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

Author: Lloyd Clark, Microchip Technology Inc.

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

Introduction......................................................................................................................1

Features..........................................................................................................................1

1. Relevant Devices.......................................................................................................3
   1.1. tinyAVR® 1-series................................................................................................. 3
   1.2. megaAVR® 0-series............................................................................................... 3

2. Oscillator Types.........................................................................................................5

3. Theory.......................................................................................................................6

4. Implementation..........................................................................................................7

5. Get Source Code from Atmel | START....................................................................10

6. Revision History.......................................................................................................11

The Microchip Web Site................................................................................................12

Customer Change Notification Service........................................................................12

Customer Support........................................................................................................12

Microchip Devices Code Protection Feature...............................................................12

Legal Notice................................................................................................................13

Trademarks...................................................................................................................13

Quality Management System Certified by DNV.............................................................14

Worldwide Sales and Service........................................................................................15
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.
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 \((3\times1024)-1 = 3071\), 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 \(3s\times32768\) 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

**MAIN CODE**

Configure main clock as ULP32K, initialize RTC, EVSYS, & TCB

Switch main clock to XOSC32K

Inform ISR that system is in measurement mode

Wait for ISR to make measurement

Inform ISR that system is out of measurement mode

Switch main clock to ULP32K

**INTERUPT SERVICE ROUTINE**

RTC overflow interrupt (approx. every 3 seconds)

Increment measurement mode on/off counters

Measurement complete?

Yes

Read measurement from TCB capture register and save as updated measurement

Update time counter by adding measured value

Return to main code

No

Time for another measurement?

Yes

Sleep

Awaken from interrupt
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 $3s \times 32768$ 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 $(1/(3 \times 32768))$ 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](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](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.
## Revision History

<table>
<thead>
<tr>
<th>Doc. Rev.</th>
<th>Date</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>10/2018</td>
<td>The chapter on Relevant Devices has been updated to include 8/16 KB megaAVR 0-series devices and 32 KB tinyAVR 1-series devices.</td>
</tr>
<tr>
<td>A</td>
<td>01/2018</td>
<td>Initial document release</td>
</tr>
</tbody>
</table>
The Microchip Web Site

Microchip provides online support via our web site at http://www.microchip.com/. This web site is used as a means to make files and information easily available to customers. Accessible by using your favorite Internet browser, the web site contains the following information:

- **Product Support** – Data sheets and errata, application notes and sample programs, design resources, user’s guides and hardware support documents, latest software releases and archived software
- **General Technical Support** – Frequently Asked Questions (FAQ), technical support requests, online discussion groups, Microchip consultant program member listing
- **Business of Microchip** – Product selector and ordering guides, latest Microchip press releases, listing of seminars and events, listings of Microchip sales offices, distributors and factory representatives

Customer Change Notification Service

Microchip’s customer notification service helps keep customers current on Microchip products. Subscribers will receive e-mail notification whenever there are changes, updates, revisions or errata related to a specified product family or development tool of interest.


Customer Support

Users of Microchip products can receive assistance through several channels:

- Distributor or Representative
- Local Sales Office
- Field Application Engineer (FAE)
- Technical Support

Customers should contact their distributor, representative or Field Application Engineer (FAE) for support. Local sales offices are also available to help customers. A listing of sales offices and locations is included in the back of this document.

Technical support is available through the web site at: http://www.microchip.com/support

Microchip Devices Code Protection Feature

Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
- There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip’s Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.
- Microchip is willing to work with the customer who is concerned about the integrity of their code.
Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as "unbreakable."

Code protection is constantly evolving. We at Microchip are committed to continuously improving the code protection features of our products. Attempts to break Microchip’s code protection feature may be a violation of the Digital Millennium Copyright Act. If such acts allow unauthorized access to your software or other copyrighted work, you may have a right to sue for relief under that Act.

**Legal Notice**

Information contained in this publication regarding device applications and the like is provided only for your convenience and may be superseded by updates. It is your responsibility to ensure that your application meets with your specifications. MICROCHIP MAKES NO REPRESENTATIONS OR WARRANTIES OF ANY KIND WHETHER EXPRESS OR IMPLIED, WRITTEN OR ORAL, STATUTORY OR OTHERWISE, RELATED TO THE INFORMATION, INCLUDING BUT NOT LIMITED TO ITS CONDITION, QUALITY, PERFORMANCE, MERCHANTABILITY OR FITNESS FOR PURPOSE. Microchip disclaims all liability arising from this information and its use. Use of Microchip devices in life support and/or safety applications is entirely at the buyer’s risk, and the buyer agrees to defend, indemnify and hold harmless Microchip from any and all damages, claims, suits, or expenses resulting from such use. No licenses are conveyed, implicitly or otherwise, under any Microchip intellectual property rights unless otherwise stated.

**Trademarks**

The Microchip name and logo, the Microchip logo, AnyRate, AVR, AVR logo, AVR Freaks, BitCloud, chipKIT, chipKIT logo, CryptoMemory, CryptoRF, dsPIC, FlashFlex, flexPWR, Heldo, JukeBlox, KeeLoq, Kleer, LANCheck, LINK MD, maXSylus, maXTouch, MediaLB, megaAVR, MOST, MOST logo, MPLAB, OptoLyzer, PIC, picoPower, PICSTART, PIC32 logo, Prochip Designer, QTouch, SAM-BA, SpyNIC, SST, SST Logo, SuperFlash, tinyAVR, UNI/O, and XMEGA are registered trademarks of Microchip Technology Incorporated in the U.S.A. and other countries.

ClockWorks, The Embedded Control Solutions Company, EtherSynch, Hyper Speed Control, HyperLight Load, IntelliMOS, mTouch, Precision Edge, and Quiet-Wire are registered trademarks of Microchip Technology Incorporated in the U.S.A.


SQTP is a service mark of Microchip Technology Incorporated in the U.S.A.

Silicon Storage Technology is a registered trademark of Microchip Technology Inc. in other countries.

GestIC is a registered trademark of Microchip Technology Germany II GmbH & Co. KG, a subsidiary of Microchip Technology Inc., in other countries.

All other trademarks mentioned herein are property of their respective companies.
ISO/TS 16949
Microchip received ISO/TS-16949:2009 certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona; Gresham, Oregon and design centers in California and India. The Company’s quality system processes and procedures are for its PIC® MCUs and dsPIC® DSCs, KEELQ® code hopping devices, Serial EEPROMs, microperipherals, nonvolatile memory and analog products. In addition, Microchip’s quality system for the design and manufacture of development systems is ISO 9001:2000 certified.
### AMERICAS
- **Corporate Office**
  - 2355 West Chandler Blvd.
  - Chandler, AZ 85224-6199
  - Tel: 480-792-7200
  - Fax: 480-792-7277
  - Technical Support: http://www.microchip.com/support
  - Web Address: www.microchip.com
- **Atlanta**
  - Duluth, GA
  - Tel: 678-957-9614
  - Fax: 678-957-1455
- **Austin, TX**
  - Tel: 512-257-3370
- **Boston**
  - Westborough, MA
  - Tel: 774-760-0087
  - Fax: 774-760-0088
- **Chicago**
  - Itasca, IL
  - Tel: 630-285-0071
  - Fax: 630-285-0075
- **Dallas**
  - Addison, TX
  - Tel: 972-818-7423
  - Fax: 972-818-2924
- **Detroit**
  - Novi, MI
  - Tel: 248-848-4000
- **Houston, TX**
  - Tel: 281-894-5983
- **Indianapolis**
  - Noblesville, IN
  - Tel: 317-773-8323
  - Fax: 317-773-5453
- **Los Angeles**
  - Mission Viejo, CA
  - Tel: 949-462-9523
  - Fax: 949-462-9608
  - Tel: 951-273-7800
- **Raleigh, NC**
  - Tel: 919-844-7510
- **New York, NY**
  - Tel: 631-435-6000
- **San Jose, CA**
  - Tel: 408-735-9110
  - Tel: 408-436-4270
- **Canada - Toronto**
  - Tel: 905-695-1980
  - Fax: 905-695-2078

### ASIA/PACIFIC
- **Australia - Sydney**
  - Tel: 61-2-9868-6733
- **China - Beijing**
  - Tel: 86-10-8569-7000
- **China - Chengdu**
  - Tel: 86-28-8665-5511
- **China - Chongqing**
  - Tel: 86-23-8980-9588
- **China - Dongguan**
  - Tel: 86-769-8702-9880
- **China - Guangzhou**
  - Tel: 86-20-8755-8029
- **China - Hangzhou**
  - Tel: 86-571-8792-8115
- **China - Hong Kong SAR**
  - Tel: 852-2943-5100
- **China - Nanjing**
  - Tel: 86-25-8473-2460
- **China - Qingdao**
  - Tel: 86-632-8502-7355
- **China - Shanghai**
  - Tel: 86-21-3326-8000
- **China - Shenyang**
  - Tel: 86-24-6233-2829
- **China - Shenzhen**
  - Tel: 86-755-8864-2200
- **China - Suzhou**
  - Tel: 86-20-6233-5300
- **China - Xian**
  - Tel: 86-29-8833-7252
- **China - Xiamen**
  - Tel: 86-592-2388138
- **China - Zhuhai**
  - Tel: 86-756-3210040
- **India - Bangalore**
  - Tel: 91-80-3090-4444
- **India - New Delhi**
  - Tel: 91-11-4160-8631
- **India - Pune**
  - Tel: 91-20-4121-0141
- **Japan - Osaka**
  - Tel: 81-6-6152-7160
- **Japan - Tokyo**
  - Tel: 81-3-6880-3770
- **Korea - Daegu**
  - Tel: 82-53-744-4301
- **Korea - Seoul**
  - Tel: 82-2-554-7200
- **Malaysia - Kuala Lumpur**
  - Tel: 60-3-7651-7906
- **Malaysia - Penang**
  - Tel: 60-4-227-8870
- **Philippines - Manila**
  - Tel: 63-2-634-9065
- **Singapore**
  - Tel: 65-6334-8870
- **Taiwan - Hsin Chu**
  - Tel: 886-3-577-8366
- **Taiwan - Kaohsiung**
  - Tel: 886-7-213-7830
- **Taiwan - Taipei**
  - Tel: 886-2-2508-8600
- **Thailand - Bangkok**
  - Tel: 66-2-694-1351
- **Vietnam - Ho Chi Minh**
  - Tel: 84-28-5448-2100

### EUROPE
- **Austria - Wels**
  - Tel: 43-7242-2244-39
  - Fax: 43-7242-2244-393
- **Denmark - Copenhagen**
  - Tel: 45-4450-2828
  - Fax: 45-4485-2829
- **Finland - Espoo**
  - Tel: 358-9-4520-820
- **France - Paris**
  - Tel: 33-1-69-53-63-20
  - Fax: 33-1-69-30-90-79
- **Germany - Garching**
  - Tel: 49-8931-9700
- **Germany - Haan**
  - Tel: 49-2129-3766400
- **Germany - Heilbronn**
  - Tel: 49-7131-67-3636
- **Germany - Karlsruhe**
  - Tel: 49-721-625370
- **Germany - Munich**
  - Tel: 49-89-627-144-0
  - Fax: 49-89-627-144-44
- **Germany - Rosenheim**
  - Tel: 49-8031-354-560
- **Israel - Ra’anana**
  - Tel: 972-9-744-7705
- **Italy - Milan**
  - Tel: 39-0331-742611
  - Fax: 39-0331-466781
- **Italy - Padova**
  - Tel: 39-049-7625286
- **Netherlands - Drunen**
  - Tel: 31-416-690399
  - Fax: 31-416-690340
- **Norway - Trondheim**
  - Tel: 47-72884388
- **Poland - Warsaw**
  - Tel: 48-22-3325373
- **Romania - Bucharest**
  - Tel: 40-21-407-87-50
- **Spain - Madrid**
  - Tel: 34-91-708-08-90
  - Fax: 34-91-708-08-91
- **Sweden - Gothenberg**
  - Tel: 46-31-704-60-40
- **Sweden - Stockholm**
  - Tel: 46-8-5090-4654
- **UK - Wokingham**
  - Tel: 44-118-921-5800
  - Fax: 44-118-921-5820

© 2018 Microchip Technology Inc.