# Comparing the energy requirements of current Bluetooth Smart solutions

Jachen Bernegger, Marcel Meli
Zurich University of Applied Sciences
Institute of Embedded Systems
Winterthur, Switzerland
Marcel.Meli@zhaw.ch

***Abstract***— **Bluetooth is becoming a popular way to get access to data delivered by sensors. To be convenient in use and low cost in maintenance, those sensors should consume as less energy as possible. Near the energy consideration of the sensing element, 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. The work was done at the end of 2013 and early in 2014**

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

## I. INTRODUCTION

The proliferation of smart phones and tablets has opened up new ways of accessing the information delivered by sensors. 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 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 Low Energy radio and software stack used to transmit sensor data is a central aspect. There are several solutions on the market, with various claims with regard to the power consumption. It is often not easy for the application engineers to verify those claims or derive them on the basis of the datasheets that are given by the module or chip manufacturers.

This work offers some help to the application engineer. We have measured the energy consumption of many 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 document can be helpful to application engineers in their quest to find an appropriate module or chip for their low power design. It can also be helpful to chip or module manufacturers and those writing communication stacks, to correct or improve their solutions.

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 Ble solutions. Below are some of them.

- Devices should be used for a long time without the user having to change the batteries. This leads to low maintenance costs.
- Devices that do not need 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.
- 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 obviously difficult to cover all possible elements that influence the energy requirements. In the same way, we do not cover all the Ble 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 Ble market.

We are not aware of any previous comparison of the energy consumption of Ble solutions on this scale.

## 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 [1, 2].

Bluetooth Smart operates in the 2.4 GHz ISM band, where several other radios are active (WLAN, ZigBee … etc.). Because many devices operate in that band, there are interferences and collisions issues. At 1Mbit/s, the raw data rate of Ble 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.

Ble 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. There is no mandatory "listen before talk" process, which increases the likelihood of collisions. Retransmission due to loss of data generally leads to an increase of the energy consumption.

40 channels are available for communication, making it possible for connected parties to regularly change channels in order to avoid interference. This is also very helpful in the implementation of concurrent communications in the same physical space.

Communicating parties 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 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 called advertisement channels. These channels have been chosen to reduce the effect of the interference from other popular wireless protocols. Parameters needed to establish a connection are negotiated using the advertisement channels.

The basic network topology in Ble 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 take 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 so 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.

Since slaves can spend long 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 constrains 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 also important. 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 first switched on, 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 transmit mode. But the transmit current is not the only parameter. It should be remembered that before transmitting, 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 receive mode (see send mode above).
- 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. Leakage currents 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, the start-up constraints and their effect on the radio input signal 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.

- The environment of use. As discussed earlier, temperature changes and electromagnetic interferences 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.

Many of the parameters listed above affect the energy consumption in phases which are important for the Ble 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

- Energy requirements in connected phase

- Energy needed in negotiation phase. This has not been measured in this work because 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. A SHORT PRESENTATION OF THE DEVICES AND SYSTEMS THAT HAVE BEEN MEASURED

Below is short presentation of the systems that have been evaluated in this work. We have sought to bring out relevant information for our work. For a complete picture, the reader should consult the data sheets, 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 Ble stack. In some instances we have made small modifications to allow the energy to be measured properly (same packet length, removal of extra peripherals such as accelerometers …etc.).

### *A. CC2540 [3] Device manufactured by Texas Instruments.*

See below

### *B. CC2541 [4] Device manufactured by Texas Instruments*

Both devices (CC2540 and CC2541) integrate a microcontroller (8-bit) and a radio with the appropriate memory and peripherals. These devices are among the first Ble SoC on the market. They have a current consumption in transmit/receive mode that is higher than that of the most recent devices. However, a combination with a buck converter can help. For some measurements, we had to remove the supporting components from the TI kit and make changes on the DC/DC converter.

### *C. nRF51822 [5] Device manufactured by Nordic*

This is a single chip solution that includes a radio and microcontroller functions based on a Cortex M0 core. It can easily be programmed by the user. The nRF51822 has been used in a number of projects that integrate Ble.

### *D. CSR1011 [6] Device manufactured by Cambridge Silicon Radio*

This device from CSR integrates a microcontroller and a radio. The program is run from RAM and first has to be loaded from an external NV memory. The chip integrates a buck converter that helps save energy.

### E. EM9301 and variants [7] Device manufactured by EM Microelectronic Marin

The basic version of this device should be associated to an external microcontroller. It can then be controlled using either an SPI or a UART interface, with layers above HCI implemented in the host microcontroller. The radio can directly be connected to a 200 ohm PCB antenna. There are several variations of this device. Supply voltage range from 0.8 up to 3.3 Volts.

We have used the EM9301 with our own stack. Higher layers of the stack were implemented on a very low power and low cost 8-bit microcontroller. The same has also been done with 32-bit microcontrollers.

Thanks to low energy requirements at start-up, this device has been very useful for applications where communication in form of broadcasting was needed, with the device been totally switched off between beacons for maximal energy gains [8].

### F. D14580 [9] Device manufactured by Dialog

This is the most recent device that we measured in this work. Current consumption (in TX, RX, low power modes) is among the lowest we have seen so far. It is a SoC with a low power radio and a microcontroller with a cortex M0 core. The device has 3 types of memory (RAM, OTP, ROM). A DC/DC converter that can work in buck or in boost mode helps extend the voltage range (0.9 – 3.3 Volts). Care should be taken when using the DC/DC converter to remain efficient and properly supply all the memory blocks.

The device includes an 84kB ROM that stores the Bluetooth Smart stack and some basic profiles. The 32kB OTP memory is used to store some profiles and the user application. The RAM of 32kB is used for data and for code loaded from the NV memory. The use of RAM to run the program helps reduce the energy consumption. However, the program must be loaded at power up, which affects the start-up energy. 8kB retention RAM is available to allow important data to be kept in very low power mode. The device includes many microcontroller peripherals such as IOs, serial interfaces, ADC converter. This makes it possible to use the SoC as stand-alone (without an external processor) if the available resources are sufficient.

### G. ML7105-00x series [10] Device manufactured by Lapis

According to the manufacturer, this device is an improvement of the ML7105, with up to 50% improvement in the current consumption

“This LSI series has been adopted in the newest model of the G-SHOCK BLUETOOTH WATCH (GB-6900B/GB-X6900B) manufactured by CASIO COMPUTER CO.,LTD”[11].

We received this device late and could not yet make the same measurements we made for other devices. An update is planned.

### H. Icytrx [12,13] This device is manufactured by CSEM

The Icytrx is a low voltage radio with many special features. The device works at 1.2 Volt. It can also be integrated in a 3 Volts system since it includes the needed level shifters. More information can be found in the references.

Since we did not have a stack for the device, we wrote an own software to make measurements in a broadcast application. A microcontroller working at 1.2 Volt was used and the device made to broadcast a given packet on the 3 ADV channels. This allowed us to evaluate the potential of a solution based on this radio.

## VI. 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 [14]. 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.

A few measurements at “hot” were made simply by heating the DUT with a hair dryer. No attempt was made to measure the temperature, since the objective of measurement at “hot” was to show the tendency of the current in very low power mode to increase with temperature.

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 Ble applications is the CR2032, which starts around 3 Volts. Many devices can work down to 1.8 Volt, or even lower, especially when they integrate a DC/DC converter (CSR, Dialog devices). In the case of the Icytrx, measurements were made only at 1.2 Volt.

For tests needing a connection, we used a kit provided by the manufacturers or one of our own devices as host. During the measurements, frames were captured for verification and monitoring using a TI Ble sniffer or a multi-channel sniffer from Ellisys [15]

### 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, turns the transmitter off and switches the receiver on to receive an eventual 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.

The measurements were made whenever possible with ADV frames of the same packet length (44 octets as total frame size). In the case of the dialog chip, we could not change the frame size. The measurements shown are for packets that are smaller.

Measurements were made for 2 ADV interval times: 100mS and 1S. In the case of the Dialog device, the programmed 500mS interval was used.

Since some devices or boards integrate a DC/DC converter, measurements over a long period (1 minute) were also made, and the average current consumption shown in tables.

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.

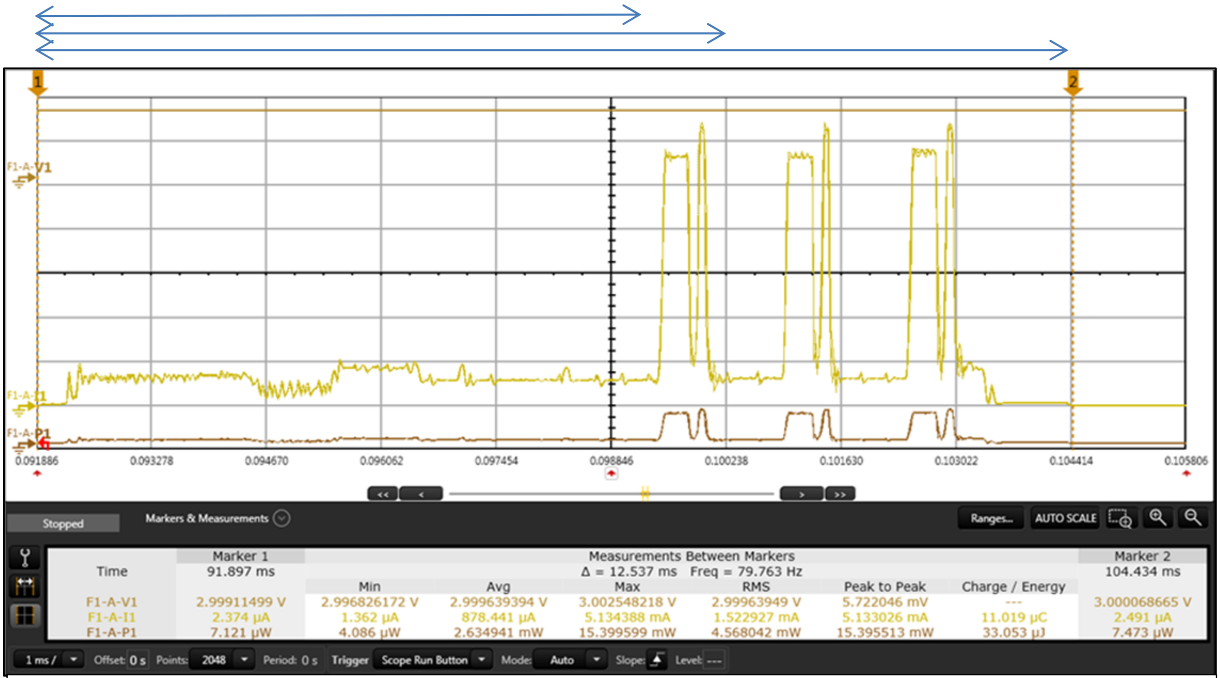
### *C. Other.*

We did no measure the energy requirements when the devices exchange connection parameters before they can establish a connection (negotiation phase).

## VII. 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. Measurements at lower voltages are not shown.

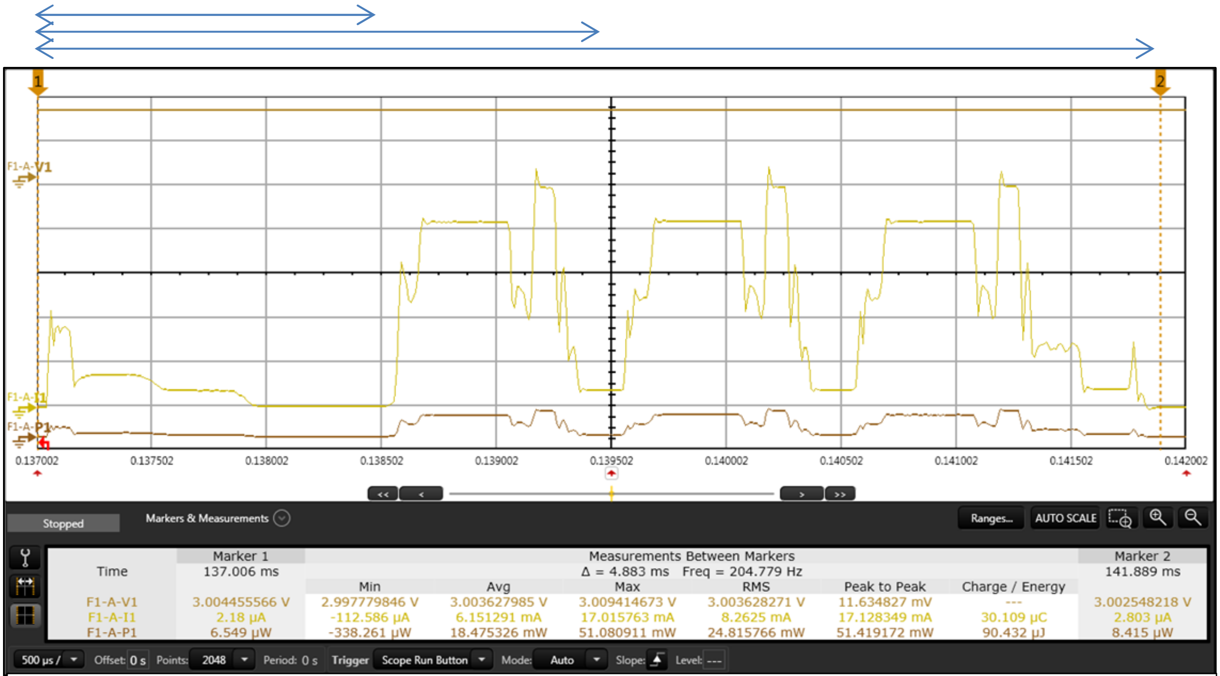
Energy at different times during ADV (µJ): 10.4;   17.1;  33




800 µA/div     2 V/div     1 ms/div  Average IDD between 2 ADV events: 1.9 µA
Averages TX: 4.5 mA   RX: 4.95 mA  (first channel)    TX : 4.6 mA    RX : 4.98 mA  (third channel)

Fig. 1.   ADV for DA14580 device at 3 Volts.

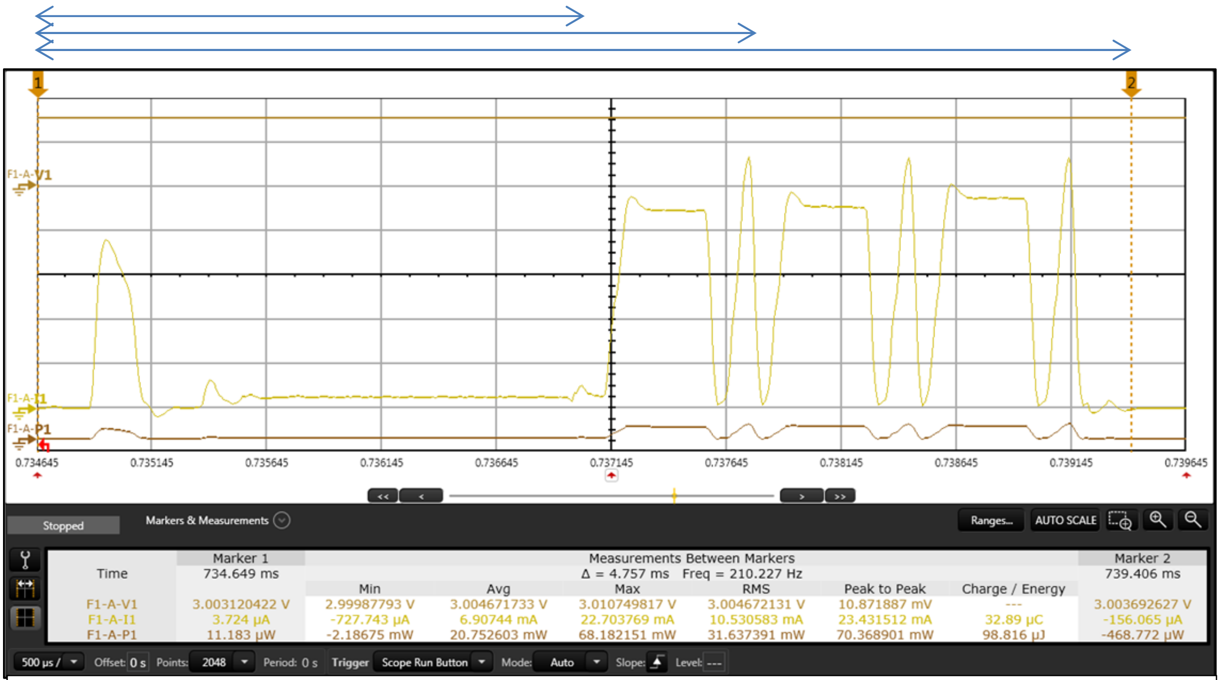
Energy at different times during ADV (µJ): 5.5;   32.3;  90.4




3 mA/div     2 V/div     500 µS/div  80 mW/div  Average IDD between 2 ADV events: 3.14 µA
Averages TX: 13 mA   RX: 15.3  mA  (first channel)

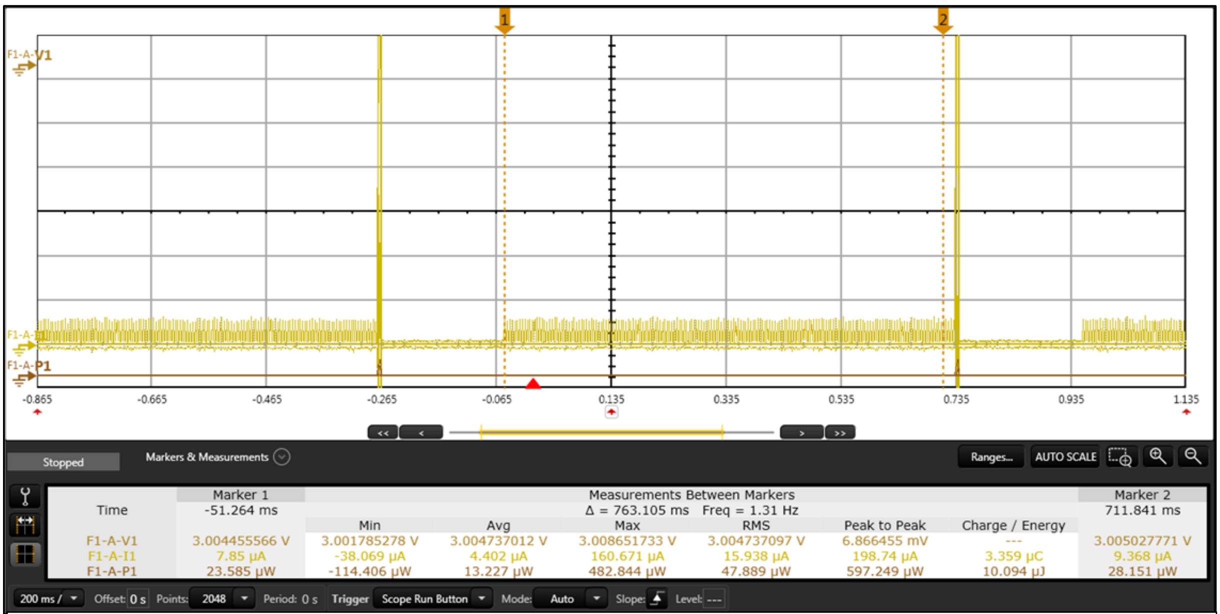
Fig. 2.   ADV for nRF51822 device at 3 Volts.

Energy at different times during ADV (µJ): 12.3;   40.8;  98.8




4 mA/div    2 V/div   200mW/div   500 µS/div   Average IDD between 2 ADV events variable.
Averages TX: 18 mA   RX: 21 mA  (first channel)    TX : 19.1 mA    RX : 22.6 mA  (third channel)

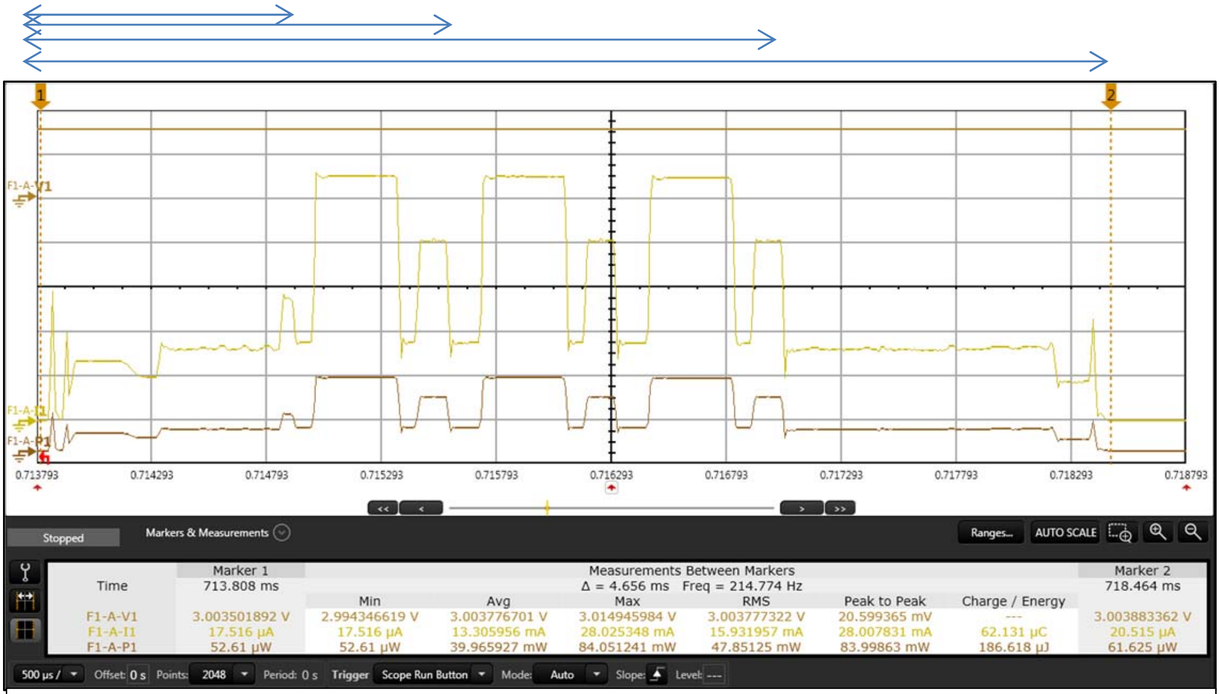
Fig. 3.   ADV for CSR1011 device at 3 Volts. (Average IDD between 2 ADV events: depends on time between the events).




The figure above shows that for an interval less than 200 ms, the average current between events is 2.8 µA otherwise it goes up (4. 4 µA in this case)

Fig. 4.   ADV for CSR1011 device at 3 Volts. Zoom on current between events

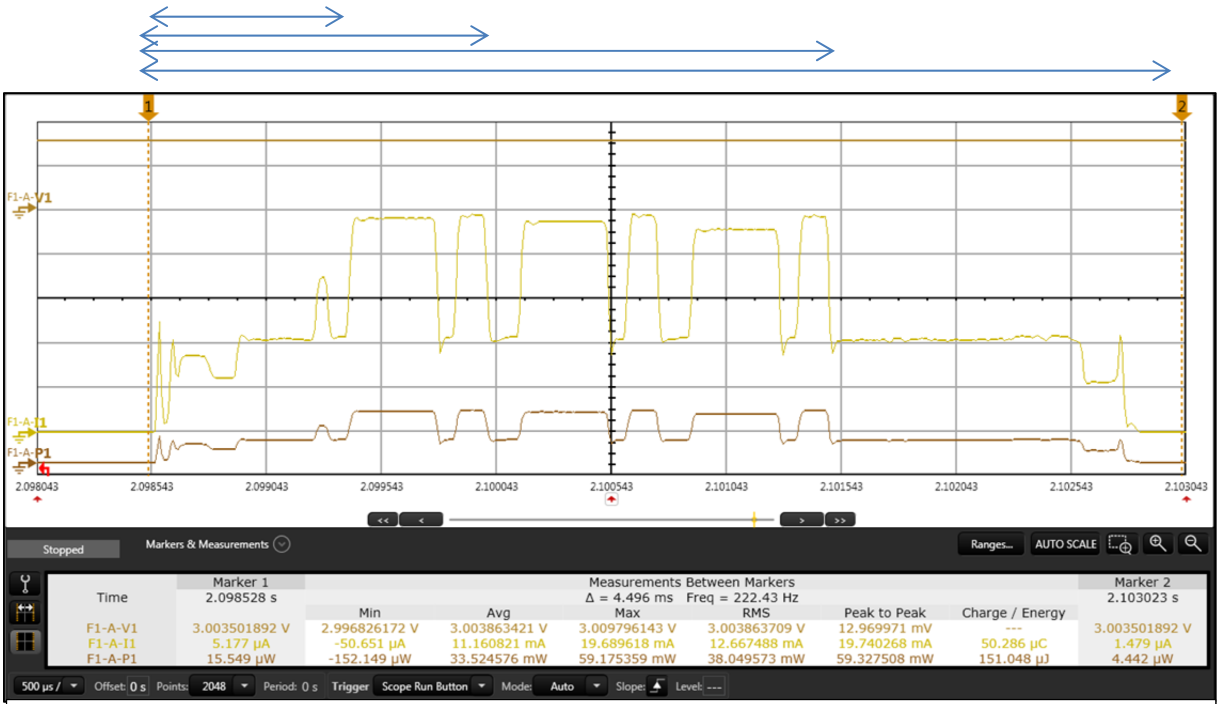
Energy at different times during ADV (µJ): 25.4;   67.2;  155.9; 186.6




5 mA/div     2 V/div      50mW/div  500 µS/div          Average IDD between 2 ADV events: 17.2 µA
Averages TX: 27.3 mA   RX: 20.3 mA  (first channel)     TX: 27.3 mA    RX: 20.3 mA  (third channel)

Fig. 5.   ADV for CC2540 device at 3 Volts.

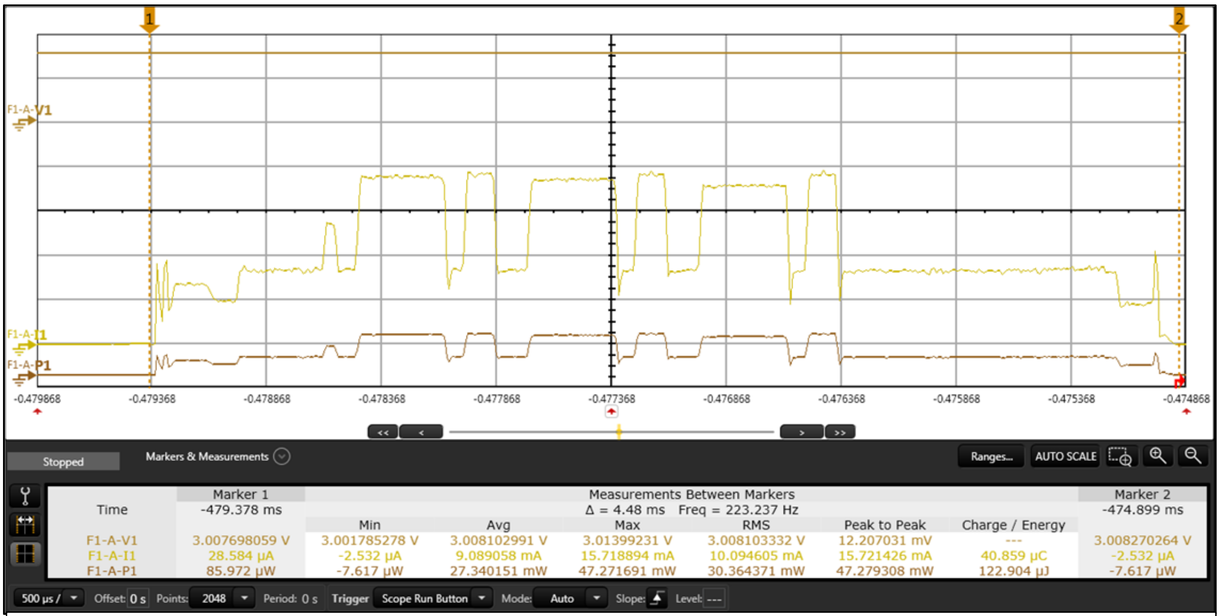
Energy at different times during ADV (µJ): 18.8;   51.8;  122; 151




4 mA/div     2 V/div      500µS/div   50mW/div  Average IDD between 2 ADV events: 1.14 µA
Averages TX: 19.1 mA   RX : 19.4  mA  (first channel) TX 18.2 mA    RX 19.4 mA  (third channel)

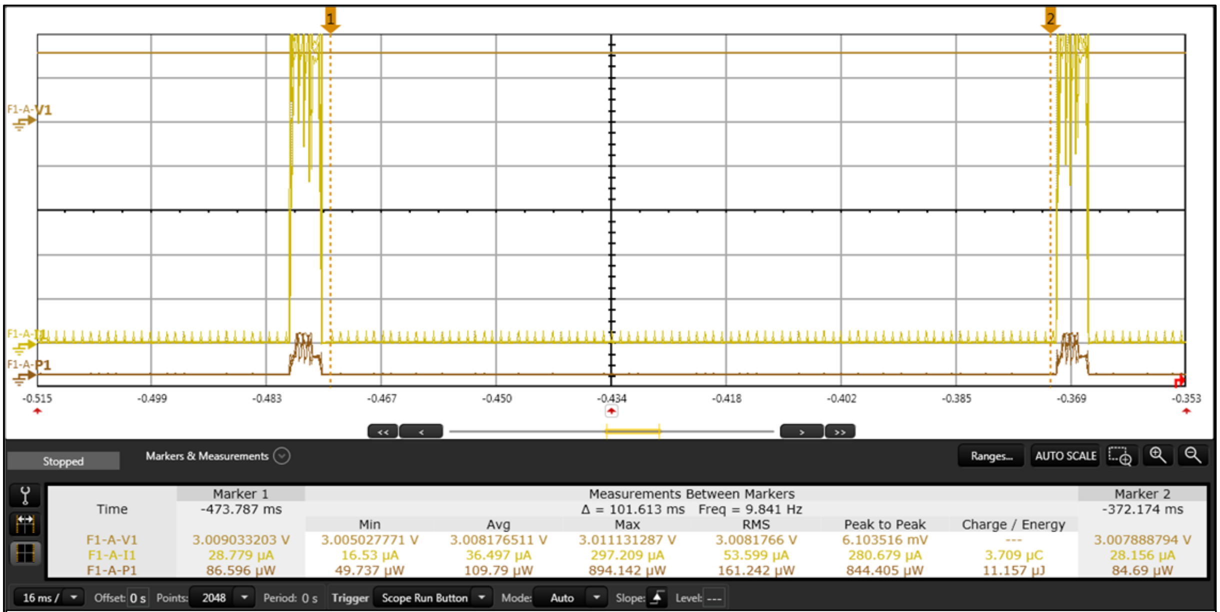
Fig. 6.   ADV for CC2541 device at 3 Volts. System without buck converter

Energy of active part of ADV event is reduced if a buck converter is used (µJ): 123 compared to 151 without buck




4 mA/div 2 V/div 50mW/div 500 µS/div Average IDD between 2 ADV (see below)
Averages TX: 15.1 mA RX: 15.2 mA (first channel) TX: 14.3 mA RX: 15.3 mA (third channel)

Fig. 7. ADV for CC2541 device at 3 Volts. System uses a Buck converter. Leads to some inprovements




The energy required between events goes up (now 36.5 uA). Energy is 12 µJ for about 100 ms interval.
2 V/div 1 mA/div 50 mW/div 16 ms/div
Buck pulses interval is about 1 ms. Peak of pulses around 300 µA

Fig. 8. ADV for CC2541 device at 3 Volts. System with buck converter. Zoom on base current. The base current increases if the buck is not controlled

Energy in power down mode is also reduced if buck is controlled properly (µJ): 125

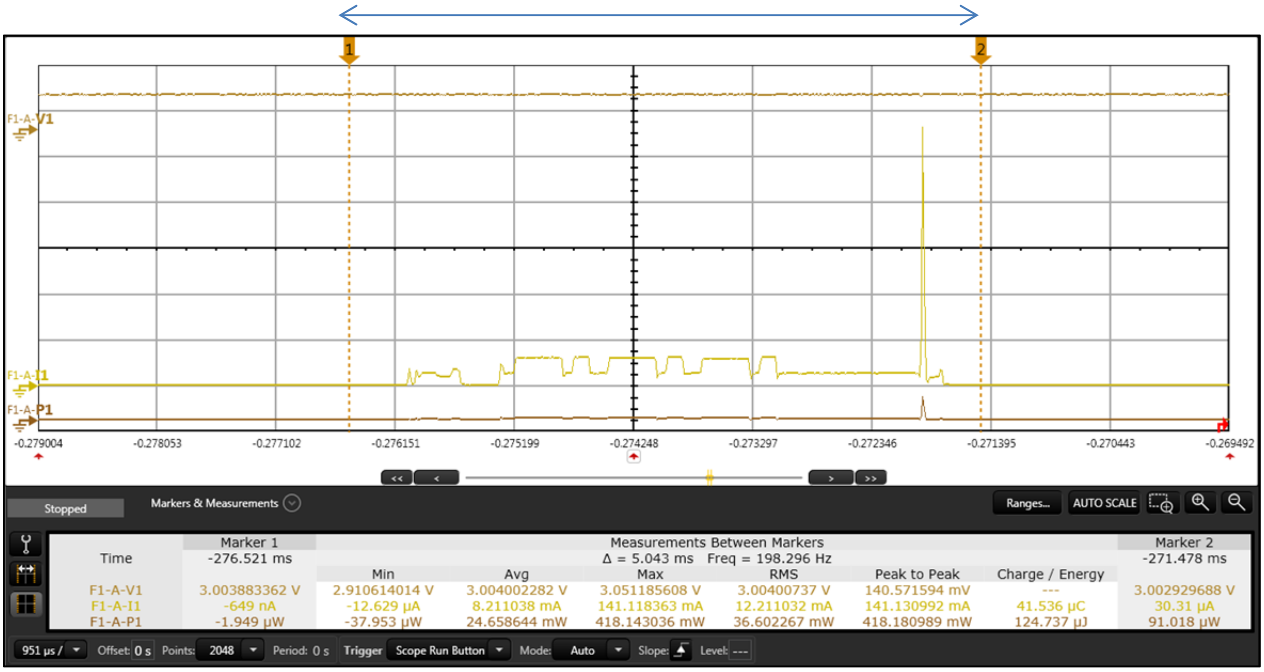



Fig. 9. ADV for CC2541 device at 3 Volts. System uses a buck converter. Buck active for high currents, but off (bypass) for small currents

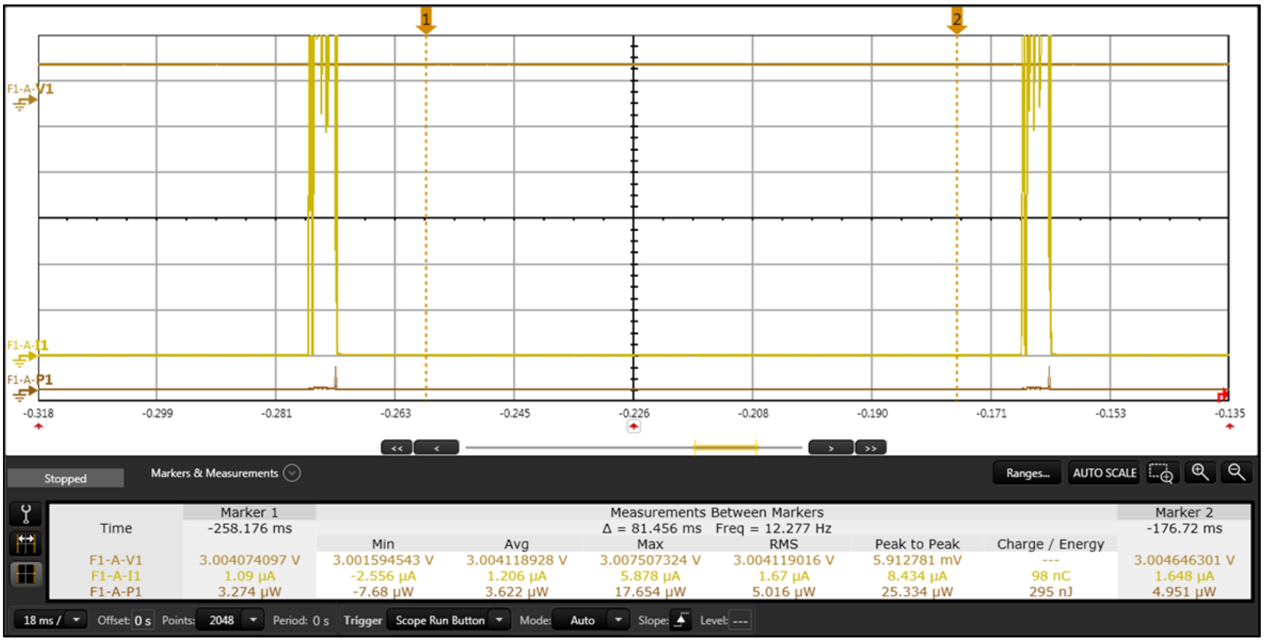
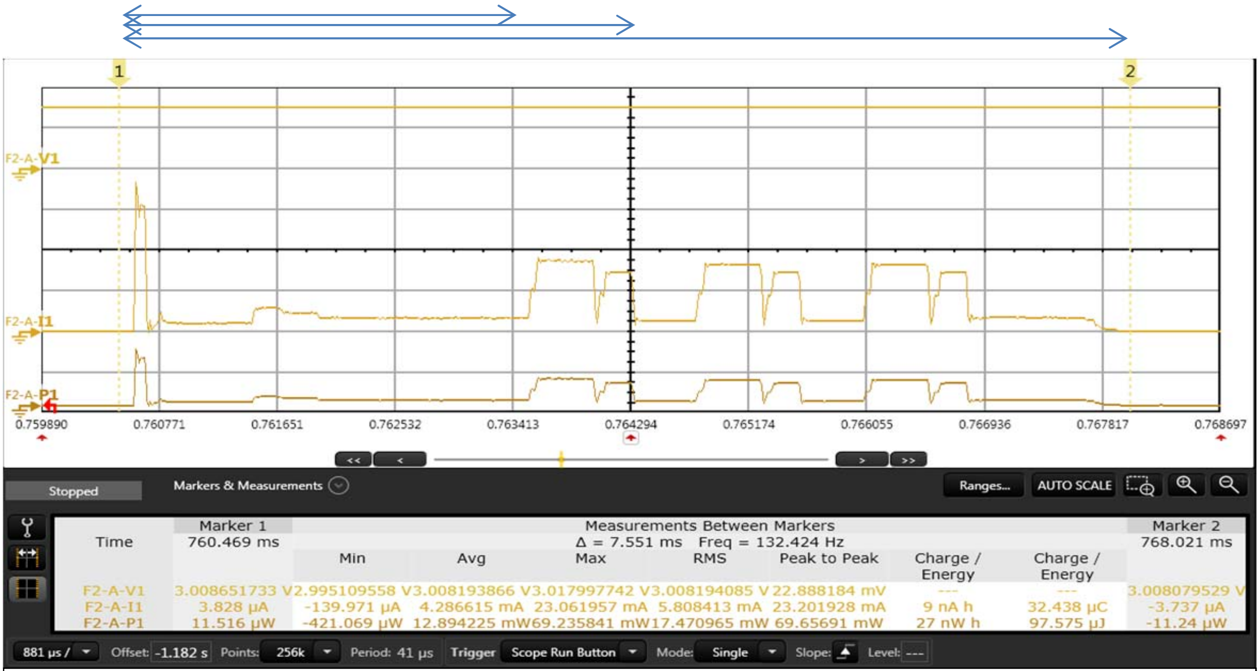


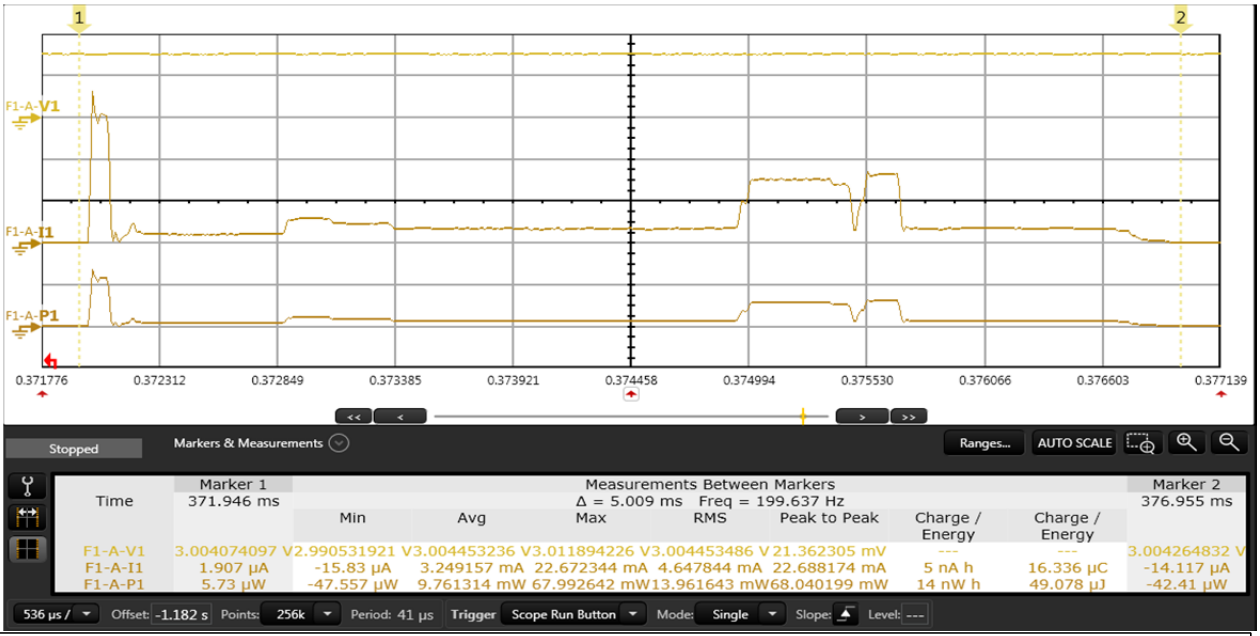

Fig. 10. ADV for CC2541 device at 3 Volts. By controlling the buck converter, the power don current is now only 1.2 µA (average)

Energy at different times during ADV (µJ): 22.7; 45; 97.6




6 mA/div 2 V/div 50mW/div 0.881 ms/div Average IDD between 2 ADV events: The Demo Board we measured have different ways to clock the Radio in sleep. 1. With external oscillator (ML7105 & 32kHzOSC U2 & EEPROM) = 2.9uA (Just ML7105$_{(1000ms)}$ = 0.645uA) 2. (With quartz crystal X1$_{(1000ms)}$ = 2.67uA)
Averages TX: 10.9 mA RX: 8.91 mA (first channel)

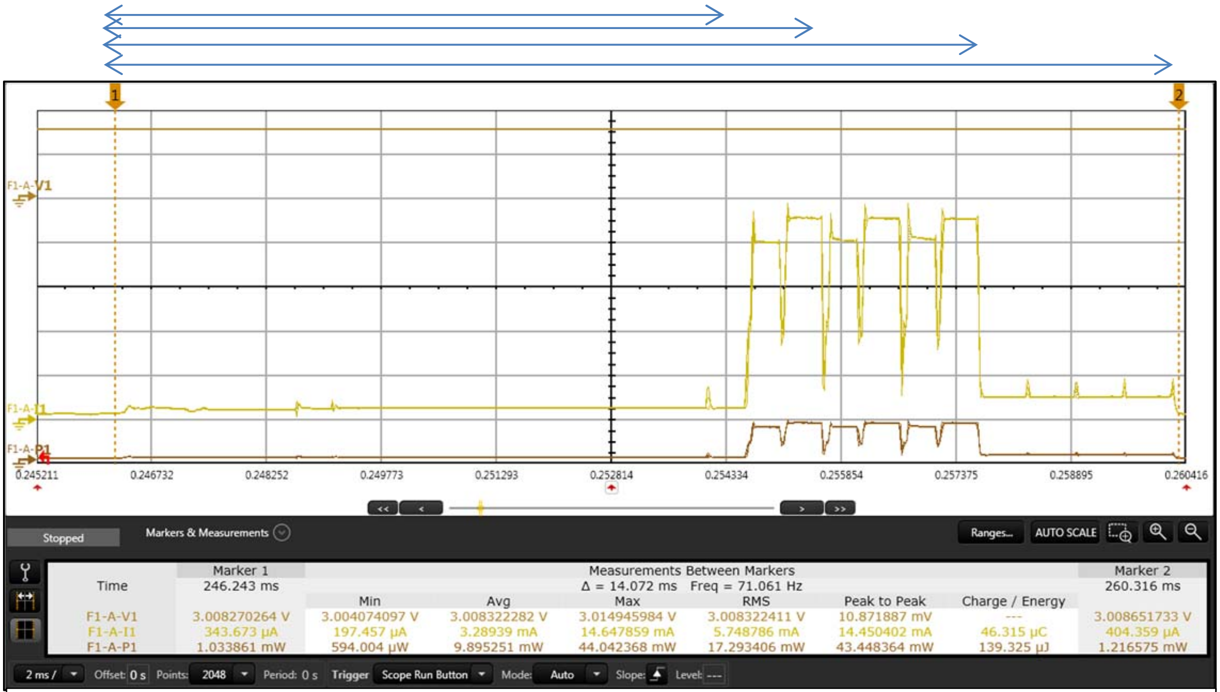
Fig. 11. ADV for ML7105-005GD ES3 Board with ML7105 & 32kHzOSC U2 & EEPROM at 3 Volts.




3 mA/div 4 V/div 50mW/div 536 ms/div
Averages TX: 10.1 mA RX 9.2 mA

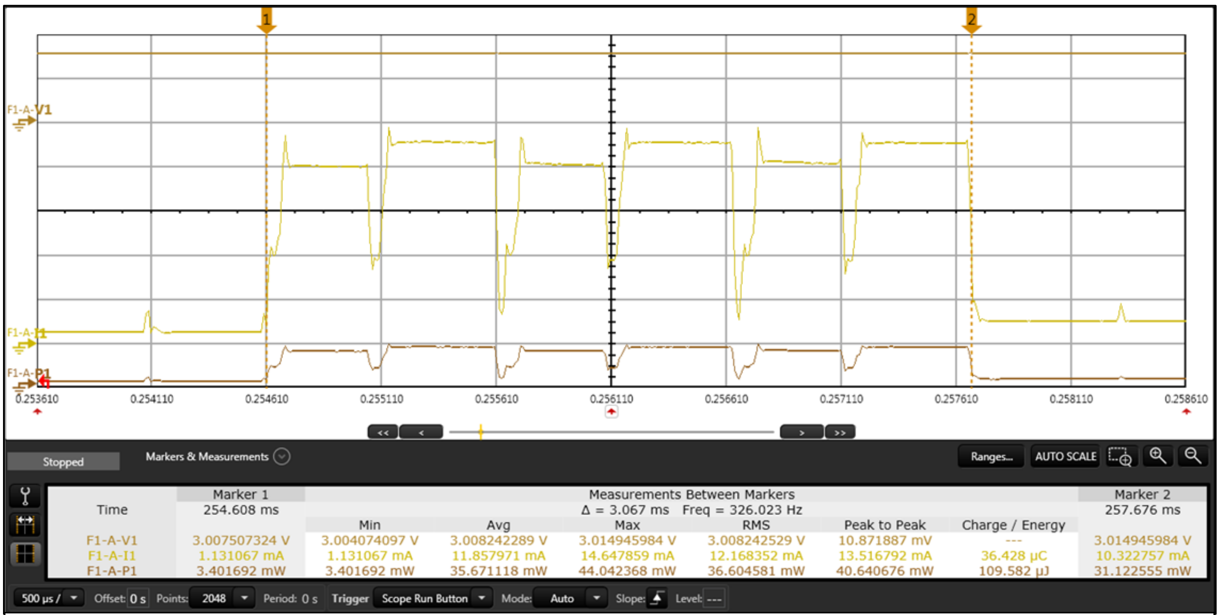
Fig. 12. Connection mode for ML7105-005GD ES3 Board with ML7105 & 32kHzOSC U2 & EEPROM at 3 Volts.

Energy at different times during ADV (µJ): 17.6;   54.2;  127.6; 139.3




3 mA/div     2 V/div      50mW/div  2 µS/div
Averages TX: 12 mA   RX: 13 mA (first channel). Note that RX window is 457 µS. That is much larger than for other devices. Average IDD between events is 318 µA if the 26 MHz Xtal is used for timings (the case here). This goes down to 60 µA if the internal oscillator is used. This goes down to about 10 µA if the 32 KHz oscillator (and xtal) of the host microcontroller used

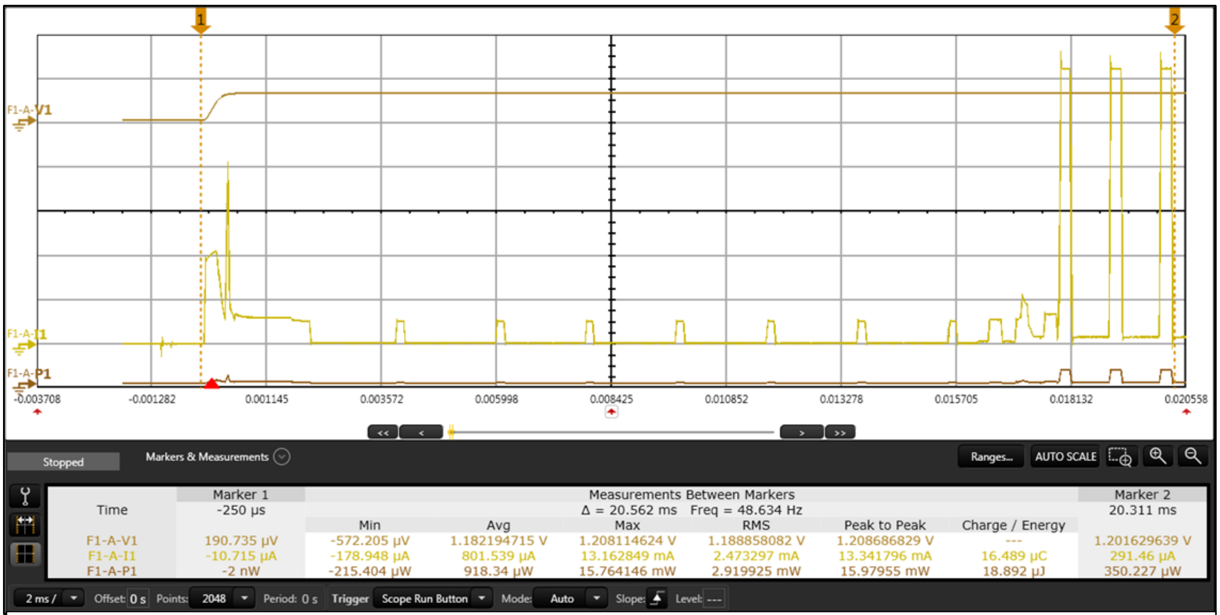
Fig. 13. ADV for EM9301 device at 3 Volts.




Time scale of 500µS/div   The ADV window (that is the time needed for all 3 ADV TX/RX operations) is 3 ms. That is much larger than that of other devices (2 ms – 2.5 ms). More time in RX means a higher probability to receive frames but at the expense of energy.

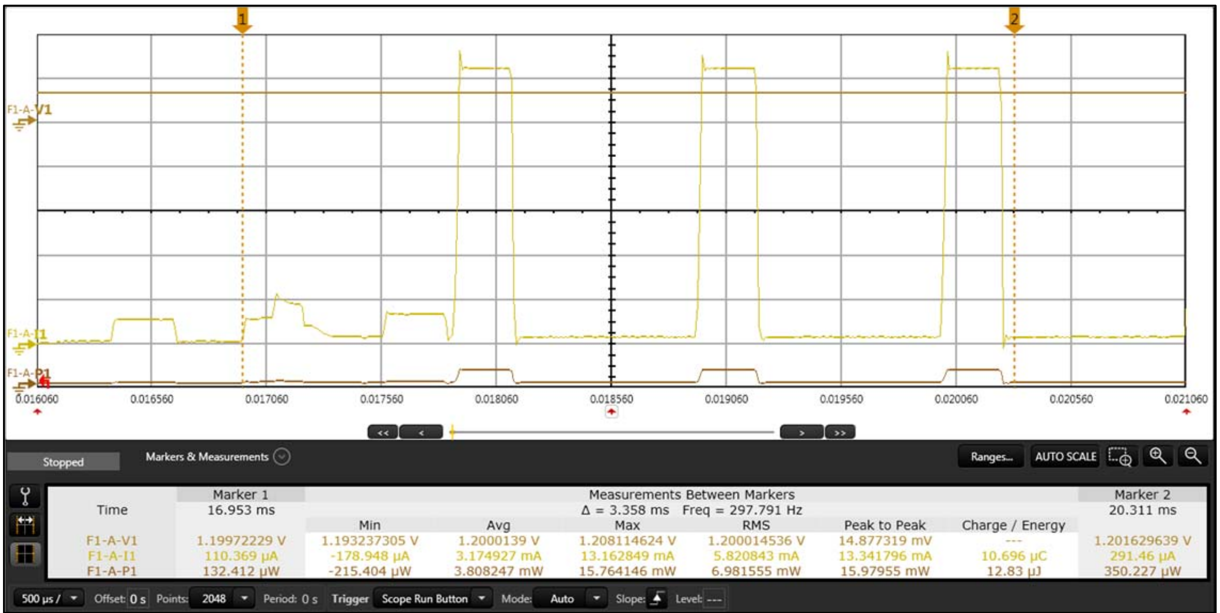
Fig. 14. ADV for EM9301 device at 3 Volts. Zoom on timing

Energy while broadcasting with the CSEM device. A low voltage microcontroller is used with the radio.




2 mA/div 2 V/div 50mW/div 2 ms/div
The CSEM device is only used here in broadcast mode to show its potential.
3 frames (total of 29 bytes per frame) are sent in broadcast mode (measured RF output slightly below 0dBm).
3 broadcasts + startup sequence require 19 µJ at 1.2 Volt (13 µJ for broadcasting)

Fig. 15. Broadcasting with the Icytrx device at 1.2 Volt.




Time scale of 500µS/div
TX 11.7 mA (average of first channel) . 12 uJ needed for the 3 transmission on 3 channels

Fig. 16. Energy needed to broadcast with the Icytrx at 1.2 Volt. Zoom on timing

Measurement of start-up times for different solutions.
The energy needed for systems initializations (power-up until ready to send the first ADV)

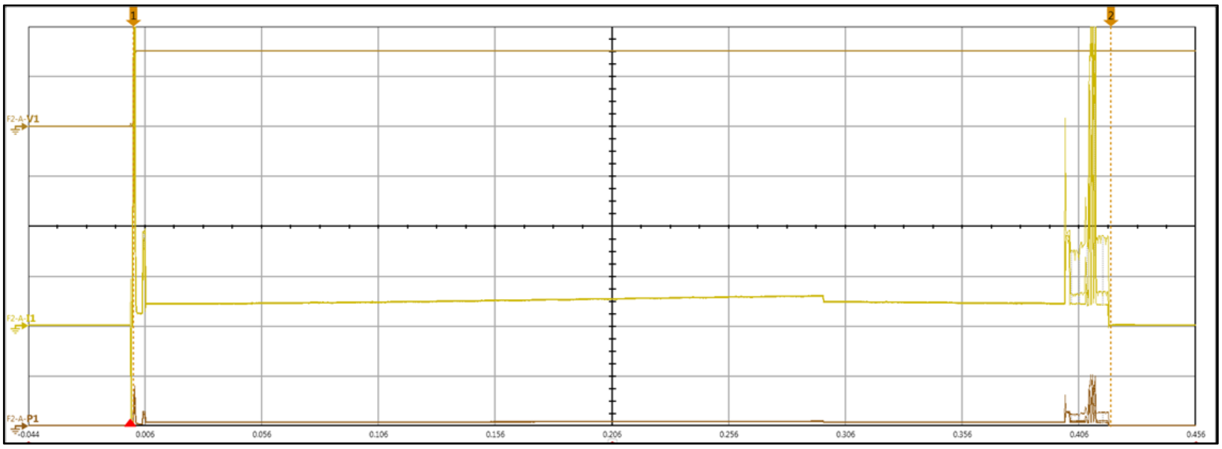
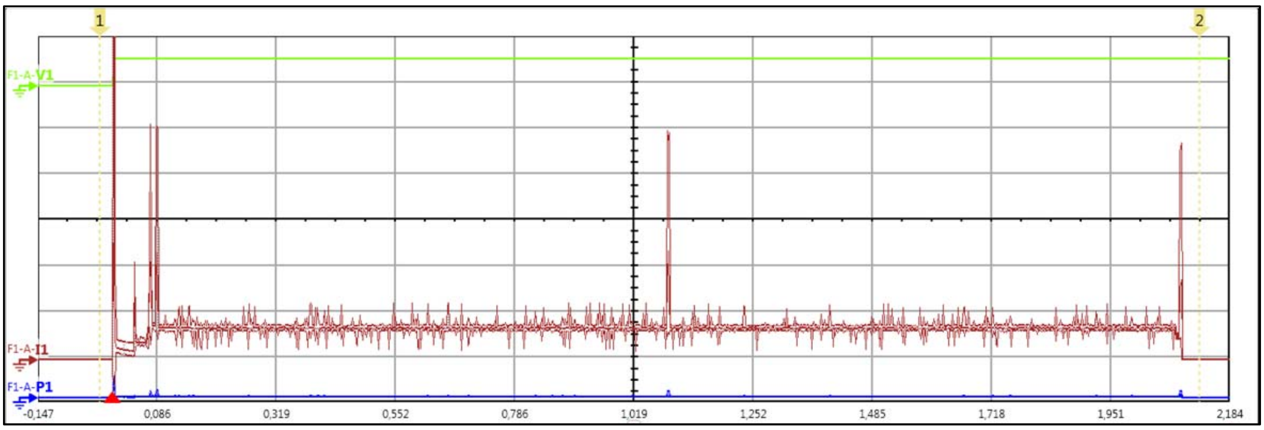


Fig. 17. Example of start-up sequence for the Nordic device (voltage, current, power)

TABLE I. ENERGY AND TIME RREQUIRED AT START-UP

| Devices | Parameters | | | |
|---|---|---|---|---|
| | ***Measurement Voltage(V)*** | ***Start-up Time (ms)*** | ***Start-up Energy (mJ)*** | ***Remarks*** |
| nRF51822 | 3.0 | 417 | 1.66 | |
| CC2540 | 3.0 | 541 | 13.2 | |
| CC2541 | 3.0 | 520 | 12.4 | |
| CSR1011 | 3.0 | 570 | 4.99 | Loads from serial non volatile |
| EM9301+EM6819 (InES stack) | 3.0 | 90 | 0.14 | The system can be ready earlier (if using InES Ble stack) |
| ML7105-002 | | | | Measurements not yet available (Loads application from serial NV. No tools to load our own application) |
| DA14580 | 3.0/3.0 | 88/2100 | 0.154/4.2 | |
| Icytrx + EM6819 | 1.2 | 18 | 0.006 | Measured at 1.2 Volt (The device starts up is initialised and goes into broadcasting) |

The values for the dialog devices are given in 2 cases. Following the first ADV completion after the reset and then at the points where the device goes in sleep.



Measurement of ADV event energy for different Ble solutions (100 ms and with 1000 ms interval).

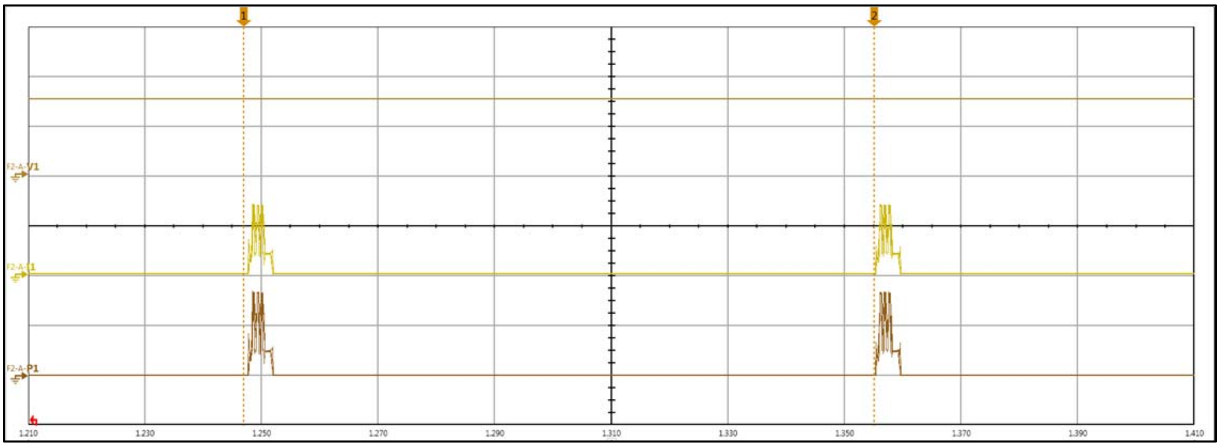


Fig. 18. Example of CC2540 for 100 ms ADV interval

A frame length of 44 octets in total was used for all ADV frames.

TABLE II. ENERGY NEEDED FOR THE TOTAL ADV EVENT CYCLE

| **Devices** | **Parameters** | | | |
|---|---|---|---|---|
| | ***Measurement Voltage(V)*** | ***ADV event cycle (ms)*** | ***Total Energy ($\mu$J)*** | ***Remarks*** |
| nRF51822 | 3.0 | 108 | 91.3 | |
| CC2540 | 3.0 | 107 | 191.9 | |
| CC2541_bypass | 3.0 | 108 | 156 | |
| CC2541_dcdc | 3.0 | 109 | 125 | |
| CSR1011 | 3.0 | 108 | 98.9 | |
| DA14580 | 3.0 | 105 | 35.3 | |
| ML7105 | 3.0 | 106 | 97.6 | ML7105 & 32kHzOSC U2 & EEPROM |
| EM9301 | | | | Measurements not yet available |
| Icytrx | | | | Measurements not yet available |
| | | | | |
| nRF51822 | 3.0 | 1004 | 100 | |
| CC2540 | 3.0 | 1008 | 232 | |
| CC2541_bypass | 3.0 | 1006 | 157 | |
| CC2541_dcdc | 3.0 | 1003 | 130 | |
| CSR1011 | 3.0 | 1006 | 111 | |
| DA14580 | 3.0 | 1007 | 40.2 | |
| ML7105 | 3.0 | 1008 | 109 | ML7105 & 32kHzOSC U2 & EEPROM |
| EM9301 | | | | Measurements not yet available |
| Icytrx | | | | Measurements not yet available |

Measurement of ADV event energy for different solutions (100 ms and with 1000 ms interval).

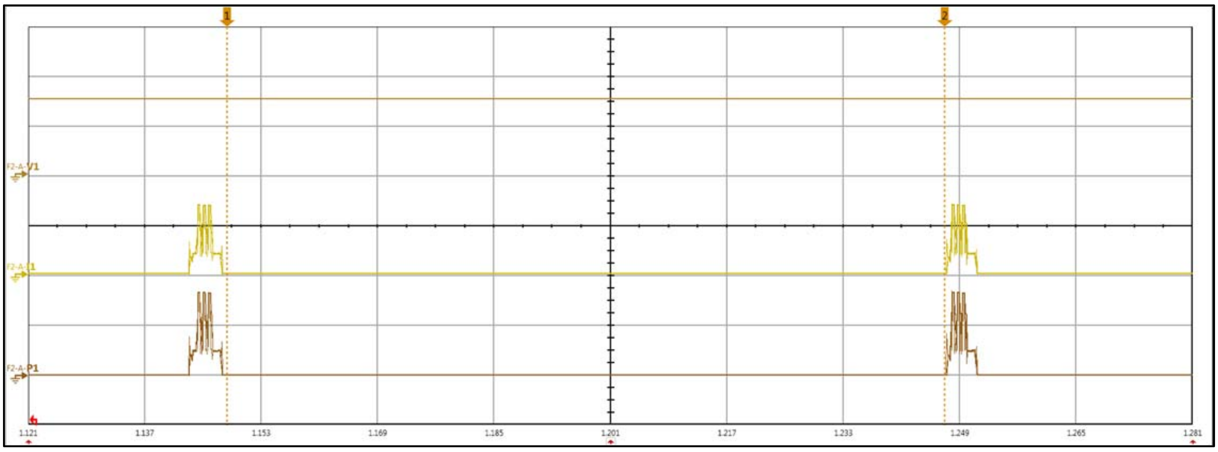


Fig. 19. Example of CC2540 for 100 ms ADV interval

A frame length of 44 octets in total was used for all ADV frames.

TABLE III. ENERGY NEEDED FOR THE ADV SLEEP

| Devices | Parameters | | | | |
|---|---|---|---|---|---|
| | ***Measurement Voltage(V)*** | ***ADV event cycle (ms)*** | ***Average current ($\mu$A)*** | ***Sleep Energy ($\mu$J)*** | ***Remarks*** |
| nRF51822 | 3.0 | 98.6 | 3.17 | 0.94 | |
| CC2540 | 3.0 | 98 | 17.2 | 5.01 | |
| CC2541_bypass | 3.0 | 97.3 | 1.17 | 0.341 | |
| CC2541_dcdc | 3.0 | 96 | 1.25 | 0.496 | |
| CSR1011 | 3.0 | 98.3 | 2.86 | 0.849 | |
| DA14580 | 3.0 | 91 | 1.9 | 0.532 | |
| ML7105 | 3.0 | 95 | 2.9 | 0.84 | ML7105 & 32kHzOSC U2 & EEPROM |
| EM9301 | | | | | |
| Icytrx | | | | | |
| | | | | | |
| nRF51822 | 3.0 | 997 | 3.15 | 9.45 | |
| CC2540 | 3.0 | 999 | 17.2 | 51.6 | |
| CC2541_bypass | 3.0 | 1000 | 1.13 | 3.4 | |
| CC2541_dcdc | 3.0 | 998 | 1.18 | 3.53 | |
| CSR1011 | 3.0 | 1002 | 4.85 | 14.6 | |
| DA14580 | 3.0 | 990 | 1.9 | 5.65 | |
| ML7105 | 3.0 | 1001 | 3.5 | 10.6 | ML7105 & 32kHzOSC U2 & EEPROM |
| EM9301 | | | | | |
| Icytrx | | | | | |

- According to Dialog, a lowest current 0f 0.9 uA is possible. But it leads to more energy when restarting. So it makes sense only if the sleeping time is long enough. We could not yet measure that lowest current.
- We could measure a current of 0.9uA with the ML7105 while using an external RTC. But this did not include the energy consumption of the external clock device

Measurement of ADV event energy for different solutions (100 ms and with 1000 ms interval). Averaging several periods

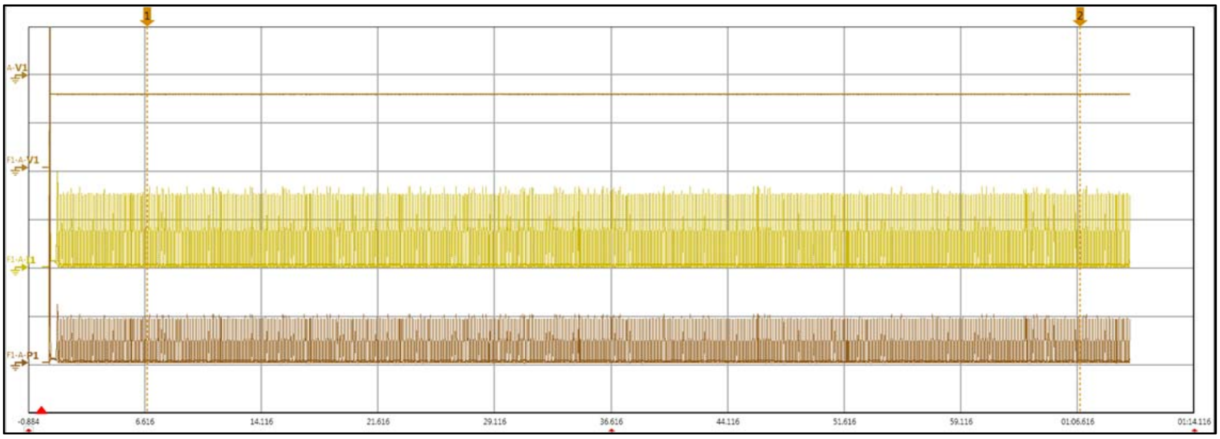


Fig. 20. Example of CSR 1011. Averaging several ADV events over 1 minute

A frame length of 44 octets in total was used for all ADV frames.
ADV events with 100 ms or 1000 ms cycles are averaged over a minute in order to reduce the effects of elements such as Buck converters.

TABLE IV. ENERGY NEEDED FOR THE ADV EVENT (AVERAGING SEVERAL CYCLES)

| Devices | Parameters | | | | | |
|---|---|---|---|---|---|---|
| | *Measurement Voltage (V)* | *ADV event cycle (ms)* | *Average current (μA)* | *Energy (mJ)* | *Energy per cycle (μJ)* | *Remarks* |
| nRF51822 | 3.0 | 100 ms for 1 min | 286 | 51.5 | 85.8 | |
| CC2540 | 3.0 | 100 ms for 1 min | 595 | 107 | 178.5 | |
| CC2541_bypass | 3.0 | 100 ms for 1 min | 492 | 88.8 | 147.6 | |
| CC2541_dcdc | 3.0 | 100 ms for 1 min | 400 | 72.4 | 120 | |
| CSR1011 | 3.0 | 100 ms for 1 min | 347 | 62.5 | 104.1 | |
| DA14580 | 3.0 | 100 ms for 1 min | 112 | 20.2 | 33.6 | |
| ML7105 | 3.0 | 100 ms for 1 min | 316 | 57.1 | 95.1 | ML7105 & 32kHzOSC U2 & EEPROM |
| EM9301 | | | | | | |
| Icytrx | | | | | | |
| | | | | | | |
| nRF51822 | 3.0 | 1000 ms for 1 min | 33.1 | 5.96 | 99.3 | |
| CC2540 | 3.0 | 1000 ms for 1 min | 101 | 18.1 | 303 | |
| CC2541_bypass | 3.0 | 1000 ms for 1 min | 55.6 | 10.1 | 166.8 | |
| CC2541_dcdc | 3.0 | 1000 ms for 1 min | 46.1 | 8.32 | 138.3 | |
| CSR1011 | 3.0 | 1000 ms for 1 min | 42 | 7.57 | 126 | |
| DA14580 | 3.0 | 1000 ms for 1 min | 13.5 | 2.44 | 40.6 | |
| ML7105 | 3.0 | 1000 ms for 1 min | 37.2 | 6.72 | 112 | ML7105 & 32kHzOSC U2 & EEPROM |
| EM9301 | | | | | | |
| Icytrx | | | | | | |

Measurement of energy in connection mode for different Ble solutions (100 ms and with 1000 ms interval).

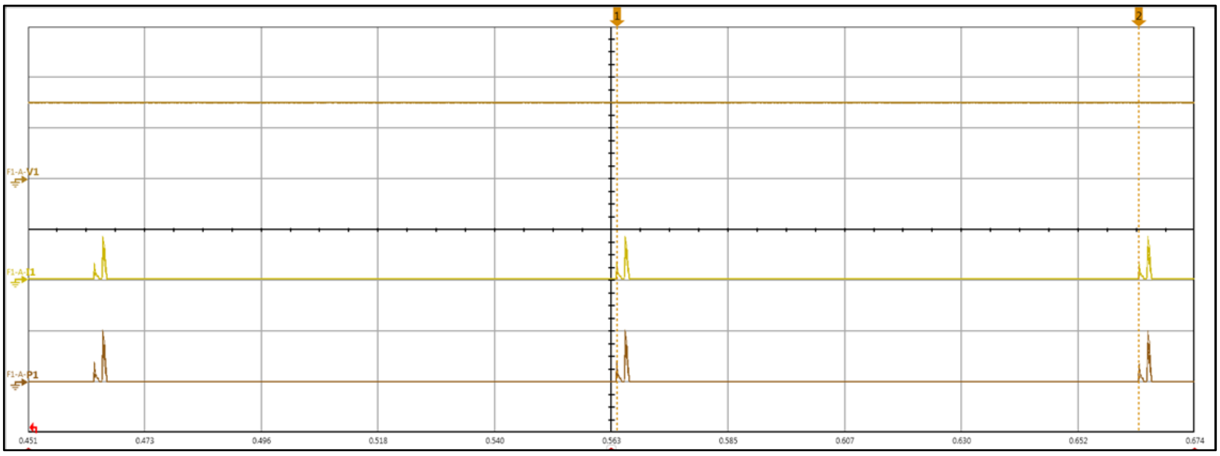


Fig. 21. Example of CC2540. Connection cycle of 100 ms

The connection is maintained by sending and receiving “empy” data frames at predetermined intervals. When the connection time is reached, the device wakes up and switches on its receiver to get data from the host. It then sends an answer to the host. The whole procedure and proper timing costs energy. The energy consumption is for a total interval or for the sleep part of the connection cycle.

TABLE V. ENERGY NEEDED FOR THE CONNECTION EVENT

| **Devices** | **Parameters** | | | |
|---|---|---|---|---|
| | ***Measurement Voltage (V)*** | ***Connection event cycle (ms)*** | ***Energy of connection cycle ($\mu$J)*** | ***Remarks*** |
| nRF51822 | 3.0 | 100 | 27.9 | |
| CC2540 | 3.0 | 100 | 81.6 | |
| CC2541_bypass | 3.0 | 100 | 77.9 | |
| CC2541_dcdc | 3.0 | 100 | 65.3 | |
| CSR1011 | 3.0 | 100 | 29.7 | |
| DA14580 | 3.0 | 100 | 17.7 | |
| ML7105 | 3.0 | 100 | 44.1 | ML7105 & 32kHzOSC U2 & EEPROM |
| EM9301 | | | | |
| Icytrx | | | | |
| | | | | |
| nRF51822 | 3.0 | 1000 | 39.7 | |
| CC2540 | 3.0 | 1000 | 135 | |
| CC2541_bypass | 3.0 | 1000 | 92.6 | |
| CC2541_dcdc | 3.0 | 1000 | 78.9 | |
| CSR1011 | 3.0 | 1000 | 47.8 | |
| DA14580 | 3.0 | 1000 | 30.8 | |
| ML7105 | 3.0 | 1000 | 61.8 | ML7105 & 32kHzOSC U2 & EEPROM |
| EM9301 | | | | |
| Icytrx | | | | |

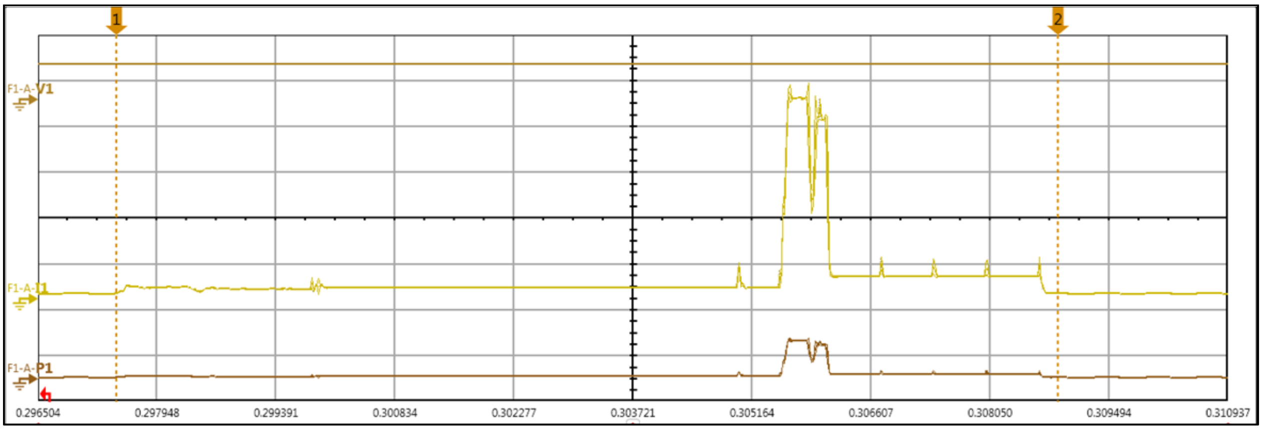



Fig. 22. Example of connection transfer for the EM9301. The device wakes up, synchronises, receives a frame, sends a frame, goes back to sleep

TABLE VI. ENERGY NEEDED FOR THE CONNECTION EVENT. CONNECTION CYCLES OF 100 MILLISECONDS ADDED UP OVER 1 MINUTE

| Device | Voltage (V) | Time (min) | IAvg (uA) | Energy (mJ) |
|---|---|---|---|---|
| nRF51822 | 3.0 | 1 | 94.5 | 17 |
| CC2540 | 3.0 | 1 | 277 | 50 |
| CC2541_bypass | 3.0 | 1 | 255 | 46.2 |
| CC2541_dcdc | 3.0 | 1 | 218 | 39.3 |
| CSR1011 | 3.0 | 1 | 96.3 | 17.4 |
| DA14580 | 3.0 | 1 | 82.6 | 14.9 |
| ML7105 | 3.0 | 1 | 155 | 28 |

TABLE VII. ENERGY NEEDED FOR THE CONNECTION EVENT. CONNECTION CYCLES OF 1000 MILLISECONDS ADDED UP OVER 1 MINUTE

| Device | Voltage (V) | Time (min) | IAvg (uA) | Energy (mJ) |
|---|---|---|---|---|
| nRF51822 | 3.0 | 1 | 14.3 | 2.58 |
| CC2540 | 3.0 | 1 | 48.3 | 8.72 |
| CC2541_bypass | 3.0 | 1 | 32.5 | 5.87 |
| CC2541_dcdc | 3.0 | 1 | 27.8 | 5.03 |
| CSR1011 | 3.0 | 1 | 20.5 | 3.69 |
| DA14580 | 3.0 | 1 | 10.7 | 1.93 |
| ML7105 | 3.0 | 1 | 20 | 3.6 |

TABLE VIII. ENERGY NEEDED FOR A THE ACTIVE PART OF A CONNECTION EVENT (WAKE UP, RECEIVE, TRANSMIT).

| Device | Voltage (V) | Time (ms) | Energy (µJ) |
|---|---|---|---|
| nRF51822 | 3.0 | 2.45 | 27 |
| CC2540 | 3.0 | 2.88 | 76.5 |
| CC2541_bypass | 3.0 | 2.91 | 77.6 |
| CC2541_dcdc | 3.0 | 2.93 | 65 |
| CSR1011 | 3.0 | 2.87 | 28.9 |
| DA14580 | 3.0 | 8.91 | 17.1 |
| ML7105 | 3.0 | 4.9 | 43.3 |

TABLE IX. ENERGY NEEDED FOR THE SLEEP PART OF A CONNECTION EVENT . 100 MILLISECONDS CONNECTION CYCLE.

| Device | Voltage (V) | Time (ms) | IAvg (µA) | Energy (µJ) |
|---|---|---|---|---|
| nRF51822 | 3.0 | 97.6 | 3.11 | 0.913 |
| CC2540 | 3.0 | 96.9 | 17.2 | 5.01 |
| CC2541_bypass | 3.0 | 96.9 | 1.14 | 0.333 |
| CC2541_dcdc | 3.0 | 97 | 1.51 | 0.442 |
| CSR1011 | 3.0 | 97 | 2.95 | 0.86 |
| DA14580 | 3.0 | 91 | 1.95 | 0.532 |
| ML7105 | 3.0 | 95 | 2.9 | 0.841 |

TABLE X. ENERGY NEEDED FOR THE SLEEP PART OF A CONNECTION EVENT. 1000 MILLISECONDS CONNECTION CYCLE.

| Device | Voltage (V) | Time (ms) | IAvg (µA) | Energy (µJ) |
|---|---|---|---|---|
| nRF51822 | 3.0 | 999 | 3 | 9.45 |
| CC2540 | 3.0 | 996 | 17.2 | 51.5 |
| CC2541_bypass | 3.0 | 996 | 1.13 | 3.39 |
| CC2541_dcdc | 3.0 | 997 | 1.17 | 3.49 |
| CSR1011 | 3.0 | 997 | 3.88 | 11.6 |
| DA14580 | 3.0 | 990 | 1.9 | 5.65 |
| ML7105 | 3.0 | 995 | 3.5 | 10.5 |

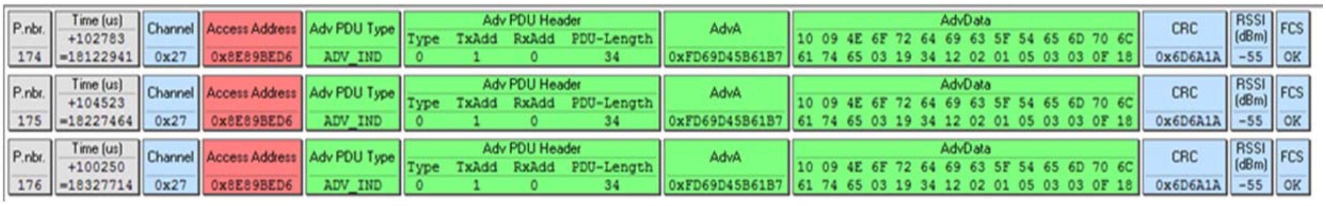



Fig. 23. ADV_IND format frame used for all devices (except Lapis)

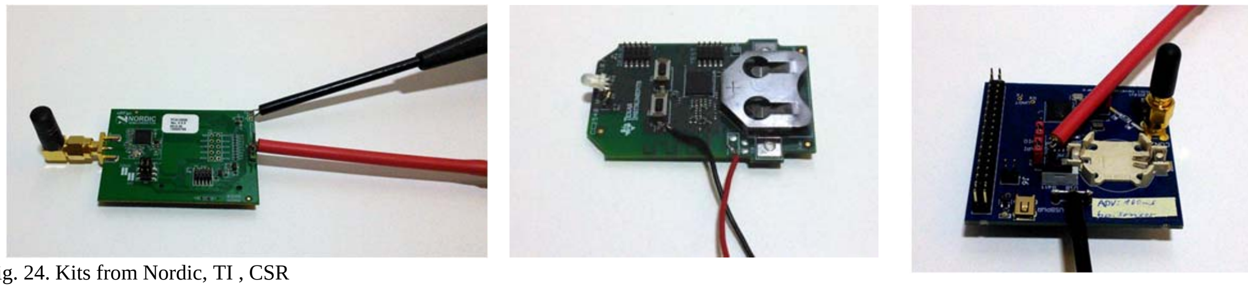
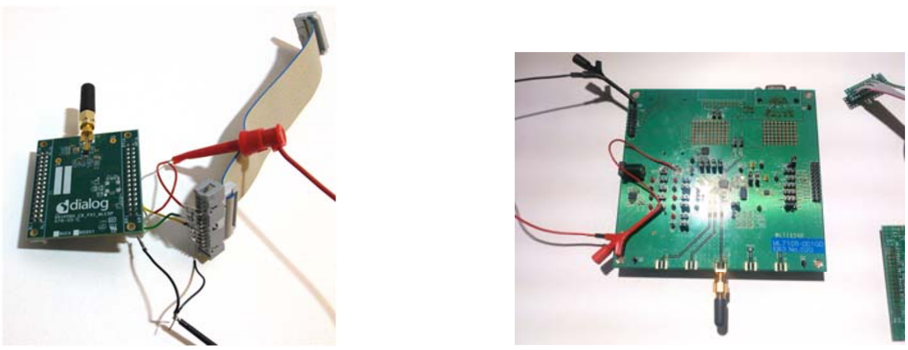


Fig. 24. Kits from Nordic, TI , CSR

Fig. 25. Kits from Dialog, Lapis



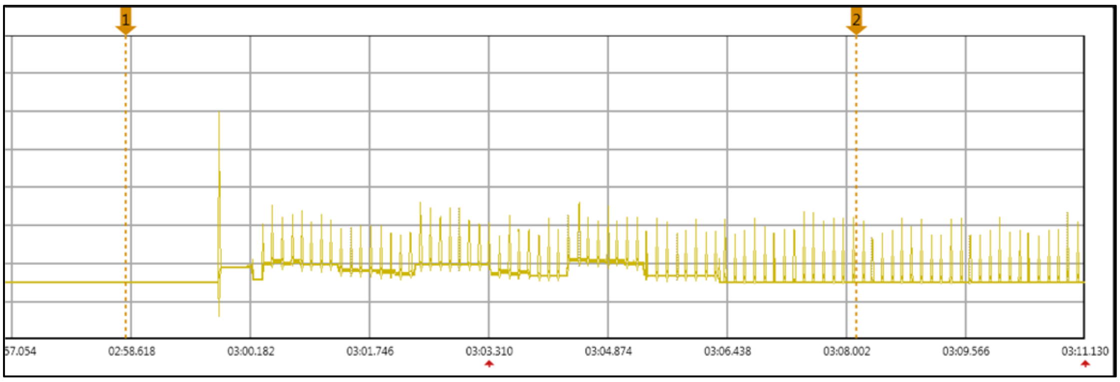



Fig. 26. Impact of temperature. This figure is only meant to show that temperature changes can significantly affect the energy, especially in low power modes. A system was simply heated and cooled and the current during the ADV phase recorded. It can be clearly seem that there are changes. With one device, we measured up to 10 µA difference in a very low power mode (between room temperature and hot temperatures). In some cases, the body temperature was enough to induce changes of several µA.

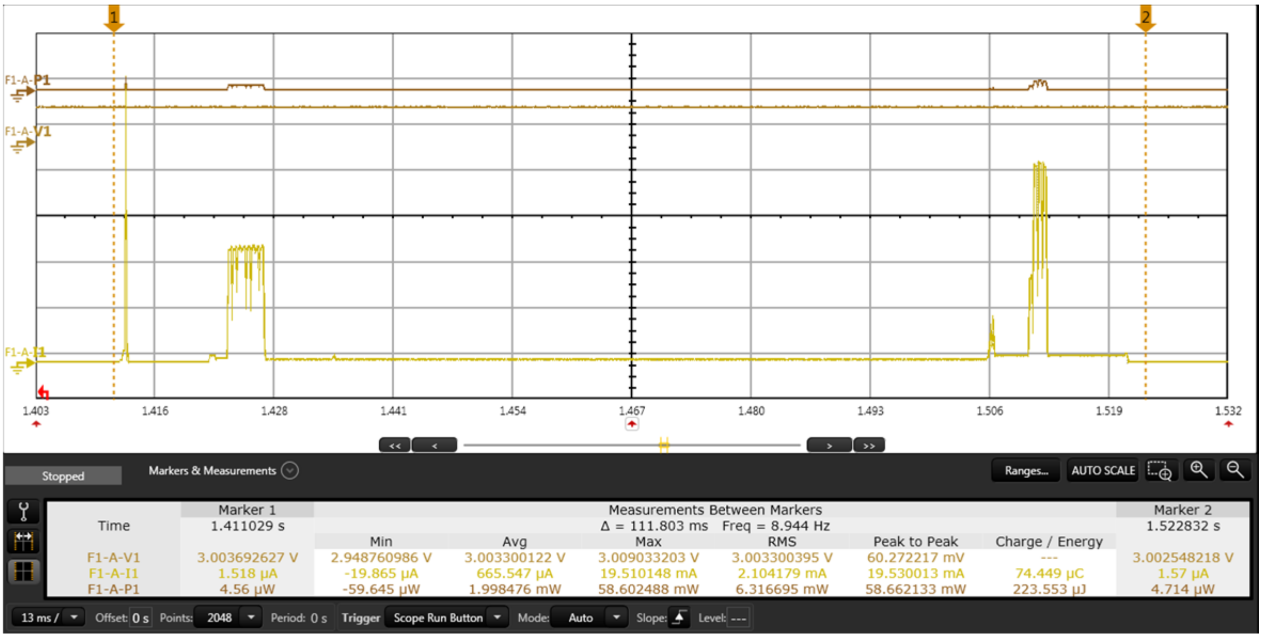



Fig. 27. A start-up procedure with the EM9301 ROM version. The radio can be switched off for several seconds, and restarted using the microcontroller. After the radio is started, it goes into calibration. After that, it is ready for communication with the microcontroller. The last peak results from transmission of data on the 3 ADV channels. The whole sequence requires about 224 µJ. 140 µJ for start-up and calibration. The rest comes from the SPI communication (between radio and microcontroller) and the Ble transmission). The calibration here is made several times at start-up, leading to the 140 µJ. In principle, 1 calibration with the EM9301 costs about 10µJ. The frames senst have maximal length.

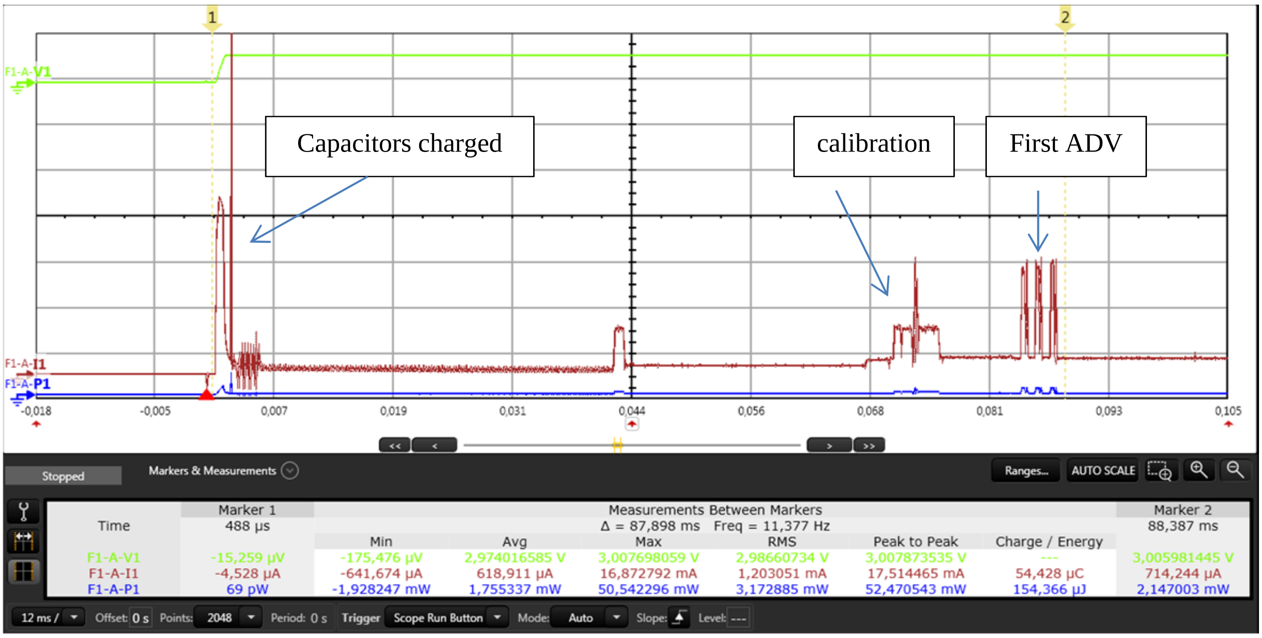



Fig. 28. A start-up procedure with the DA14580. The application program is in OTP. At cold start it is loaded in the RAM. The device is calibrated and a first ADV frame is generated. The cold start takes about 88ms and 154µJ until the end of the first ADV. The systems remains acive as shown below. The calibration costs about 25µJ

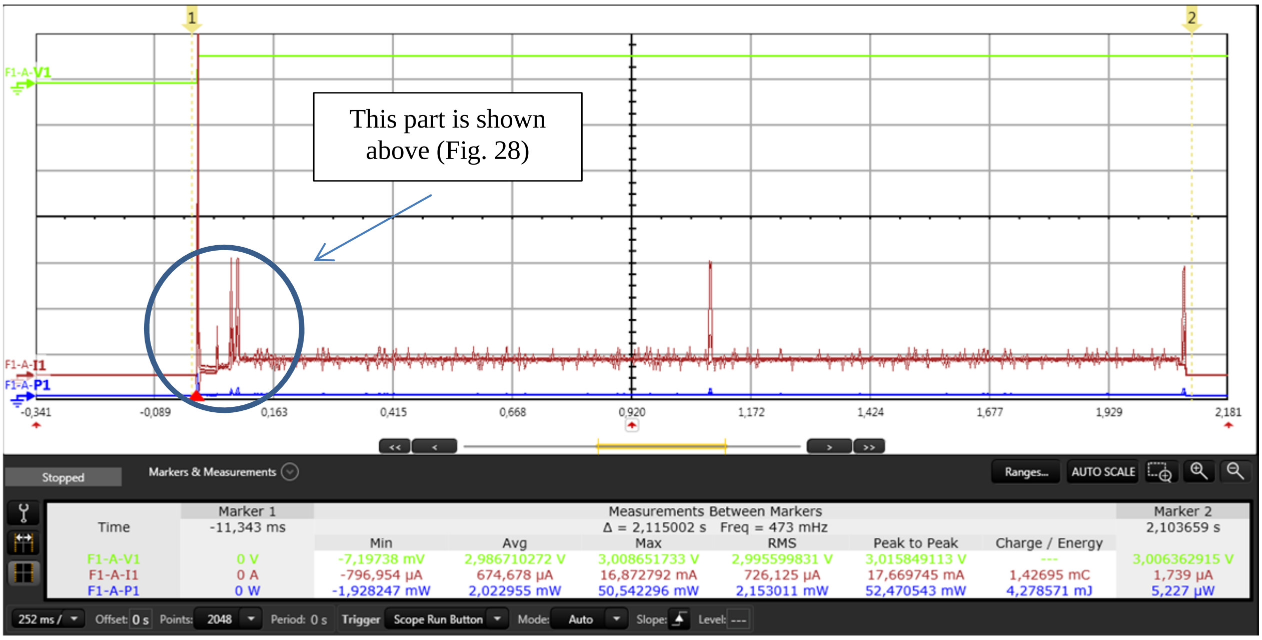



Fig. 29. The start-up procedure with the DA14580. After about 2.1 seconds, the device goes into sleep mode. The energy until the first sleep is about 4.2 mJ. In the case illustrated above, the ADV interval is 1000ms.

## VIII. CONCLUSION

In this paper, we have presented results of measurements made on various Bluetooth Low Energy devices. The measurement give elements needed to compare devices in various application modes. Application engineers can use some of these results with the datasheets of the devices to determine the devices that are suitable for their applications. IC manufacturers can use the result to improve their devices. Since new devices are continuously appearing on the market, this work will be repeated in the coming years.

## ACKNOWLEDGMENTS

We would like to thank Dialog, EM, Lapis, CSEM for providing us with kits or devices for tests.

## REFERENCES

[1] Ble specifications v4.0, v4.1:
https://www.bluetooth.org/en-us/specification/adopted-specifications

[2] Training on Ble: https://www.bluetooth.org/en-us/training-resources

[3] Datasheet CC2540: http://www.ti.com/

[4] Datasheet CC2541: http://www.ti.com/

[5] Datasheet nRF51822: https://www.nordicsemi.com/

[6] Datasheet of CSR1011: http://www.csr.com/

[7] Datasheet of EM9301 and variants: http://www.emmarin.com/

[8] Using Bluetooth Smart with Energy Harvesting
Embedded World 2013 presentation. Beerli, Kizhakenath, Meli
http://www.ines.zhaw.ch

[9] Datasheet of DA14540:
http://www.dialogsemiconductor.com/products/bluetooth-smart

[10] http://www.lapis-semi.com/en/company/news/r20130925.html

[11] http://www.lapis-semi.com/en/semicon/telecom/ml7105.html

[12] Paper on Icytrx:
A low power miniaturized 1.95mm2 fully integrated transceiver with fastPLL mode for IEEE 802.15.4/bluetooth smart and proprietary 2.4GHz applications Pengg, F.; Barras, D. ; Kucera, M. ; Scolari, N. ; Vouilloz, A.
http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=6569525&queryText%3Dpengg

[13] CSEM announcement:
http://www.csem.ch/docs/Show.aspx/19930/docname/CP12_IcyTRX_EN.pdf

[14] http://cp.literature.agilent.com/litweb/pdf/N6705-90001.pdf

[15] Ellisys sniffer: http://www.ellisys.com/products/bex400/index.php