AN3342

SleepWalking with Event System Using the SAM E54 AN

Introduction

The SAM E54 is a 32-bit ARM® Cortex®-M4F based Flash microcontroller that provides features to reduce power consumption through different sleep modes, such as Idle, Standby, Hibernate, and Off. Additionally, the SAM E54 provides an advanced Low-Power Operation mode known as SleepWalking. SleepWalking enables the SAM E54 microcontrollers to wake up peripherals temporarily and asynchronously without waking up the CPU.

SleepWalking is based on event propagation managed by the Event System. It allows peripherals to work together without CPU intervention to solve complex tasks using minimal gates and the lowest possible power consumption.

To illustrate the benefits of SleepWalking using the Event System, a demonstrative application is provided along with this document. This application uses an ADC with a Window Monitoring feature in Standby mode for the following use cases:

- Standby mode with Interrupts (IRQ)
- Standby mode with Event System (SleepWalking)

This document also provides comparison on power consumption between these two use cases.

This demo application is developed using the MPLAB® X IDE on the MPLAB Harmony 3 Software Framework.

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1. SAM E54 Low-Power Features Overview

1.1 Event System (EVSYS)

The EVSYS is part of the SAM E54 architecture, which allows autonomous, low-latency, and configurable communication between peripherals.

Several peripherals can be configured to generate and respond to signals known as events. The exact condition to generate an event, or the action taken upon receiving an event is specific to each peripheral.

Peripherals that respond to events are called event users, and peripherals that generate events are called event generators. A peripheral can receive events from multiple generators, and generate events for multiple users. Communication is made without CPU intervention and without consuming system bus or RAM. This reduces the load of the CPU and other system resources, compared to a traditional interrupt-based system.

The following figures compare an application without an Event System to an application with an Event System. In both the applications, Timer Counter 0 triggers the ADC conversion after a periodic interval of ‘x’ milliseconds and Timer Counter 1 triggers the DAC after ‘x’ milliseconds, and AC triggers the PWM.

Application without EVSYS shows that for a typical application the CPU is quickly overloaded, which increases power consumption. Whereas in Application with EVSYS, the Event System allows all the peripherals to interact without requiring CPU intervention, until a relevant event occurs.

Figure 1-1. Application without EVSYS

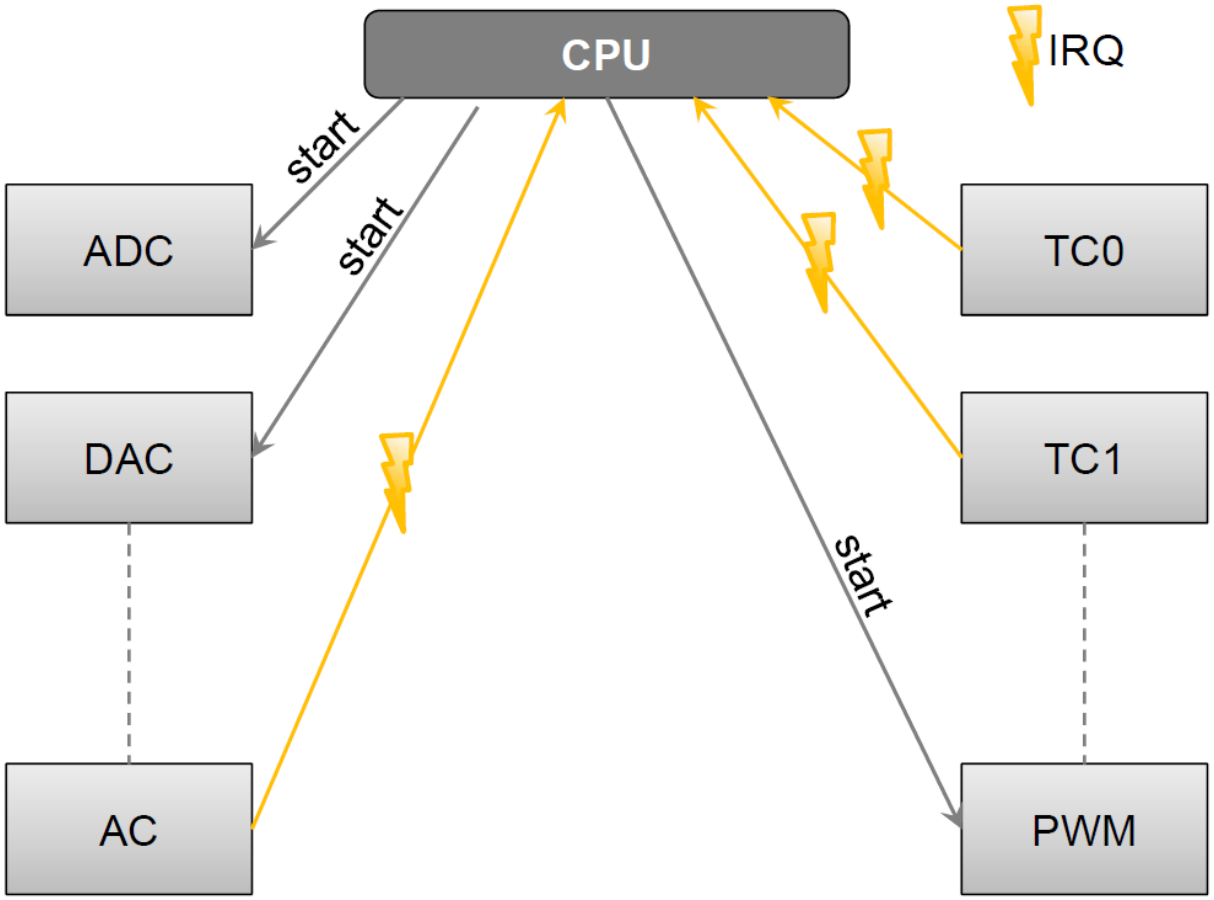
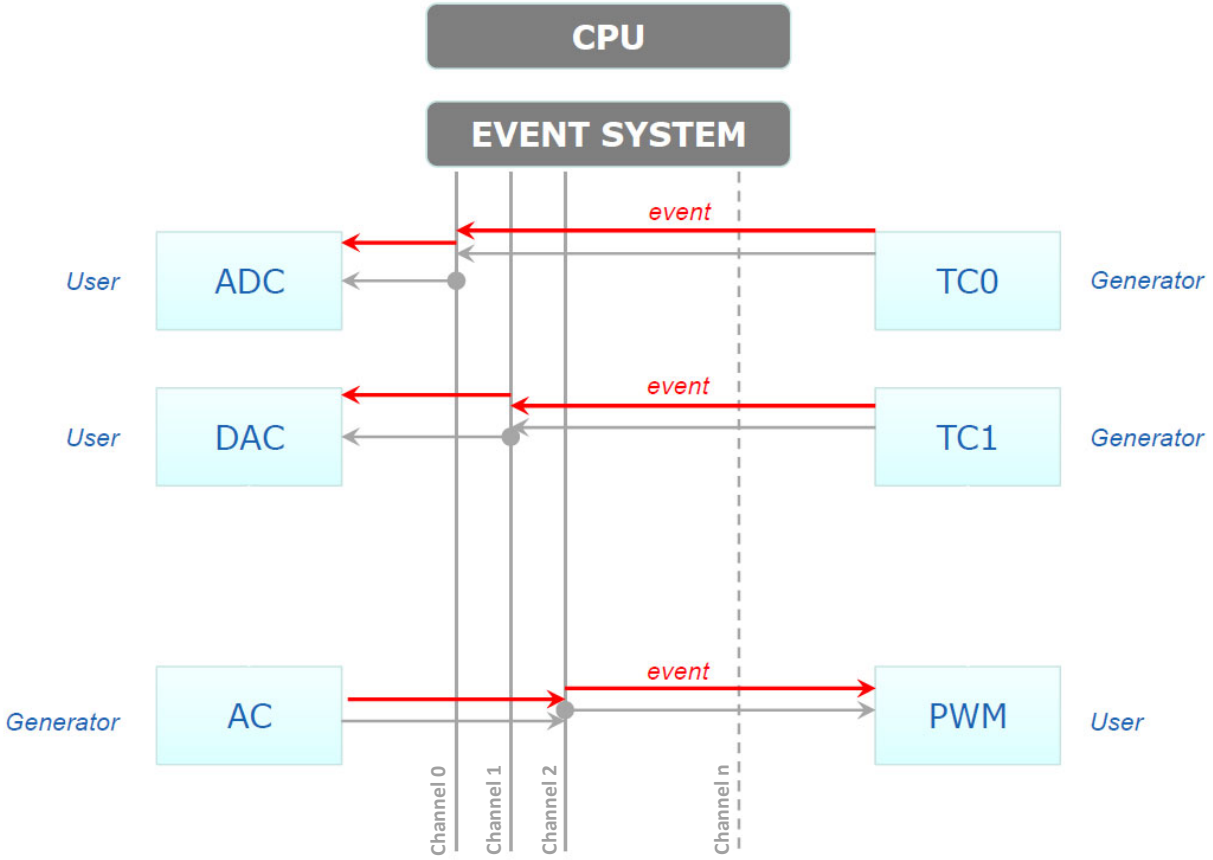


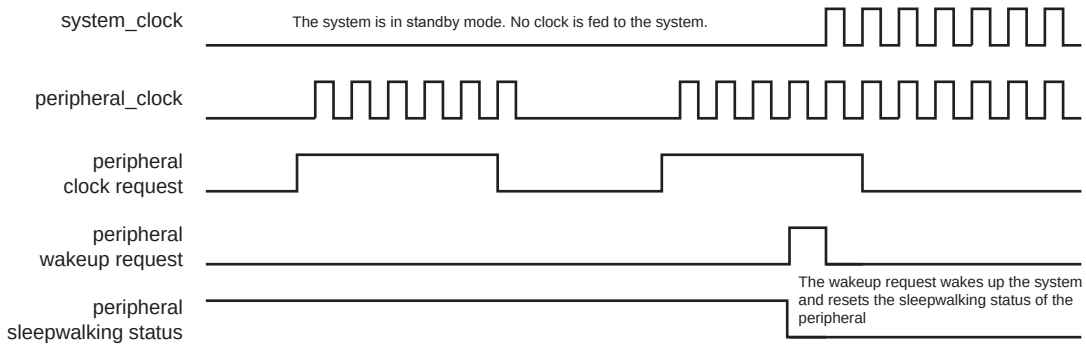
Figure 1-2. Application with EVSYS



1.2 SleepWalking

SleepWalking is the capability of a device to temporarily and asynchronously wake up clocks for a peripheral to perform a task without waking up the CPU from Standby mode. SleepWalking allows the CPU to sleep until a relevant interrupt occurs. To perform SleepWalking, the Event System is required to interconnect peripherals. The Event System is used to connect an event generator peripheral to an event user peripheral. When CPU is in Standby mode, the event user peripheral can request its clock using an on-demand feature. Upon receiving an event generator peripheral trigger, it will perform its task autonomously as shown in the following figure:

Figure 1-3. SleepWalking Principle



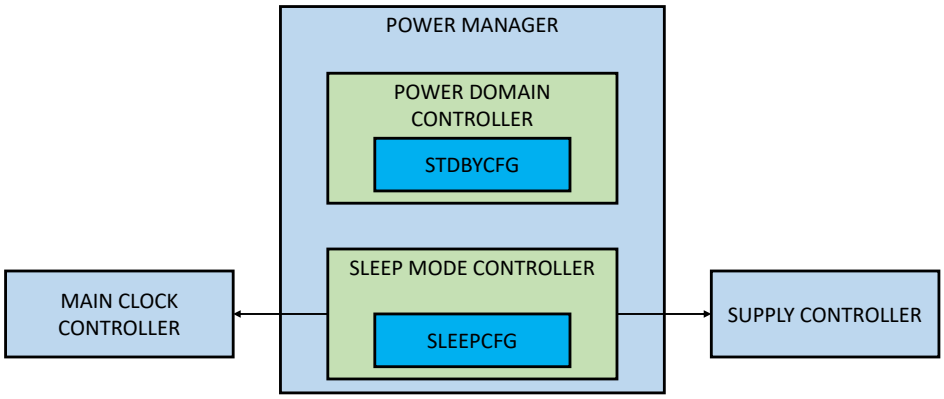
In the figure above, the peripheral requests its clock and runs without waking up the system clock. Once the peripheral is met with a valid condition during its second clock request, a wake-up request is sent to the CPU, which wakes up the CPU from Standby Sleep mode, and activates all clocks of the device (system and peripheral clocks).

SleepWalking is accomplished by the peripheral using the Event System to interconnect the peripherals in Standby mode without CPU intervention. The CPU will not wake up and the SRAM retention will still active until the appropriate condition or interrupt occurs.

1.3 Power Manager (PM)

The PM controls the sleep modes of the device and the power domain gating of the device.

Figure 1-4. Power Manager Block Diagram



PM controls the following:

- Sleep modes: Idle, Standby, Hibernate, Backup and Off
- SleepWalking available in Standby mode
- I/O lines retention in Backup mode
- SRAM and Backup RAM Retention
- Fast Wake-Up for NVM and Main Regulator

2. Low-Power Application Overview

This application is accompanied by a Low-Power Application example. The goal of this application is to compare two different low-power implementations in terms of power consumption to show the benefits of the SleepWalking feature. Alternatively the following modes run in the application:

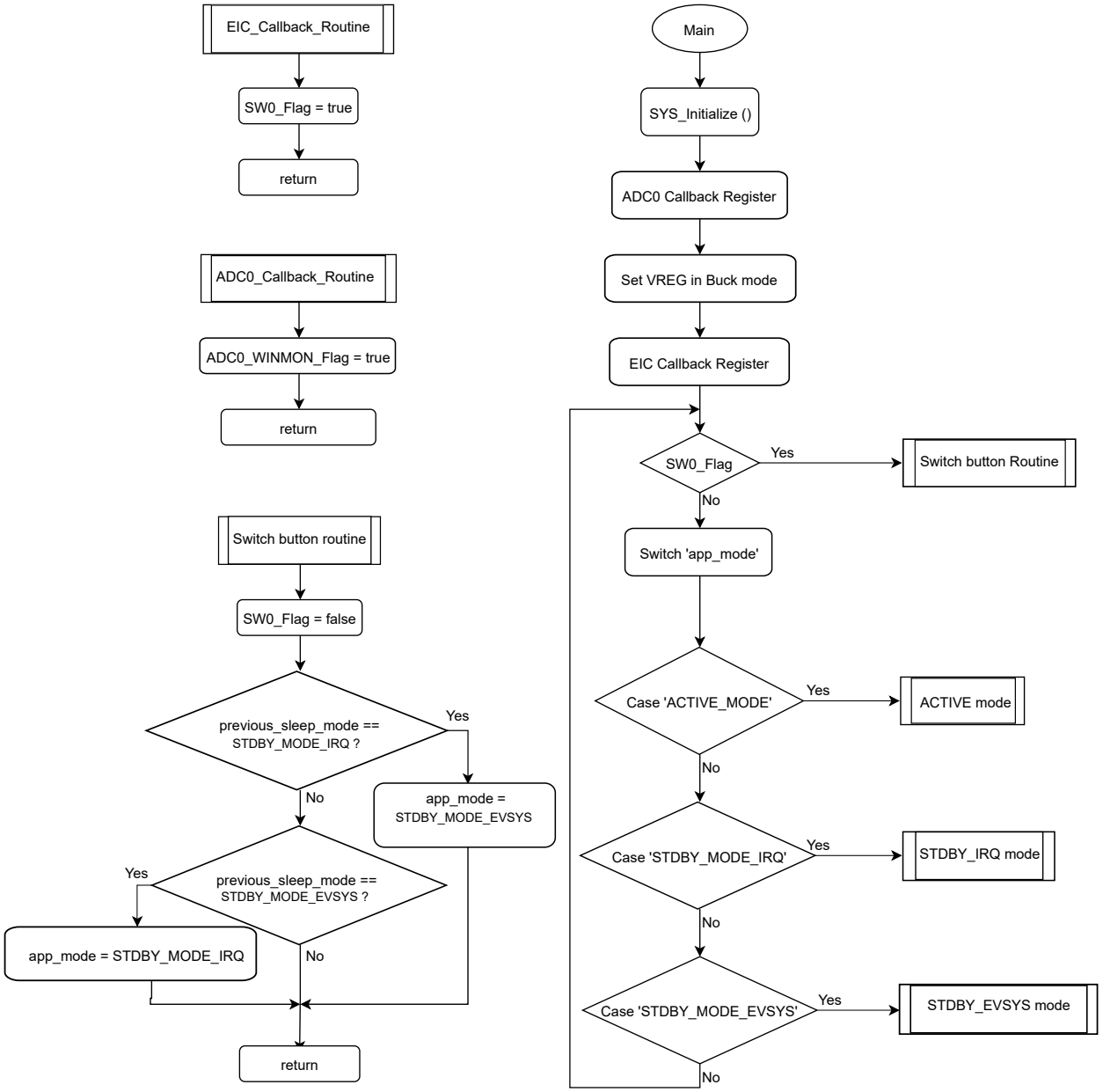
- Standby mode with Interrupts (`STDBY_IRQ_MODE`)
- Standby mode with Event System also known as SleepWalking (`STDBY_EVSYS_MODE`)
- Active mode (`ACTIVE_MODE`)

On power up, the application is in `STDBY_IRQ_MODE`. It is possible to switch from `STDBY_IRQ_MODE` to `STDBY_EVSYS_MODE` by pressing the switch button (SW0) embedded on the SAM E54 Xplained Pro board. The application wakes up from Sleep mode and enters into `ACTIVE_MODE` when the embedded light sensor on the I/O1 Xplained Pro extension kit is covered.

To implement the above functionality, the application uses the ADC peripheral in Window Monitoring mode.

The flowcharts below illustrate the additional information on the application and its different modes:

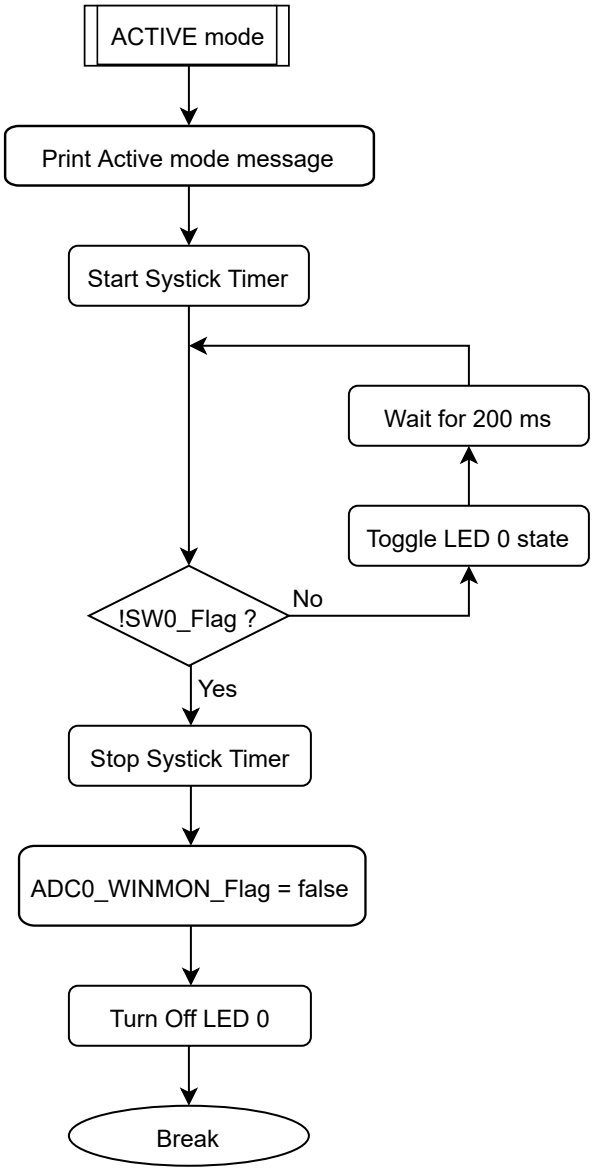
Figure 2-1. Application Flowchart



2.1 ACTIVE Mode

The application enters Active mode when an ADC Window Monitoring interrupt occurs. The application will be in the Active mode until the user presses the SW0 button to go in one of the two sleep modes:

Figure 2-2. Active Mode Flowchart

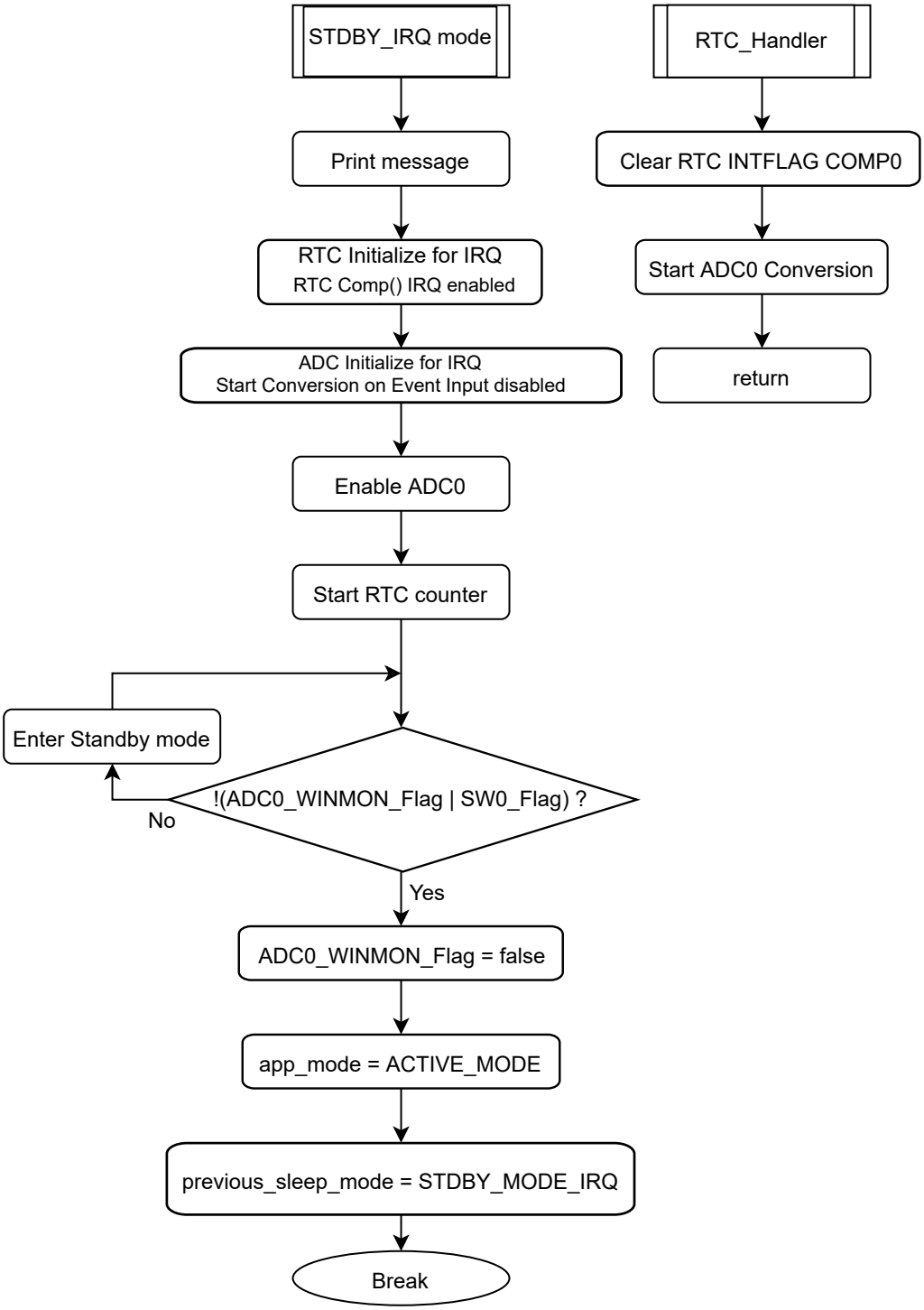


Note: The RTC and ADC peripherals are separately initialized in IRQ mode. The default initialization is using the RTC and ADC to generate events in STDBY_MODE_EVSYS. The customized initialization is used in STDBY_MODE_IRQ.

2.2 STDBY_IRQ Mode

After reset the application enters `STDBY_IRQ` mode. In this mode, the CPU is woken up every 10 milliseconds using an RTC interrupt, to start the ADC conversion. The converted value is then compared with the ADC window condition. If the converted value matches the window condition, an ADC window match interrupt occurs, and the CPU enters into Active mode, printing a message on the serial terminal. If the converted ADC value does not match the ADC window condition, the CPU goes back to sleep mode until the next RTC interrupt occurs. While the CPU is in Sleep mode, it is possible to switch to the other Sleep mode (`STDBY_MODE_EVSYS`) by pressing the SW0 button.

Figure 2-3. Standby Mode with IRQ Flowchart

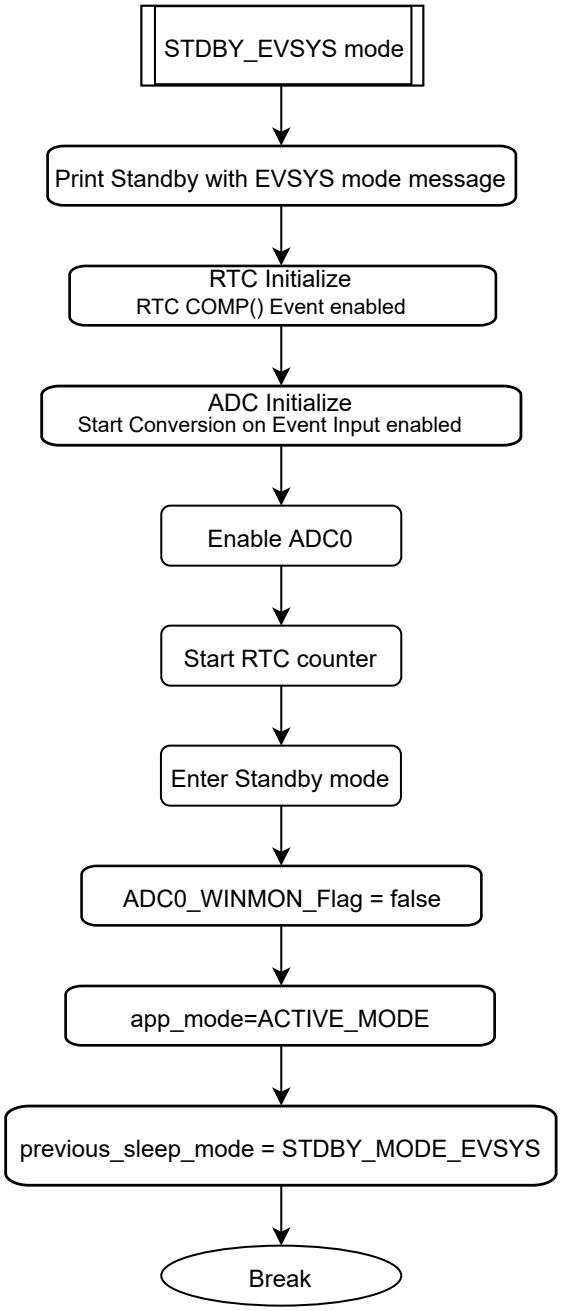


2.3 STDBY_EVSYS Mode

In this mode, Standby is used with the Event System to achieve SleepWalking. An RTC event occurs every 10 milliseconds that is transmitted from the RTC to the ADC through the Event System to launch an ADC conversion. With this method the CPU remains asleep, until an ADC Window Monitoring Interrupt, or an External Interrupt by

pressing SW0 button is detected. In the first case, the CPU wakes up and enters into Active mode. The CPU enters `STDBY_IRQ_MODE` when the SW0 button is pressed.

Figure 2-4. Standby Mode with Event System (SleepWalking) Flowchart



3. Software and Hardware Requirements

The Low-Power Application demonstration requires the following software and hardware:

Software Requirements:

- MPLAB X IDE v5.25
- MPLAB Harmony Configurator 3
  - csp v3.5.0
  - dev_packs v3.5.0
  - mhc v3.3.2
- Standalone Data Visualizer
- Tera Term or any other serial terminal

Hardware Requirements:

- 1 x Microchip SAM E54 Xplained Pro evaluation kit (board rev. 5)
- 1 x I/O1 Xplained Pro extension board
- 1 x Micro USB cable (type-A or Micro-B)

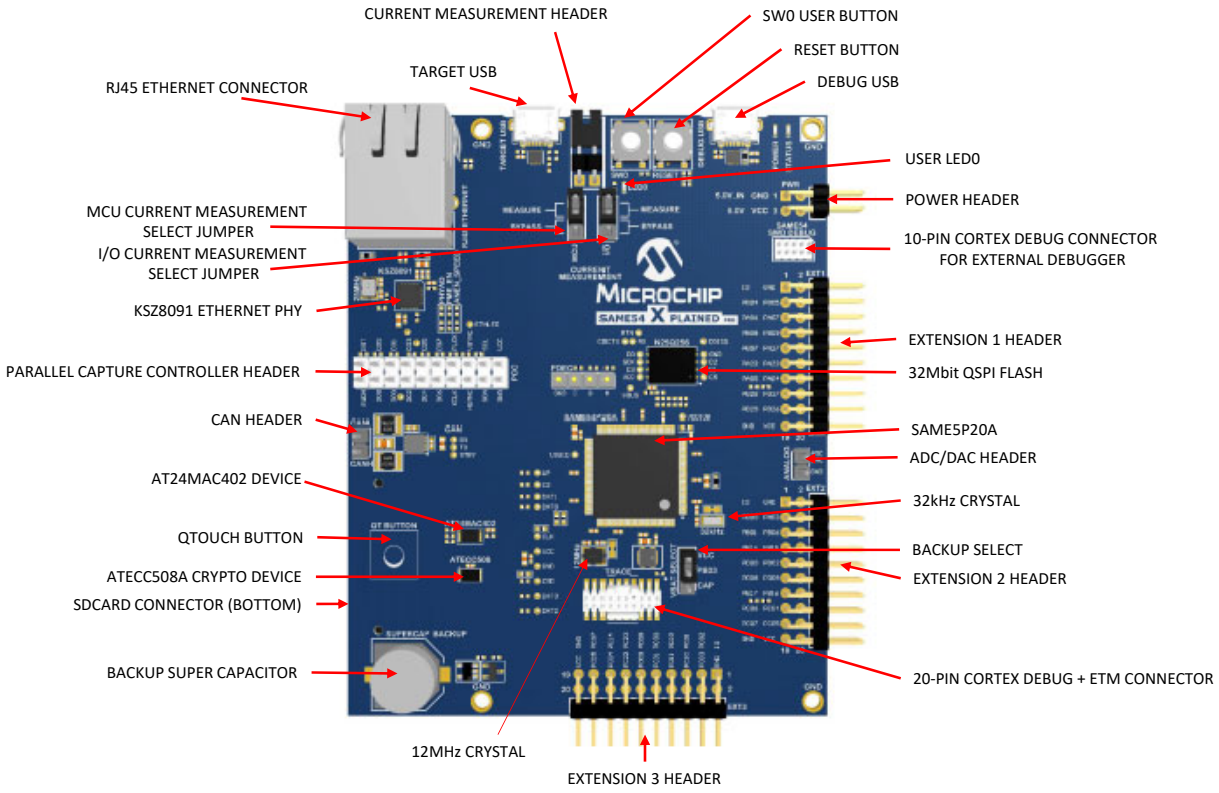
3.1 Hardware Requirements

3.1.1 SAM E54 Xplained Pro Evaluation Kit

The Microchip SAM E54 Xplained Pro Evaluation Kit is a hardware platform used to evaluate the ATSAME54P20A microcontroller. Supported by the MPLAB X integrated development platform, the evaluation kit provides an easy access to the features of the ATSAME54P20A and explains how to integrate the device in a custom design.

The Xplained Pro MCU series evaluation kits include an on-board embedded debugger, which overcomes the need of external tools to program or debug the on-board microcontroller. The Xplained Pro extension kits offer additional peripherals to extend the features of the board and ease the development of custom designs. The following figure illustrates the features of the SAM E54 Xplained Pro board.

Figure 3-1. SAM E54 Xplained Pro Evaluation Kit



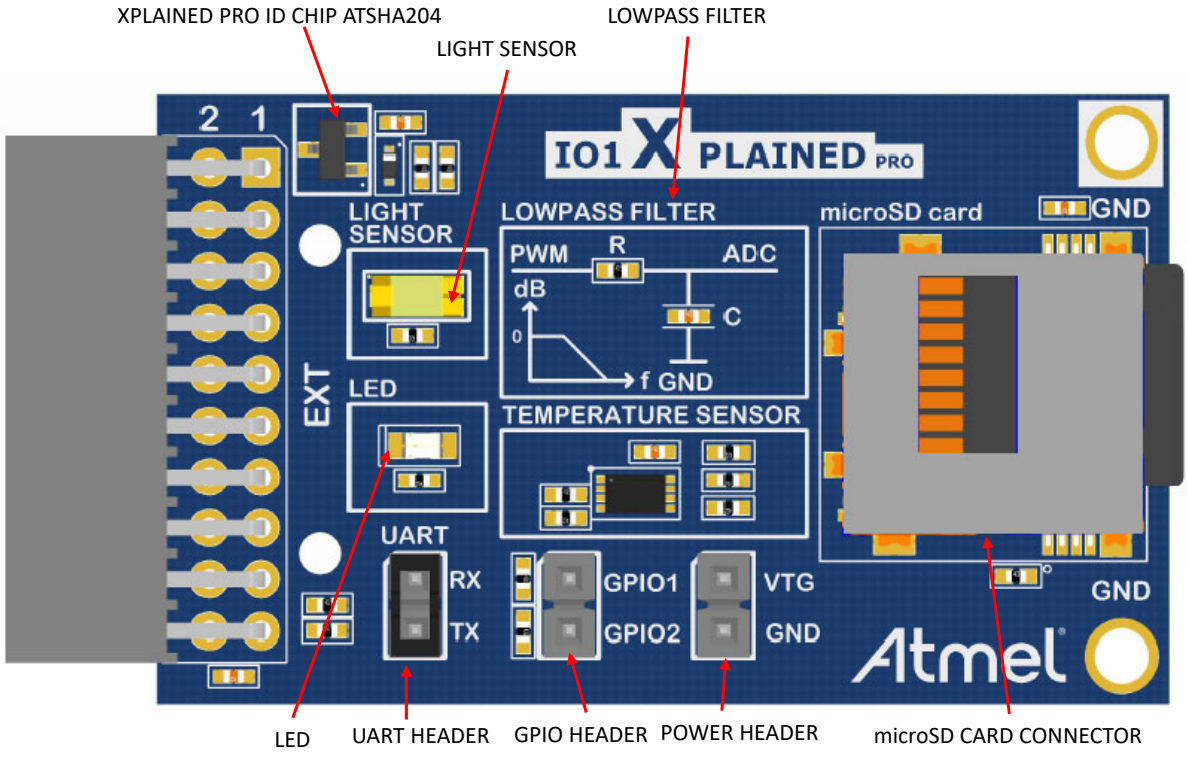
3.1.2 I/O1 Xplained Pro Extension Board

The Microchip I/O1 Xplained Pro Extension Board is a generic extension board for the Xplained Pro platform. It connects to any Xplained Pro standard extension header on any Xplained Pro MCU board.

The extension board uses the following functions on the standard Xplained Pro extension header to enhance the features of the Xplained Pro MCU boards:

- SPI
  - MicroSD card connector
  - 2 GB microSD card included
- PWM
  - LED control
  - PWM > Low pass filter > ADC
- ADC
  - PWM > Low pass filter > ADC
  - Light sensor
- UART
  - Loopback interface through pin header
- TWI
  - AT30TSE758 temperature sensor with EEPROM

Figure 3-2. I/O1 Xplained Pro Extension Board



3.2 Software Requirements

3.2.1 MPLAB X Integrated Development Environment

Figure 3-3. MPLAB X IDE

MPLAB® X Integrated Development Environment (IDE) is an expandable, highly configurable software program that incorporates powerful tools to help you discover, configure, develop, debug and qualify embedded designs for most of the Microchip's microcontrollers and digital signals controllers. MPLAB X IDE works seamlessly with the MPLAB development ecosystem of software and tools. Users can download MPLAB X IDE from the Microchip's web site: https://www.microchip.com/mplab/mplab-x-ide.

3.2.2 MPLAB Harmony

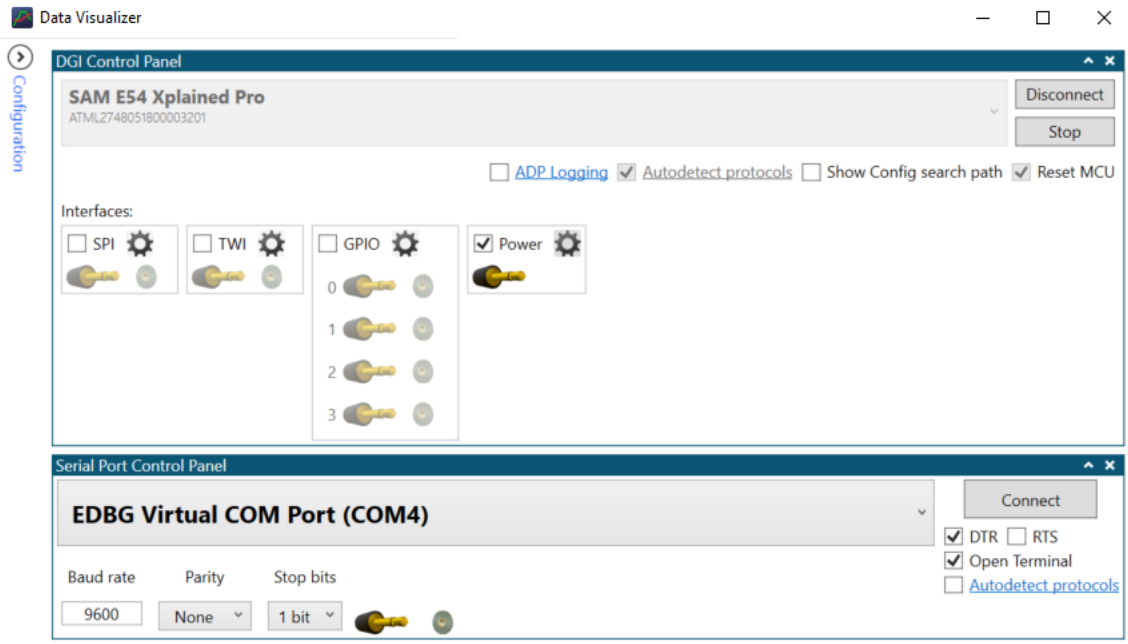
Figure 3-4. MPLAB Harmony

MPLAB® Harmony 3 is a fully integrated embedded software development framework that provides flexible and interoperable software modules that allow for dedicated resources to create applications for 32-bit PIC® and SAM devices, rather than dealing with device details, complex protocols and library integration challenges. It works seamlessly with MPLAB X IDE to enable a smooth transition and maximum code reuse between PIC32 MCUs, SAM MCUs, and MPUs.

It includes the MPLAB Harmony Configurator (MHC), an easy-to-use development tool with a Graphical User Interface (GUI) that simplifies device setup, library selection, configuration and application development. Refer to the following website for additional information on MPLAB Harmony: https://www.microchip.com/mplab/mplab-harmony.

3.2.3 Data Visualizer

Figure 3-5. Data Visualizer

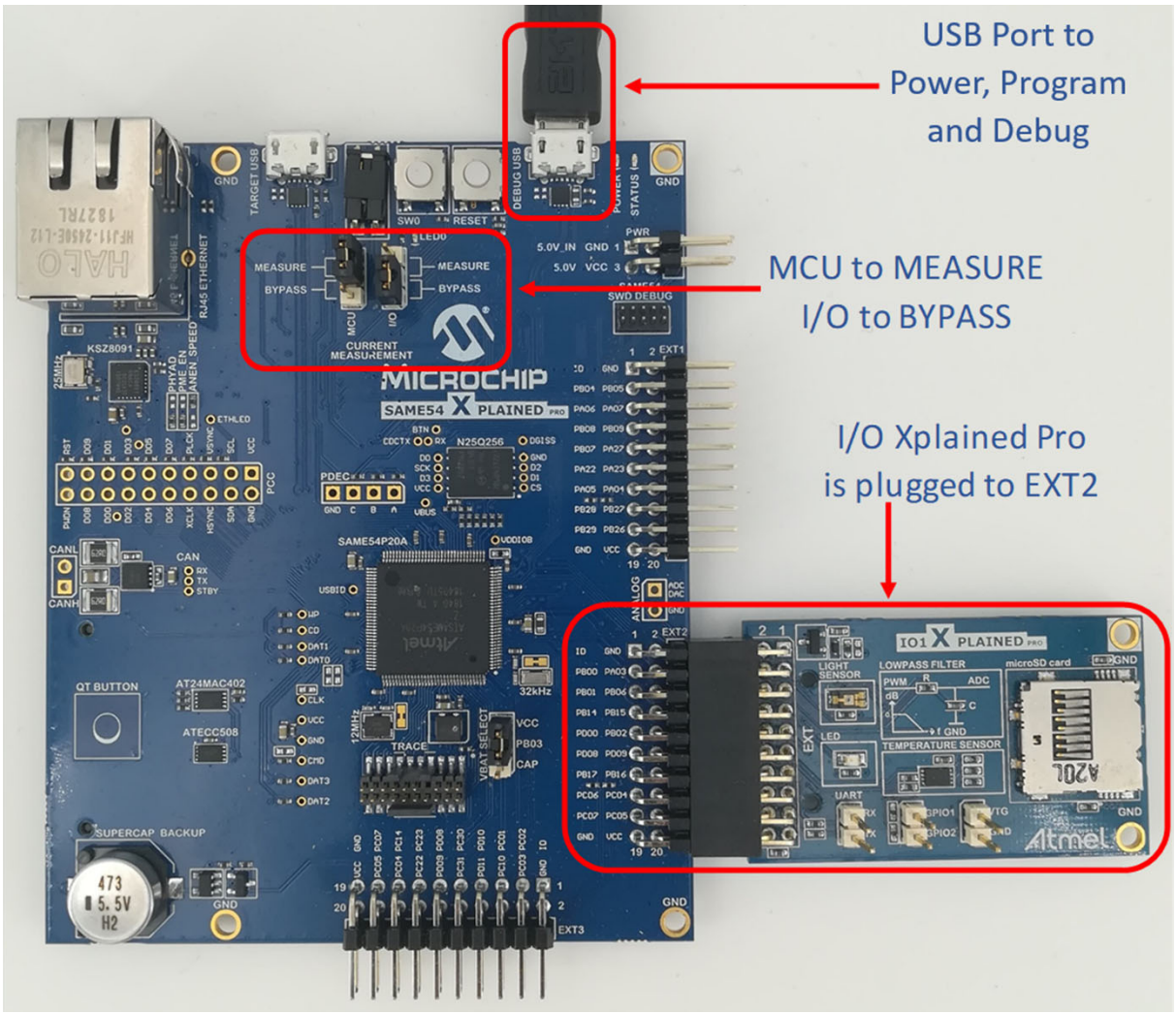


The Data Visualizer is a program to process and visualize data. The Data Visualizer can receive data from various sources such as the Embedded Debugger Data Gateway Interface (EDBG DGI) and COM ports. It is possible to track an application in run-time using a terminal graph or oscilloscope. It analyzes the power consumption of an application through correlation of code execution and power consumption, when used together with a supported probe or board. For additional information on Data Visualizer, refer to the Microchip web site: https://www.microchip.com/mplab/avr-support/data-visualizer.

3.3 Example Configuration

3.3.1 Hardware Setup

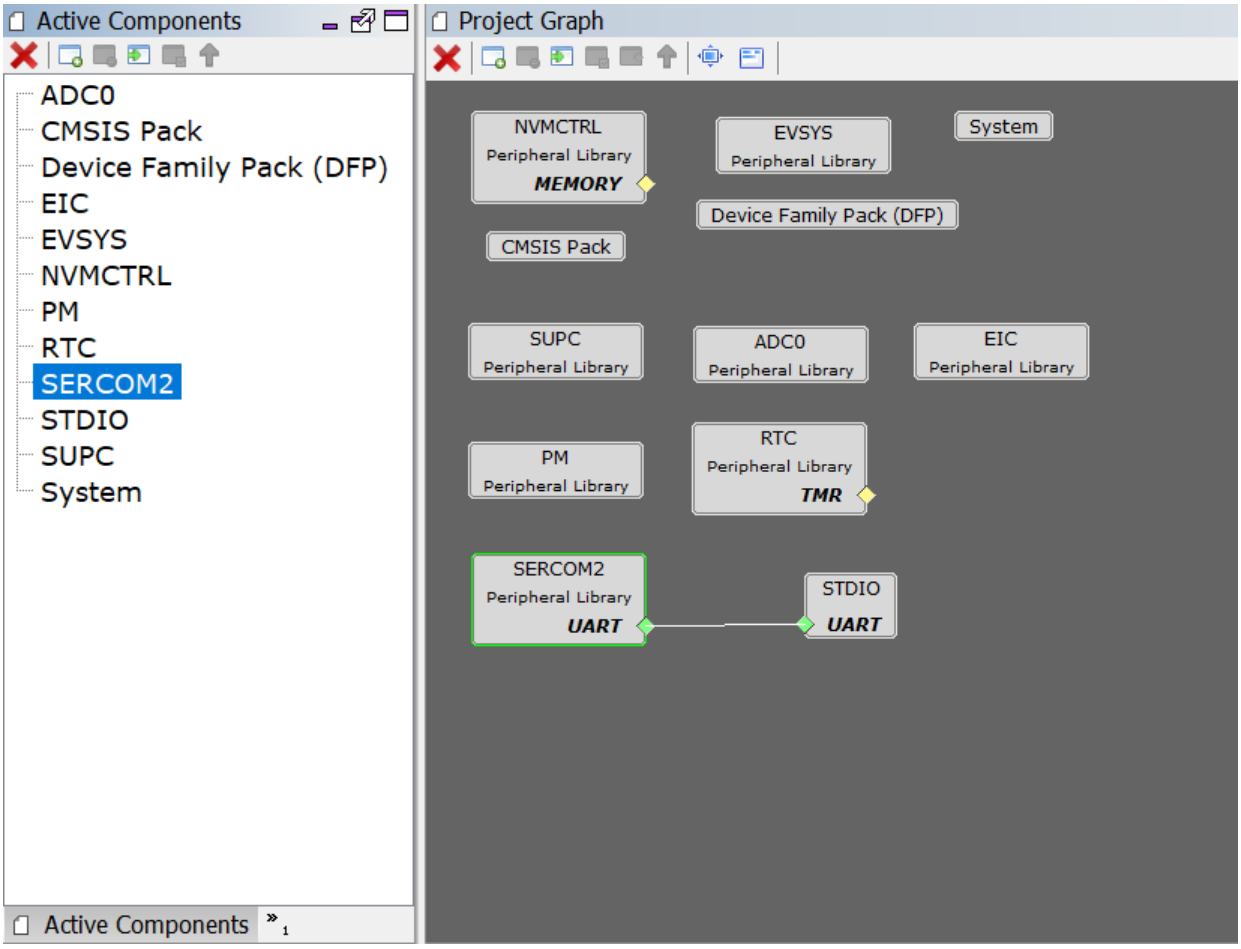
Figure 3-6. SAM E54 Xplained Pro Hardware Setup



3.3.2 Software Setup

The figure below illustrates the peripherals used for this demo application:

Figure 3-7. Harmony 3 (H3) Project Graph and Active Components



- The following peripherals are listed under Active Components:
  - ADC0 - Configured to start conversion upon an RTC interrupt or event depending on which mode the application is in. Because both sleep modes are running simultaneously on the device, the ADC0 is configured for the Event System during initialization, but is reconfigured on-the-fly for the IRQ. The Window Monitoring feature is also enabled to generate an interrupt when the converted value is greater than a Window Low Threshold value.
  - EIC - Cconfigured to generate an interrupt when the user button is pressed.
  - RTC - Generates an event or an interrupt every 10 milliseconds depending on which mode the application is in. Since both sleep modes are running simultaneously on the device, the RTC is configured for the Event System during initialization but is reconfigured on-the-fly for the IRQ.
  - SERCOM2 - Configured to display application output information on a serial terminal.

3.3.2.1 Pins Configuration

In the MHC user interface, users can access the Pin Configuration window: in the toolbar, select *Tools* > *Pin Configuration*.

Figure 3-8. H3 Pin Configuration

Pin Number	Pin ID	Custom Name	Function	Mode	Direction	Latch
72	PC18	LED0	GPIO	Digital	Out	High
75	PC21	ETH_RESET	GPIO	Digital	Out	Low
100	PB24	SERCOM2_PAD1	SERCOM2_PAD1	Digital	High Impedance	n/a
101	PB25	SERCOM2_PAD0	SERCOM2_PAD0	Digital	High Impedance	n/a
122	PB31	SW0	EIC_EXTINT15	Digital	Out	n/a
125	PB00	ADC0_AIN12	ADC0_AIN12/X30/Y30	Analog	High Impedance	n/a

The pins are configured as follows:

- PC18 is assigned to the user LED as an output high
- PC21 is set to output low to reset the on-board Ethernet PHY KSZ8091 for power consumption considerations

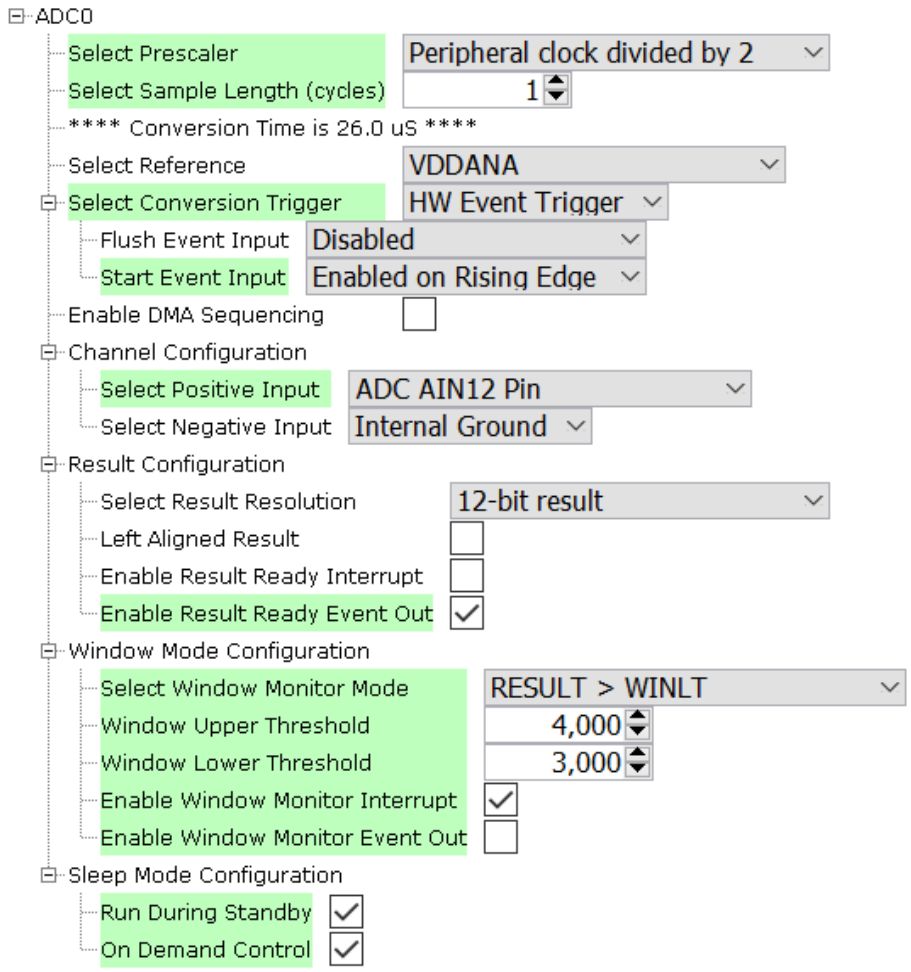
Note: For additional information, refer to the *SAM E54 Xplained Pro User's Guide* (DS70005321).

- PB24 is assigned to SERCOM2 input for data reception from the terminal
- PB25 is assigned to SERCOM2 output for data transmission to the terminal
- PB31 is assigned to the user button
- PB00 is assigned to the ADC0 Channel 12 input for data conversion

3.3.2.2 ADC0 Configuration

The ADC0 is used to convert incoming values from the embedded light sensor of the I/O1 Xplained Pro. It is possible to see the whole configuration of the ADC0 in the Configuration Options window by clicking on the peripheral in the Project Graph View in the MHC 3 as shown in the following figure:

Figure 3-9. H3 ADC0 Configuration

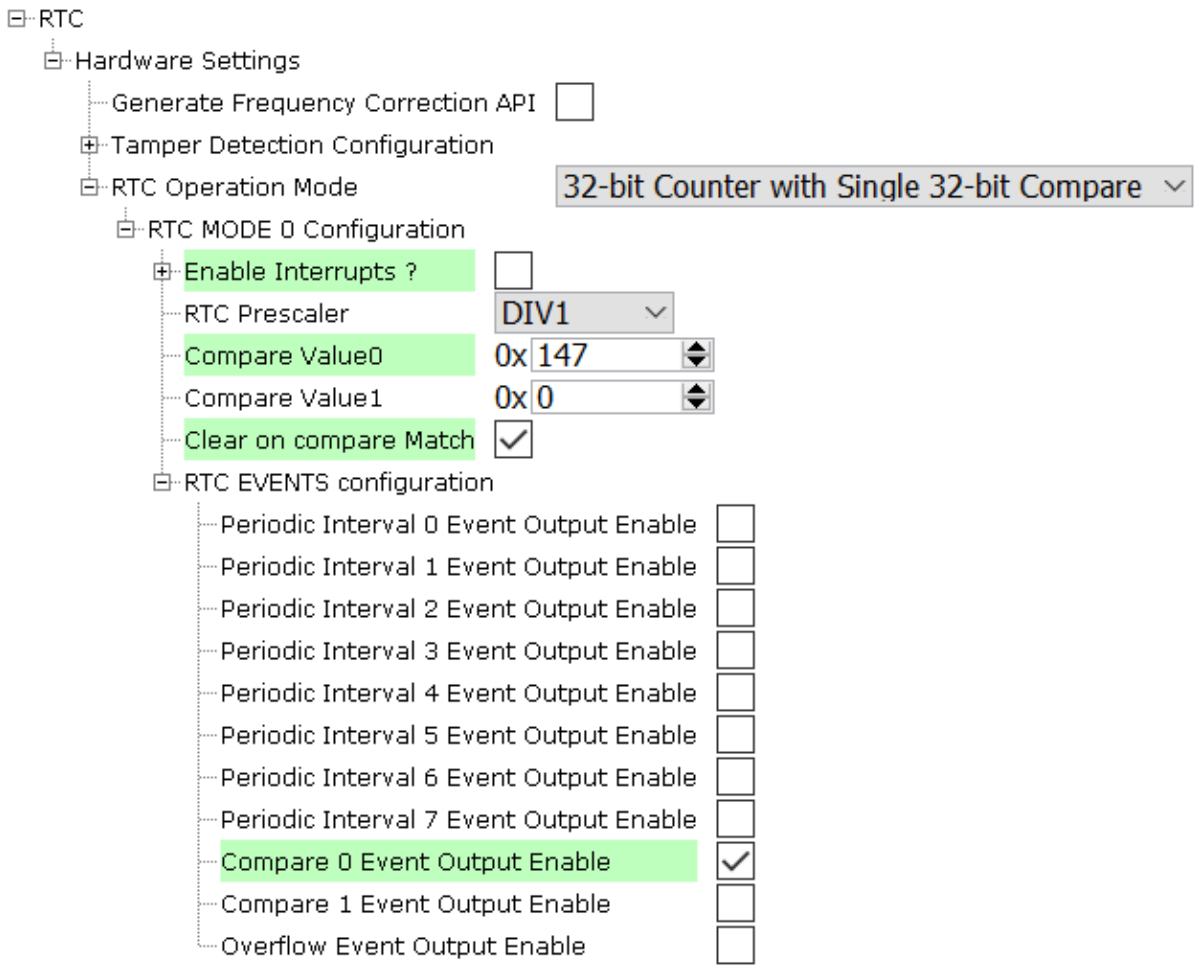


To have both modes running simultaneously on the same application, ADC0 is initialized by modifying its registers on-the-fly at each mode start. The ADC Start Conversion in the Event Input is then disabled while running in Standby with IRQ, and is enabled when running in Standby with the Event System.

3.3.2.3 RTC Configuration

The Real-Time Controller is configured to generate an event every 10 milliseconds. The following figure shows the peripheral configuration through the Configuration Options view:

Figure 3-10. H3 RTC Configuration

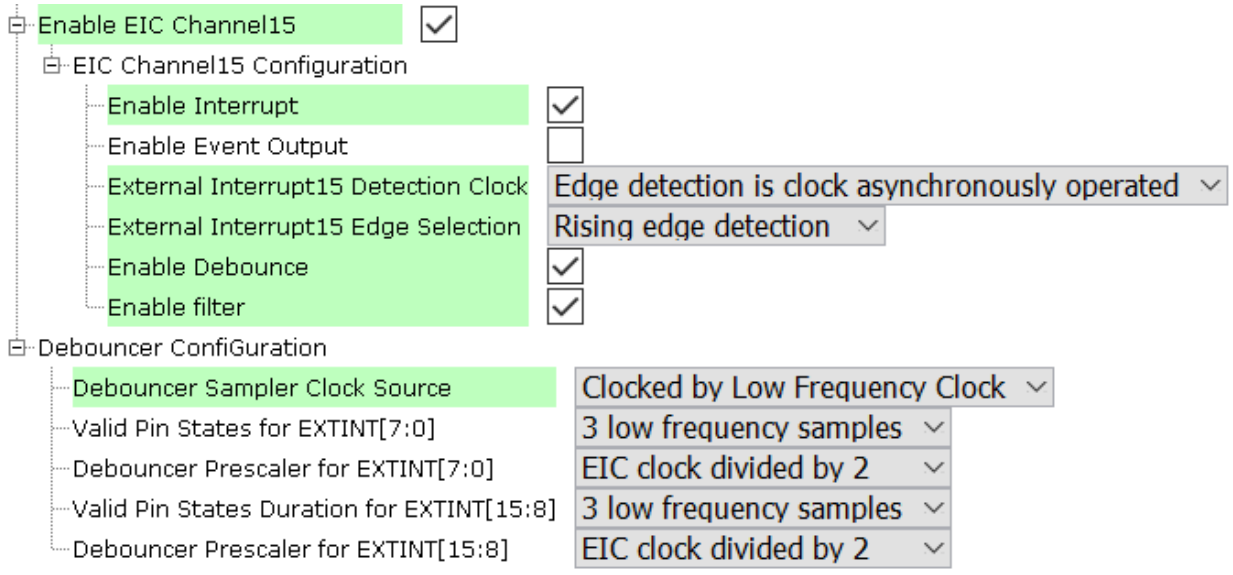


To have both sleep modes running on the same application, the RTC is initialized by modifying its registers on-the-fly at each mode start. The interrupt on the RTC Compare ‘0’ is enabled when running in Standby mode with the IRQ, and is disabled while running in Standby with the Event System.

3.3.2.4 EIC Configuration

To enable interrupts on the embedded user button, the EIC is configured in the MHC 3 as follows:

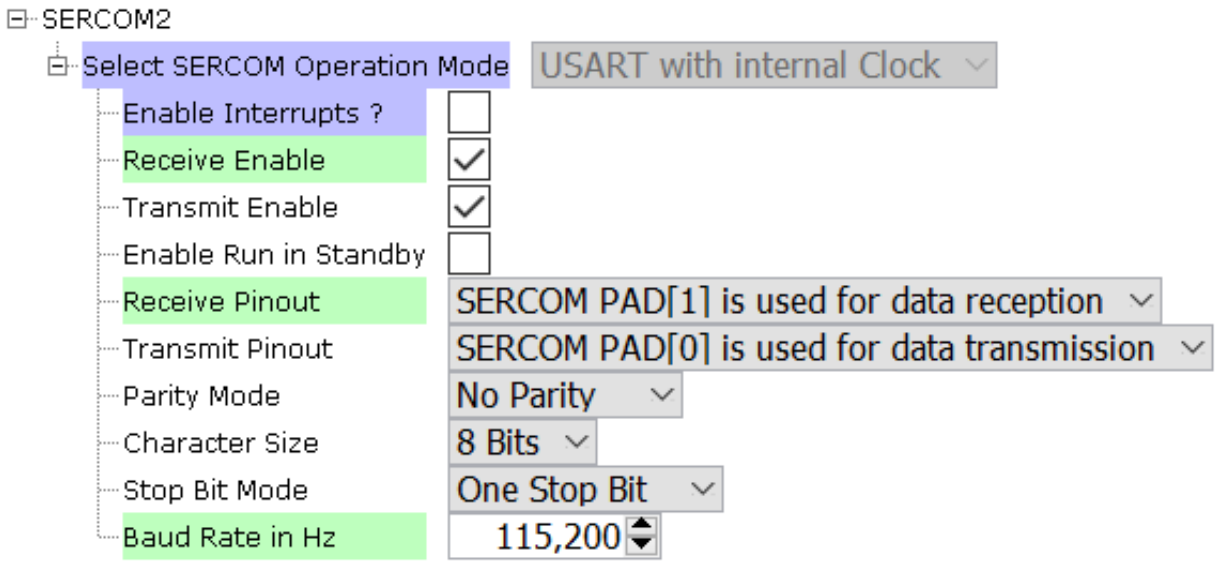
Figure 3-11. H3 EIC Channel 15 Configuration



3.3.2.5 SERCOM2 Configuration

To allow SERCOM2 display information on a terminal, the peripheral is set as SERCOM USART. The STDIO library is plugged to the SERCOM2 USART to redirect output of standard IO stream functions to the serial terminal. The peripheral configuration is available in the Configuration Options view, which is shown in the following figure:

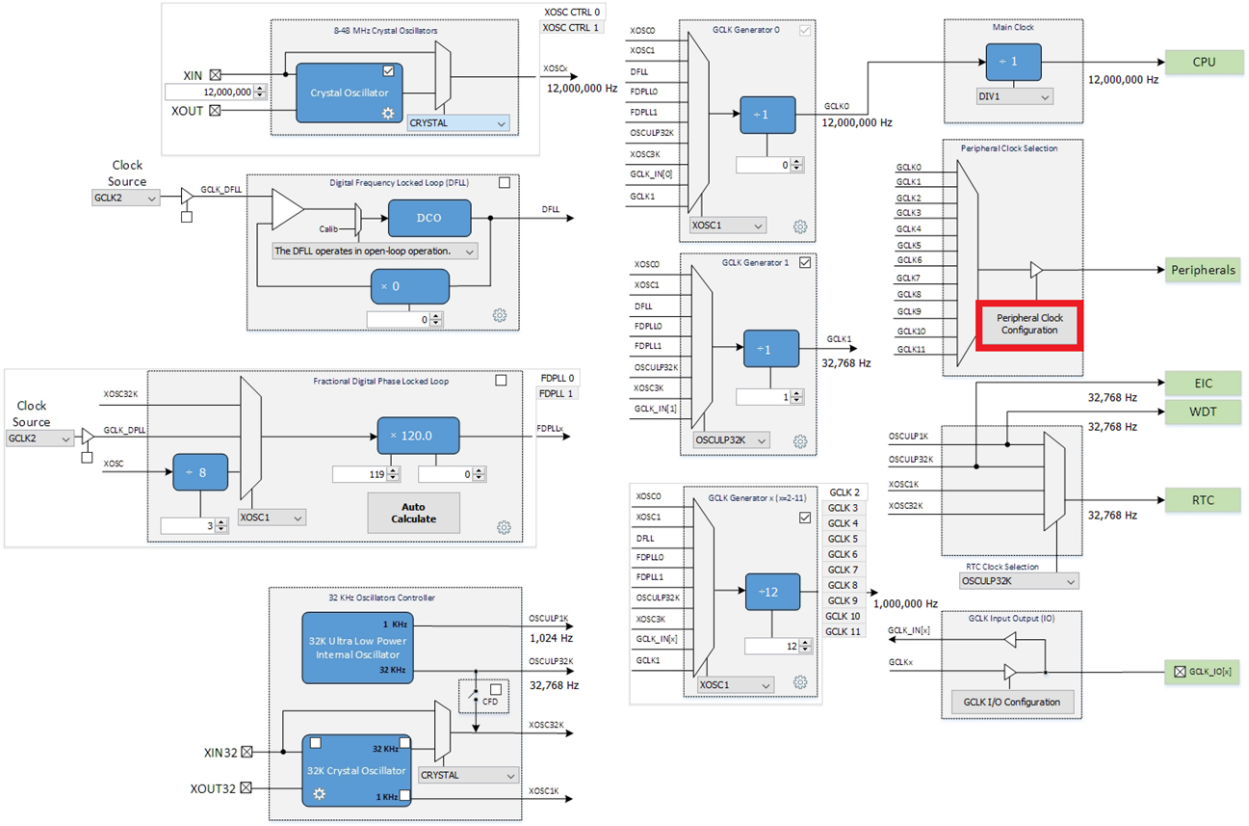
Figure 3-12. H3 SERCOM2 Configuration



3.3.2.6 Clock Configuration

Harmony 3 provides a graphical interface to configure the clocks. The following figure illustrates the clock configuration:

Figure 3-13. Harmony 3 Clock Configuration Overview



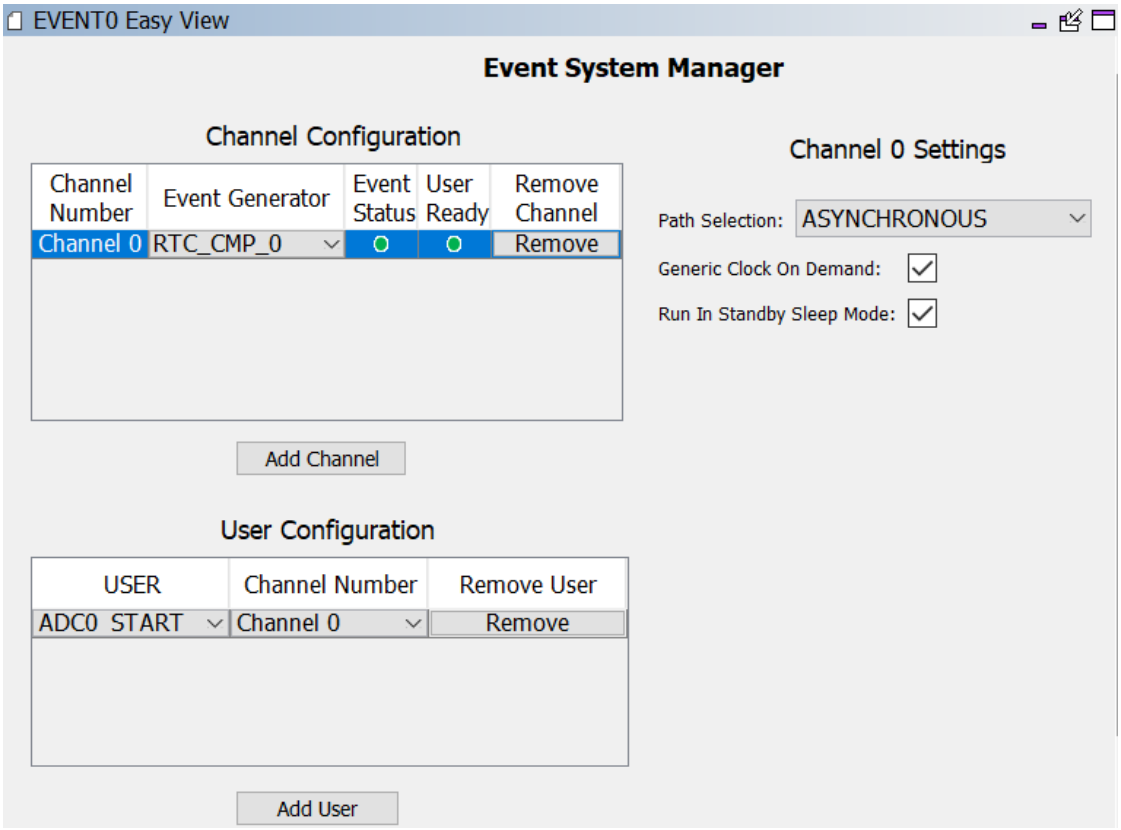
- The XOSC1 is configured to run at 12 MHz and feeds the Generic Clock Generator 0 (GCLK0) and Generic Clock Generator 2 (GCLK2). GCLK0 runs at 12 MHz and GCLK2 runs at 1 MHz.
- The OSCULP32K is configured to provide a 32 kHz source clock to the Generic Clock Generator 1 (GCLK1)
- The Generic Clock Controller (GCLK) is used to route oscillators to the peripherals. GCLK0 provides a 12 MHz source clock to the CPU. The GCLK1 is used to clock the Event System and SERCOM2 slow clocks. The GCLK2 clocks the ADC0, EIC, and the SERCOM2 main clock.

Note: Users can set the source clock for peripherals by clicking on the *Peripheral Clock Configuration* block highlighted in the figure above.

3.3.2.7 Event System (EVSYS) Configuration

The EVSYS can be configured using Harmony 3. In this application, event generation on compare is enabled for the RTC. The ADC0 is configured to start the conversion on incoming events from the RTC. It is possible to see the EVSYS configuration in the *Configuration Options* window after clicking on the EVSYS box in the *Project Graph* as shown in the following figure:

Figure 3-14. H3 Event 0 Easy View



3.4 Running the Demo Application and Configuring the Environment

This section of the document describes the following steps:

- Loading, Compiling and Running the application
- Configuring the Serial Terminal
- Configuring the Data Visualizer

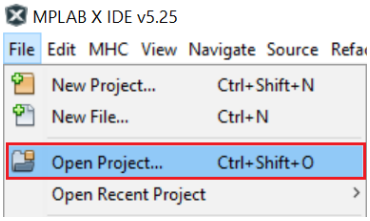
3.4.1 Loading, Compiling and Running the Application

Ensure that MPLAB X IDE and MPLAB Harmony 3 are installed before loading and compiling the application.

To load and compile the application project, follow these steps:

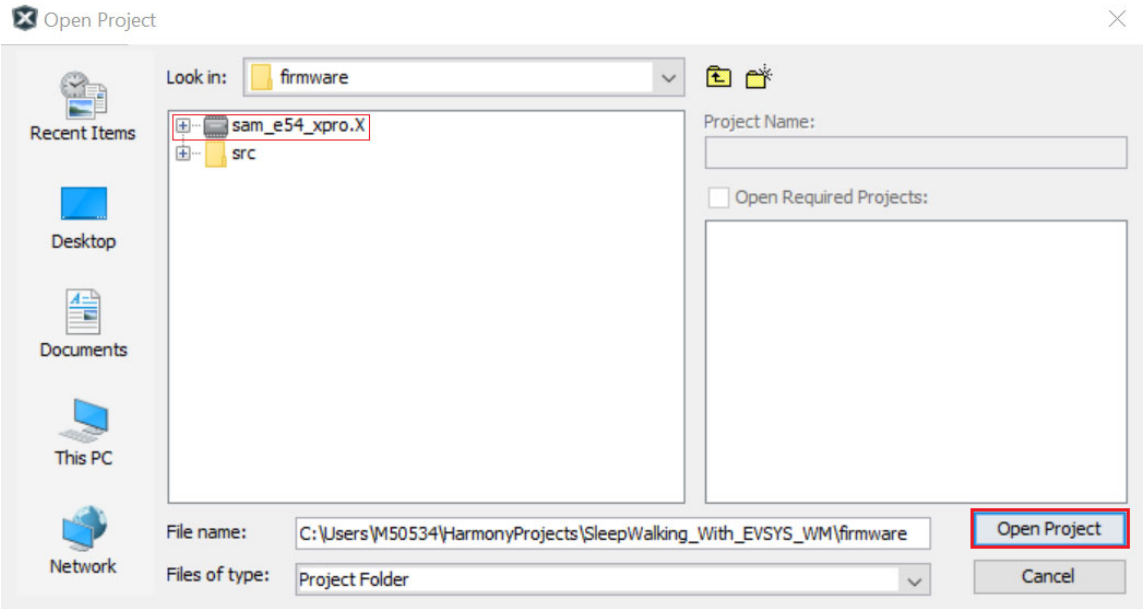
1. Launch MPLAB X IDE.
2. To open the project file, in the MPLAB X IDE toolbar select *File* > *Open Project*.

Figure 3-15. MPLAB X IDE - Open Project Folder



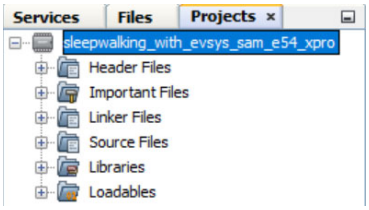
3. In the Open Project window, browse and select the application project file `sam_e54_xpro.X`.

Figure 3-16. MPLAB X IDE - Open Project File



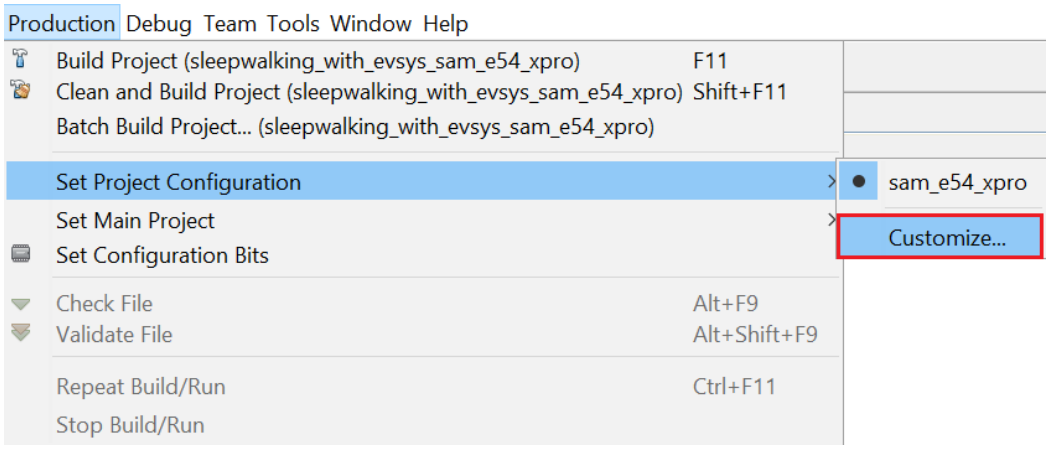
4. Click **Open Project**, the project window will display the project architecture as shown below.

Figure 3-17. MPLAB X IDE - Project Architecture



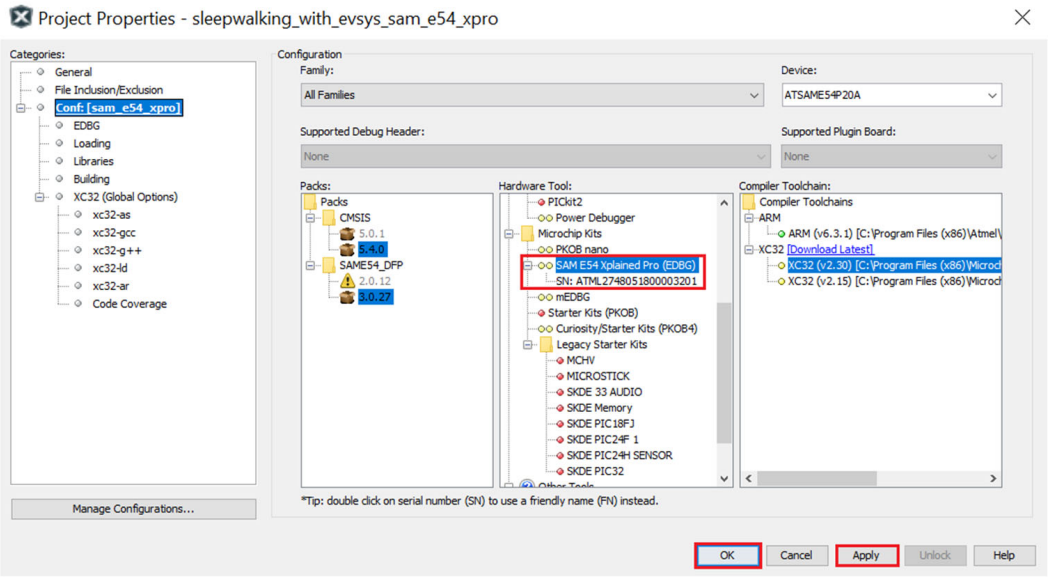
5. Select the connected board EDBG hardware tool, and then perform this action:
   5.1. To open project properties, from the MPLAB X IDE toolbar select *Production* > *Set Project Configuration*, and then click **Customize.**

Figure 3-18. MPLAB X IDE - Open Project Properties



   5.2. In the Project Properties window, under Categories select Conf: (sam_e54_xpro)
   5.3. Under Configuration section, select Hardware Tool, and Compiler Toolchain as shown below.

Figure 3-19. MPLAB X IDE - Project Properties Window



5.4. Click **Apply**, and then click **OK**.

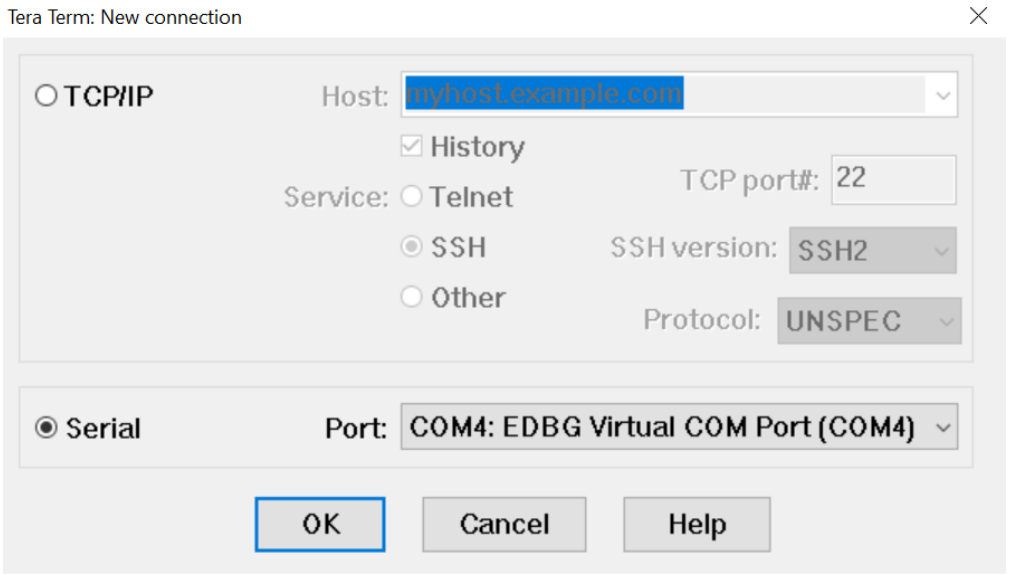
6. To build the application, select *Production* , and then click (Build Project icon).
7. Flash the application software on the hardware by clicking .

3.4.2 Configuring Tera Term

To configure the serial terminal, follow these steps:

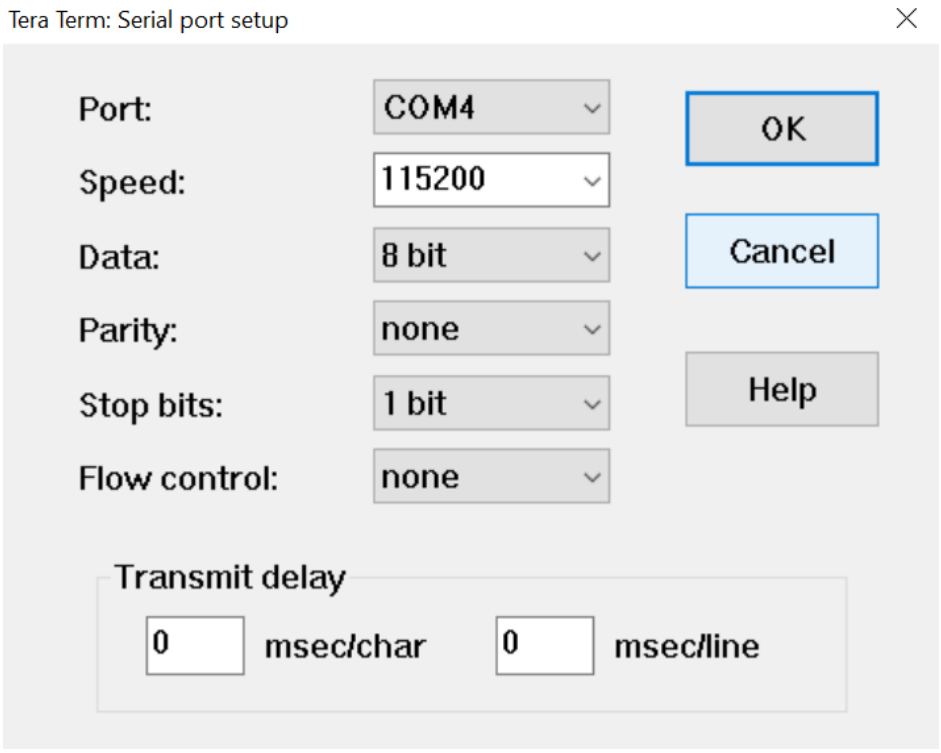
1. Open Tera Term or any equivalent tool.
2. In the Tera Term: New Connection window, select the Serial Port number allocated to the connected SAM E54 Xplained Pro board, and then click **OK.**

Figure 3-20. Tera Term - New Connection Window



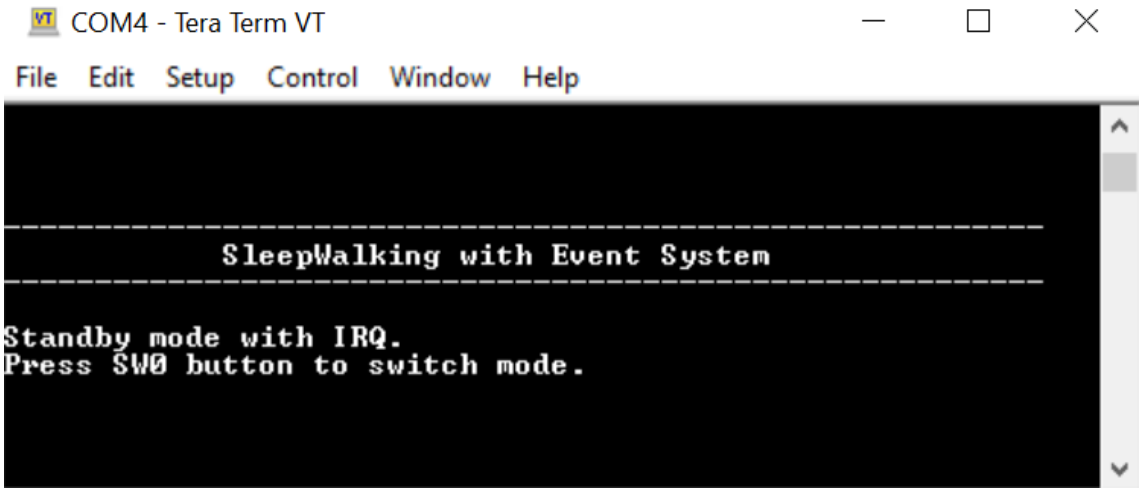
3. Configure the Tera Term Serial port interface as shown in the image below, and then click **OK.**

Figure 3-21. Tera Term - Serial Port Setup



4. Reset the board by pressing the reset button. The application will start by displaying the following message on the serial terminal.

Figure 3-22. Tera Term - Application Message Displayed

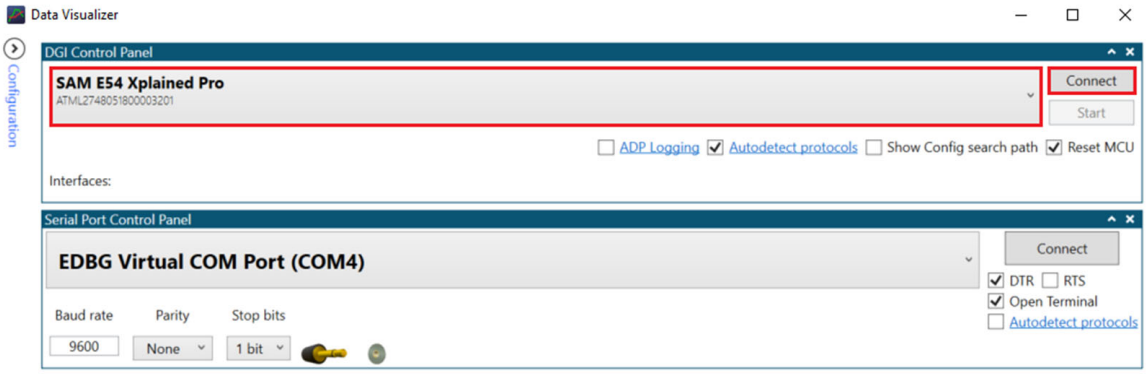


3.4.3 Configuring the Data Visualizer

The following process is used to configure the Data Visualizer for power consumption measurement:

1. Open the standalone Data Visualizer tool.
2. In the Data Visualizer window, select SAM E54 Xplained Pro, and then click **Connect**.

Figure 3-23. Data Visualizer - DGI Control Panel

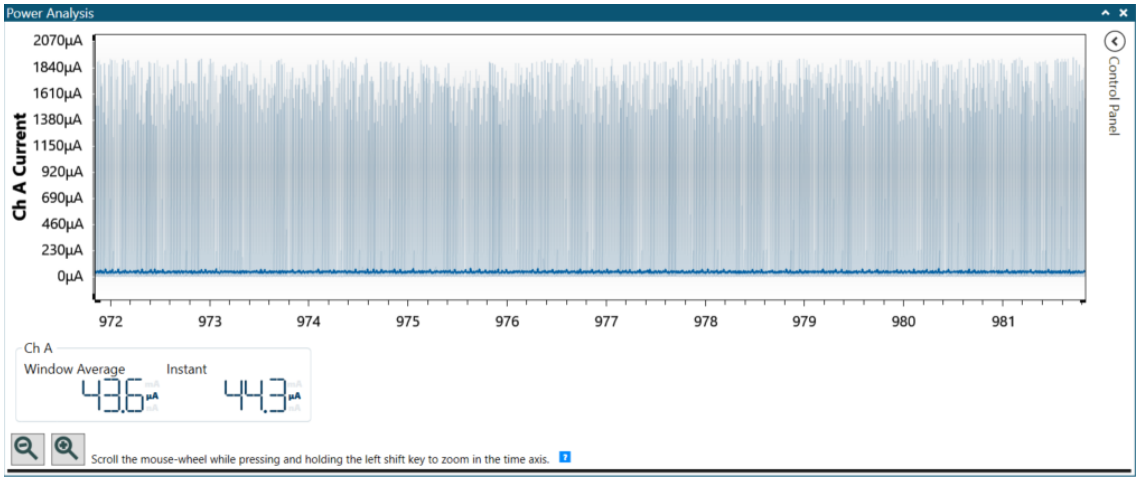


3. Once the protocols are displayed, select the protocol **Power** and then click **Start**.

Figure 3-24. Data Visualizer - Power Protocol

4. The Data Visualizer will display the power consumption details in the **Power Analysis** window.

Figure 3-25. Data Visualizer - Power Analysis



4. Results and Interpretation

4.1 Power Consumption

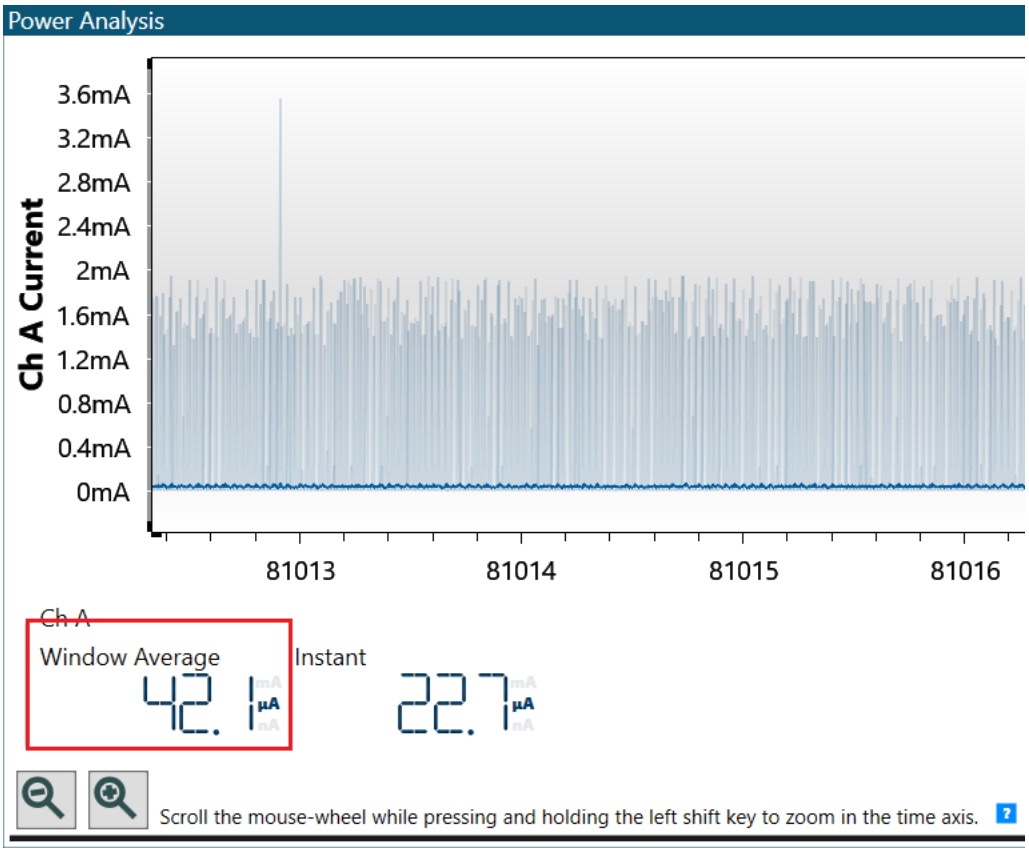
When the application is running, the dynamic current consumption of the application can be measured with the Data Visualizer standalone tool.

Note: The average value will be considered when comparing power consumption between different sleep modes, because the instant current is measured at any time and does not illustrate stable power consumption values.

4.1.1 Standby Mode with IRQ

When the application starts, the device will run on Standby with IRQ mode. The following figure shows the power consumption of the device when the CPU is woken up every 10 milliseconds by an RTC Compare '0' interrupt to start an ADC conversion:

Figure 4-1. Power Consumption in Standby with IRQ



The Data Visualizer displays a 42.1 µA average for power consumption while running in STDBY_IRQ_MODE. By comparing this value with the minimal possible power consumption documented in the product data sheet, it is noted that the value during Sleep mode is higher than expected as shown in the table below:

Figure 4-2. Power Consumption Expectations

Fast wake-up disabled (PM.STDBYCFG.FASTWKUP = 0x0), RTC running on XOSC32K Full System RAM retained (PM.STDBYCFG.RAMCFG = 0x0). 8 KB backup RAM retained	LDO	1.8V		53	1068
		3.3V		53	1067
	BUCK	1.8V		32	702
		3.3V		22	537

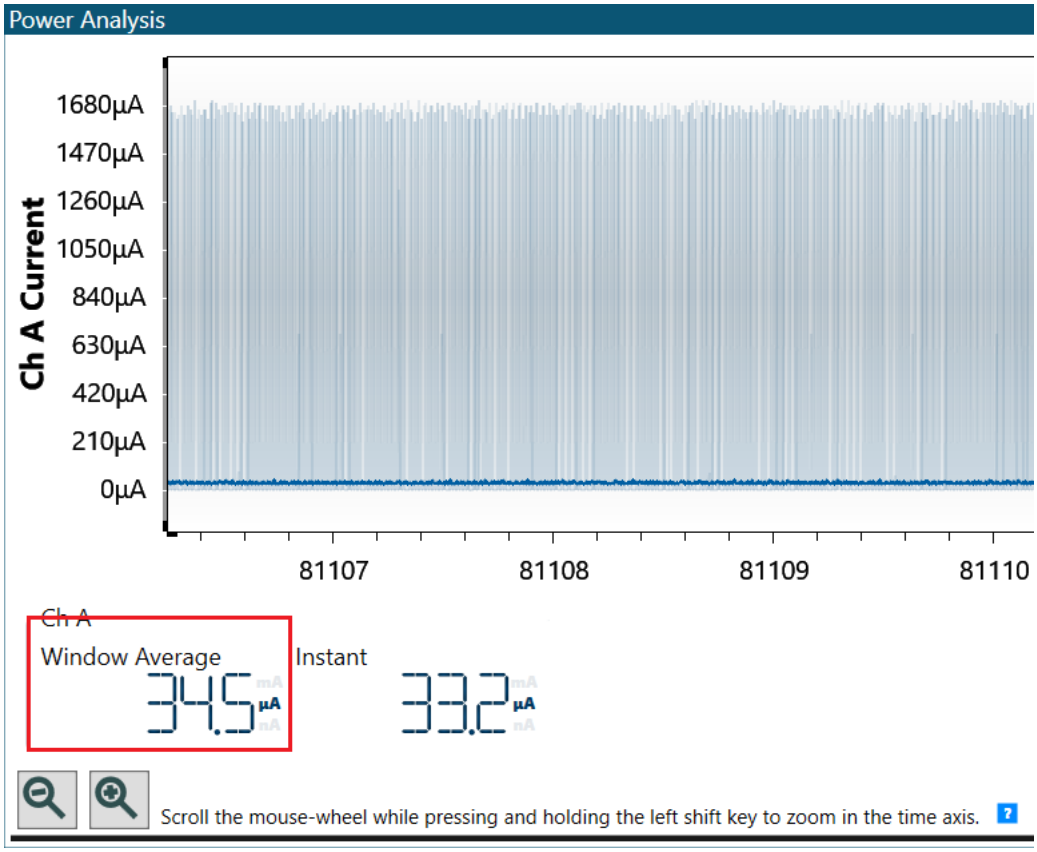
This difference in power consumption values is due to the following reasons:

- Clock configuration is different. All GCLK are OFF during Standby mode as provided in the data sheet example configuration, while some peripherals request the GCLK 2 that is connected to the XOSC1 which runs at 1 MHz in the low-power application.
- Only the RTC is running during the measurement of the values as provided in the data sheet; however, the peripherals, such as RTC, ADC and EIC run in Standby mode in this application.
- In the application under consideration, the CPU is woken up every 10 milliseconds, which increases power consumption.

4.1.2 SleepWalking (Standby with Event System)

Using the SW0 push button, it is possible to change the application mode from Standby with IRQ to SleepWalking. In this mode the CPU is woken up only when an ADC window monitoring interrupt occurs. The following figure shows the power consumption of the device when running in Standby with the Event System:

Figure 4-3. Power Consumption in Standby with Event System



Because several peripherals are running during SleepWalking operations, such as RTC, ADC, Event System, and EIC, the power consumption is higher than it is documented in the product data sheet.

However, by comparing the power consumption of the device while running in Standby with IRQ, with the power consumption of the device while running in Standby with the Event System, a gap can be observed. The first mode (`STDBY_IRQ_MODE`) consumes over 42.1 µA although the second mode (Sleepwalking) consumes 34.5 µA. This is because in `STDBY_IRQ_MODE`, the CPU is woken up every 10 milliseconds and is clocked by a 12 MHz clock source while in the `STDBY_EVSYS_MODE`, the CPU is in Sleep mode until an interrupt occurs.

Important: The product data sheet is developed on the specified version of the hardware, hence power consumption values may differ when evaluated on a different hardware. Power consumption values will always be higher in `STDBY_IRQ_MODE` than in `STDBY_EVSYS_MODE` across different boards.

4.1.3 Battery Life Comparison

To go deeper in the analysis and understand the impact in terms of power consumption, a better comparison can be made by observing the application as if it was running on a battery power supply.

For this example, a standard battery with configurations as shown in the following table, can be considered to calculate the battery life of the application for each Sleep mode.

Table 4-1. Battery Characteristics

Nominal Voltage	Capacitance	Battery type
3 V	620 mAh	Lithium – Manganese – Dioxide

The battery life is characterized by following formula:

$$T_{BL}(h) = \frac{Battery\ Capacitance\ (Ah)}{PowerConsumption(A)}$$

Standby Mode with IRQ:

For a capacitance of 620 mAh and a 42.1 µA power consumption, the battery life TBL will be as follows:

$$T_{BL} = \frac{620\ x\ 10^{-3}}{42.1\ x\ 10^{-6}} = 14,276h$$

By converting the computed value, it leads to a battery lifetime over 613 days and 14 hours.

Standby Mode with Event System:

For a capacitance of 620 mAh and a 34.5 µA power consumption, the battery life TBL will be as follows:

$$T_{BL} = \frac{620\ x\ 10^{-3}}{34.5\ x\ 10^{-6}} = 17,971\ h$$

By converting the computed value, it leads to a battery lifetime over 748 days and 19 hours.

To conclude, if the device was running with SleepWalking feature, it would last 135 days more than if it was running on Standby mode with IRQ.

5. Conclusion

This document provided an overview on the benefits of SleepWalking (Standby with Event System) over using Standby with IRQ. It also showed that an application based on events instead of interrupts allows the reduction of power consumption and keeps the CPU asleep for longer time. The more interrupts in Standby mode the more the CPU will be woken up, which will increase the power consumption. In SleepWalking the CPU will not wake up on events therefore reducing power consumption.

However, if there are less frequent interrupts occurring, the difference between Standby mode with IRQ and SleepWalking operations is less in terms of power consumption.

6. References

For additional information, refer to the following documents which are available for download from the Microchip website:

- SAM D5x/E5x Family Data Sheet:
  http://ww1.microchip.com/downloads/en/DeviceDoc/60001507E.pdf
- SAM E54 Xplained Pro User's Guide:
  http://ww1.microchip.com/downloads/en/DeviceDoc/70005321A.pdf
- What is SleepWalking? How it Helps to Reduce Power Consumption:
  http://ww1.microchip.com/downloads/en/DeviceDoc/90003183A.pdf

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