nd frequency). It then sets the trimming bits HSITRIM[4:0] to the default calibration value and returns ERROR, meaning that the calibration has failed and did not find any frequency with an error lower than or equal to ***MaxAllowedError***.
  The frequency measurement starts with HSTRIM = 16. The HSITRIM value is computed in loops to find the next value. That is, the HSITRIM value starts from 16, then goes to the next value to the left, then to the next to the right, then to the second to the left and so on until it reaches 31, forming a “spring loop” (as shown in *Figure 10*).

  This algorithm is based on the fact that the probability of finding the frequency that has the minimum error increases when the HSITRIM[4:0] value tends to 16. This algorithm is implemented so as to minimize the time consumed by the calibration process.

Figure 10. “Spring loop”

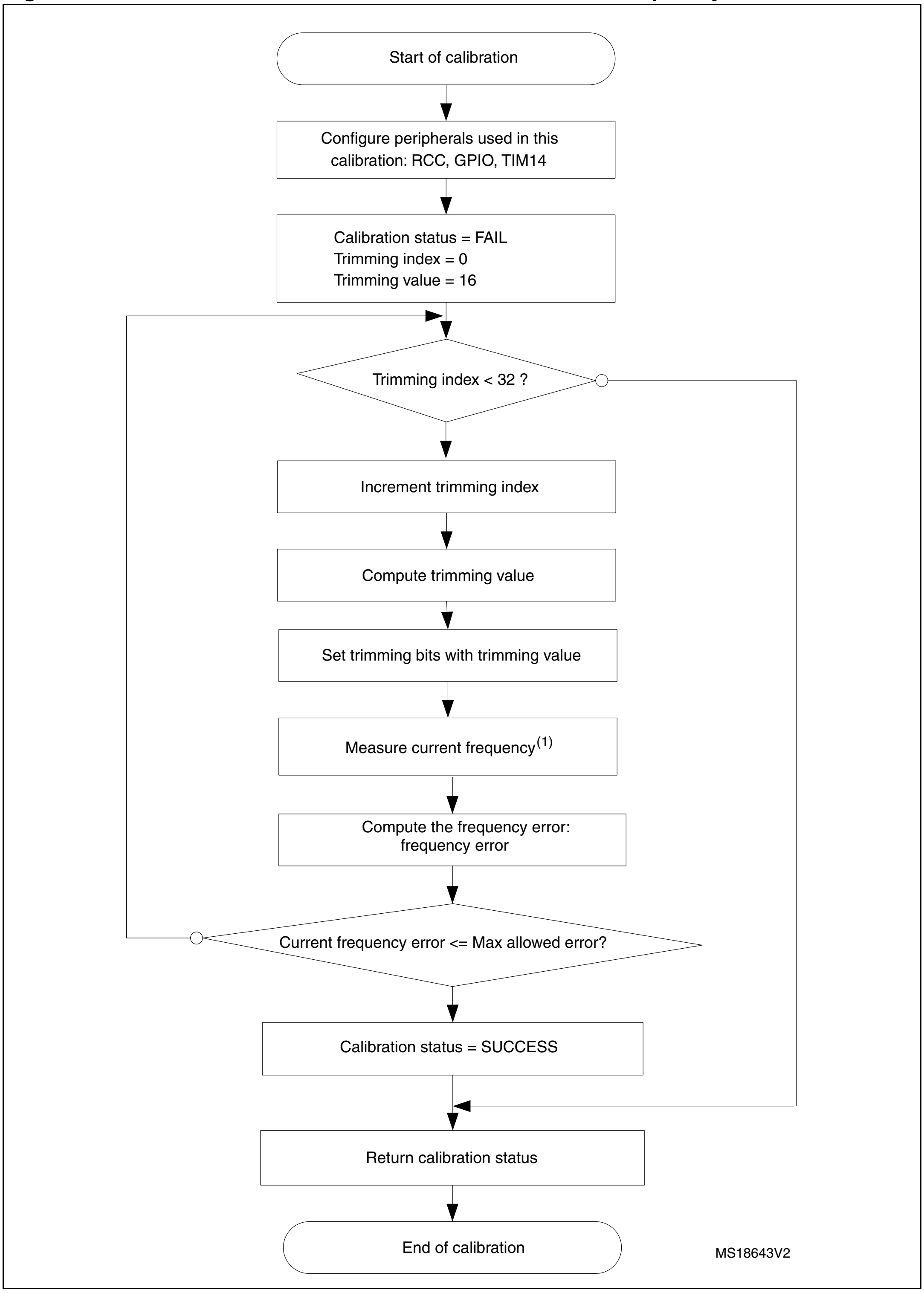


The second parameter is used to get the frequency (in Hertz) after calibration in the form of an unsigned 32-bit integer (unit32_t).

In case of an HSI14 calibration, the **HSI14_CalibrateFixedError()** function should be used instead of **HSI_CalibrateFixedError().**

The flowchart in *Figure 11* provides the algorithm for this function.

Figure 11. HSI calibration flowchart: maximum allowed frequency error



1. The frequency measurement is detailed in *Section 2.3.3: Internal oscillator frequency measurement*.

2.3.3 Internal oscillator frequency measurement

The internal oscillator frequency measurement is performed by Timer 14 capture interrupt. In the timer TIM14 ISR, an entire period of internal oscillator frequency is computed. The number of periods to be measured for each trimming value is configurable by the user in the *InternOscCalibration.h* file, as follows:

```
#define NUMBER_OF_LOOPS 50
```

The averaging method is used to minimize frequency error measurements. So, if the counter of loops reaches NUMBER_OF_LOOPS, the average of all measured frequencies is computed.

You can easily configure the frequency of the reference source. It is defined in the *InternOscCalibration.h* header file, as follows:

- If the LSE clock is used as the reference frequency, uncomment the line below to make sure the LSE is configured and internally connected to Timer 14 channel 1:

  ```
  #define USE_REFERENCE_LSE
  ```

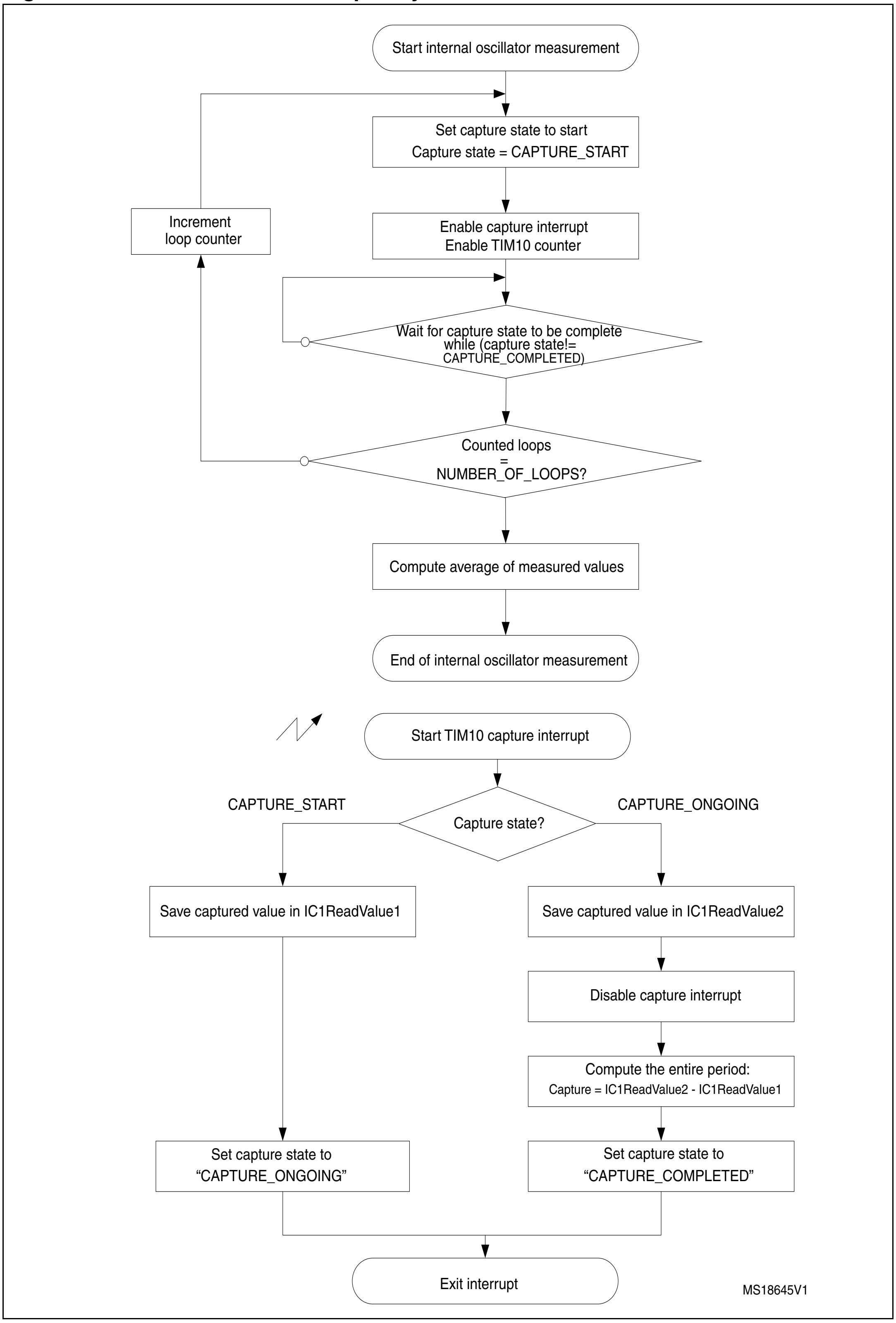
- If the reference frequency is a mains source frequency equal to 50 Hz, then comment the line above and define the reference frequency as shown below:

  ```
  #define REFERENCE_FREQUENCY (uint32_t)50 /* The reference
  frequency value in Hz */
  ```

The computation of the frequency measurements does not depend on the duty cycle of the source reference signal. It depends on its frequency since the capture 1 interrupt is configured to occur on every rising edge of the reference signal (refer to *Figure 4*).

Note: Figure 12 provides the frequency measurement algorithm.

Figure 12. Internal oscillator frequency measurement flowchart



2.4 Recommendations on the use of the calibration library

1. If the external signal frequency is lower than system clock / 65535, the TIM14 counter prescaler should be used to support low frequencies.
2. If the external signal frequency is higher than system clock / 100, TIM14 input capture prescaler (divider) should be used to support high frequencies.
3. It is recommended to stop all application activities before the calibration process, and to restart them after calling the calibration functions.

   Therefore, the application has to stop the communications, the ADC measurements and any other processes (except when using the ADC for the calibration, refer to Step *5.* below).

   These processes normally use clock configurations that are different from those used in the calibration process. Otherwise, errors might be introduced in the application: errors while reading/sending frames, ADC reading errors since the sampling time has changed, and so on.
4. The internal RC oscillator calibration firmware uses the following peripherals: Reset and Clock Control (for trimming internal RC oscillators), Timer 14 (for measuring internal RC oscillators). Therefore, it is recommended to reconfigure these peripherals (if used in the application) after running the calibration routine.
5. Real-time calibration vs. temperature can be used when the ambient temperature changes noticeably while the application is running. The internal temperature sensor can be used with the ADC watchdog with two thresholds. Each time an ADC watchdog interrupt occurs, a new calibration process has to be performed and the two thresholds are updated according to the current temperature (this feature is not implemented in the firmware provided with this application note):

   Threshold_High = CurrentTemperatureValue + TemperatureOffset

   Threshold_Low = CurrentTemperatureValue – TemperatureOffset

2.5 Calibration process performance

2.5.1 Duration of the calibration process

The duration of the calibration process depends on:

1. the frequency of the reference signal (prescaled value) “REFERENCE_FREQUENCY”,
2. the number of measured periods per trimming value “NUMBER_OF_LOOPS”,
3. the number of measured frequencies during the calibration process “number of steps”.

Once the peripherals are configured and ready (mainly the LSE oscillator), the duration of the calibration process is approximated by:

duration = (2 x (NUMBER_OF_LOOPS + 1) x number of steps) / REFERENCE_FREQUENCY

If the calibration process is run with a minimum frequency error for an HSI oscillator (***HSI_CalibrateMinError()***), the number of steps is equal to 32. If the LSE oscillator is used as the reference frequency (REFERENCE_FREQUENCY = LSE value / Input capture prescaler = 32768/8 = 4096 Hz) and the selected number of measured periods is 10, the calibration consumes approximately:

duration = (2 x 51 x 32) / 4096 = 797 ms

The duration of the calibration process with a maximum allowed error is lower than or equal to the duration of calibration when using the minimum frequency error process.

Note: *Multiplying by 2 in the duration formula above is due to the fact that there is no synchronization between the reference signal and the start of counting by the timer.*

3 Internal oscillator measurement

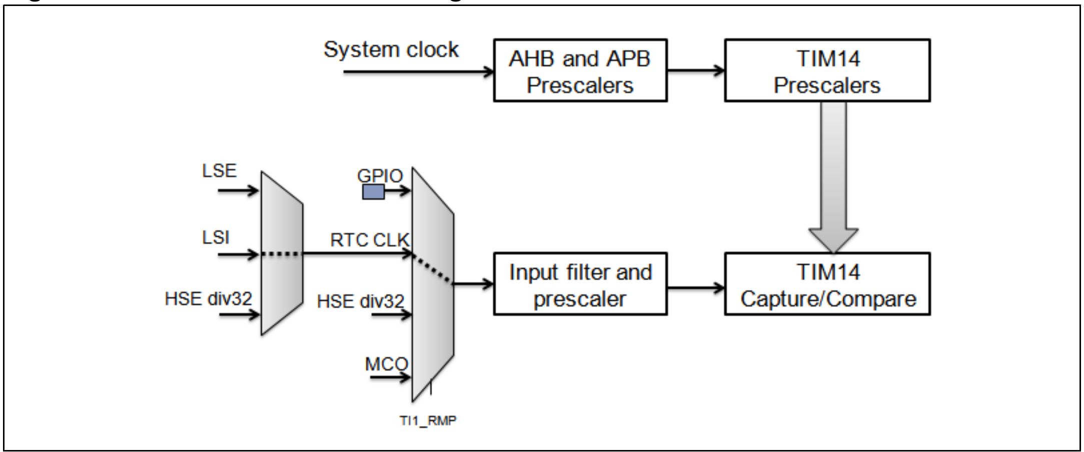
The internal LSI RC oscillator is a low-power clock source. In the STM32F0x microcontroller family, an internal and indirect connection is provided between the internal RC oscillator LSI and the embedded timer TIM14 to facilitate the measurement procedure.

3.1 Measurement principle

The internal RC oscillator measurement procedure consists in running the timer counter using the HSI clock, configuring the internal RC oscillator LSI as the clock source for RTC, configuring the timer in Input capture mode and then connecting the RTC to the timer.

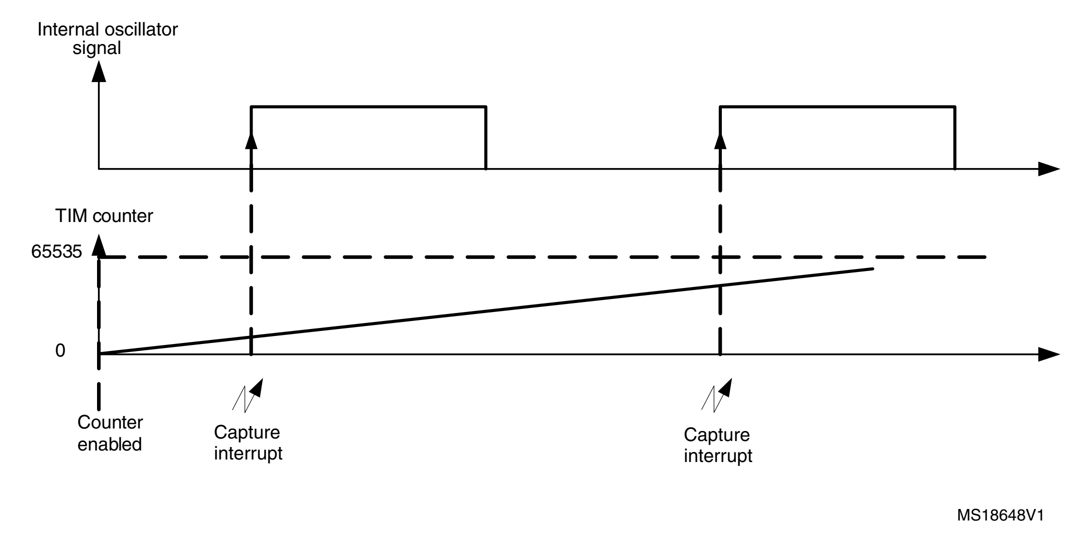
Figure 13 shows the configuration used to perform an LSI measurement.

Figure 13. 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. *Figure 14* shows the timing diagram of an internal RC oscillator measurement.

Figure 14. Timing diagram of an internal RC oscillator measurement



The internal oscillator frequency value is computed as shown by the following formula:

internal oscillator frequency = HSI_Value / Capture

where:

- HSI_Value is the HSI frequency value: typical value is 8 MHz,
- Capture represents an entire period of internal RC oscillator LSI: IC1ReadValue2 - IC1ReadValue1.

As you can conclude from the formula above, the frequency measurement accuracy depends on the HSI frequency accuracy. Consequently, if a reference signal is available, you can run the internal RC oscillator calibration routine described in *Section 2: Internal RC oscillator calibration* before performing the internal RC oscillator measurement procedure.

The input capture prescaler can be used for better measurement accuracy so the formula above becomes:

LSI_Frequency = InputCapturePrescaler * HSI_Value / Capture_Value.

3.2 Description of the internal oscillator measurement firmware

The internal oscillator measurement firmware provided with this application note includes one C source files:

- LSIMeasurement.c performing LSI frequency measurement using LSI_FreqMeasure() function

The internal RC oscillator LSI is measured for a predefined number of periods. Then it returns the average value to minimize the error of the measured frequency.

You can change this parameter (number of LSI periods) in the lsi_measurement.h file:

```
#define LSI_PERIOD_NUMBERS 10
```

4 Internal oscillator calibration/measurement example description

The example provided with this application note shows the ability of the firmware to calibrate the internal RC oscillators (HSI and HSI14) and explains how to use it to measure the internal RC oscillators (HSI14 and LSI) of the STM32F0xx microcontroller.

In this example:

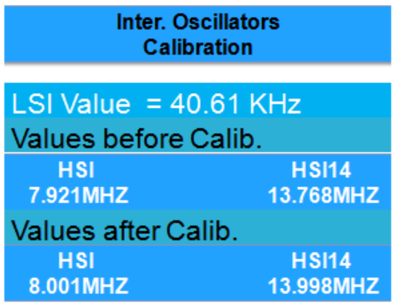
- After system reset, the HSI is selected to be used as the system clock source.
- The HSI is calibrated using the LSE oscillator as a reference clock.
- When the HSI oscillator has been calibrated, the PLL (clocked by HSI) is configured to 48 MHz and used as the system clock source.
- Then, the HSI14 is calibrated according to HSI precision.
- After that, the LSI frequency is measured.
- Finally, the measured frequency of the different oscillators is displayed on the STM320518-EVAL board's LCD, as shown in *Figure 15*.

By default, the example uses the minimum error method to calibrate the HSI and HSI14 oscillators.

To run the calibration process that provides the frequency with fixed error, you have to comment out the following define in the main.c file:

```
#define CALIBRATION_MIN_ERROR
```

Figure 15. HSI calibration



5 Conclusion

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

This application note provides two routines:

- **High-speed internal oscillator (HSI and HSI14) 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 internal RC oscillator (HSI): LSE crystal, AC line, etc. Whatever the reference frequency source, the internal oscillator 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. From this, the calibration value is calculated and then programmed in the trimming bits.

The second section of this application note is about the measurement of LSI oscillators. The internal connection between internal oscillators and embedded timers in the STM32F0xx microcontroller family is used for this purpose. The timer is clocked using the system clock source and configured in the Input capture mode. The captured time between two consecutive rising edges of internal oscillator represents an entire period.

6 Revision history

Table 2. Document revision history

Date	Revision	Changes
22-Nov-2012	1	Initial release.