AN2633

Precise, Ultra-Low-Power Timing using Periodic Enabling of the 32.768 kHz External Crystal Oscillator for Recalibration of the ULP Internal Oscillator

Introduction

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An increasing number of AVR® devices contain both an ultra-low-power (ULP) internal oscillator and an oscillator module that functions only when an external 32.768 kHz crystal is connected to the device. This application note describes a method of achieving both precise timing and ultra-low power consumption by periodically enabling the 32.768 kHz external crystal oscillator for recalibration of the ULP internal oscillator. Example code is provided for an ATtiny416 device. The Real-Time Counter (RTC) module on the device is continuously driven by the ULP internal oscillator to keep track of time. Most of the time, the 32.768 kHz crystal oscillator is disabled so that it does not consume power. However, periodically (every 15 minutes in the example code) the crystal oscillator is enabled for several seconds and used by the 16-bit Timer/Counter Type B (TCB) to accurately measure the duration between successive "ticks" of the RTC module. This allows crystal-oscillator-like timing precision to be achieved as well as ultra-low power consumption because the crystal oscillator is disabled more than 99% of the time.

Features

- Achieve timing precision of external crystal oscillator with ultra-low power consumption of internal oscillator

Table of Contents

1. Relevant Devices

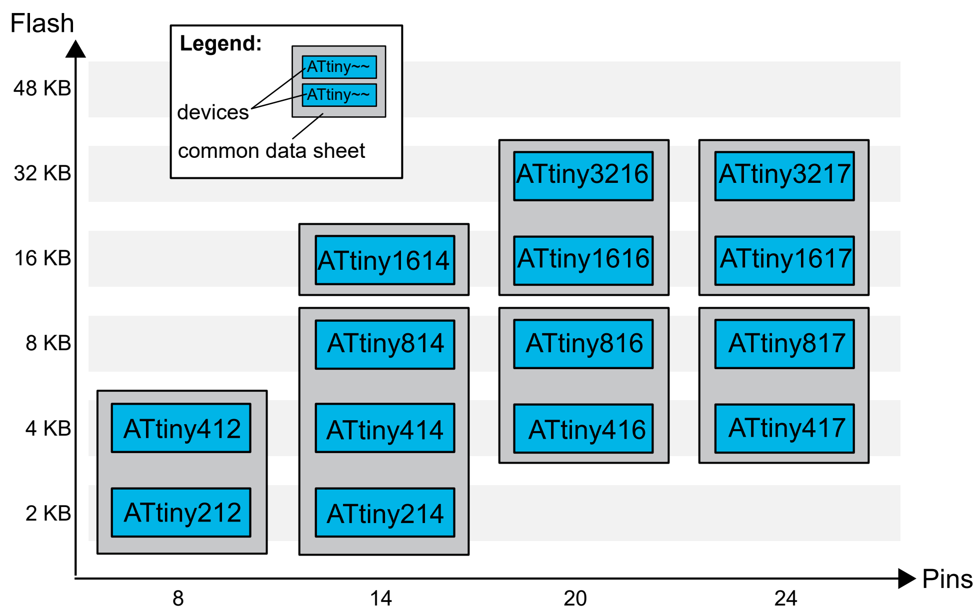
This chapter lists the relevant devices for this document.

1.1 tinyAVR® 1-series

The figure below shows the tinyAVR® 1-series devices, laying out pin count variants and memory sizes:

- Vertical migration upwards is possible without code modification, as these devices are pin compatible and provide the same or more features. Downward migration may require code modification due to fewer available instances of some peripherals.
- Horizontal migration to the left reduces the pin count and therefore, the available features.

Figure 1-1. tinyAVR® 1-series Overview



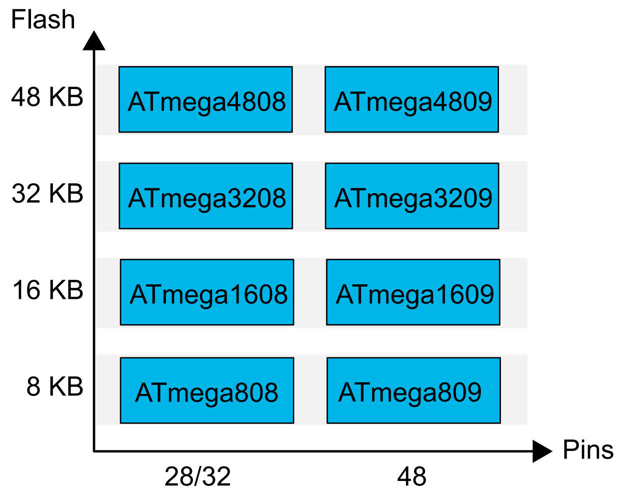
Devices with different Flash memory size typically also have different SRAM and EEPROM.

1.2 megaAVR® 0-series

The figure below shows the megaAVR® 0-series devices, laying out pin count variants and memory sizes:

- Vertical migration is possible without code modification, as these devices are fully pin and feature compatible.
- Horizontal migration to the left reduces the pin count and therefore the available features.

Figure 1-2. megaAVR® 0-series Overview



Devices with different Flash memory size typically also have different SRAM and EEPROM.

2. Oscillator Types

An increasing number of AVR devices contain both an ultra-low-power (ULP) internal oscillator and an oscillator module that functions only when an external 32.768 kHz crystal is connected to the device. The internal oscillator achieves extremely low power consumption, but its timing accuracy is not sufficient for some applications. A typical ULP oscillator may have a ±1% frequency tolerance. For some applications this is not an issue, but in other applications such as long-term timing, this can result in an error of 14 minutes per 24-hour day.

For applications that require precise timing, the external 32.768 kHz crystal oscillator circuit is provided. A crystal oscillator may have a frequency tolerance on the order of ±10ppm or less than one second of timing error per 24-hour day, so it is well suited for applications that require precise long-term timing. It does, however, have two disadvantages. First, an external crystal must be connected to the AVR device, adding cost and area to the printed circuit board. Second, the crystal oscillator has higher power consumption than the internal oscillator.

3. Theory

For a timing-critical application, there is no way to avoid the requirement for an external crystal to make the crystal oscillator circuit operational, but it is possible to do something about its power consumption. Instead of allowing the crystal oscillator to run continuously, it is possible to just enable the crystal oscillator on an occasional basis and use it to precisely measure the frequency of the internal ULP oscillator. Then the crystal oscillator can be disabled while the ULP oscillator continues to run. As long as the ULP oscillator is reasonably stable until the next measurement, it is possible to keep accurate time using it because its frequency is precisely known. Fortunately, AVR devices provide additional internal modules that make it feasible to implement this approach.

On the ATtiny416 device used in this example, there are two key modules that make this feasible; the Real-Time Counter (RTC) and the 16-bit Timer/Counter Type B (TCB). With appropriate setup, the RTC can be clocked by the internal ULP oscillator to generate a periodic interrupt/event every *n* ULP oscillator cycles, where *n* is configurable. The TCB can count the number of *crystal* oscillator cycles between successive interrupts/events from the RTC, thereby providing a precise measurement of the internal ULP oscillator timing.

Once the precise measurement of the internal ULP oscillator is available, it can be used to update a time counter every time a ULP oscillator interrupt is received, instead of updating the time counter with a nominal value for the ULP oscillator.

4. Implementation

The example implementation for the ATtiny416 is written in C. The two key modules used are the Real-Time Counter (RTC) and the 16-bit Timer/Counter Type B (TCB). The Event System (EVSYS) is also used to connect the output of the RTC to the input of the TCB. With proper configuration of the RTC, EVSYS, and TCB, the TCB can be used to count the number of 32.768 kHz external crystal oscillator cycles between consecutive overflow events from the RTC.

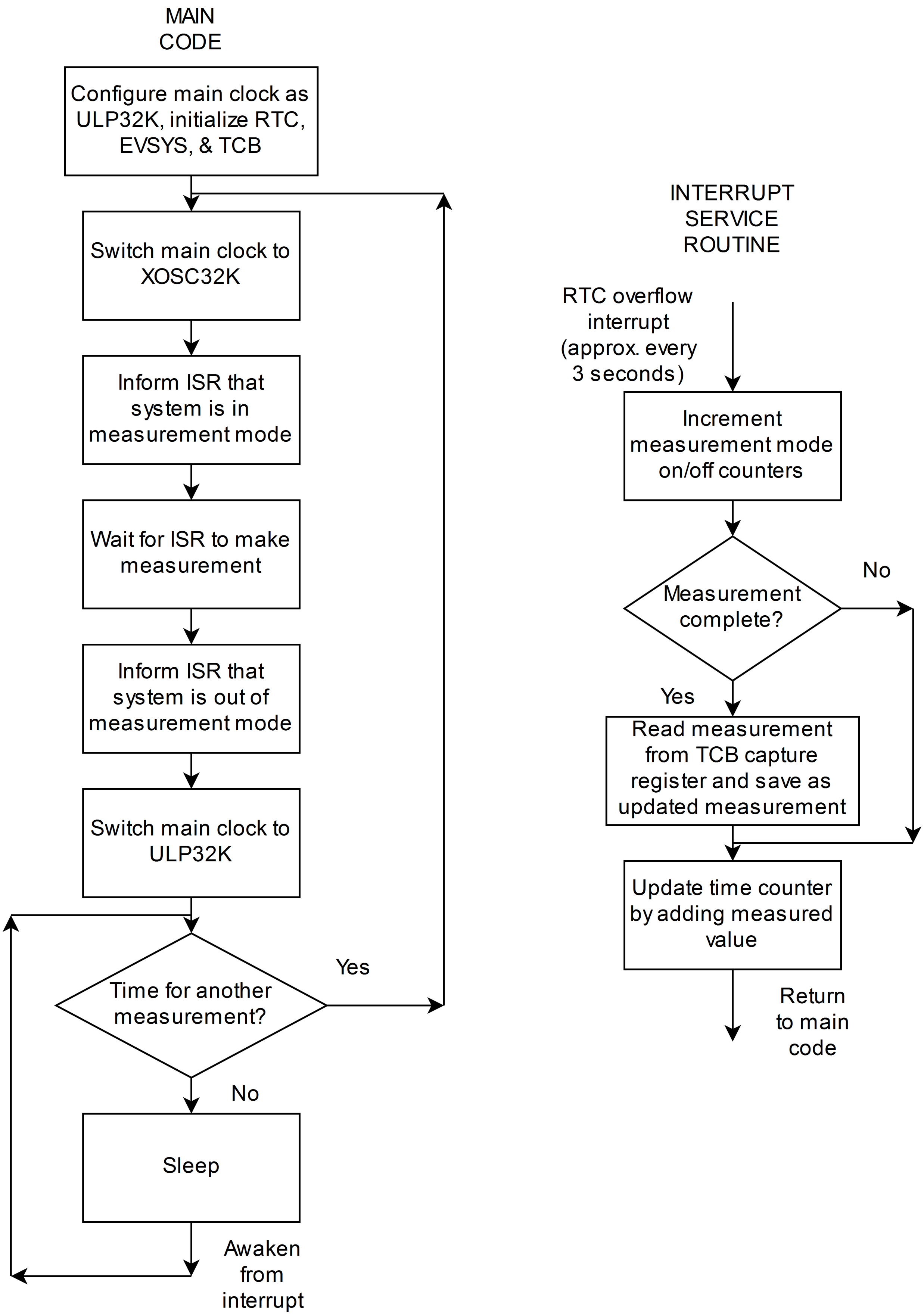
The clock of the RTC is configured to be the OSCULP32 *divided by 32*, for a nominal clock frequency of 1024 Hz. The RTC prescaler is configured with one, and the RTC.PER (period) register is configured with (3*1024)-1 = 3071, so the RTC will generate an overflow interrupt/event approximately every three seconds. The RTC RUNSTDBY bit is configured to one so that the RTC will continue running while the device is in sleep mode.

The EVSYS is configured with the RTC overflow event connected to the TCB input.

The TCB is configured with its clock source as the main clock of the device with no prescaling. When a measurement is in progress, the main clock of the device is the 32.768 kHz external crystal oscillator. The TCB count mode (CNTMODE) is configured as *input capture frequency measurement*, and the capture event input (CAPTEI) is enabled. With this configuration, the TCB will capture and store its count value at each RTC overflow event, then reset its counter. This allows the TCB to effectively count the number of 32.768 kHz clock cycles between consecutive input events. Because the TCB counter is only 16 bits wide (maximum count of 65535) and there will be roughly 3s*32768 Hz = 98304 clock cycles between ticks, the TCB counter will have overflowed once during the measurement. Thus, 65536 must be added to the value read from the TCB capture register to obtain the true number of counts between consecutive events.

A flowchart for the software implementation is shown in the following figure.

Figure 4-1. Flowchart



After the device starts up, the main code performs the following steps:

1. The main clock of the device is switched to the internal 32.768 kHz ULP oscillator (OSCULP32K). By default, the device starts up with a different main clock, so the main clock must be explicitly changed. The main clock provides the clock to the CPU, RAM, NVM, and many peripherals. The RTC, EVSYS, and TCB are configured as described earlier so that the TCB can measure the interval between successive RTC overflow interrupts/events.
2. The main clock of the device is switched to the external 32.768 kHz crystal oscillator (XOSC32K). The crystal oscillator is allowed a two-second start-up time to become stable, so there will be about two seconds before the main clock is actually switched.
3. The value of a variable is changed to indicate to the RTC ISR that the system is now in Measurement mode.
4. The main code waits for the interrupt service routine to read the captured value (measurement) from the TCB.
5. After the main code detects that the measurement is complete, it changes the value of a variable to indicate that system is not in Measurement mode.
6. The main clock of the device is switched back to OSCULP32K. Since nothing is using the crystal oscillator (XOSC32K), it will be disabled automatically by hardware in the device to save power.
7. The RTC ISR counts the number of RTC ticks that have occurred while the system is *not* in Measurement mode. The CPU remains in sleep mode until the number of RTC ticks reaches 300 (approximately 900 seconds or 15 minutes). When it is time for another measurement, the CPU goes back to step two.

The RTC ISR performs the following steps each time it is triggered:

1. Counters are incremented to keep track of how many RTC interrupts have occurred while not in Measurement mode and while in Measurement mode.
2. If two ticks have occurred while in Measurement mode, a new measurement is complete, so the captured count is read from the TCB and saved in a variable. Because the TCB is only 16 bits wide (maximum count of 65535) and there will be approximately 3s*32768 Hz = 98304 clock cycles between ticks, the TCB will have overflowed once during the measurement. Thus, 65536 must be added to the measurement to account for this. Once this has been done, the measurement represents the precise number of 32.768 kHz crystal oscillator cycles in each RTC tick.
3. The measurement is added to a counter that keeps track of time in terms of (1/32768)s = 30.518 μs units.

One important consideration in this example is the choice of duration between consecutive ticks of the RTC. Since a 32768 Hz clock is being used to measure the duration, using a one-second RTC tick would have led to only (1/32768) or 31 ppm resolution in measuring the tick duration. This could have led to errors on the order of several seconds per day. A three-second RTC tick was therefore chosen in order to improve the measurement resolution to (1/(3*32768)) or 10 ppm. However, this also meant that the 16-bit TCB counter would overflow once while making a measurement, so 65536 must always be added to the TCB result to get the true measurement value.

Depending on the detailed requirements of the application, it is possible that the 16-bit Timer/Counter Type A (TCA) could be used to count RTC events or ticks instead of using an RTC ISR for this purpose. This could provide additional power savings since the device would remain in sleep mode for longer periods of time. The TCA could be programmed, for example, to generate an interrupt every 20 RTC ticks, which is one minute.

5. Get Source Code from Atmel | START

The example code is available through Atmel | START, which is a web-based tool that enables configuration of application code through a Graphical User Interface (GUI). The code can be downloaded for both Atmel Studio and IAR Embedded Workbench® via the direct example code-link(s) below or the *BROWSE EXAMPLES* button on the Atmel | START front page.

Atmel | START web page: http://microchip.com/start

Example Code

Precise ULP Timing P4

- http://start.atmel.com/#example/Atmel:precise_ulp_timing_p4:1.0.0::Application:Precise_ULP_Timing_P4:

Press *User guide* in Atmel | START for details and information about example projects. The *User guide* button can be found in the example browser, and by clicking the project name in the dashboard view within the Atmel | START project configurator.

Atmel Studio

Download the code as an .atzip file for Atmel Studio from the example browser in Atmel | START, by clicking *DOWNLOAD SELECTED EXAMPLE*. To download the file from within Atmel | START, click *EXPORT PROJECT* followed by *DOWNLOAD PACK*.

Double-click the downloaded .atzip file and the project will be imported to Atmel Studio 7.0.

IAR Embedded Workbench

For information on how to import the project in IAR Embedded Workbench, open the Atmel | START user guide, select *Using Atmel Start Output in External Tools*, and *IAR Embedded Workbench*. A link to the Atmel | START user guide can be found by clicking *About* from the Atmel | START front page or *Help And Support* within the project configurator, both located in the upper right corner of the page.

6. Revision History

Doc. Rev.	Date	Comments
B	10/2018	The chapter on Relevant Devices has been updated to include 8/16 KB megaAVR 0-series devices and 32 KB tinyAVR 1-series devices.
A	01/2018	Initial document release

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