Comparing the energy requirements of current Bluetooth Smart solutions (February 2016)

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***Abstract*— Bluetooth has become a popular way to get access to data delivered by sensors and beacons. To be convenient in use and low cost in maintenance, those sensors and beacons should consume as less energy as possible. Near the energy consideration of the sensing elements, the proper selection of the Bluetooth Low Energy radio and software stack is vital to achieve low power consumption. There are several solutions on the market, with various claims with regard to power consumption. These claims are not easy to verify on the basis of the data sheets alone, making it long and difficult for engineers to choose the appropriate solutions. We have measured the energy consumption of several Bluetooth Smart solutions that can be found on the market today. The measurements were based on the important communication phases and the information available in various documents (datasheets, application notes). The result of that work is presented here. This work was done at the end of 2015 and early in 2016.**

Keywords—Ble; Bluetooth Smart; microcontroller; connection; advertisement; sleep mode;

I. INTRODUCTION

The proliferation of smart phones, tablets, PCs equipped with Bluetooth interfaces has opened up new ways of wirelessly communicating with small embedded systems. For instance, host devices with Bluetooth Smart Ready capability can connect to sensors with Bluetooth Smart features in a range of tens of meters, get their data and display them for the user. The captured data can also be sent to other stations using the long range communication features available on most smart phones or tablets. Sensors or other peripherals can address various needs such as the monitoring of environmental parameters, indoor navigation …etc. To be convenient in use and low cost in maintenance, they should consume as less energy as possible. Reducing the amount of energy required by the sensing system is basically a low power design issue. The proper selection of the Bluetooth Smart radio, microcontroller and software stack used is a central aspect. There are several solutions on the market, with various claims with regard to the power consumption. It is not easy for application engineers to verify those claims or derive them on the basis of the datasheets that are given by the module or chip manufacturers.

It is our intention to offer some help through this work. We have measured the energy consumption of several of the Bluetooth Smart solutions that can be found on the market today. We have looked at the important phases of the communication and also at what the data sheets say (and do not say). This paper can be helpful to application engineers in their quest of an appropriate module or chip for their low power application. It can also be helpful to chip or module manufacturers and those writing communication stacks, by showing aspects in their solutions that need corrections or improvements. Two years ago, we published a first version of this comparison, using devices that were available at that time. Since then, many manufacturers have brought out new devices, prompting us to update the past work. We concentrate on devices that fulfill the 4.0, 4.1 specifications. One difference with the previous work is that we now use full frames in ADV mode. That means 47 octets instead of 44 octets in the previous work.

In what follows, we will shortly remind the reader of the importance of controlling energy consumption. We will then talk about the critical energy phases of the communication process in Bluetooth Smart. We will introduce the devices we have tested. Finally, we will present and explain the power consumption measurements made and show the results in form of power profiles and tables.

II. MOTIVATION

There are several reasons to care about the energy consumption of Bluetooth Smart solutions.

- Devices should be used for a long time without the user having to change batteries. This leads to low maintenance costs.

- Devices that do not need (frequent) battery change give more options as to the place where they can be installed.
- The less energy is required, the smaller a product can be, since small batteries can be used. This also leads to lower costs for the products.
- It is easier to use Energy Harvesting if the energy requirements of the target solution are low. This helps implement energy autonomous systems. It is a key issue as the number of connected devices grows.
- Reducing the amount of batteries needed is a good thing for the environment.
- From a marketing point of view, it is of course important to be able to say that one's solution is low power.

In this work, we have sought to present a picture of the energy requirements that says more than the information that can be found in datasheets or application notes from manufacturers. However, it is difficult to take into account all the parameters that can influence the energy requirements. Obviously, we do not cover all the Bluetooth Smart solutions that exist, although we have made an effort to get as many devices as possible. The solutions discussed in this document reflect the normal time evolution of the standard and the devices that address the Bluetooth Smart market.

We are not aware of any previous comparison of the energy consumption of Bluetooth Smart solutions on this scale, except the work we presented in 2014 [1].

III. A SHORT REMINDER OF THE WAY BLE WORKS

In order to interpret some of the measurements in this document, a reminder of the basic principles of Bluetooth Smart is necessary. For a deeper understanding, the references or other appropriate documents can be consulted [2][3].

Bluetooth Smart operates in the 2.4 GHz ISM band, where several other radios are active (WLAN, 802.15.4, ZigBee … etc.). Because many devices operate in that band, there are interference and collisions issues. At 1Mbit/s, the raw data rate of Bluetooth Smart is high compared to that of other Wireless Personal Area Networks (WPAN) protocols. This helps keep frames short and reduces energy needs, but has a negative impact on the range.

Frames are tens to hundreds of microseconds long (a frame is 10 octets to 47 octets long), which helps reduce collisions but increases the proportion of the overhead with respect to the whole frame. Longer frames are possible with the new 4.2 specifications. There is no mandatory "listen before talk" process, which increases the likelihood of collisions. Retransmission due to loss of data will generally lead to an increase of the energy consumption.

40 channels are available for communication, making it possible for connected parties to hop through channels in order to avoid interference. This is also very helpful when implementing concurrent communications in the same physical space.

Communicating parties can exchange data in connected mode or in non-connected mode.

- The connected mode implies that communicating devices have agreed upon parameters needed for their connection. They then use these parameters to meet at the right time and channel in order to exchange information. Data is transferred using some of the 37 channels attributed to data transfer.
- In a non-connected mode, information is exchanged using one or several of the 3 special channels known as advertisement channels. These have been chosen to reduce interference from other popular wireless protocols. Parameters needed to establish a connection are negotiated using the advertisement channels.

The basic network topology is star. One node acts as a central node. It can connect to several other parties and exchange data in a time multiplexed way. Smart phones and other devices with enough resources will often act as central nodes, while sensors will assume a slave role. A master connected to several slaves exchanges information with them at determined time points. Between the "rendez-vous", the slave can sleep (and save energy).

Once connected to a master, a typical slave will wake up at the "appointed time", receive data from the master, send information to the master and then go back to sleep (or other activities).

Since slaves can spend long time intervals sleeping, the energy consumption in that state is very important. It can even be dominant in certain applications. Waking up on time (not too early and not too late) is also important. This places important constraints on how well the slave keeps time and how fast it wakes up. Accurate time keeping and fast wake-up are activities that require energy.

The accuracy of the frequency at which the device communicates is very important. Wrong frequencies will eventually lead to no communication. Many radios have a way of calibrating their frequency generator, which also costs energy. Depending on the design, calibration might have to be done often in order to mitigate the effects of temperature and the variations of some component values.

IV. FACTORS THAT AFFECT ENERGY CONSUMPTION

There are different factors that affect the energy consumption. It is important to look at the individual parameters, but very important to remember that the different components function together. In the end, software and hardware in a specific application and environment will determine the costs and characteristics of the system, including the power consumption. Some of the important elements will now be listed.

- Start-up energy at power on. When the device is powered up, internal and external capacitors are charged. Certain registers are initialized and some basic functions such as calibration may be performed. In the case of devices that run from RAM, the copying of code from a non-volatile memory should be taken into account. All these activities cost energy. Devices with a high start-up energy consumption present extra difficulties in applications where a frequent restart from power-off is needed.

- Energy needed to send frames. This is related to the current in transmission mode. But that is not the only parameter. Before transmission, there are a certain number of activities that should be performed by the radio. These activities draw some energy.
- Energy needed to receive a frame. This is related to the current in reception mode.
- Energy in low power modes and leakages. This depends on the low power mode implemented and how long the device remains in them. The lowest power modes basically lead to less accuracy in time keeping. They also lead to longer wake-up times. A correct balance should be found between the frequency of operation and the power modes. Applications that span an important temperature range should consider the effect of temperature. Unfortunately, manufacturers do not always provide information about the effect of temperature on the low power current. Leakages are often included in the value of the current consumption.
- Timing system, oscillators, PLL, type of clock references. Generally, a PLL system plays an important role in generating the right frequencies for communication. A crystal (or another accurate component) in used to provide a stable frequency reference. These elements need time and energy to start up and to stabilize. In connection mode, they are regularly switched on and off. Temperature variations or even ageing might lead to the frequent need to recalibrate the system, thus increasing the energy needs.
- The energy consumption of the microcontroller during the different application and communication phases should be taken into account when assessing the system’s energy requirements. The part of the communication stack that is in the microcontroller should be implemented such as to avoid unnecessary activities.
- The voltage at which the system works obviously influences the system’s energy. Most solutions on the market will work from 3.3 Volts down to 1.8 Volt. The user is well advised to consider the voltage need of all elements in the system. Appropriate DC/DC converters can be helpful. Their efficiency at different voltages and current, the start-up constraints and their effect on the radio input signal (noise) should not be ignored.
- The way the communication host (central node) works. In a simple case this relates to how fast the host sees the advertisement frames of a sensor and initiates the connection procedure. In a more complex case, the same host might react differently, depending on its work load. There are differences between hosts (manufacturers of smart phones have different priorities and use different operating systems). Therefore, the energy consumption when working with one host can be different to what is measured while working with another host. Especially during the phases when connection parameters are negotiated.
- The environment of use. As discussed earlier, temperature changes and electromagnetic interference can lead to extra activities and substantially increase the power consumption. A device that is portable (e.g. wearable devices) is likely to work in different temperature and electromagnetic environments. The receiver sensitivity can also be crucial, especially when signals are weak. Connection problems (due to poor receiver sensitivity) can lead to frequent reconnect, and thus increase the overall energy consumption. Beware the resulting loss of data and user’s frustration.

Many of the parameters listed above affect the energy consumption in phases which are important for the communication system and which have been measured in this work.

- Start-up energy (very important in case of broadcast. The system can quickly be switched on or off to minimize energy needs).
- Energy requirements in advertisement phase. This is important for beacons or sensors that simply beacon their data in ADV channels.
- Energy requirements in connected phase.
- Energy needed in negotiation phase. Examples are shown, but this has not been systematically measured in this work. There are too many variations, depending on the host that is used. Important information pertaining to this case can still be derived from the other measurements.

V. LIMITATIONS

The following restrictions should be kept in mind while reading/using this document:

We concentrated on 4.0 and 4.1 Bluetooth Specifications. We tested a very limited amount of devices per device type. This is therefore not representative as the devices could have been the best (or worst).

In most cases, we used the software stacks that were given by the manufacturer (if available). There are differences in the optimization levels and qualities of those stacks, which can result in higher energy requirements. It is therefore possible that some solutions can be improved by using better versions of the stack (as the product matures). We welcome suggestions from manufacturers in that sense, especially if they have improved versions of the stacks that are also “fit for use” by customers. It is also a purpose of this work to challenge manufacturers to bring out more appropriate versions of stacks.

Some of the devices listed and tested are new, and thus still have hardware issues that need to be corrected on the ICs themselves. We could only do partial tests with such devices, since some characteristics could not yet be properly evaluated. This is especially the case for the Atmel and Nordic devices. Our understanding is that manufacturers are in the process of making the needed corrections.

Rx sensitivity is important. Devices with poor receiver sensitivity might miss more frames, leading to repetition of messages and thus more energy consumption. This factor is not taken into account in our measurements, but can be found in datasheet of ICs and modules.

There are more devices on the market than we tested. In some cases, manufacturers were not willing to let us test their devices. In other cases, we were simply not able to measure all ICs.

During the tests variations related to parameters such as clock accuracy, POR level, charged capacitors, etc. led to slight variations in the measurement results. The measurements were made at room temperature.

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VII. A SHORT PRESENTATION OF THE DEVICES AND SYSTEMS THAT HAVE BEEN MEASURED

We have included some data about the systems that have been evaluated in this work. This is information that we took from the manufacturers' web site and slightly edited to fit this paper. For a complete picture, the reader should consult the datasheets, application notes or talk with the competent person in the manufacturer's structure. Datasheet can be found in certain cases on the web sites of the respective manufacturers. In other cases, an NDA is required.

Whenever possible, we have used kits from manufacturers, loaded with their own recommended software stack. In some instances we have made small modifications to allow the energy to be measured properly (same packet length, removal of code for not needed peripherals such as accelerometers, etc.). Devices mentioned in this work are:

A. BTLC1000 [4] manufactured by Atmel

This device is a link controller. It can also be used as microcontroller for an application, if an external non-volatile memory is provided. A version with on-chip flash ATSAMB11 has been announced by Atmel. For our tests, we used the BTLC1000 on ATBTLC1000-XSTK. We measured only the energy of the radio, and not that of the external host controller that controls the Link controller. The stack used came from the manufacturer. Due to some bugs that should soon be corrected, measurements of start-up time and energy were not possible. The module has a 32.768kHz crystal with +/- 20ppm.

B. CC2640, CC2650 [5][6]manufactured by Texas Instruments

Our tests were done using the CC2650 on modules CC2650EM-7ID (non-connectable) and CC2650EM-4XS (connectable). We used an optimized stack for non-connected mode and a different stack for connected mode. The chip supports a 32kHz RC oscillator (refer to the datasheet for tolerance information) and there is a 32.768kHz crystal with a tolerance of +/- 10PPM on the board.

C. nRF52832 [7] manufactured by Nordic

Tests were done using the Engineering B version of the nRF52832 (PCA10040, 2015.47) on a nrf52 Preview DK. Some parameters such as the sleep currents in some settings could not be measured. Once ready, a new revision of the device (and module) where the bugs are corrected will be used for new measurements. The kit uses a 32.768kHz crystal with +/- 20PPM.

D. RL78/G1D [8] manufactured by Renesas

There are several variants of this device, with different memory sizes. According to the development tool web site, the device on the RTK0EN0002C01001BZ module is the RL78/G1D. Two different stacks were used: one for non-connected mode communication, optimized for that purpose. For connected mode, the normal Bluetooth Smart stack was used. Both stacks came from the manufacturer. The module has a 32kHz crystal with +/- 50ppm.

E. DA14580, DA14581 [9] Devices manufactured by Dialog

The DA14580 was already part of our first measurement series [13]. After considering its low power performances, we decided to keep the family in this measurement series as well. In this work, we mainly used the DA14581 which shows slight improvement with respect to the DA14580. The DA14581ATDB-P was measured on the DA14580DEVKT-P kit. The stack provided by the manufacturer was used for measurements. This device family has different memory type's combinations. The user should therefore carefully consider the options. In some cases, measurements were performed using the OTP, and in other cases we used the RAM (program downloaded in RAM from external serial Flash). The chip supports a 10kHz RCX oscillator with +/- 500PPM and there is a 32kHz crystal soldered on the board. We could not find out the tolerance of that crystal.

F. BlueNRG-MS [10] Device manufactured by ST Microelectronics

This device is a link controller, meaning that it should be used with another (external) microcontroller. A stand-alone device will be a good addition for a device that can deliver a strong output signal. For all measurements, we used the stack provided by the manufacturer. Only the energy of the link controller was measured on an X-NUCLEO-IDB05A1, which is equipped with an SPBTLE-RF module. An STM32 Nucleo board was used for communicating with the extension board via SPI. The chip supports an internal 37.4kHz ring oscillator with +/- 500PPM and there is a 32.768kHz crystal on the board. We could not find out the tolerance of the crystal. It does not seem to us that the ring oscillator is used by the stack.

G. *CY8C4247LQI-BL483 [10] manufactured by Cypress*

PSoC combines programmable and reconfigurable analog and digital blocks and flexible automatic routing with an ARM Cortex-M0 CPU. The CY8C4247LQI-BL483 from the PSoC 4XX7_BLE Family was measured. This standalone chip is included in the CY8CKIT-042-BLE Bluetooth® Low Energy (BLE) Pioneer Kit. The PSoC was measured without the baseboard. We used a modified version of the "constant broadcaster" code for the non-connectable mode, which is provided by Cypress. A modified version of the example code "find me target" was used to measure the connectable mode. This code is also provided by Cypress. The chip supports a 32.768kHz crystal with +/- 50PPM.

VIII. SET UPS FOR MEASUREMENTS

A. *General set up*

We connected the DUT to a measurement tool and worked in most cases at room temperature.

In order to measure voltage, current and power, we used the N6705B power analyzer from Agilent [12][13]. This tool allows forcing a given voltage and measuring the dynamic profile of the current flowing through the DUT. The instrument automatically selects the best range for the measurement. The energy required within a period chosen with 2 markers is computed and displayed.

Whenever possible, measurements were made at 3 Volts in order to have the same comparison voltage. That voltage was chosen because the typical battery targeted by applications is the CR2032, which starts around 3 Volts. Many devices can work down to 1.8 Volt, or even lower. All devices include a DC/DC converter. That was not the case 2 years ago. That converter helps reduce power consumption. However, in low current mode, the inefficiency can be a drawback. We also made measurements at 2 Volts.

For all devices, we determined the lowest voltage that is allowed, and made measurements at those voltages. Due to space, we could not include all results in this paper.

For tests needing a connection, we used a CY5670 CySmart USB Dongle as host. During the measurements, frames were captured for verification and monitoring using a simple sniffer, a multi-channel sniffer from Ellisys [14] and the CySmart tool from Cypress.

B. *What we measured*

Start-up energy

This is the energy needed by the DUT (on the provided kit) when the system starts up from power off. This parameter is especially important if the system is regularly switched off and then restarted. It could be the case if one works in connected mode or with some intermittent energy harvesting sources.

This parameter is less important in cases where the system is in connected mode or has enough energy to keep the contents of critical memory elements.

Advertisement energy

Energy needed for events in advertisement mode was measured. In this mode, the system switches the transmitter on to send the ADV frames and turns the transmitter off. In the case of connectable ADV, the radio switches the receiver on to receive a potential answer from a scanner. This procedure is repeated 3 times, for the 3 ADV channels. The measurement shows the current when the system is transmitting and when it is receiving. It shows the current between ADV activities. It also shows some of the consequences of clock timing on the energy.

In the case of non-connectable ADV, the receiver stays off. This is a scenario sometimes used to transfer data in ADV mode (e.g. broadcasting of sensor data).

The measurements were made with ADV frames of the same packet length (47 octets as total frame size). The ADV frames are always sent on all three advertising channels.

Measurements were made for 2 ADV interval times: 100ms and 1s. This was done to see the effect of different clocking schemes on the energy.

Since devices integrate a DC/DC converter, measurements over a long period (1 minute) were also made, and the average current consumption shown in tables. This helps integrate the activity of the converter and get more realistic values.

Connection energy

As in the case of ADV, we measured the energy used by the system during a connection. The device receives an empty packet from the host and then sends an empty packet to the host. Between 2 connections, the device goes in a low power state. After a given time, it wakes up. The oscillator is started and the device brought to the proper communication frequency (channel). Therefore, the energy requirement results from several states: The low power mode, the wake-up procedure (timers, PLL, oscillator), the reception and transmission.

In this case as well, averaging over 1 minute was used to give a better picture of the power consumption.

C. *Other.*

We did not systematically measure and report the energy requirements when the devices exchange connection parameters before they can establish a connection (negotiation phase).

All measurements were done using a TX power of 0dBm, or as close as possible. Dialog devices have a typical TX power of -1dBm (Max: 0dBm). This should be taken into consideration when interpreting the results.

IX. DEVICE DESCRIPTIONS FROM MANUFACTURERS

A. Atmel ATBTLC1000 [4]

The Atmel® ATBTLC1000 is an ultra-low power Bluetooth® SMART (BLE 4.1) System on a Chip with Integrated MCU, Transceiver, Modem, MAC, PA, TR Switch, and Power Management Unit (PMU). It can be used as a Bluetooth Low Energy link controller or data pump with external host MCU or as a standalone applications processor with embedded BLE connectivity and external memory. The qualified Bluetooth Smart protocol stack is stored in dedicated ROM. The firmware includes L2CAP service layer protocols, Security Manager, Attribute protocol (ATT), Generic Attribute Profile (GATT), and the Generic Access Profile (GAP). Additionally, application profiles such as Proximity, Thermometer, Heart Rate, Blood Pressure, and many others are supported and included in the protocol stack.

- Complies with Bluetooth V4.1, ETSI EN 300 328 and EN 300 440 Class 2,
- FCC CFR47 Part 15 and ARIB STD-T66
- 2.4GHz transceiver and modem
    - -95dBm/-93dBm programmable receiver sensitivity
    - -20 to +3.5dBm programmable TX output power
    - Integrated T/R switch
    - Single wire antenna connection
- ARM® Cortex®-M0 32-bit processor
    - Single wire Debug (SWD) interface
    - Four-channel DMA controller
    - Brownout detector and Power On Reset
    - Watch Dog Timer
- Memory
    - 128kB embedded RAM (96kB available for application)
    - 128kB embedded ROM
- Hardware Security Accelerators
    - AES-128
    - SHA-256
- Peripherals
    - 12 digital and one wakeup GPIOs with 96kΩ internal pull-up resistors, two
- Mixed Signal GPIO
    - 2x SPI Master/Slave
    - 2x I2C Master/Slave and 1x I2C Slave
    - 2x UART
    - 1x SPI Flash
    - Three-axis quadrature decoder
    - 4x Pulse Width Modulation (PWM), three General Purpose Timers, and one Wakeup Timer
    - 2-channel 11-bit ADC
- Clock
    - Integrated 26MHz RC oscillator
    - 26MHz crystal oscillator
    - Integrated 2MHz sleep RC oscillator
    - 32.768kHz RTC crystal oscillator
- Ultra-Low power
    - 1.1µA sleep current (8KB RAM retention and RTC running)
    - 3.0mA peak TX current (0dBm, 3.6V)
    - 3.0mA peak RX current (3.6V, -93dBm sensitivity)
    - 9.7µA average advertisement current (three channels, 1s interval)
- Integrated Power management
    - 1.8 to 4.3V battery voltage range
- Fully integrated Buck DC/DC converter
- Bluetooth SIG Certification
    - QD ID Controller (see declaration D028678)
    - QD ID Host (see declaration D028679)

B. Texas Instruments CC2650 SimpleLink™ Multistandard Wireless MCU [6]

The CC2650 device is a wireless MCU targeting Bluetooth Smart, ZigBee® and 6LoWPAN, and ZigBee RF4CE remote control applications. The device is a member of the CC26xx family of cost-effective, ultralow power, 2.4-GHz RF devices. Very low active RF and MCU current and low-power mode current consumption provide excellent battery lifetime and allow for operation on small coin cell batteries and in energy-harvesting applications. The CC2650 device contains a 32-bit ARM Cortex-M3 processor that runs at 48 MHz as the main processor and a rich peripheral feature set that includes a unique ultralow power sensor controller. This sensor controller is ideal for interfacing external sensors and for collecting analog and digital data autonomously while the rest of the system is in sleep mode. Thus, the CC2650 device is ideal for applications within a whole range of products including industrial, consumer electronics, and medical. The Bluetooth Low Energy controller and the IEEE 802.15.4 MAC are embedded into ROM and are partly running on a separate ARM Cortex-M0 processor. This architecture improves overall system performance and power consumption and frees up flash memory for the application. The Bluetooth Smart and ZigBee stacks are available free of charge from www.ti.com.

- Microcontroller
    - Powerful ARM® Cortex®-M3; EEMBC CoreMark® Score: 142; Up to 48-MHz Clock Speed
    - 128KB of In-System Programmable Flash; 8KB of SRAM for Cache; 20KB of Ultralow-Leakage SRAM
- Ultralow-Power Sensor Controller
    - Can Run Autonomous From the Rest of the system; 16-Bit Architecture
    - 2KB of Ultralow-Leakage SRAM for Code and Data
- Efficient Code Size Architecture, Placing Drivers, *Bluetooth*® Low Energy Controller, and Bootloader in ROM
- RoHS-Compliant Packages
    - 4-mm × 4-mm RSM VQFN32 (10 GPIOs); 5-mm × 5-mm RHB VQFN32 (15 GPIOs)
    - 7-mm × 7-mm RGZ VQFN48 (31 GPIOs)
- RF Section
    - 2.4-GHz RF Transceiver Compatible With *Bluetooth* Low Energy (BLE) 4.1 Specification
    - Excellent Receiver Sensitivity (–97 dBm for BLE), Selectivity, and Blocking Performance
    - Link budget of 102 dB/105 dB (BLE/802.15.4); Programmable Output Power up to +5 dBm
    - Single-Ended or Differential RF Interface
    - Suitable for Systems Targeting Compliance With Worldwide Radio Frequency Regulations
- Low Power
- Wide Supply Voltage Range
- Normal Operation: 1.8 to 3.8 V; External Regulator Mode: 1.7 to 1.95 V
- Active-Mode RX: 5.9 mA; Active-Mode TX at 0 dBm: 6.1 mA : Active-Mode TX at +5 dBm: 9.1 mA
    - Active-Mode MCU: 61 µA/MHz; Active-Mode MCU: 48.5 CoreMark/mA
    - Active-Mode Sensor Controller: 8.2 µA/MHz
    - Standby: 1 µA (RTC Running and RAM/CPU Retention)
    - Shutdown: 100 nA (Wake Up on External Events)
- Peripherals
    - All Digital Peripheral Pins Can Be Routed to Any GPIO
    - Four General-Purpose Timer Modules (Eight 16-Bit or Four 32-Bit Timers, PWM Each)
    - 12-Bit ADC, 200-ksamples/s, 8-Channel Analog MUX
    - Continuous Time Comparator; Ultralow-Power Analog Comparator; Programmable Current Source
    - UART; 2× SSI (SPI, MICROWIRE, TI) ; I2C ; I2S
    - Real-Time Clock (RTC)
    - AES-128 Security Module; True Random Number Generator (TRNG)
    - 10, 15, or 31 GPIOs, Depending on Package Option
    - Support for Eight Capacitive-Sensing Buttons; Integrated Temperature Sensor
- External System
    - On-Chip internal DC-DC Converter
- Very Few External Components
- Seamless Integration With the SimpleLink™ CC2590 and CC2592 Range Extenders
- Pin Compatible With the SimpleLink CC13xx in 4-mm × 4-mm and 5-mm × 5-mm VQFN Packages

C. Nordic nRF52832 [7]

The nRF52832 SoC is a powerful, highly flexible ultra-low power multiprotocol SoC ideally suited for *Bluetooth*® Smart ANT and 2.4GHz ultra low-power wireless applications. The nRF52832 SoC is built around a 32-bit ARM® Cortex™-M4F CPU with 512kB + 64kB RAM. The embedded 2.4GHz transceiver supports Bluetooth Smart, ANT and proprietary 2.4 GHz protocol stack. It is on air compatible with the nRF51 Series, nRF24L and nRF24AP Series products from Nordic Semiconductor. NFC™-A tag support is included on chip. Out-of-Band (OOB) pairing using NFC simplifies the process of authenticated pairing between two Bluetooth devices by exchanging authentication information over an NFC link.

- Supports concurrent Bluetooth Smart/ANT protocol operation
- On-chip NFC tag for Out-of-Band (OOB) pairing
- On-chip balun

- Frequency band
  - Single chip, highly flexible, 2.4 GHz ISM (2.36000 – 2.4835GHz) multi-protocol SoC
- On-air data rate
  - 1 Mbps or 2 Mbps
- Modulation
  - GFSK
- Output power
  - Programmable: +4 to -20dBm in 4dB steps
- Sensitivity
  - -96dBm Bluetooth, -92.5dBm at 1Mbs ANT, -89dBm at 2Mbs, -30dBm whisper mode
- Radio current consumption DC-DC at 3V
  - 7.5mA – TX at +4dBm output power
  - 5.3mA – TX at 0dBm output power
  - 5.4mA – RX at 1Mbs
- Microcontroller
  - 32-bit ARM Cortex M4F
- Program Memory
  - 512kB Flash with cache
- RAM
  - 64kB
- Oscillators
  - 32MHz crystal oscillator, 64MHz RC oscillator, 32kHz crystal oscillator, 32kHz RC oscillator (±250 ppm)
- System current consumption
  - 0.4µA – No RAM retention, 1.4uA – All peripherals in IDLE mode, 1.8uA – All peripherals in IDLE mode and 32KHz XO and RTC running, 40nA per 4KB - RAM retention
- Hardware Security
  - 128-bit AES ECB/CCM/AAR co-processor
- GPIO
  - 32 configurable
- Digital I/O
  - 3 x Hardware SPI master, 3 x Hardware SPI slave, 2 x 2-wire master, 2 x 2-wire slave, UART, Quadrature demodulator, 1x I2S, 1xPDM
- Peripherals
  - 12-bit/200KSPS ADC, RNG, Temperature sensor, general compararator, low power comparator
- PPI
  - 20-channel
- Voltage regulator
  - LDO (1.7 to 3.6V), Buck DC/DC (1.7 to 3.6V)
- Timers/counters
  - 5 x 32bit, 3 x 24bit RTC
- Package options

RoHS compliant 48-pin 6x6 QFN / 3.0x3.2 Ultra-compact Wafer Level Chip Scale Package (WLCSP)

D. Renesas RL78/G1D (R5F11AGG, R5F11AGH, R5F11AGJ) [8]

(Program flash/ data flash/ RAM = 128KB/8KB/12KB, 192KB/8KB/16KB, 256KB/8KB/20KB)
The RL78/G1D is a microcomputer incorporating the RL78 CPU core and low power consumption RF transceiver supporting the Bluetooth ver.4.1 (Low Energy Single mode) specifications.

- Low Power Technology (3.0V / MCU part: STOP)
    - RF transmitter active: 4.3 mA (TYP.). RF receiver active: 3.5 mA (TYP.)
    - RF sleep (POWER_DOWN mode) operation: 0.3 µA (TYP.)
- On-Chip RF Transceiver
    - Bluetooth v4.1 Spec. (Low Energy, Single mode)
    - 2.4 GHz ISM Band, GFSK modulation, TDMA/TDD Frequency Hopping (included AES encryption circuit)
    - Adaptivity, exclusively for use in operation as a slave device. Single ended RF interface
- 16-bit RL78 CPU Core
    - CISC Architecture (Harvard) with 3-stage pipeline
    - Minimum instruction execution time: Can be changed from high speed (0.03125 µs: @ 32 MHz operation with high-speed on chip oscillator) to ultra-low speed (30.5 µs: @ 32.768 kHz operation with subsystem clock)
    - Multiply Signed & Unsigned: 16 x 16 to 32-bit result in 1 clock cycle
    - 1-wire on-chip debug function
- Main Flash Memory
    - 128 KB / 192KB / 256 KB (Block size: 1 KB)
    - On-chip single voltage flash memory with protection from block erase/writing
    - Self-programming with secure boot swap function and flash shield window function
- Data Flash Memory
    - Data Flash with background operation. Data flash size: 8 KB size (Erase block size: 1 KB)
    - Erase Cycles: 1 Million (typ.). Erase/programming voltage: 1.8 V to 3.6 V
- RAM. 12 KB / 16KB / 20 KB size. Supports operands or instructions. Back-up retention in all modes
- On-chip Oscillator
    - High accuracy on-chip Oscillator for MCU, 15kHz low-speed on-chip oscillator for MCU
    - 32.768 kHzOn-chip oscillator for the RF slow clock
- Data Memory Access (DMA) Controller
    - Up to 4 fully programmable channels
    - Transfer unit: 8- or 16-bit
- Multiple Communication Interfaces
    - I2C master×2, CSI/ SPI (7-, 8-bit) ×2, UART (7-, 8-, 9-bit) ×2, Multi-master I2C ×1
- Supply voltage Management
    - Low voltage detection (LVD) with 12 setting options (Notification to Interrupt and/or reset function)
    - Power-on reset (POR) monitor/generator
- Extended-Function Timers
    - Multi-function 16-bit timers: 8 channels
    - Real-time clock (RTC): 1 channel (full calendar and alarm function with watch correction function)
    - Interval Timer: 12-bit, 1 channel. Watchdog timer: 1 channel (window function)
- Rich Analog
    - 8/10-bit resolution A/D converter (VDD = 1.6 to 3.6 V), Analog input: 8 channels
    - Internal voltage reference (1.45 V) and temperature sensor (Can be selected only in HS (high-speed main) mode)
- Safety Functions. Comply with the IEC60730 and IEC61508 safety standards
- General Purpose I/O
    - I/O port: 32
    - Different potential interface support: Can connect to a 1.8/2.5 V device
- Standby function
    - MCU part: Low power consumption mode: HALT, STOP Power saving mode: SNOOZE
    - RF part :Low power saving mode with 6 setting (min. 0.1 µA)
- Operating Voltage / Operating Ambient Temperature
    - 1.6 V to 3.6 V / -40 to +85°C
- Package Type and Pin Count 48-pin HWQFN (6 x 6) (0.4mm pitch)

E. Dialog DA14581 [9]

The DA14581 integrated circuit is an optimized version of the DA14580, offering a reduced boot time and supporting up to 8 connections. It has a fully integrated radio transceiver and baseband processor for Bluetooth® Smart. It can be used as a standalone application processor or as a data pump in hosted systems. The DA14581 supports a flexible memory architecture for storing Bluetooth profiles and custom application code, which can be updated over the air (OTA). The qualified Bluetooth Smart protocol stack and the HCI ready software are stored in a dedicated ROM. All software runs on the ARM® Cortex®-M0 processor via a simple scheduler. The Bluetooth Smart firmware includes the L2CAP service layer protocols, Security Manager (SM), Attribute Protocol (ATT), the Generic Attribute Profile (GATT) and the Generic Access Profile (GAP). All profiles published by the Bluetooth SIG as well as custom profiles are supported. The transceiver interfaces directly to the antenna and is fully compliant with the Bluetooth 4.1 standard. The DA14581 has dedicated hardware for the Link Layer implementation of Bluetooth Smart and interface controllers for enhanced connectivity capabilities.

- Complies with Bluetooth V4.1, ETSI EN 300 328 and EN 300 440 Class 2 (Europe), FCC CFR47 Part 15 US) and ARIB STD-T66 (Japan)
- Supports up to 8 Bluetooth Smart connections
- Fast cold boot in less than 30 ms
- Processing power
    - 16 MHz 32 bit ARM Cortex-M0 with SWD interface
    - Dedicated Link Layer Processor
    - AES-128 bit encryption Processor
- Memories
    - 32 kB One-Time-Programmable (OTP) memory
    - 42 kB System SRAM
    - 84 kB ROM
    - 8 kB Retention SRAM
- Power management
    - Integrated Buck/Boost DCDC converter
    - P0, P1 and P2 ports with 3.3 V tolerance
    - Easy decoupling of only 4 supply pins
    - Supports coin (typ. 3.0 V) and alkaline (typ. 1.5 V) battery cells
    - 10-bit ADC for battery voltage measurement
- Digital controlled oscillators
    - 16 MHz crystal (±20 ppm max) and RC oscillator
    - 32 kHz crystal (±50 ppm, ±500 ppm max) and RCX oscillator
- General purpose, Capture and Sleep timers
- Digital interfaces
    - Gen. purpose I/Os: 14 (WLCSP34), 24 (QFN40)
    - 2 UARTs with hardware flow control up to 1 MBd
    - SPI+™ interface
    - I2C bus at 100 kHz, 400 kHz
    - 3-axes capable Quadrature Decoder
- Analog interfaces
    - 4-channel 10-bit ADC
- Radio transceiver
    - Fully integrated 2.4 GHz CMOS transceiver
    - Single wire antenna: no RF matching or RX/TX switching required
    - Supply current at VBAT3V: TX: 3.4 mA, RX: 3.7 mA (with ideal DC-DC)
    - 0 dBm transmit output power
    - -20 dBm output power in “Near Field Mode”
    - -93 dBm receiver sensitivity
- Packages:
    - WLCSP 34 pins, 2.436 mm x 2.436 mm
    - QFN 40 pins, 5 mm x 5 mm

F. ST Microelectronics BlueNRG-MS [10]

The BlueNRG-MS is a very low power Bluetooth low energy (BLE) single-mode network processor, compliant with Bluetooth specification v4.1. The BlueNRG-MS supports multiple roles simultaneously, and can act at the same time as Bluetooth Smart sensor and hub device.

The entire Bluetooth low energy stack runs on the embedded Cortex M0 core. The non-volatile Flash memory allows on-field stack upgrading. The BlueNRG-MS allows applications to meet of the tight advisable peak current requirements imposed with the use of standard coin cell batteries. The maximum peak current is only 10 mA at 1 dBm of output power. Ultra low-power sleep modes and very short transition times between operating modes allow very low average current consumption, resulting in longer battery life. The BlueNRG-MS offers the option of interfacing with external microcontrollers using SPI transport layer.

- Bluetooth specification v4.1 compliant master and slave single-mode Bluetooth low energy network processor
- Embedded Bluetooth low energy protocol stack: GAP, GATT, SM, L2CAP, LL, RF-PHY
- Bluetooth low energy profiles provided separately
- Operating supply voltage: from 1.7 to 3.6 V
- 8.2 mA maximum TX current (@0 dBm, 3.0 V)
- Down to 1.7 µA current consumption with active BLE stack
- Integrated linear regulator and DC-DC step-down converter
- Up to +8 dBm available output power (at antenna connector)
- Excellent RF link budget (up to 96 dB)
- Accurate RSSI to allow power control
- Proprietary application controller interface (ACI), SPI based, allows interfacing with an external host application microcontroller
- Full link controller and host security
- High performance, ultra-low power Cortex-M0 32-bit based architecture core
- On-chip non-volatile Flash memory
- AES security co-processor
- Low power modes
- 16 or 32 MHz crystal oscillator
- 12 MHz ring oscillator
- 32 kHz crystal oscillator
- 32 kHz ring oscillator
- Battery voltage monitor
- Compliant with the following radio frequency regulations: ETSI EN 300 328, EN 300 440, FCC CFR47 Part 15, ARIB STD-T66
- Available in QFN32 (5 x 5 mm) and WLCSP34 (2.66 x 2.56 mm) packages
- Operating temperature range: -40 °C to 85 °C

SPBTLE-RF – Very low power module for Bluetooth Smart v4.1

The SPBTLE-RF is an easy to use Bluetooth® Smart master/slave network processor module, compliant with Bluetooth® v4.1. The SPBTLE-RF B-SmarT module supports multiple roles simultaneously, and can act at the same time as Bluetooth Smart sensor and hub device.

The entire Bluetooth Smart stack and protocols are embedded into SPBTLE-RF B-SmarT module. The external host application processor, where the application resides, is connected to the SPBTLE-RF B-SmarT module through a standard SPI interface.

The SPBTLE-RF B-SmarT module provides a complete RF platform in a tiny form factor. Radio, antenna, high frequency and LPO oscillators are integrated to offer a certified solution to optimize the time to market of the final applications.

The SPBTLE-RF can be powered directly with a standard 3 V coin cell battery, a pair of AAA batteries or any power source from 1.7 to 3.6 V.

G. Cypress PSoC 4XX7_BLE [10]

PSoC® 4 is a scalable and reconfigurable platform architecture for a family of programmable embedded system controllers with an ARM® Cortex®-M0 CPU. It combines programmable and reconfigurable analog and digital blocks with flexible automatic routing. The PSoC 4XX7_BLE product family, based on this platform, is a combination of a microcontroller with an integrated Bluetooth Low Energy (BLE), also known as Bluetooth Smart, radio and subsystem (BLESS). The other features include digital programmable logic, high-performance analog-to-digital conversion (ADC), opamps with comparator mode, and standard communication and timing peripherals. The PSoC 4XX7_BLE products will be fully upward compatible with members of the PSoC 4 platform for new applications and design needs. The programmable analog and digital subsystems allow flexibility and in-field tuning of the design.

- 32-bit MCU Subsystem and BLE Radio and Subsystem
  - 48-MHz ARM Cortex-M0 CPU with single-cycle multiply; Up to 128 KB of flash with Read Accelerator; Up to 16 KB of SRAM
  - 2.4-GHz RF transceiver with 50-Ω antenna drive; Digital PHY; Link Layer engine supporting master and slave modes
  - RF output power: –18 dBm to +3 dBm; RX sensitivity: –89 dBm
  - RX current: 16.4 mA; TX current: 15.6 mA at 0 dBm ; Received Signal Strength Indication (RSSI): 1-dB resolution
- Programmable Analog
  - Four opamps with reconfigurable high-drive external and high-bandwidth internal drive, comparator modes, and ADC input buffering capability; can operate in Deep-Sleep mode.
  - 12-bit, 1-Msps SAR ADC with differential and single-ended modes; channel sequencer with signal averaging
  - Two current DACs (IDACs) for general-purpose or capacitive sensing applications on any pin
  - Two low-power comparators that operate in Deep-Sleep mode
- Programmable Digital
  - Four programmable logic blocks called universal digital blocks, (UDBs), each with eight macrocells and datapath
  - Cypress-provided peripheral Component library, user-defined state machines, and Verilog input
- Power Management
  - Active mode: 1.7 mA at 3-MHz flash program execution
  - Deep-Sleep mode: 1.3 µA with watch crystal oscillator (WCO) on; Hibernate mode: 150 nA with RAM retention
  - Stop mode: 60 nA
- Capacitive Sensing
  - Cypress CapSense Sigma-Delta (CSD) provides best-in-class SNR (> 5:1) and liquid tolerance
  - Cypress-supplied software component makes capacitive-sensing design easy; Automatic hardware-tuning algorithm (SmartSense™)
- Segment LCD Drive
  - LCD drive supported on all pins (common or segment); Operates in Deep-Sleep mode with four bits per pin memory
- Serial Communication
  - Two independent runtime reconfigurable serial communication blocks (SCBs) with reconfigurable I2C, SPI, or UART functionality
- Timing and Pulse-Width Modulation
  - Four 16-bit timer, counter, pulse-width modulator (TCPWM) blocks; Center-aligned, Edge, and Pseudo-random modes
  - Comparator-based triggering of Kill signals for motor drive and other high-reliability digital logic applications
- Up to 36 Programmable GPIOs
  - 7 mm × 7 mm 56-pin QFN package; 3.51 mm × 3.91 mm 68-ball CSP package
  - Any GPIO pin can be CapSense, LCD, analog, or digital
  - Two overvoltage-tolerant (OVT) pins; drive modes, strengths, and slew rates are programmable

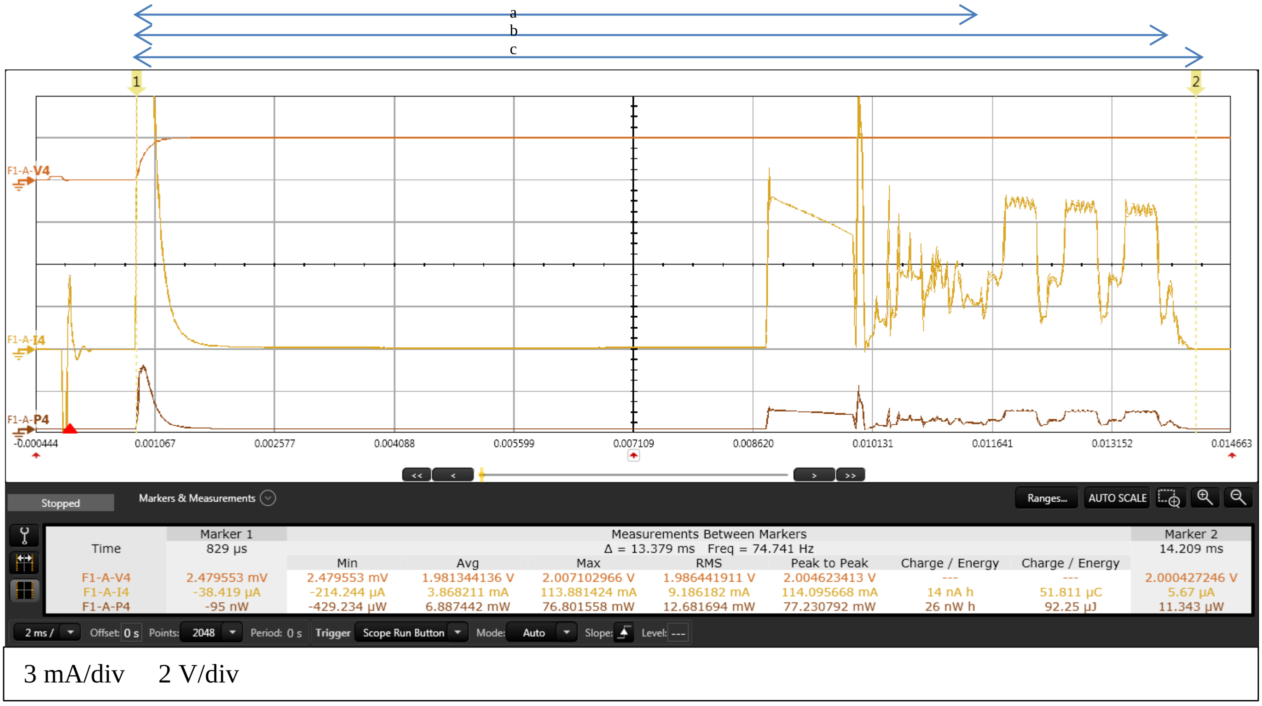
New PSoC 4XX8 BLE 4.2 product family (not measured)

- 48-MHz ARM Cortex-M0 CPU with single-cycle multiply and DMA
- Up to 256 KB of flash with Read Accelerator; Up to 32 KB of SRAM
- 2.4-GHz RF transceiver with 50-Ω antenna drive; Digital PHY; Link-Layer engine supporting master and slave modes
- RF output power: –18 dBm to +3 dBm; RX sensitivity: –92 dBm
- RX current: 18.7 mA; TX current: 16.5 mA at 0 dBm ; RSSI: 1-dB resolution

X. RESULTS OF MEASUREMENTS

Results are shown below in form of dynamic power profiles and tables. At least one profile of each device is shown, which allows the user to derive the current consumption and see something of the "internal life" of the solution. Due to practical reasons, we could not include all the measurements in this report. The results of non-connectable mode (only ADV_NONCONN_IND) are shown first. Afterwards, the measurements in connectable mode (ADV_IND followed by a connection) are listed.

Energy at different times during Startup & ADV_NONCONN_IND (µJ): 55.4 (a); 90.7 (b); 92.3 (c)

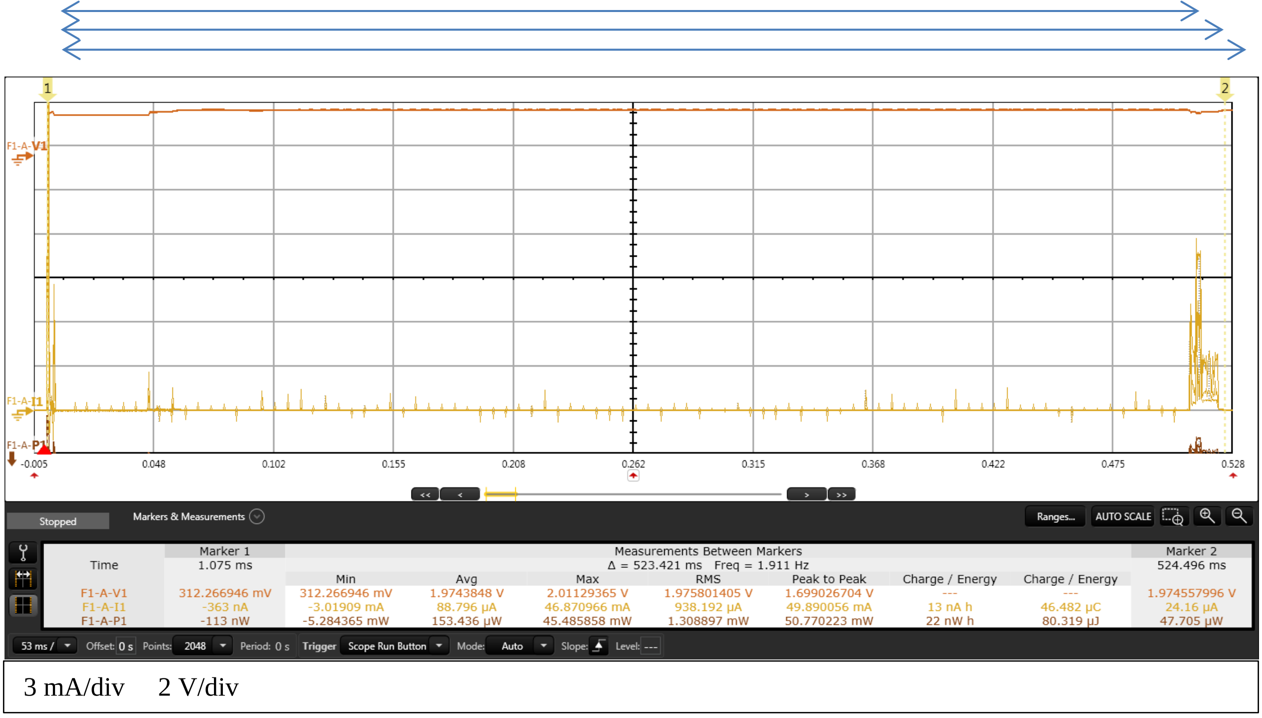


Time	Marker 1 829 µs	Measurements Between Markers Δ = 13.379 ms Freq = 74.741 Hz							Marker 2 14.209 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V4	2.479553 mV	2.479553 mV	1.981344136 V	2.007102966 V	1.986441911 V	2.004623413 V	---	---	2.000427246 V
F1-A-I4	-38.419 µA	-214.244 µA	3.868211 mA	113.881424 mA	9.186182 mA	114.095668 mA	14 nA h	51.811 µC	5.67 µA
F1-A-P4	-95 nW	-429.234 µW	6.887442 mW	76.801558 mW	12.681694 mW	77.230792 mW	26 nW h	92.25 µJ	11.343 µW

3 mA/div 2 V/div

Fig. 1. Startup & ADV_NONCONN_IND for CC2650 device at 2.0 Volts.

Energy at different times during Startup & ADV_NONCONN_IND (µJ): 34.6; 63.1; 80.3



Time	Marker 1 1.075 ms	Measurements Between Markers Δ = 523.421 ms Freq = 1.911 Hz							Marker 2 524.496 ms
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V1	312.266946 mV	312.266946 mV	1.9743848 V	2.01129365 V	1.975801405 V	1.699026704 V	---	---	1.974557996 V
F1-A-I1	-363 nA	-3.01909 mA	88.796 µA	46.870966 mA	938.192 µA	49.890056 mA	13 nA h	46.482 µC	24.16 µA
F1-A-P1	-113 nW	-5.284365 mW	153.436 µW	45.485858 mW	1.308897 mW	50.770223 mW	22 nW h	80.319 µJ	47.705 µW

3 mA/div 2 V/div

Fig. 2. Startup & ADV_NONCONN_IND for NRF52 device at 2.0 Volts.

Some devices offer the advantage of choosing between different types of oscillators at start-up. This is good for the user as it gives more flexibility for the application. Use of a crystal in order to achieve better timing accuracy will often imply more energy than in cases where an internal RC oscillator is used, especially when a delay is built in in order to wait for the stabilization of the crystal oscillator.

For the measurements below (tables I –VI), we have worked with internal RC oscillators as it is enough for the type of application in mind. We however added extra measurements using the Renesas device (we could have used others) in order to illustrate the effect of the start-up oscillator choice. That measurement shows that a crystal can also be used at start-up, at the expense of energy. The measurements of the Renesas device using a crystal are shown in grey in the table.

In the case of the Cypress device, we unfortunately only had an example with crystal at start up, which means that a direct comparison is not possible. The measurements of the ST, Atmel and Nordic chips are also done using a low frequency crystal oscillator.

TABLE I. ENERGY AND TIME REQUIRED AT START-UP (WITH ADV_NONCONN_IND, 3V)

Devices	**Parameters**			
	Measurement Voltage(V)	***Start-up Time (ms)***	***Start-up Energy (µJ)***	***Remarks***
DA14581	3.0	31	113.1	OTP memory, DCDC enabled, RCX20
RL78/G1D	3.0	12.7	121.2	DCDC enabled, internal oscillator
RL78/G1D	3.0	1016	1441.5	DCDC enabled, XT1 enabled (1s to settle)
CC2650	3.0	12.7	128.4	DCDC enabled, LF RCOSC
SPBTLE-RF	3.0	139.9	1030.5	DCDC enabled, LSOSC
BTLC1000	3.0	-	-	DCDC enabled, XOSC32K
NRF52	3.0	490.4	118.5	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3.0	518.5	9945.3	PSoC, External Crystal Oscillator ECO

TABLE II. ENERGY AND TIME REQUIRED AT START-UP (WITH ADV_NONCONN_IND, MINIMAL VOLTAGE)

Devices	**Parameters**			
	Measurement Voltage(V)	***Start-up Time (ms)***	***Start-up Energy (µJ)***	***Remarks***
DA14581	2.35	31	102.0	OTP memory, DCDC enabled, RCX20
RL78/G1D	1.8	12.5	65.0	DCDC enabled, internal oscillator
RL78/G1D	1.8	1015.9	610.6	DCDC enabled, XT1 osc. (1s to settle)
CC2650	1.8	13.9	86.9	DCDC enabled, LF RCOSC
CC2650	1.7	12.5	77.8	DCDC bypassed, LF RCOSC
SPBTLE-RF	2*	141	748.9	DCDC enabled, LSOSC
BTLC1000	1.9*	-	-	DCDC enabled, XOSC32K
NRF52	2.0*	525.2	80.4	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	518.7	4957	PSoC, External Crystal Oscillator ECO

*A lower minimal voltage is possible. This is described in the following section.

The BTLC1000 has an operating supply voltage down to 1.8V. We were only able to operate the device down to 1.9V, which is the voltage used in the tables as minimal voltage. The startup measurements are not stated, an ATSAML21 is used as a microcontroller. The available silicon does not allow a meaningful measurement of startup.

In the case of nRF52, an Engineering B version was used for the measurements. A list of the errata can be found on the website [15]. The errata affecting the current measurements are described in [16]. The workaround to switch off DCDC in System ON IDLE mode has been used. NFCT may still draw current when the supply voltage is higher than 2.5V. The minimal supply voltage of the nRF52 is 1.7V. A voltage of 2.0V is used as the minimal voltage due to high negative currents when supplied with 1.7V.

The DA14581 is used in different settings. For ADV_NONCONN_IND measurements with an advertising interval of 1000ms, the One-Time-Programmable (OTP) memory was used. For the other measurements, an external Flash memory has been used. On the development kit, the jumpers to the Flash were detached after startup to achieve correct sleep current measurements. In these tables, the selected clock is either generated by an internal RCX20 or an external XTAL32 oscillator.

The CC2650 uses an internal DCDC regulator, which leads to a minimal voltage of 1.8V. Using the External Regulator Mode allows voltages down to 1.7V. Hardware changes on the module were needed to achieve this. The measurements of the ADV-NON-CON-IND packets at an interval of 100ms were made with the External Regulator Mode at 1.7V. The other measurements use the normal operation mode.

In the case of the ST device, an operating supply voltage of 1.7V is possible according to the datasheet. We were able to measure down to 1.76V. In this paper, we are using 2.0V as the minimal voltage. The SPBTLE-RF is a certified module design.

Fig. 3 explains how the following tables should be read. Advertising packets on all advertising channels are sent every 100 or 1000 ms during the active part. Between these transmissions, the devices switch into a low-power mode. This is called the sleep part. An ADV event cycle is the combination of one active and one sleep part and has a length of one interval.

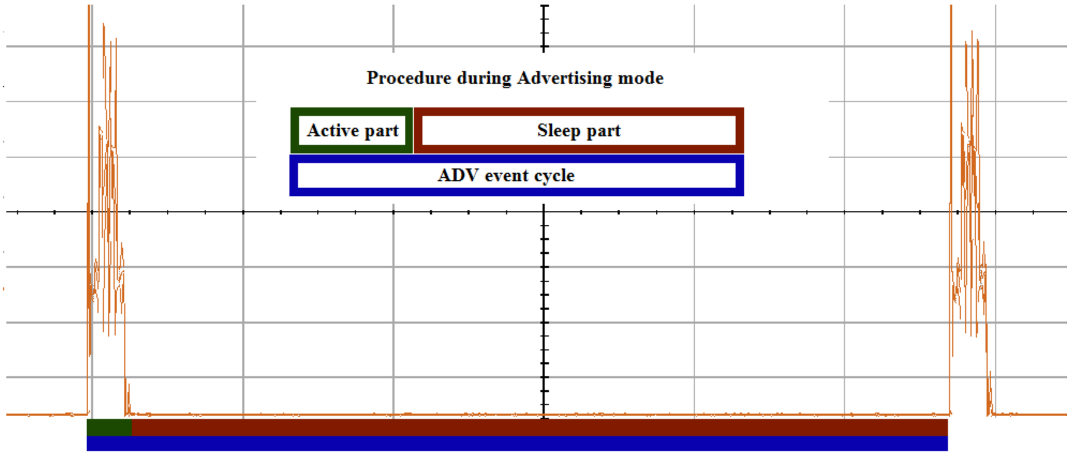
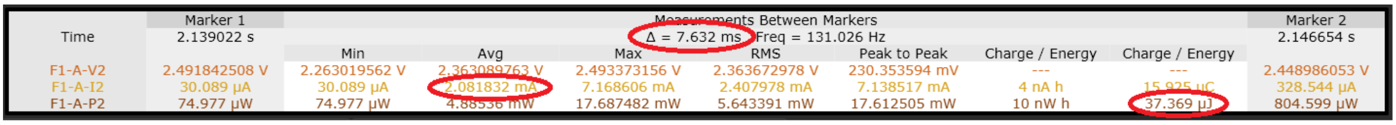


Fig. 3. Explanation of an ADV event cycle separated into active and sleep part

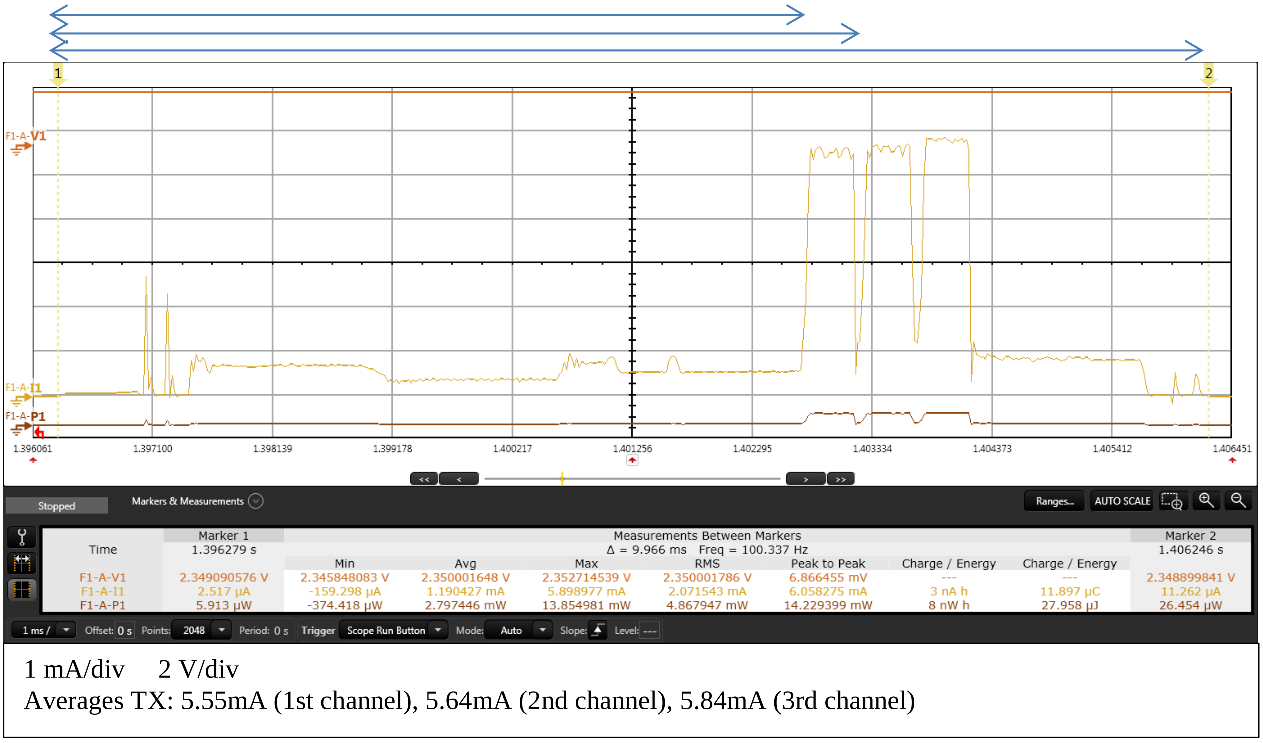


	Marker 1	Measurements Between Markers							Marker 2
Time	2.139022 s			Δ = 7.632 ms	Freq = 131.026 Hz				2.146654 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V2	2.491842508 V	2.263019562 V	2.363089763 V	2.493373156 V	2.363672978 V	230.353594 mV	---	---	2.448986053 V
F1-A-I2	30.089 µA	30.089 µA	2.081832 mA	7.168606 mA	2.407978 mA	7.138517 mA	4 nA h	15.925 µC	328.544 µA
F1-A-P2	74.977 µW	74.977 µW	4.88536 mW	17.687482 mW	5.643391 mW	17.612505 mW	10 nW h	37.369 µJ	804.599 µW

Averaged current between markers **Time span** **Energy between markers**

Fig. 4. Measurement tool of Agilent 14585A Control and Analysis Software

Energy at different times during ADV_NONCONN_IND event (µJ): 7.6; 13.2; 27.96



Time	Marker 1 1.396279 s	Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	Marker 2 1.406246 s
		Measurements Between Markers Δ = 9.966 ms Freq = 100.337 Hz							
F1-A-V1	2.349090576 V	2.345848083 V	2.350001648 V	2.352714539 V	2.350001786 V	6.866455 mV	---	---	2.348899841 V
F1-A-I1	2.517 µA	-159.298 µA	1.190427 mA	5.898977 mA	2.071543 mA	6.058275 mA	3 nA h	11.897 µC	11.262 µA
F1-A-P1	5.913 µW	-374.418 µW	2.797446 mW	13.854981 mW	4.867947 mW	14.229399 mW	8 nW h	27.958 µJ	26.454 µW

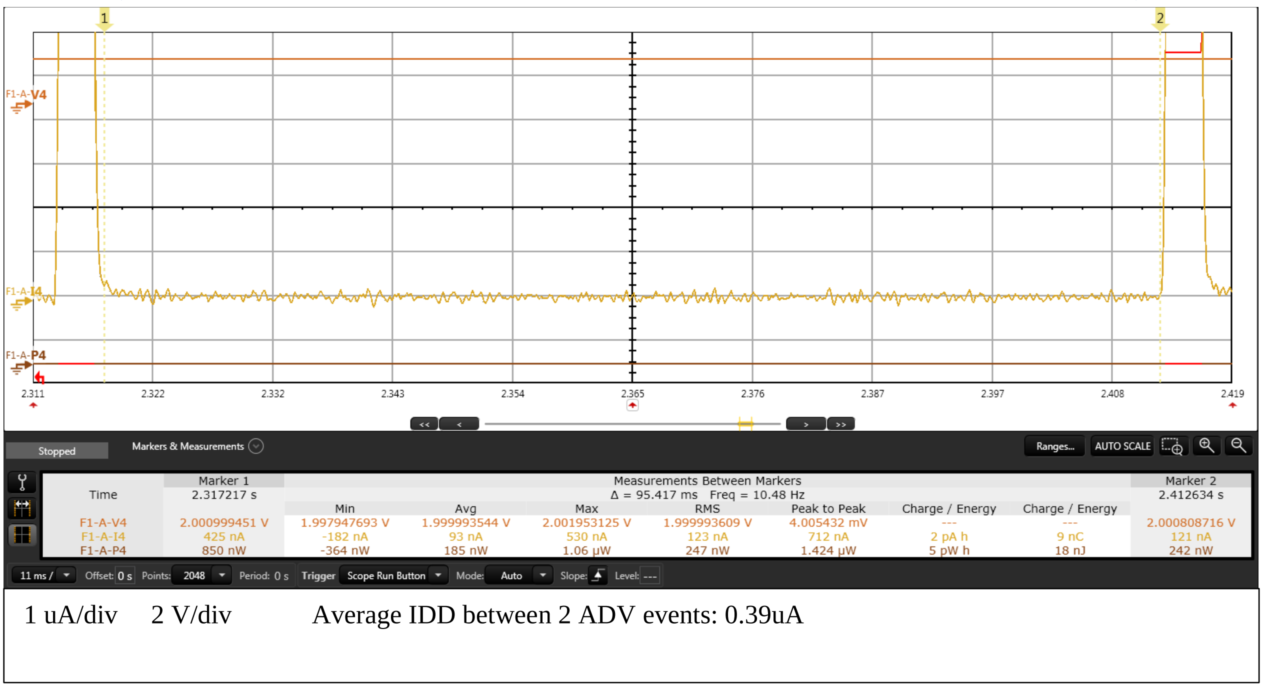
1 ms / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

1 mA/div 2 V/div

Averages TX: 5.55mA (1st channel), 5.64mA (2nd channel), 5.84mA (3rd channel)

Fig. 5. ADV_NONCONN_IND event for DA14581 device at 2.35 Volts (OTP, 1000ms).

Energy between two ADV_NONCONN_IND events (µJ): 0.018



Time	Marker 1 2.317217 s	Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	Marker 2 2.412634 s
		Measurements Between Markers Δ = 95.417 ms Freq = 10.48 Hz							
F1-A-V4	2.000999451 V	1.997947693 V	1.999993544 V	2.001953125 V	1.999993609 V	4.005432 mV	---	---	2.000808716 V
F1-A-I4	425 nA	-182 nA	93 nA	530 nA	123 nA	712 nA	2 pA h	9 nC	121 nA
F1-A-P4	850 nW	-364 nW	185 nW	1.06 µW	247 nW	1.424 µW	5 pW h	18 nJ	242 nW

11 ms / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

1 uA/div 2 V/div Average IDD between 2 ADV events: 0.39uA

Fig. 6. Sleep phase for CC2650 device at 2.0 Volts (100ms interval, non-con, 10µA range).

TABLE III. ENERGY AND TIME REQUIRED FOR A TOTAL ADV_NONCONN_IND EVENT CYCLE (NON-CONNECTABLE, 3V)

Devices	**Parameters**						
	Measurement Voltage (V)	***ADV event cycle (ms)***	***Cycle Energy (µJ)***	***Active part Energy (µJ)***	***Sleep part Avg. current (µA)***	***Sleep part Energy (µJ)***	***Remarks***
DA14581	3	106	31.3	30.9	1.3	0.38	External Flash, DCDC enabled, RCX20
RL78/G1D	3	100	32.8	32.4	1.4	0.39	DCDC enabled, internal oscillator
RL78/G1D	3	100	31.9	31.6	1.1	0.32	DCDC enabled, XT1 enabled
CC2650	3	100	44.2	44.1	0.1	0.03	DCDC enabled, LF RCOSC
SPBTLE-RF	3	104	41.8	40.9	2.5	0.77	DCDC enabled, LSOSC
BTLC1000	3	108	28.7	28.2	1.4	0.38	DCDC enabled, XOSC32K
NRF52	3	109	33.9	33.3	2.0	0.62	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	109	94.1	93.7	1.8	0.51	PSoC, External Crystal Oscillator ECO
DA14581	3	1003	33.3	29.1	1.4	4.05	OTP memory, DCDC enabled, RCX20
RL78/G1D	3	1001	36.7	32.5	1.4	4.29	DCDC enabled, internal oscillator
RL78/G1D	3	1000	35.9	32.2	1.3	3.89	DCDC enabled, XT1 oscillator
CC2650	3	1001	46.9	45.5	0.5	1.4	DCDC enabled, LF RCOSC
SPBTLE-RF	3	1002	48.1	41.0	2.4	7.3	DCDC enabled, LSOSC
BTLC1000	3	1009	32.9	29.0	1.3	3.96	DCDC enabled, XOSC32K
NRF52	3	1004	41.4	34.1	2.4	7.32	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	1006	98.4	94.5	1.3	4.00	PSoC, External Crystal Oscillator ECO

TABLE IV. ENERGY AND TIME REQUIRED FOR A TOTAL ADV_NONCONN_IND EVENT CYCLE (NON-CONNECTABLE, MINIMAL VOLTAGE)

Devices	**Parameters**						
	Measurement Voltage (V)	***ADV event cycle (ms)***	***Cycle Energy (µJ)***	***Active part Energy (µJ)***	***Sleep part Avg. current (µA)***	***Sleep part Energy (µJ)***	***Remarks***
DA14581	2.35	101	29.5	29.3	1.3	0.30	External Flash, DCDC enabled, RCX20
RL78/G1D	1.8	100	24.7	24.5	1.1	0.19	DCDC enabled, internal oscillator
RL78/G1D	1.8	100	24.5	24.3	1.0	0.17	DCDC enabled, XT1 enabled
CC2650	1.7	100	40.6	40.4	1.1	0.17	DCDC bypassed, LF RCOSC
SPBTLE-RF	2.0	104	37.3	36.8	2.4	0.49	DCDC enabled, LSOSC
BTLC1000	1.9	106	25.4	24.8	3.0	0.58	DCDC enabled, XOSC32K
NRF52	2.0	109	29.3	28.6	3.5	0.73	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	102	49.4	49.1	1.3	0.21	PSoC, External Crystal Oscillator ECO
DA14581	2.35	1009	31.1	28.0	1.3	3.10	OTP memory, DCDC enabled, RCX20
RL78/G1D	1.8	1001	26.5	24.6	1.1	1.97	DCDC enabled, internal oscillator
RL78/G1D	1.8	1000	25.9	24.2	1.0	1.77	DCDC enabled, XT1 oscillator
CC2650	1.8	1001	45.2	44.0	0.7	1.2	DCDC enabled, LF RCOSC
SPBTLE-RF	2.0	1006	41.6	36.8	2.4	4.7	DCDC enabled, LSOSC
BTLC1000	1.9	1000	30.8	25.4	3.0	5.75	DCDC enabled, XOSC32K
NRF52	2.0	1003	33.7	29.1	2.3	4.66	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	1004	52.2	50.1	1.2	2.07	PSoC, External Crystal Oscillator ECO

TABLE V. ENERGY NEEDED FOR THE ADV_NONCONN_IND EVENT (AVERAGING SEVERAL CYCLES, NON-CONNECTABLE, 3V)

Devices	**Parameters**					
	Measurement Voltage(V)	***ADV event cycles***	***Average current (µA)***	***Energy (mJ)***	***Energy per cycle (µJ)***	***Remarks***
DA14581	3	100 ms for 1 min	97.5	17.6	30.7	External Flash, DCDC enabled, RCX20
RL78/G1D	3	100 ms for 1 min	109.2	19.7	32.8	DCDC enabled, internal oscillator
RL78/G1D	3	100 ms for 1 min	107.2	19.3	32.2	DCDC enabled, XT1 enabled
CC2650	3	100 ms for 1 min	146.3	26.3	44.0	DCDC enabled, LF RCOSC
SPBTLE-RF	3	100 ms for 1 min	132.0	23.8	41.6	DCDC enabled, LSOSC
BTLC1000	3	100 ms for 1 min	92.5	16.6	28.7	DCDC enabled, XOSC32K
NRF52	3	100 ms for 1 min	111.5	19.6	34.2	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	100 ms for 1 min	299.8	54.0	94.3	PSoC, External Crystal Oscillator ECO
DA14581	3	1000 ms for 1 min	11.2	2.0	33.6	OTP memory, DCDC enabled, RCX20
RL78/G1D	3	1000 ms for 1 min	12.2	2.2	36.7	DCDC enabled, internal oscillator
RL78/G1D	3	1000 ms for 1 min	11.9	2.1	35.6	DCDC enabled, XT1 oscillator
CC2650	3	1000 ms for 1 min	15.4	2.8	46.2	DCDC enabled, LF RCOSC
SPBTLE-RF	3	1000 ms for 1 min	15.8	2.9	48.3	DCDC enabled, LSOSC
BTLC1000	3	1000 ms for 1 min	10.8	1.9	32.9	DCDC enabled, XOSC32K
NRF52	3	1000 ms for 1 min	13.9	2.5	40.9	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	1000 ms for 1 min	34.3	6.2	102.8	PSoC, External Crystal Oscillator ECO

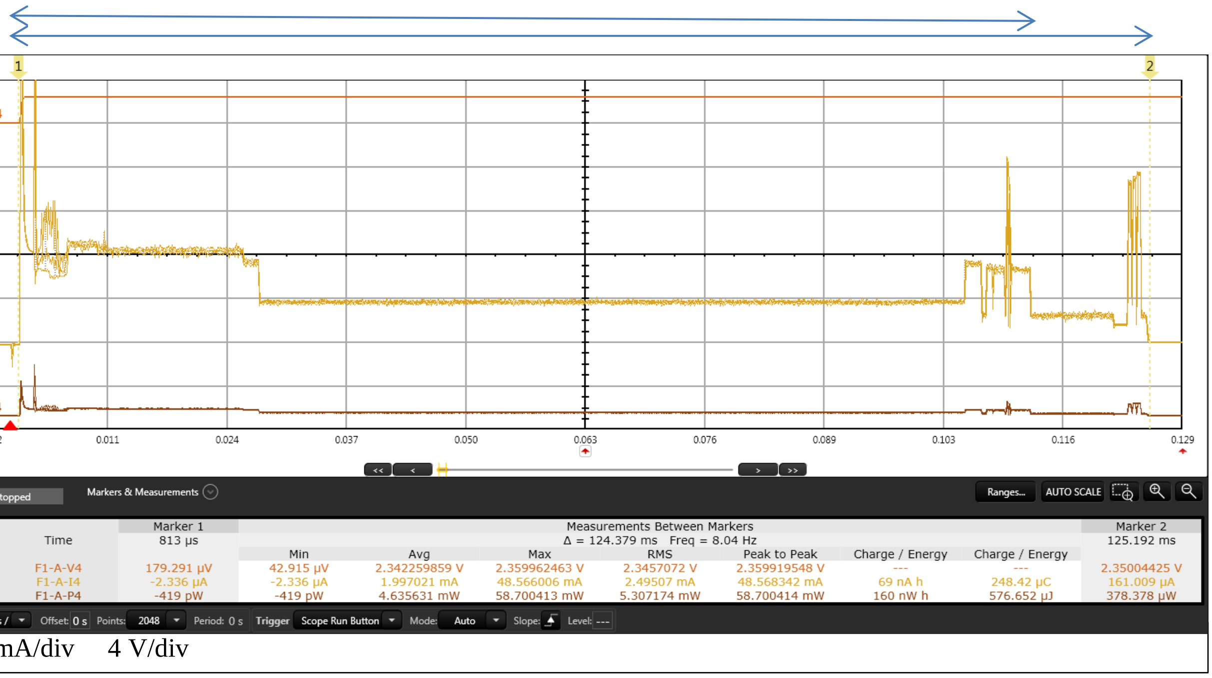
TABLE VI. ENERGY NEEDED FOR THE ADV_NONCONN_IND EVENT (AVERAGING SEVERAL CYCLES, NON-CONNECTABLE, MINIMAL VOLTAGE)

Devices	**Parameters**					
	Measurement Voltage(V)	***ADV event cycles***	***Average current (µA)***	***Energy (mJ)***	***Energy per cycle (µJ)***	***Remarks***
DA14581	2.35	100 ms for 1 min	119.9	16.9	29.6	External Flash, DCDC enabled, RCX20
RL78/G1D	1.8	100 ms for 1 min	137.3	14.8	24.7	DCDC enabled, internal oscillator
RL78/G1D	1.8	100 ms for 1 min	136.6	14.8	24.6	DCDC enabled, XT1 enabled
CC2650	1.7	100 ms for 1 min	237.9	24.6	41.2	DCDC bypassed, LF RCOSC
SPBTLE-RF	2.0	100 ms for 1 min	177.5	21.3	37.3	DCDC enabled, LSOSC
BTLC1000	1.9	100 ms for 1 min	129.2	14.7	25.4	DCDC enabled, XOSC32K
NRF52	2.0	100 ms for 1 min	147.7	16.6	29.0	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	100 ms for 1 min	275.5	28.1	49.2	PSoC, External Crystal Oscillator ECO
DA14581	2.35	1000 ms for 1 min	13.3	1.9	31.2	OTP memory, DCDC enabled, RCX20
RL78/G1D	1.8	1000 ms for 1 min	14.7	1.6	26.5	DCDC enabled, internal oscillator
RL78/G1D	1.8	1000 ms for 1 min	14.5	1.6	26.1	DCDC enabled, XT1 oscillator
CC2650	1.8	1000 ms for 1 min	24.9	2.7	44.8	DCDC enabled, LF RCOSC
SPBTLE-RF	2.0	1000 ms for 1 min	20.8	2.5	41.5	DCDC enabled, LSOSC
BTLC1000	1.9	1000 ms for 1 min	16.2	1.8	30.7	DCDC enabled, XOSC32K
NRF52	2.0	1000 ms for 1 min	17.6	2.0	33.2	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	1000 ms for 1 min	30.0	3.1	51.0	PSoC, External Crystal Oscillator ECO

Note: Exact number of cycles was counted and used in operation to calculate energy per cycle.

The following measurements show the behavior of the devices in connectable mode (ADV_IND and connection).

Energy at different times during Startup & ADV_IND event (µJ): 560.0; 576.7



Time	Marker 1	Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	Marker 2
	813 µs	Measurements Between Markers Δ = 124.379 ms Freq = 8.04 Hz							125.192 ms
F1-A-V4	179.291 µV	42.915 µV	2.342259859 V	2.359962463 V	2.3457072 V	2.359919548 V	---	---	2.35004425 V
F1-A-I4	-2.336 µA	-2.336 µA	1.997021 mA	48.566006 mA	2.49507 mA	48.568342 mA	69 nA h	248.42 µC	161.009 µA
F1-A-P4	-419 pW	-419 pW	4.635631 mW	58.700413 mW	5.307174 mW	58.700414 mW	160 nW h	576.652 µJ	378.378 µW

13 ms / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

1 mA/div 4 V/div

Fig. 7. Startup & ADV_IND (CONNECTABLE) for DA1581 device at 2.35 Volts.

An external Flash is used in Fig. 7. Using the integrated One-Time-Programmable (OTP) memory reduces the energy consumption at startup drastically (see Fig. 2 for OTP numbers in non-connectable mode).

TABLE VII. ENERGY AND TIME REQUIRED AT START-UP (WITH ADV_IND, 3V)

Devices	**Parameters**			
	Measurement Voltage(V)	***Start-up Time (ms)***	***Start-up Energy (µJ)***	***Remarks***
DA14581	3.0	124	767.1	External Flash, DCDC enabled, XTAL32
RL78/G1D	3.0	-	-	DCDC enabled, XT1 oscillator
CC2650	3.0	116	736.8	DCDC enabled, LF XOSC
SPBTLE-RF	3.0	151	1124.5	DCDC enabled, LSOSC
BTLC1000	3.0	-	-	DCDC enabled, XOSC32K
NRF52	3.0	490	135.0	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3.0	531	10268	PSoC, External Crystal Oscillator ECO

TABLE VIII. ENERGY AND TIME REQUIRED AT START-UP (WITH ADV_IND, MINIMAL VOLTAGE)

Devices	**Parameters**			
	Measurement Voltage(V)	***Start-up Time (ms)***	***Start-up Energy (µJ)***	***Remarks***
DA14581	2.35	124	576.7	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	-	-	DCDC enabled, XT1 oscillator
CC2650	1.8	118	663.9	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	149	816.4	DCDC enabled, LSOSC
BTLC1000	1.9	-	-	DCDC enabled, XOSC32K
NRF52	2.0	516	98.5	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	530	4985	PSoC, External Crystal Oscillator ECO

The connectable advertising event allows an initiator to respond with a connect request. To establish a connection, the initiator sends a connect request (CONNECT_REQ PDU) to request the Link Layer to enter the Connection State.

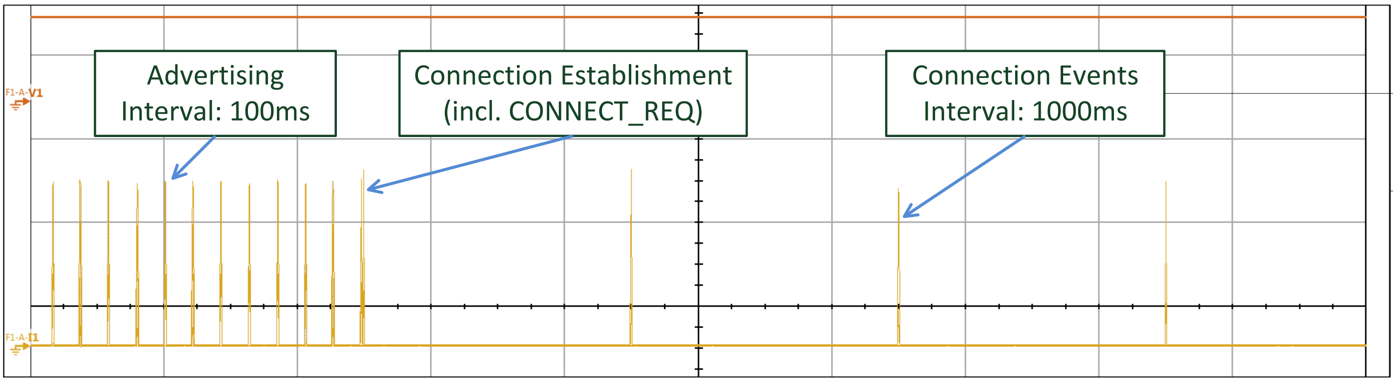
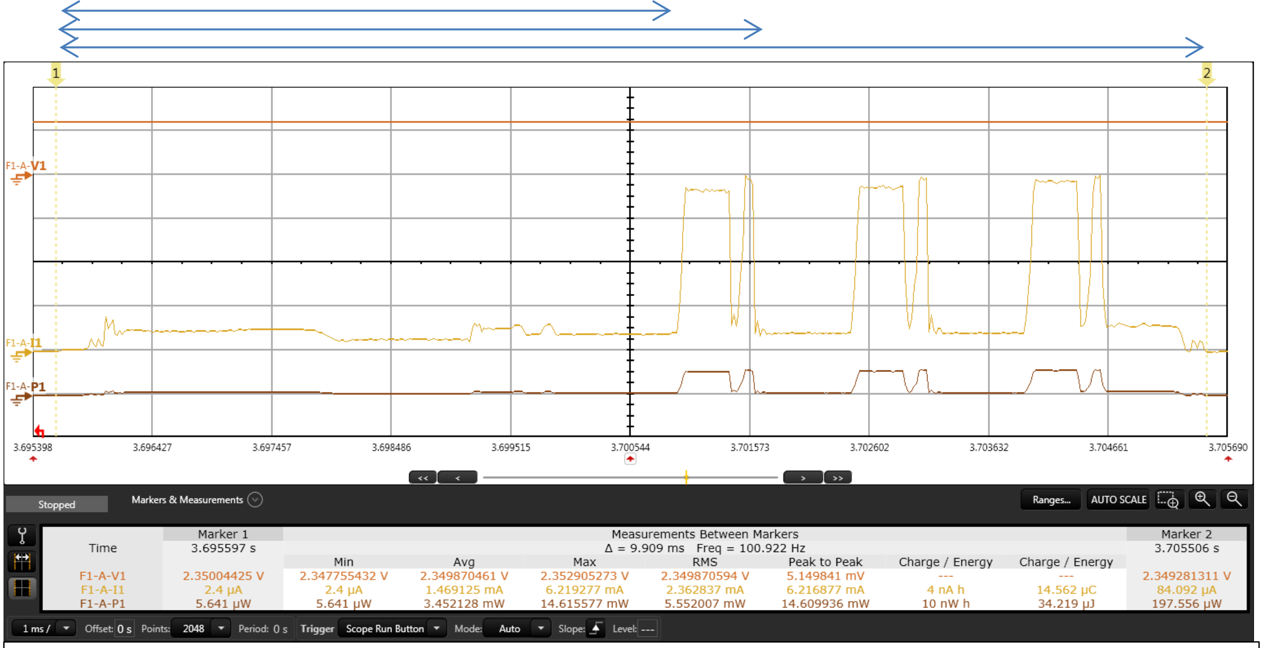


Fig. 8. Connection establishment for SPBTLE-RF device at 2.0 Volts

Energy at different times during ADV_IND event (µJ): 8.0; 15.6; 34.2



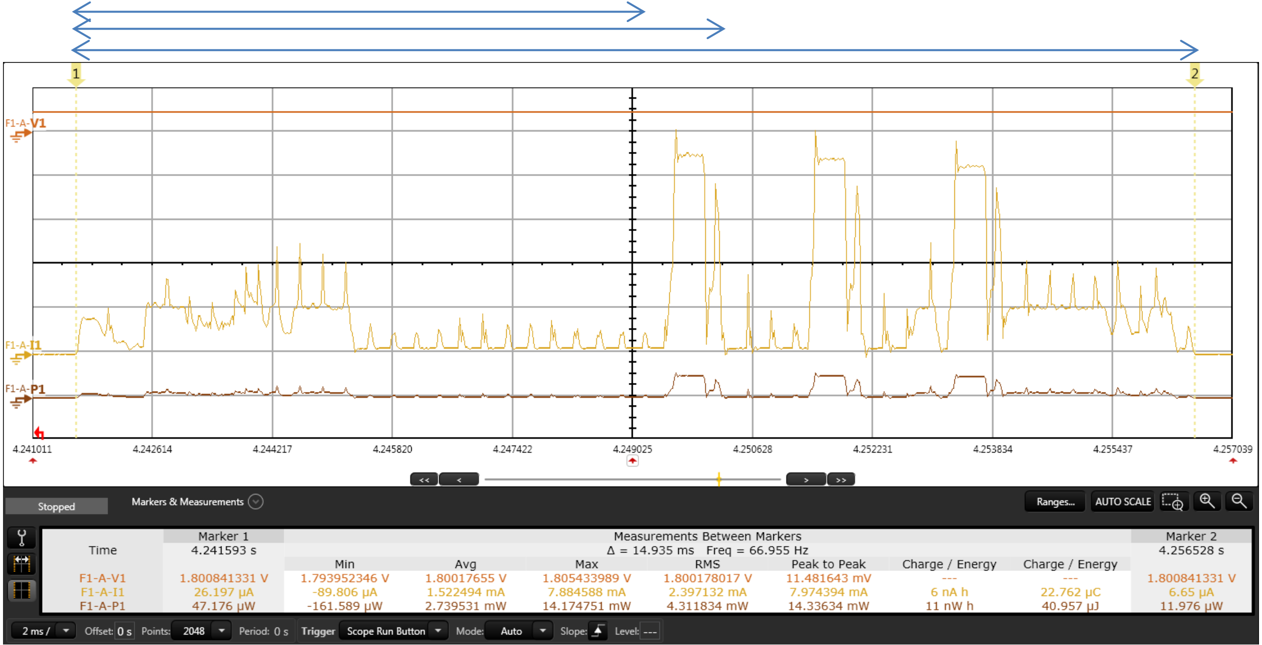
Time	Marker 1	Measurements Between Markers							Marker 2
	3.695597 s	Δ = 9.909 ms Freq = 100.922 Hz							3.705506 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V1	2.35004425 V	2.347755432 V	2.349870461 V	2.352905273 V	2.349870594 V	5.149841 mV	---	---	2.349281311 V
F1-A-I1	2.4 µA	2.4 µA	1.469125 mA	6.219277 mA	2.362837 mA	6.216877 mA	4 nA h	14.562 µC	84.092 µA
F1-A-P1	5.641 µW	5.641 µW	3.452128 mW	14.615577 mW	5.552007 mW	14.609936 mW	10 nW h	34.219 µJ	197.556 µW

1 ms / Offset: 0 s Points: 2048 Period: 0 s Trigger: Scope Run Button Mode: Auto Slope: Level: ---

2 mA/div 2 V/div Average IDD between 2 ADV events:
Averages TX: 5.63mA (1st channel), 5.97mA (3rd channel) RX: 6.09mA

Fig. 9. ADV_IND event for DA14581 device at 2.35 Volts (Flash, 31B, 100ms, XTAL).

Energy at different times during ADV_IND event (µJ): 11.6; 18.5; 41.0

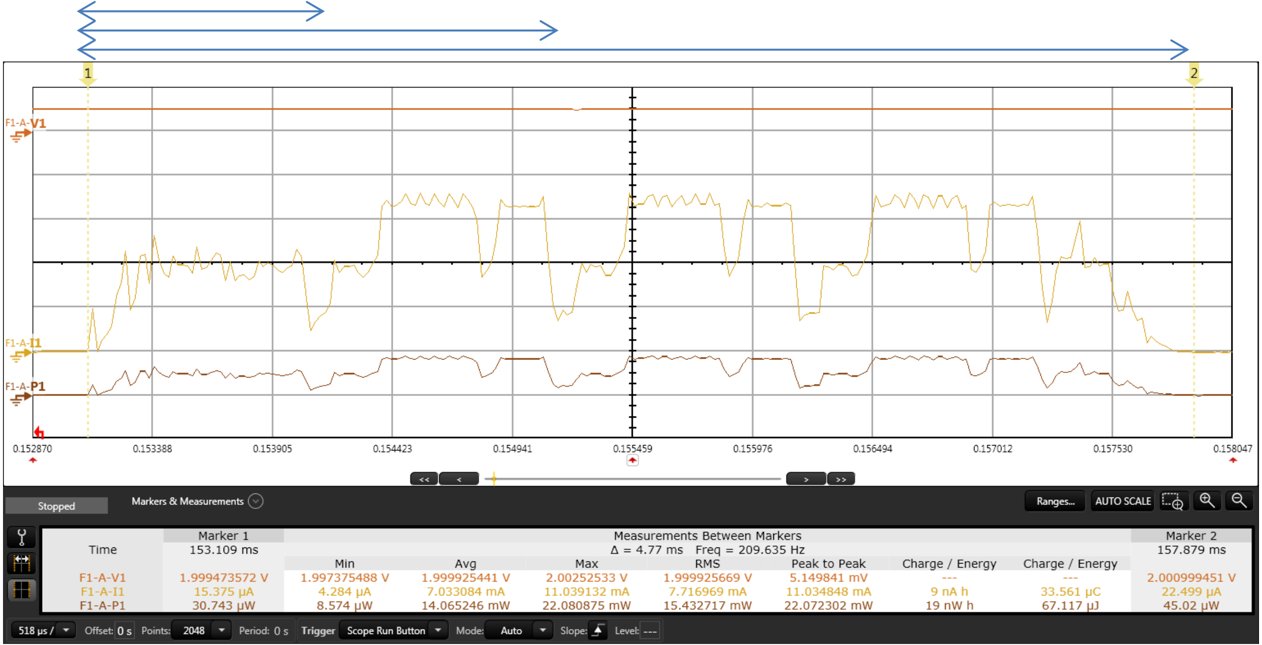


Time	Marker 1 4.241593 s	Measurements Between Markers Δ = 14.935 ms Freq = 66.955 Hz Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	Marker 2 4.256528 s
F1-A-V1	1.800841331 V	1.793952346 V	1.80017655 V	1.805433989 V	1.800178017 V	11.481643 mV	---	---	1.800841331 V
F1-A-I1	26.197 µA	-89.806 µA	1.522494 mA	7.884588 mA	2.397132 mA	7.974394 mA	6 nA h	22.762 µC	6.65 µA
F1-A-P1	47.176 µW	-161.589 µW	2.739531 mW	14.174751 mW	4.311834 mW	14.33634 mW	11 nW h	40.957 µJ	11.976 µW

2 mA/div 4 V/div
Averages TX: 6.8mA RX: 5.1mA

Fig. 10. ADV_IND event for RL78/G1D device at 1.8 Volts (UART disconnected and voltage changed after startup, 31B, 100ms, RCX20).

Energy at different times during ADV_IND event (µJ): 10.1; 27.7; 67.1

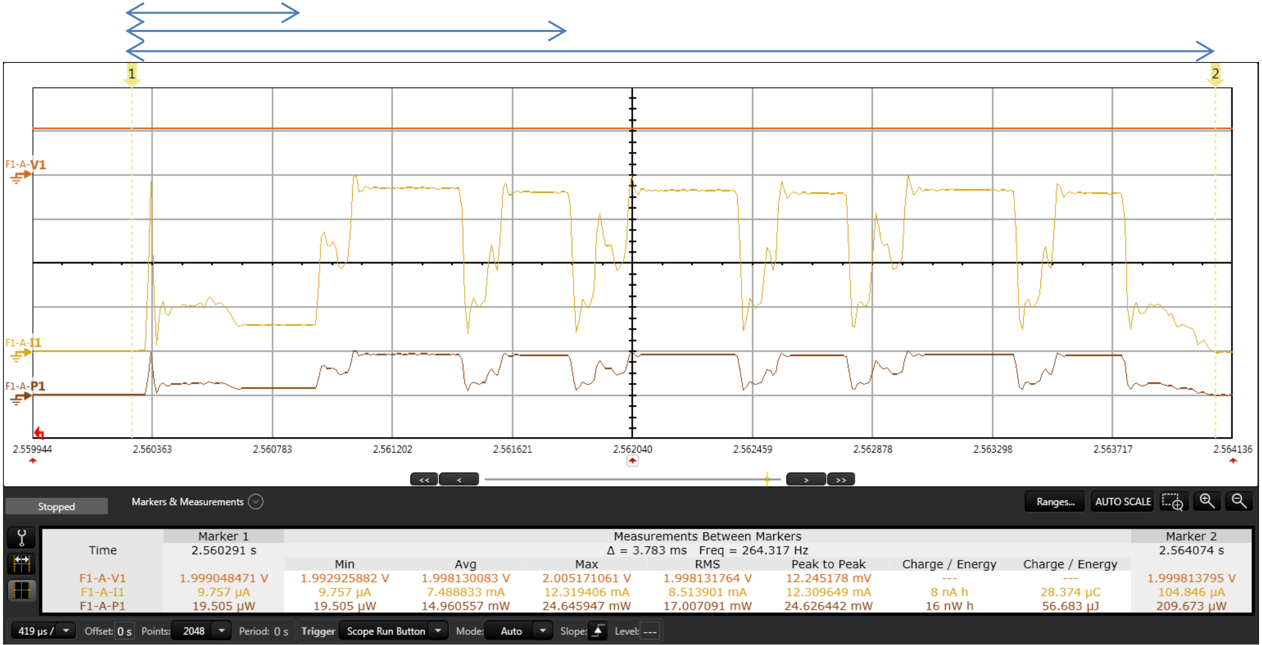


Time	Marker 1 153.109 ms	Measurements Between Markers Δ = 4.77 ms Freq = 209.635 Hz Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	Marker 2 157.879 ms
F1-A-V1	1.999473572 V	1.997375488 V	1.999925441 V	2.00252533 V	1.999925669 V	5.149841 mV	---	---	2.000999451 V
F1-A-I1	15.375 µA	4.284 µA	7.033084 mA	11.039132 mA	7.716969 mA	11.034848 mA	9 nA h	33.561 µC	22.499 µA
F1-A-P1	30.743 µW	8.574 µW	14.065246 mW	22.080875 mW	15.432717 mW	22.072302 mW	19 nW h	67.117 µJ	45.02 µW

3 mA/div 4 V/div Average IDD between 2 ADV events:
Averages TX: 10.5mA RX: 10.3mA

Fig. 11. ADV_IND event for CC2650 device at 2.0 Volts (31B, 100ms).

Energy at different times during ADV_IND event (µJ): 3.2; 20.5; 56.7



	Marker 1	Measurements Between Markers							Marker 2
Time	2.560291 s	Δ = 3.783 ms Freq = 264.317 Hz							2.564074 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V1	1.999048471 V	1.992925882 V	1.998130083 V	2.005171061 V	1.998131764 V	12.245178 mV	---	---	1.999813795 V
F1-A-I1	9.757 µA	9.757 µA	7.488833 mA	12.319406 mA	8.513901 mA	12.309649 mA	8 nA h	28.374 µC	104.846 µA
F1-A-P1	19.505 µW	19.505 µW	14.960557 mW	24.645947 mW	17.007091 mW	24.626442 mW	16 nW h	56.683 µJ	209.673 µW

3 mA/div   2 V/div   Average IDD between 2 ADV events:
Averages TX: 11.2mA   RX: 11.0mA

Fig. 12. ADV_IND event for SPBTLE-RF device at 2.0 Volts (31B, 100ms).

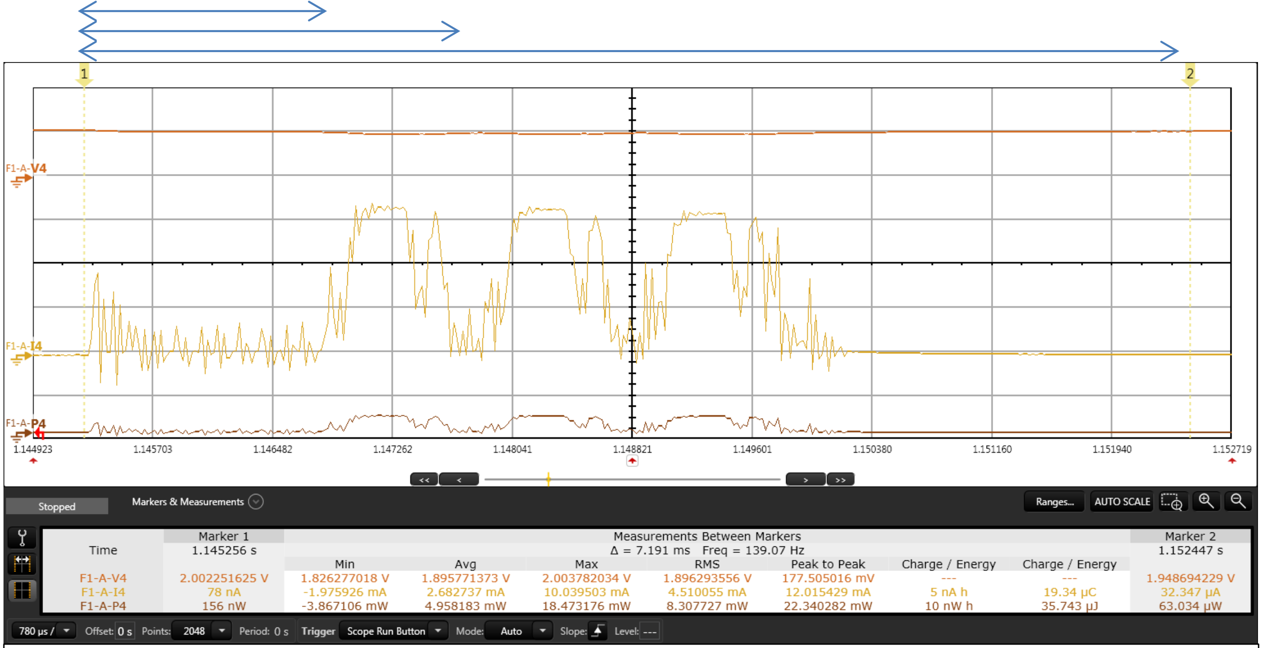
Energy at different times during ADV_IND event (µJ): 7.6; 14.0; 29.7

	Marker 1	Measurements Between Markers							Marker 2
Time	2.515816 s	Δ = 4.256 ms Freq = 234.957 Hz							2.520072 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V1	1.992925882 V	1.989864588 V	1.997137002 V	2.002109766 V	1.997138944 V	12.245178 mV	---	---	1.999048471 V
F1-A-I1	13.844 µA	13.844 µA	3.494207 mA	10.530561 mA	3.990847 mA	10.516717 mA	4 nA h	14.885 µC	75.464 µA
F1-A-P1	27.591 µW	27.591 µW	6.97699 mW	20.986628 mW	7.966944 mW	20.959037 mW	8 nW h	29.721 µJ	150.856 µW

2 mA/div   2 V/div   Average IDD between 2 ADV events:
Averages TX: 5.1mA   RX: 7.0mA

Fig. 13. ADV_IND event for BTLC1000 device at 2.0 Volts (31B, 100ms).

Energy at different times during ADV_IND event (µJ): 1.8; 12.2; 35.7



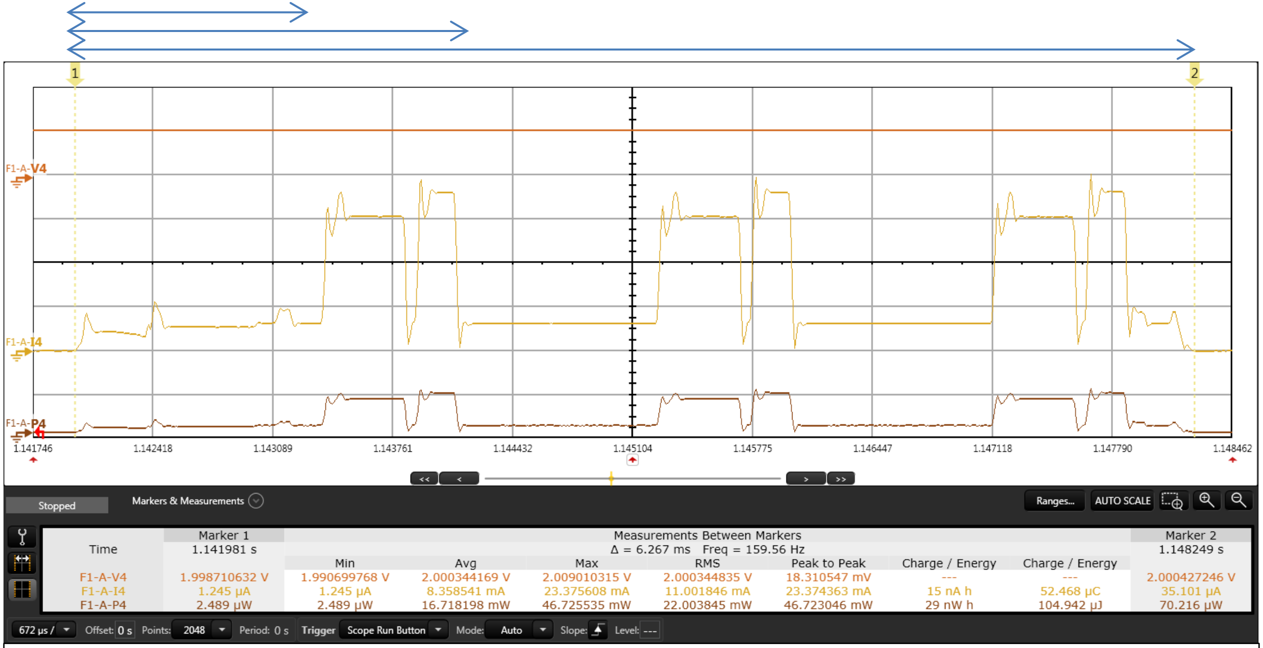
	Marker 1	Measurements Between Markers							Marker 2
Time	1.145256 s	Δ = 7.191 ms Freq = 139.07 Hz							1.152447 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V4	2.002251625 V	1.826277018 V	1.895771373 V	2.003782034 V	1.896293556 V	177.505016 mV	---	---	1.948694229 V
F1-A-I4	78 nA	-1.975926 mA	2.682737 mA	10.039503 mA	4.510055 mA	12.015429 mA	5 nA h	19.34 µC	32.347 µA
F1-A-P4	156 nW	-3.867106 mW	4.958183 mW	18.473176 mW	8.307727 mW	22.340282 mW	10 nW h	35.743 µJ	63.034 µW

780 µs / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

3 mA/div 2 V/div Average IDD between 2 ADV events:
Averages TX: 9.5mA RX: 8.3mA

Fig. 14. ADV_IND event for NRF52 device at 2.0 Volts (31B, 100ms).

Energy at different times during ADV_IND event (µJ): 8.9; 34.9; 104.9



	Marker 1	Measurements Between Markers							Marker 2
Time	1.141981 s	Δ = 6.267 ms Freq = 159.56 Hz							1.148249 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V4	1.998710632 V	1.990699768 V	2.000344169 V	2.009010315 V	2.000344835 V	18.310547 mV	---	---	2.000427246 V
F1-A-I4	1.245 µA	1.245 µA	8.358541 mA	23.375608 mA	11.001846 mA	23.374363 mA	15 nA h	52.468 µC	35.101 µA
F1-A-P4	2.489 µW	2.489 µW	16.718198 mW	46.725535 mW	22.003845 mW	46.723046 mW	29 nW h	104.942 µJ	70.216 µW

672 µs / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

3 mA/div 2 V/div Average IDD between 2 ADV events:
Averages TX: 17.7mA RX: 21.1mA

Fig. 15. ADV_IND event for CY8C4247LQI device at 2.0 Volts (31B, 100ms).

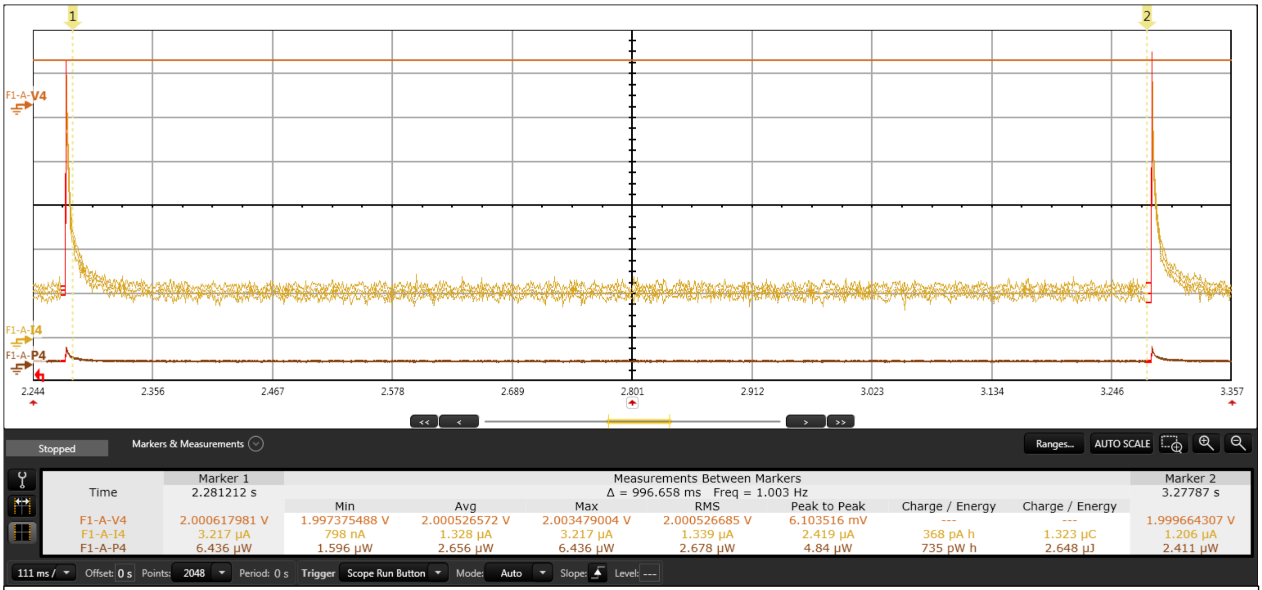
TABLE IX. ENERGY NEEDED FOR THE ADV_IND EVENT (CONNECTABLE, 3V)

Devices	**Parameters**						
	Measurement Voltage (V)	***ADV event cycle (ms)***	***Cycle Energy (µJ)***	***Active part Energy (µJ)***	***Sleep part Avg. current (µA)***	***Sleep part Energy (µJ)***	***Remarks***
DA14581	3	106	37.1	36.6	1.6	0.43	External Flash, DCDC enabled, XTAL32
RL78/G1D	3	105	58.8	58.5	1.1	0.32	DCDC enabled, XT1 oscillator
CC2650	3	108	62.9	62.4	1.9	0.56	DCDC enabled, LF XOSC
SPBTLE-RF	3	104	63.4	62.7	2.3	0.69	DCDC enabled, LSOSC
BTLC1000	3	99	33.7	33.2	1.4	0.40	DCDC enabled, XOSC32K
NRF52	3	102	43.2	42.5	2.8	0.74	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	109	158.4	157.9	2.1	0.60	PSoC, External Crystal Oscillator ECO
DA14581	3	1003	41.1	36.6	1.5	4.45	External Flash, DCDC enabled, XTAL32
RL78/G1D	3	1000	62.3	58.5	1.3	3.83	DCDC enabled, XT1 oscillator
CC2650	3	1010	66.3	63.1	1.1	3.22	DCDC enabled, LF XOSC
SPBTLE-RF	3	1006	69.4	62.8	2.2	6.5	DCDC enabled, LSOSC
BTLC1000	3	999	38.1	34.1	1.3	3.8	DCDC enabled, XOSC32K
NRF52	3	1002	51.5	42.1	3.2	9.39	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	1007	162.5	157.9	1.7	4.93	PSoC, External Crystal Oscillator ECO

TABLE X. ENERGY NEEDED FOR THE ADV_IND EVENT (CONNECTABLE, MINIMAL VOLTAGE)

Devices	**Parameters**						
	Measurement Voltage(V)	***ADV event cycle (ms)***	***Total cycle Energy (µJ)***	***Active part Energy (µJ)***	***Sleep part Avg. current (µA)***	***Sleep part Energy (µJ)***	***Remarks***
DA14581	2.35	103	34.6	34.2	1.5	0.36	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	103	41.1	40.9	1.1	0.18	DCDC enabled, XT1 oscillator
CC2650	1.8	101	60.5	60.1	2.5	0.44	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	105	57.1	56.7	2.1	0.42	DCDC enabled, LSOSC
BTLC1000	1.9	99	29.9	29.3	3.0	0.53	DCDC enabled, XOSC32K
NRF52	2.0	106	36.5	36.0	2.8	0.49	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	107	83.3	83.04	1.5	0.26	PSoC, External Crystal Oscillator ECO
DA14581	2.35	1004	38.1	34.5	1.5	3.45	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	1004	43.0	41.1	1.1	1.89	DCDC enabled, XT1 oscillator
CC2650	1.8	1008	63.8	60.7	1.7	3.06	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	1008	61.1	56.8	2.2	4.3	DCDC enabled, LSOSC
BTLC1000	1.9	999	35.4	29.9	2.9	5.46	DCDC enabled, XOSC32K
NRF52	2.0	1001	43.2	36.1	3.6	7.08	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	1001	85.3	82.8	1.5	2.57	PSoC, External Crystal Oscillator ECO

Energy between two ADV_IND events (µJ): 2.65



Time	Marker 1	Measurements Between Markers							Marker 2
	2.281212 s	Δ = 996.658 ms Freq = 1.003 Hz							3.27787 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V4	2.000617981 V	1.997375488 V	2.000526572 V	2.003479004 V	2.000526685 V	6.103516 mV	---	---	1.999664307 V
F1-A-I4	3.217 µA	798 nA	1.328 µA	3.217 µA	1.339 µA	2.419 µA	368 pA h	1.323 µC	1.206 µA
F1-A-P4	6.436 µW	1.596 µW	2.656 µW	6.436 µW	2.678 µW	4.84 µW	735 pW h	2.648 µJ	2.411 µW

111 ms / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

1 uA/div 2 V/div Average IDD between 2 ADV events: 1.33uA

Fig. 16. Sleep phase for CY8C4247LQI device at 2.0 Volts (1000ms interval, con, 10µA range).

TABLE XI. ENERGY NEEDED FOR THE ADV_IND EVENT (AVERAGING SEVERAL CYCLES, CONNECTABLE, 3V)

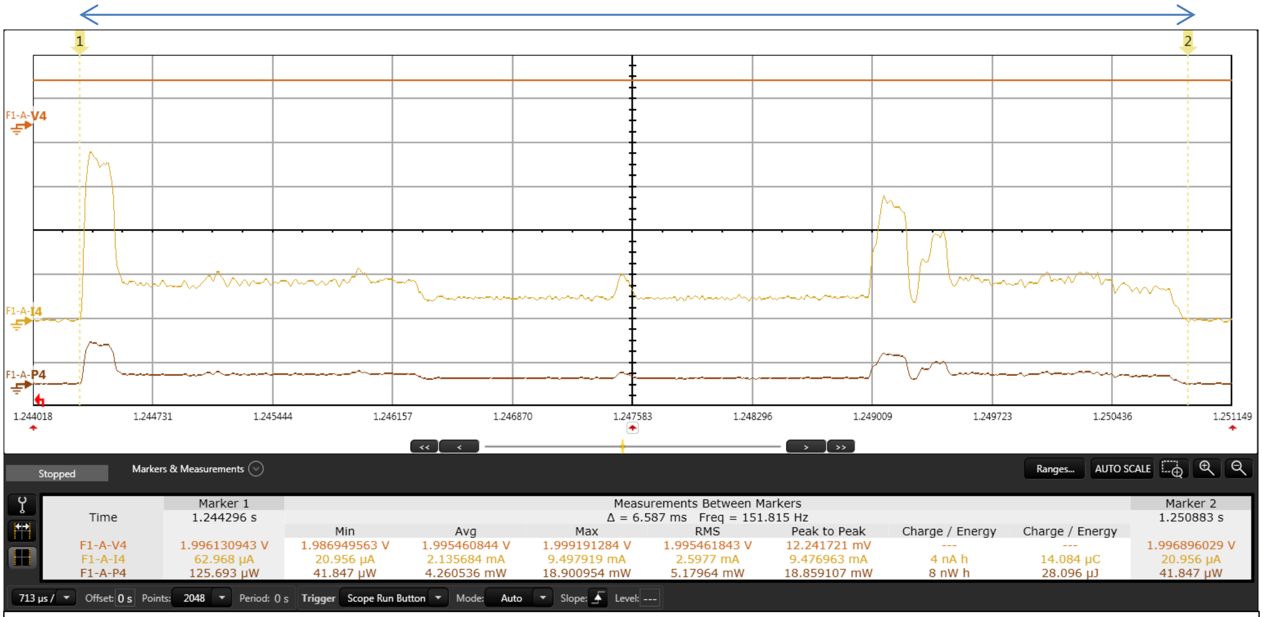
Devices	**Parameters**					
	Measurement Voltage (V)	***ADV event cycles***	***Average current (µA)***	***Energy (mJ)***	***Energy per cycle (µJ)***	***Remarks***
DA14581	3	100 ms for 1 min	136.6	24.6	42.7	External Flash, DCDC enabled, XTAL32
RL78/G1D	3	100 ms for 1 min	187.0	33.6	58.8	DCDC enabled, XT1 oscillator
CC2650	3	100 ms for 1 min	199.6	35.9	62.9	DCDC enabled, LF XOSC
SPBTLE-RF	3	100 ms for 1 min	201.5	36.3	63.4	DCDC enabled, LSOSC
BTLC1000	3	100 ms for 1 min	113.7	20.4	33.7	DCDC enabled, XOSC32K
NRF52	3	100 ms for 1 min	144.0	24.9	43.4	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	100 ms for 1 min	504.0	90.7	158.6	PSoC, External Crystal Oscillator ECO
DA14581	3	1000 ms for 1 min	14.1	2.5	42.2	External Flash, DCDC enabled, XTAL32
RL78/G1D	3	1000 ms for 1 min	20.8	3.7	62.3	DCDC enabled, XT1 oscillator
CC2650	3	1000 ms for 1 min	22.0	4.0	66.1	DCDC enabled, LF XOSC
SPBTLE-RF	3	1000 ms for 1 min	22.8	4.1	69.5	DCDC enabled, LSOSC
BTLC1000	3	1000 ms for 1 min	12.7	2.3	38.0	DCDC enabled, XOSC32K
NRF52	3	1000 ms for 1 min	18.1	3.1	52.3	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	1000 ms for 1 min	54.3	9.8	162.8	PSoC, External Crystal Oscillator ECO

TABLE XII. ENERGY NEEDED FOR THE ADV_IND EVENT (AVERAGING SEVERAL CYCLES, CONNECTABLE, MINIMAL VOLTAGE)

Devices	**Parameters**					
	Measurement Voltage (V)	***ADV event cycles***	***Average current (µA)***	***Energy (mJ)***	***Energy per cycle (µJ)***	***Remarks***
DA14581	2.35	100 ms for 1 min	144.1	20.3	35.3	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	100 ms for 1 min	218.9	23.6	41.2	DCDC enabled, XT1 oscillator
CC2650	1.8	100 ms for 1 min	321.3	34.7	60.6	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	100 ms for 1 min	272.2	32.6	57.2	DCDC enabled, LSOSC
BTLC1000	1.9	100 ms for 1 min	159.2	18.1	29.9	DCDC enabled, XOSC32K
NRF52	2.0	100 ms for 1 min	188.6	21.0	36.7	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	100 ms for 1 min	465.7	47.5	83.0	PSoC, External Crystal Oscillator ECO
DA14581	2.35	1000 ms for 1 min	16.3	2.3	38.9	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	1000 ms for 1 min	23.9	2.6	43.0	DCDC enabled, XT1 oscillator
CC2650	1.8	1000 ms for 1 min	35.4	3.8	63.7	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	1000 ms for 1 min	30.6	3.7	61.2	DCDC enabled, LSOSC
BTLC1000	1.9	1000 ms for 1 min	18.6	2.1	35.3	DCDC enabled, XOSC32K
NRF52	2.0	1000 ms for 1 min	22.2	2.5	42.2	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	1000 ms for 1 min	50.3	5.1	85.3	PSoC, External Crystal Oscillator ECO

Note: Exact number of cycles was counted and used in operation to calculate energy per cycle.

Energy at different times during Empty PDU (µJ): 28.1



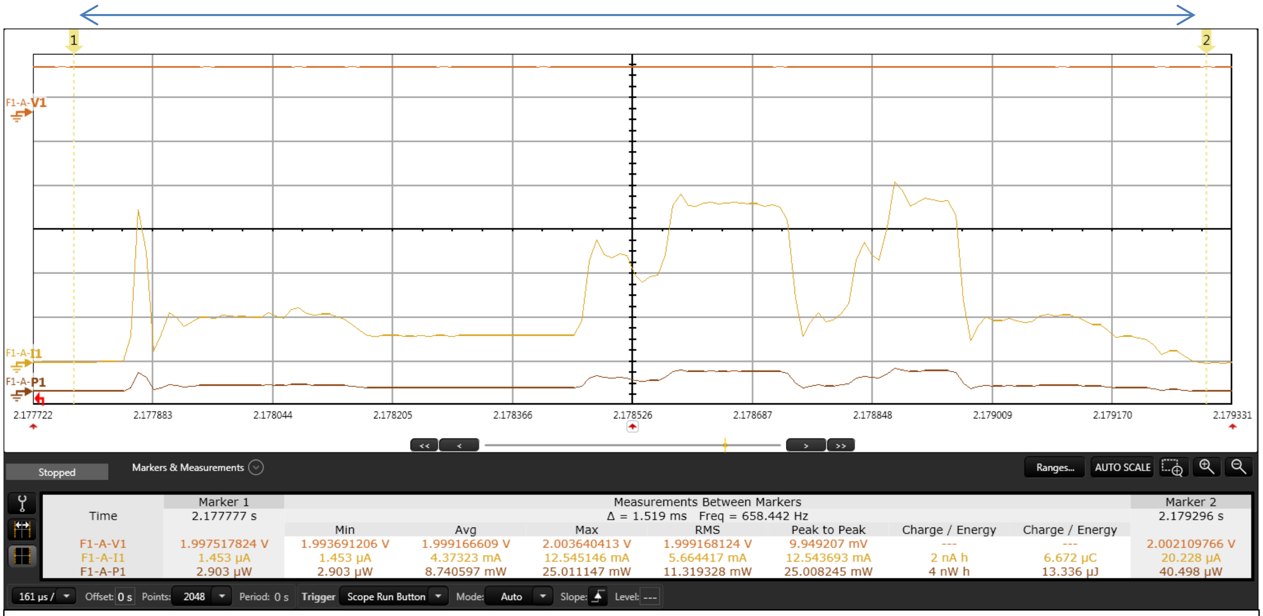
	Marker 1	Measurements Between Markers							Marker 2
Time	1.244296 s	Δ = 6.587 ms Freq = 151.815 Hz							1.250883 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V4	1.996130943 V	1.986949563 V	1.995460844 V	1.999191284 V	1.995461843 V	12.241721 mV	---	---	1.996896029 V
F1-A-I4	62.968 µA	20.956 µA	2.135684 mA	9.497919 mA	2.5977 mA	9.476963 mA	4 nA h	14.084 µC	20.956 µA
F1-A-P4	125.693 µW	41.847 µW	4.260536 mW	18.900954 mW	5.17964 mW	18.859107 mW	8 nW h	28.096 µJ	41.847 µW

713 µs / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

2 mA/div 2 V/div Average IDD between 2 ADV events:

Fig. 17. Connection keep alive event with Empty PDU packets (RX & TX) for BTLC1000 device at 2.0 Volts (100ms).

Energy at different times during Empty PDU (µJ): 13.3



	Marker 1	Measurements Between Markers							Marker 2
Time	2.177777 s	Δ = 1.519 ms Freq = 658.442 Hz							2.179296 s
		Min	Avg	Max	RMS	Peak to Peak	Charge / Energy	Charge / Energy	
F1-A-V1	1.997517824 V	1.993691206 V	1.999166609 V	2.003640413 V	1.999168124 V	9.949207 mV	---	---	2.002109766 V
F1-A-I1	1.453 µA	1.453 µA	4.37323 mA	12.545146 mA	5.664417 mA	12.543693 mA	2 nA h	6.672 µC	20.228 µA
F1-A-P1	2.903 µW	2.903 µW	8.740597 mW	25.011147 mW	11.319328 mW	25.008245 mW	4 nW h	13.336 µJ	40.498 µW

161 µs / Offset: 0 s Points: 2048 Period: 0 s Trigger Scope Run Button Mode: Auto Slope: Level: ---

3 mA/div 2 V/div Average IDD between 2 ADV events:

Fig. 18. Connection keep alive event with Empty PDU packets (RX & TX) for SPBTLE-RF device at 2.0 Volts (100ms).

TABLE XIII. ENERGY NEEDED FOR THE CON EVENT (CONNECTABLE, 3V)

Devices	**Parameters**						
	Measurement Voltage(V)	***CON event cycle (ms)***	***Cycle Energy (µJ)***	***Active part Energy (µJ)***	***Sleep part Avg. current (µA)***	***Sleep part Energy (µJ)***	***Remarks***
DA14581	3	100	15.4	15.0	1.5	0.4	External Flash, DCDC enabled, XTAL32
RL78/G1D	3	100	25.2	24.9	1.1	0.3	DCDC enabled, XT1 oscillator
CC2650	3	100	24.8	24.3	1.7	0.5	DCDC enabled, LF XOSC
SPBTLE-RF	3	100	16.6	15.9	2.3	0.7	DCDC enabled, LSOSC
BTLC1000	3	100	30.7	30.2	1.4	0.4	DCDC enabled, XOSC32K
NRF52	3	100	12.8	12.1	2.4	0.7	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	100	53.5	52.9	2.1	0.6	PSoC, External Crystal Oscillator ECO
DA14581	3	1000	31.7	26.0	1.9	5.7	External Flash, DCDC enabled, XTAL32
RL78/G1D	3	1000	29.4	25.6	1.3	3.8	DCDC enabled, XT1 oscillator
CC2650	3	1000	29.6	26.3	1.1	3.2	DCDC enabled, LF XOSC
SPBTLE-RF	3	1000	26.4	19.4	2.3	6.9	DCDC enabled, LSOSC
BTLC1000	3	1000	45.0	41.2	1.3	3.9	DCDC enabled, XOSC32K
NRF52	3	1000	20.6	12.7	2.7	7.8	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	1000	70.1	65.3	1.6	4.9	PSoC, External Crystal Oscillator ECO

TABLE XIV. ENERGY NEEDED FOR THE CON EVENT (CONNECTABLE, MINIMAL VOLTAGE)

Devices	**Parameters**						
	Measurement Voltage(V)	***ADV event cycle (ms)***	***Total cycle Energy (µJ)***	***Active part Energy (µJ)***	***Sleep part Avg. current (µA)***	***Sleep part Energy (µJ)***	***Remarks***
DA14581	2.35	100	15.1	14.7	1.5	0.3	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	100	15.3	15.2	1.1	0.2	DCDC enabled, XT1 oscillator
CC2650	1.8	100	23.4	23.0	2.2	0.4	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	100	13.9	13.5	2.3	0.45	DCDC enabled, LSOSC
BTLC1000	1.9	100	28.2	27.6	3.0	0.5	DCDC enabled, XOSC32K
NRF52	2.0	100	10.4	10.0	2.2	0.4	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	100	27.7	27.5	1.5	0.26	PSoC, External Crystal Oscillator ECO
DA14581	2.35	1000	28.2	24.6	1.6	3.6	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	1000	18.1	16.2	1.1	1.9	DCDC enabled, XT1 oscillator
CC2650	1.8	1000	27.8	25.0	1.6	2.9	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	1000	21.2	16.6	2.3	4.6	DCDC enabled, LSOSC
BTLC1000	1.9	1000	40.7	35.3	2.9	5.5	DCDC enabled, XOSC32K
NRF52	2.0	1000	14.9	10.4	2.3	4.5	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	1000	36.5	34.0	1.5	2.56	PSoC, External Crystal Oscillator ECO

TABLE XV. ENERGY NEEDED FOR THE CON EVENT (AVERAGING SEVERAL CYCLES, CONNECTABLE, 3V)

Devices	**Parameters**					
	Measurement Voltage(V)	***ADV event cycles***	***Average current (µA)***	***Energy (mJ)***	***Energy per cycle (µJ)***	***Remarks***
DA14581	3	100 ms for 1 min	53.8	9.7	16.1	External Flash, DCDC enabled, XTAL32
RL78/G1D	3	100 ms for 1 min	83.7	15.1	25.2	DCDC enabled, XT1 oscillator
CC2650	3	100 ms for 1 min	82.9	14.9	24.9	DCDC enabled, LF XOSC
SPBTLE-RF	3	100 ms for 1 min	56.1	10.1	16.8	DCDC enabled, LSOSC
BTLC1000	3	100 ms for 1 min	107.8	19.4	32.3	DCDC enabled, XOSC32K
NRF52	3	100 ms for 1 min	44.7	7.7	12.8	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	100 ms for 1 min	177.5	31.9	53.2	PSoC, External Crystal Oscillator ECO
DA14581	3	1000 ms for 1 min	10.7	1.9	32.1	External Flash, DCDC enabled, XTAL32
RL78/G1D	3	1000 ms for 1 min	9.8	1.8	29.5	DCDC enabled, XT1 oscillator
CC2650	3	1000 ms for 1 min	9.8	1.8	29.4	DCDC enabled, LF XOSC
SPBTLE-RF	3	1000 ms for 1 min	8.8	1.6	26.5	DCDC enabled, LSOSC
BTLC1000	3	1000 ms for 1 min	14.7	2.6	44.0	DCDC enabled, XOSC32K
NRF52	3	1000 ms for 1 min	7.5	1.3	21.5	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	3	1000 ms for 1 min	23.4	4.2	70.1	PSoC, External Crystal Oscillator ECO

TABLE XVI. ENERGY NEEDED FOR THE CON EVENT (AVERAGING SEVERAL CYCLES, CONNECTABLE, MINIMAL VOLTAGE)

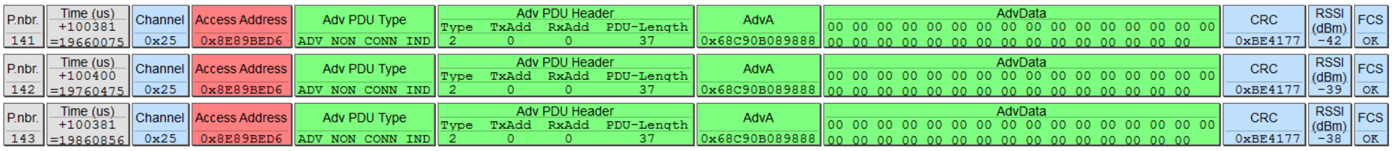
Devices	**Parameters**					
	Measurement Voltage(V)	***ADV event cycles***	***Average current (µA)***	***Energy (mJ)***	***Energy per cycle (µJ)***	***Remarks***
DA14581	2.35	100 ms for 1 min	64.1	9.0	15.1	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	100 ms for 1 min	86.9	9.4	15.6	DCDC enabled, XT1 oscillator
CC2650	1.8	100 ms for 1 min	130.2	14.1	23.4	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	100 ms for 1 min	70.0	8.4	14.0	DCDC enabled, LSOSC
BTLC1000	1.9	100 ms for 1 min	147.1	16.7	27.9	DCDC enabled, XOSC32K
NRF52	2.0	100 ms for 1 min	55.8	6.2	10.4	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	100 ms for 1 min	162.4	16.6	27.6	PSoC, External Crystal Oscillator ECO
DA14581	2.35	1000 ms for 1 min	12.1	1.7	28.5	External Flash, DCDC enabled, XTAL32
RL78/G1D	1.8	1000 ms for 1 min	10.1	1.1	18.1	DCDC enabled, XT1 oscillator
CC2650	1.8	1000 ms for 1 min	15.4	1.7	27.8	DCDC enabled, LF XOSC
SPBTLE-RF	2.0	1000 ms for 1 min	10.8	1.3	21.5	DCDC enabled, LSOSC
BTLC1000	1.9	1000 ms for 1 min	21.2	2.4	40.2	DCDC enabled, XOSC32K
NRF52	2.0	1000 ms for 1 min	8.4	1.0	15.8	Eng. B revision, DCDC enabled, LFXO
CY8C4247LQI	1.7	1000 ms for 1 min	21.5	2.2	36.6	PSoC, External Crystal Oscillator ECO

Note: Exact number of cycles was counted and used in operation to calculate energy per cycle.

The following table contains the software that was used on the devices. In some cases, modifications had to be done.

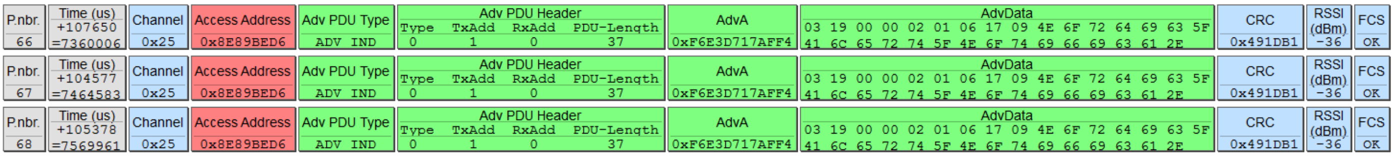
TABLE XVII. SOFTWARE USED IN CONNECTABLE AND NON-CONNECTABLE MODE

Devices	**Software**	
	Non-connectable	***Connectable***
DA14581	dialog_beacon project provided by Dialog.	dialog_beacon project provided by Dialog in undirect advertising mode.
RL78/G1D	BLE_Beacon project from BLE Beacon Stack v0.91 for RL78/G1D.	Pre-compiled software from Renesas. Must be configured from PC using rBLE_Tool and USB connection. (RL78_G1D_IM(PXP,FMP,ANP) Version 2015-10-23)
CC2650	Custom simpleBroadcaster application, a bare-bones, speed optimized program transmitting BLE advertisment packages. Written by Texas Instruments for our measurements. (Version 1.0.0)	simpleBLEPeripheral application from simplelink with software modifications done as described in application report SWRA478A. Pre-compiled software (IAR) received from TI.
SPBTLE-RF	Modified SensorDemo application from STM32CubeExpansion_BLE1_V2.5.2 (Version 1.0.0)	Modified SensorDemo application from STM32CubeExpansion_BLE1_V2.5.2 (Version 1.0.0)
BTLC1000	SIMPLE_BROADCASTER_SAM21_ XPLAINED_PRO_B application from Atmel Software Framework 3.29	SimpleBTLC1000Connection application from Atmel Software Framework 3.29
NRF52	NRF52 ble_app_beacon_132_pca10036 from nRF52 SDK 0.9.2. The power management has been modified [16].	ble_app_hts_s132_pca10036 from nRF52 SDK 0.9.2. The power management has been modified [16].
CY8C4247LQI	Constant_Broadcaster from Cypress [17] (Version 1.0)	Find_Me from Cypress [17]. (Version 1.0)



```
P.nbr. | Time (us)  | Channel | Access Address | Adv PDU Type      | Adv PDU Header                 | AdvA           | AdvData                                         | CRC      | RSSI (dBm) | FCS
141    | +100381    | 0x25    | 0x8E89BED6     | ADV NON CONN IND  | Type TxAdd RxAdd PDU-Length    | 0x68C90B089888 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 | 0xBE4177 | -42        | OK
       | =19660075  |         |                |                   | 2    0     0     37            |                | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    |          |            |
142    | +100400    | 0x25    | 0x8E89BED6     | ADV NON CONN IND  | Type TxAdd RxAdd PDU-Length    | 0x68C90B089888 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 | 0xBE4177 | -39        | OK
       | =19760475  |         |                |                   | 2    0     0     37            |                | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    |          |            |
143    | +100381    | 0x25    | 0x8E89BED6     | ADV NON CONN IND  | Type TxAdd RxAdd PDU-Length    | 0x68C90B089888 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 | 0xBE4177 | -38        | OK
       | =19860856  |         |                |                   | 2    0     0     37            |                | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    |          |            |
```

Fig. 19. ADV_NONCONN_IND format frame used for all devices (TI SmartRF Packet Sniffer)



```
P.nbr. | Time (us)  | Channel | Access Address | Adv PDU Type | Adv PDU Header                 | AdvA           | AdvData                                         | CRC      | RSSI (dBm) | FCS
66     | +107650    | 0x25    | 0x8E89BED6     | ADV IND      | Type TxAdd RxAdd PDU-Length    | 0xF6E3D717AFF4 | 03 19 00 00 02 01 06 17 09 4E 6F 72 64 69 63 5F | 0x491DB1 | -36        | OK
       | =7360006   |         |                |              | 0    1     0     37            |                | 41 6C 65 72 74 5F 4E 6F 74 69 66 69 63 61 2E    |          |            |
67     | +104577    | 0x25    | 0x8E89BED6     | ADV IND      | Type TxAdd RxAdd PDU-Length    | 0xF6E3D717AFF4 | 03 19 00 00 02 01 06 17 09 4E 6F 72 64 69 63 5F | 0x491DB1 | -36        | OK
       | =7464583   |         |                |              | 0    1     0     37            |                | 41 6C 65 72 74 5F 4E 6F 74 69 66 69 63 61 2E    |          |            |
68     | +105378    | 0x25    | 0x8E89BED6     | ADV IND      | Type TxAdd RxAdd PDU-Length    | 0xF6E3D717AFF4 | 03 19 00 00 02 01 06 17 09 4E 6F 72 64 69 63 5F | 0x491DB1 | -36        | OK
       | =7569961   |         |                |              | 0    1     0     37            |                | 41 6C 65 72 74 5F 4E 6F 74 69 66 69 63 61 2E    |          |            |
```

Fig. 20. ADV _IND format frame used for all devices (TI SmartRF Packet Sniffer)

Fig. 21. Kits from Dialog, Renesas, TI

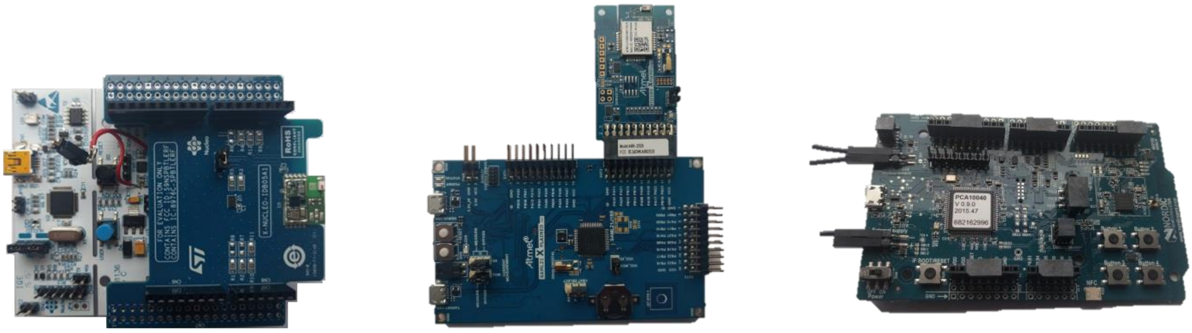


Fig. 22. Kits from ST, Atmel, Nordic

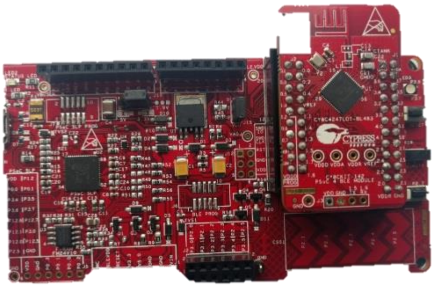


Fig. 23. Kit from Cypress

XI. CONCLUSION

In this paper, we have presented results of energy consumption measurements made on various Bluetooth Low Energy solutions. Our focus was on devices that appeared on the market since the first version of this work. However, we also included older devices when we felt that their performances were still up to date. The measurements provide information to help compare devices in various modes. Application engineers can use these results with the datasheets of the devices to determine what is suitable for their applications. IC manufacturers can use the results to improve their devices or Bluetooth stacks. The reader should not make a decision on the basis of this data alone. Several other parameters (as explained in this work) should be considered.

Since new solutions are continuously appearing on the market, this work will be updated in the coming years. We readily consider the feedback of manufacturers and users into account for the update of this work.

ACKNOWLEDGMENTS

We would like to thank Atmel, Dialog, Renesas, ST and TI for supporting us in various ways, especially the constructive discussions we had.

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