Power Consumption Measurements for IoT Applications
Application Note

Products:

- R&S®RT-ZVC02/04
- R&S®RTP
- R&S®RTO2000
- R&S®RTE1000

This application note describes power consumption measurements with Rohde & Schwarz oscilloscopes and the R&S®RT-ZVC02/04(A) Multi-Channel Probe. Especially IoT applications need to ensure accurate power and charge consumption measurements in order to estimate the lifetime of the battery and therefore the lifetime of the device itself.

Note:

Please find the most up-to-date document on our homepage:

http://www.rohde-schwarz.com/appnote/1TD07.

Application Note

Dr. Andreas Ritter,
8.2019 – 1TD07_2e

ROHDE&SCHWARZ

Table of Contents

1 Introduction

Battery life is a key aspect for the buying decision of mobile phones, Internet-of-Things (IoT) devices and any other wearable technology. Since these devices are expected to operate “anytime and anywhere”, the battery life and therefore energy consumption is perhaps one of the most important aspects for consumers. Presumably everyone can relate to the feeling when the smartphone battery is running low and no charging station is nearby. Therefore, consumers pay a lot of attention to the battery life, because it is such an important criteria and easily to compare between different devices of a certain category.

In order to keep energy consumption as low as possible, these devices work typically with special sleep modes of very low power requirements. These are interrupted only by very short activity phases of normal or high power consumption. For a successful device, the power consumption has to be optimized already in the early development phase. For this, it needs to be measured accurately which requires sophisticated probing solutions. The probe must be able to measure very small currents in the µA or even nA range, as well as currents up to several Amps.

Handling such a high dynamic range of 10^6 or even up to 10^9 is a challenge for every measurement device and may not even be possible for digital multimeters, current probes, or Source-Meter-Units (SMUs).

In contrast, the R&S®RT-ZVC02/04 multi-channel probe offers measurement ranges from 4.5 µA up to 10 A and can resolve smallest details in these ranges with its 18-bit ADC. It is well-suited for battery lifetime measurements of low power consumption devices.

In the following, the R&S®RT-ZVC02/04 probing solution and typical low-power measurement challenges are described. The focus is on the combination of the R&S®RT-ZVC with an oscilloscope, nevertheless, the content is also relevant for other measurement solutions such as the R&S®RT-ZVC(A) with CMWRun[1]. CMWRun offers long-term acquisition of data and correlation to signaling events. In addition, the battery life is estimated by the software. On the other hand, the combination of the multi-channel probe with an oscilloscope offers additional channels, a correlation with other electrical signals and is a universal toolkit for signal investigations.

[1] The use of the R&S®RT-ZVC in combination with CMWRun Test Sequencer and R&S®CMW500 Mobile Communication Tester for IoT power consumption measurements is described in a different application note: “*IoT Power Consumption Measurement - 1MA281*”. It presents a setup to embed the power consumption measurement into an emulated network scenario in which the DUT communicates with the R&S®CMW500, while CMWRun controls both the R&S®RT-ZVC(A) and the R&S®CMW500 directly.

2 Typical current profile of IoT devices and measurement use cases

The basic strategy to optimize battery lifetime is to keep the device in sleep mode as long as possible and activate it only for very short activity phases. An important factor is the sleep-mode current that directly impacts the energy consumption during this phase. Just as crucial is the energy consumption in the activity phases of the device.

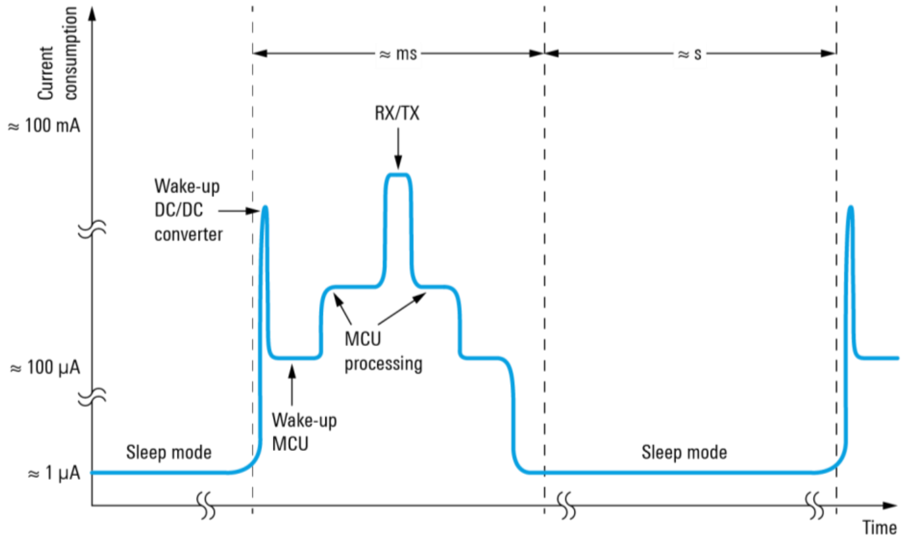

Figure 1 Typical current consumption profile of an IoT module. Long sleep-mode periods with very low current consumption are interrupted by short periods of activity in which the microcontroller unit (MCU) processes data.

Figure 1 shows a typical current consumption profile of modern IoT devices. The sleep mode usually lasts several seconds with sleep mode currents in the low µA range. The active phase usually consists of several intervals with different current consumption levels that can peak up to about 100 mA. In order to evaluate battery lifetime, the very low sleep mode currents as well as the high currents during the activity phase need to be measured and optimized.

The R&S®RT-ZVC02/04 multi-channel power probe (in the following named “ZVC”) is an ideal solution to perform these measurements. It is available in two versions with either two current and voltage channels each (RT-ZVC02) or with four current and voltage channels each (RT-ZVC04). This way the ZVC adds additional voltage and shunt-based current channels to the R&S®RTE1000, R&S®RTO2000 or R&S®RTP oscilloscopes (in the following named “RTO/RTE/RTP”). The ZVC is connected and operated via the MSO[2] interface of the oscilloscope.

The ZVC enables current measurements ranging from a few nA to 10 A, which is achieved by switching between three internal shunt resistors (10 mΩ, 10 Ω, 10 kΩ). In

[2] Mixed Signal Option

addition, an external shunt resistor can be used to enable other resistor values that might be better suited for the DUT. The vertical resolution in each measurement range is 18-bit.

To optimize the battery lifetime of IoT devices, two typical measurements are performed with the ZVC:

- **Current profiling:** The current consumption and the amount of time spent in the different operation modes (e.g. wake-up, sleep, stand-by, …) is measured.
- **Detection of software errors:** After the user application puts the DUT in a certain mode (e.g. sleep mode), the ZVC measures the current of the DUT. Thus it is possible to see whether the correct state was achieved or not.

Accurate time and current measurements are not only essential to optimize the hardwired electronics. They also help software engineers to develop the device software by correlating the measured power consumption to different device activities.

In addition, multiple measurement channels are often required for complex DUTs because the included hardware modules are active at different times. To measure their individual contribution on the total power consumption, multiple measurement channels are beneficial. Multiple channels also enable measuring several signals of different type in parallel. For example, the delay between a decoded serial bus data command (e.g. I²C) between the microprocessor unit and the transponder of the device and the corresponding RF transmission can be correlated to the current consumption in this switch-on period (cf. Figure 2).

This setup combines the capability of an oscilloscope to trigger and decode on serial busses with precise characterization of near-field signals and accurate current measurements.

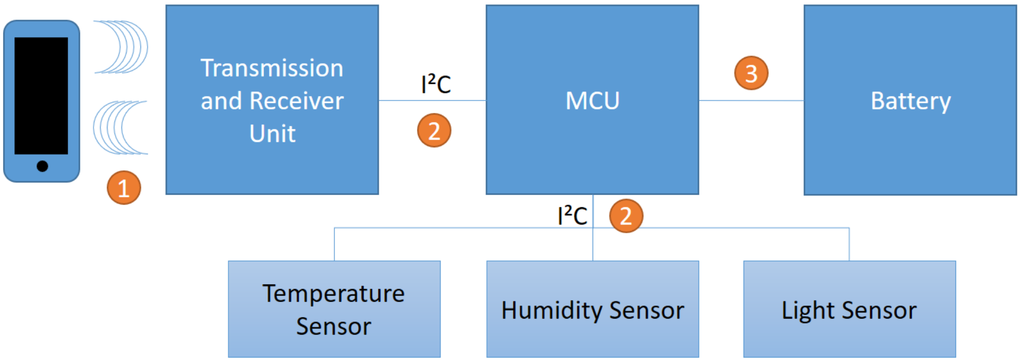

Figure 2 Internal device architecture of a low power DUT with serial buses (here I²C). Near field probes can be used at (1), while serial trigger and decode ability of an oscilloscope becomes handy at (2). Voltage and current are measured at (3).

3 Measurement method and setup

The ZVC current measurement is based on electrical shunts, i.e. the voltage drop over a defined resistor is detected and the current is calculated from Ohm's law. Several key points are significant for this type of measurement as explained below.

3.1 Influence of measurement on DUT

Burden voltage

With a shunt-based measurement an additional resistor is inserted into the DC supply of the DUT. The supply current through the shunt resistor results in a desired voltage drop for the measurement. This so-called burden voltage reduces the supply voltage for the DUT and can affect its function. As long as the burden voltage is small compared to the voltage at the DUT, the functionality will not be affected. Some batteries already have a significant internal resistance (e.g. CR2032 button cells). Adding an additional shunt resistor to such a setup might be neglected then. In addition, IoT devices often contain power control loops which compensate a decreasing battery voltage.

Capacitive loads

Another issue occurs if the DUT exhibits a capacitive load. Inserting a shunt resistor in front of the DUT creates a low pass filter that reduces the measurement bandwidth. Thus, a steep rise time of the current is flattened and buffered on a falling edge. This leads to typical charging and discharging curves of a capacitor (e.g. Figure 3).

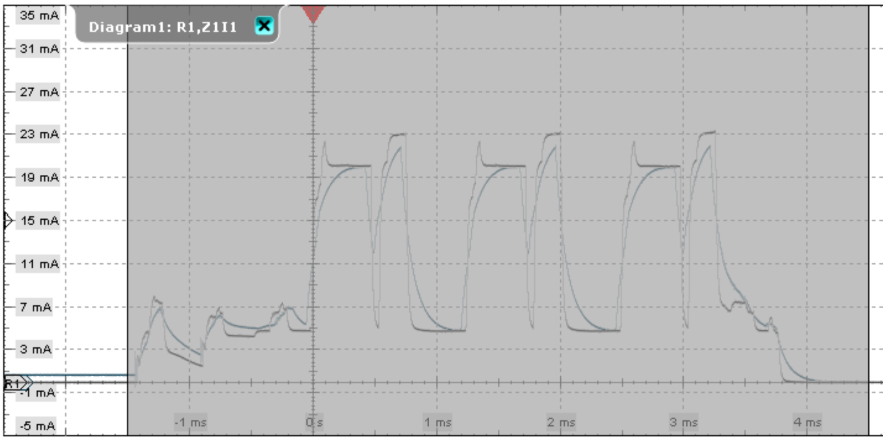

Figure 3 Bluetooth advertising event with 9.4 µF capacitance present and with almost no capacitance present. The two signals are overlaid in the grey area.

As a result, the maximum current is not as high as without a capacitance. In addition, small but fast rising edges are not visible and timing information can get lost. Therefore, it is recommended to reduce the capacitance portion of the DUT when this effect occurs. However, this action may not always be possible. In such a situation, it might also be beneficial to reduce the shunt resistance (e.g. switching to an external shunt resistor) in order to increase the cut-off frequency of the DUT.

3.2 Choosing a shunt resistor

Three different internal shunt resistors are integrated in the ZVC that can be switched by the oscilloscope (10 mΩ, 10 Ω, 10 kΩ). In addition, an external shunt mode is available where the ZVC measures the voltage across an external resistor and the oscilloscope calculates the current automatically. The external shunt mode is recommended for applications with high current since it avoids high voltage drops at the leads and connectors towards the ZVC.

To minimize the burden voltage drop at the additional resistor the relationship between shunt resistor R_S and the DUT's resistance R_{DUT} should fulfill $R_S \ll R_{DUT}$. Other aspects are power rating, temperature stability and the accuracy on the nominal value.

3.3 Location of the ammeter

There are two possibilities for connecting a shunt-based current probe to the DUT. Typically, the ammeter is connected on the high side, i.e. on the supply side. Thus the DUT experiences a real ground and potential short-circuit currents to ground inside the DUT can be detected by the probe (cf. Figure 4 (a)).

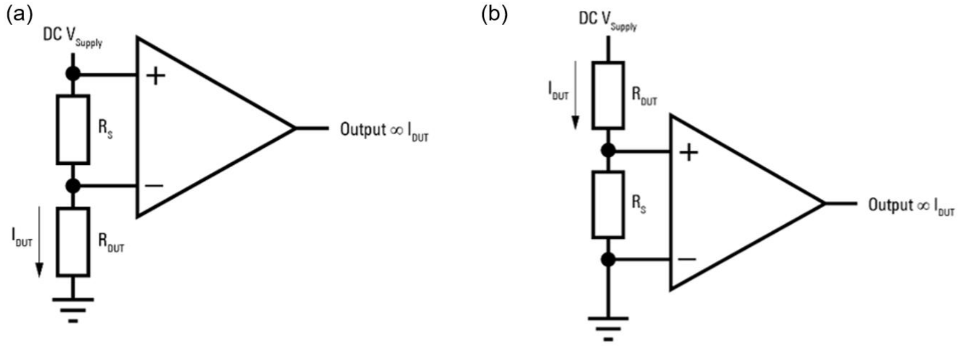

Figure 4 Shunt-based ammeter connected on the supply side of the DUT (high side). (b) Shunt-based ammeter connected on the ground side of the DUT (low side).

However, the positive and minus connectors at the shunt resistor experience a common mode voltage which can be relatively high. This voltage (and the resulting common mode current) is usually suppressed due to the characteristics of the differential amplification but a finite fraction remains present. Especially when measuring very small currents (e.g. in sleep or idle state) the common mode current can become dominant and superimposes the real current. This can lead to a "negative current". Reliable results are only achieved by subtracting the common mode current as follows:

1. Connect one current cable (while using an internal shunt) to the high side measurement point so that the supply voltage is connected to the ammeter.
2. Apply common mode voltage to ammeter:
   a) Leave the other current cable open, the DUT is switched off, or
   b) Shortcut both cables to the supply line, ensure that the DUT is switched off.

3. Measure the mean value of the current and subtract this value via the Math function of the oscilloscope from the current measurements.

Another way of connecting the ammeter is on the low side of the DUT (cf. Figure 4 (b)). In this scenario a common mode current does not appear since one of the ammeter leads is connected to ground. However, the DUT itself does not exhibit a real ground connection anymore. In fact, the burden voltage at the shunt resistor can lift the DUT's ground level quite significantly. In addition, a short circuit current to ground bypassing the shunt resistor cannot be detected and typically there are many ground connection points. These are not easy to open. Even if this is possible, the resulting connection may exhibit a non-sufficient current cross-section.

3.4 Measurement accuracy

Typically, accurate measurement results require a high precision (i.e. low noise) and resolution to resolve smallest details. The ZVC enables high-resolution measurements due to its 18-bit ADC, while an adjustable low pass filter enables lower noise values to increase the precision. The measurement accuracy is mainly determined by the selected measurement range (given by the accuracy of internal amplifiers, offset voltages, etc.).

High currents in an activity phase of the DUT also require a high measurement range. Measuring small idle or sleep currents at the same time is difficult if their magnitude is similar to the accuracy of the ZVC (see Figure 5). The ZVC datasheet specifies the accuracy in detail and should be consulted when a high dynamic range is needed to resolve the smallest currents in a combined measurement of activity and sleep phases.

As a common example, modern DC/DC converters in IoT devices achieve sleep currents in the sub-µA range. The ZVC can use its high resolution in combination with the low-pass filter to achieve minimal noise and evaluate this state.

An external shunt resistor may help by shifting the measurement range for a specific setup ensuring that the measurement accuracy range is used optimally.

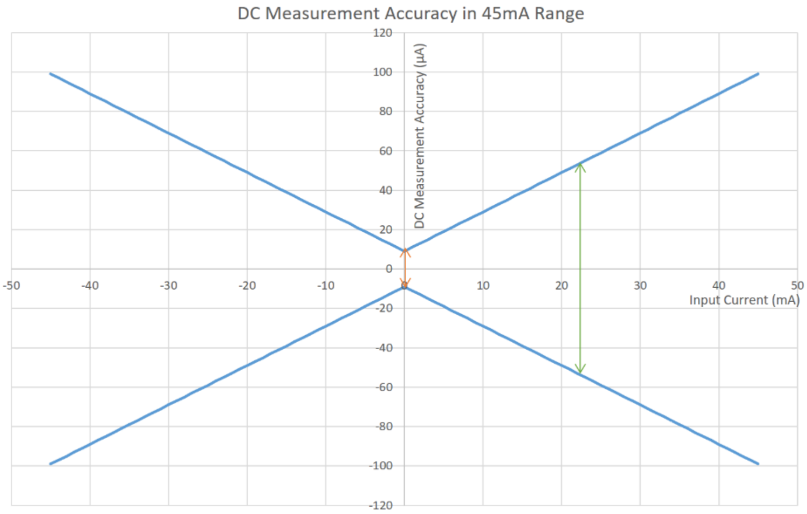

Figure 5 DC measurement accuracy in 45 mA range. A signal of approx. 22 mA (green) exhibits an accuracy of +/- 53 µA (0.21%), whereas a sleep current signal (orange) of a few µA cannot be measured due to accuracy of +/- 9µA (>100%).

4 Verifying power consumption for a Bluetooth Low Energy beacon

4.1 Measurement setup

In this example the power consumption of a Bluetooth Low Energy beacon is analyzed. This device is used as a “smart keychain” to find keys with a smartphone. It is powered by a CR2032 button cell with a capacity of ~220 mAh and a voltage of 3V. The voltage and current at the battery outlets (cf. Figure 6) are measured using solder-in cables. For that purpose, the electric power supply to the Bluetooth device is interrupted (high side measurement) and the device is connected to the I_1 channel of the ZVC for current measurement and to the V_1 channel for voltage measurement. The ZVC communicates via the MSO interface to the oscilloscope[3]. A common measurement potential (GND) is generated via a 4 mm cable (black). In addition, the near field probe R&S®HZ-15 is placed close to the DUT and connected to an analog channel of the oscilloscope to detect the transmitted RF signal of the DUT.

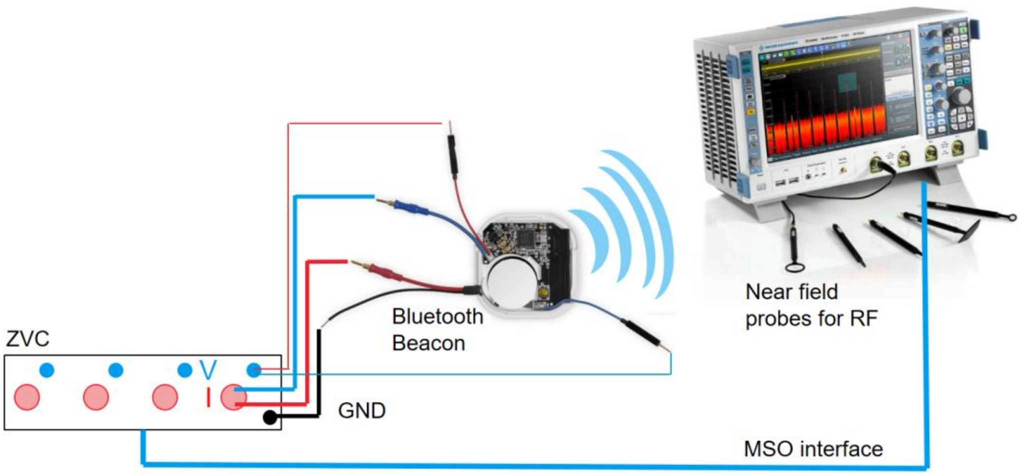

Figure 6 Measurement setup for a Bluetooth Low Energy beacon. The ZVC measures the total current and the voltage at the DUT (incl. GND). The oscilloscope detects the RF transmission on an analog channel and controls the ZVC via the MSO interface.

4.2 Current consumption in static operating modes

Evaluating the exact current draw of the DUT respective its power consumption is one of the first tasks when looking into the operating modes (e.g. sleep, transmit, receive). For these measurements the device is put into the desired operating mode and the respective voltage and current are measured. The oscilloscope calculates the power by

[3] For use with RTE/RTO/RTP oscilloscopes, additionally, the RTx-B1 Mixed Signal Option/RTx-B1E Digital Extension Port is required.

multiplying the current and voltage channels using the built-in Math functions. This calculation also applies to dynamic mode (see section 4.3) as shown in Figure 7 (top). The consumed energy can be displayed using the “Area” measurement on the Math trace (power), as well as the drawn charge from the battery capacity, which is also obtained using the “Area” measurement on the energy Math trace (cf. Figure 7 (bottom)).

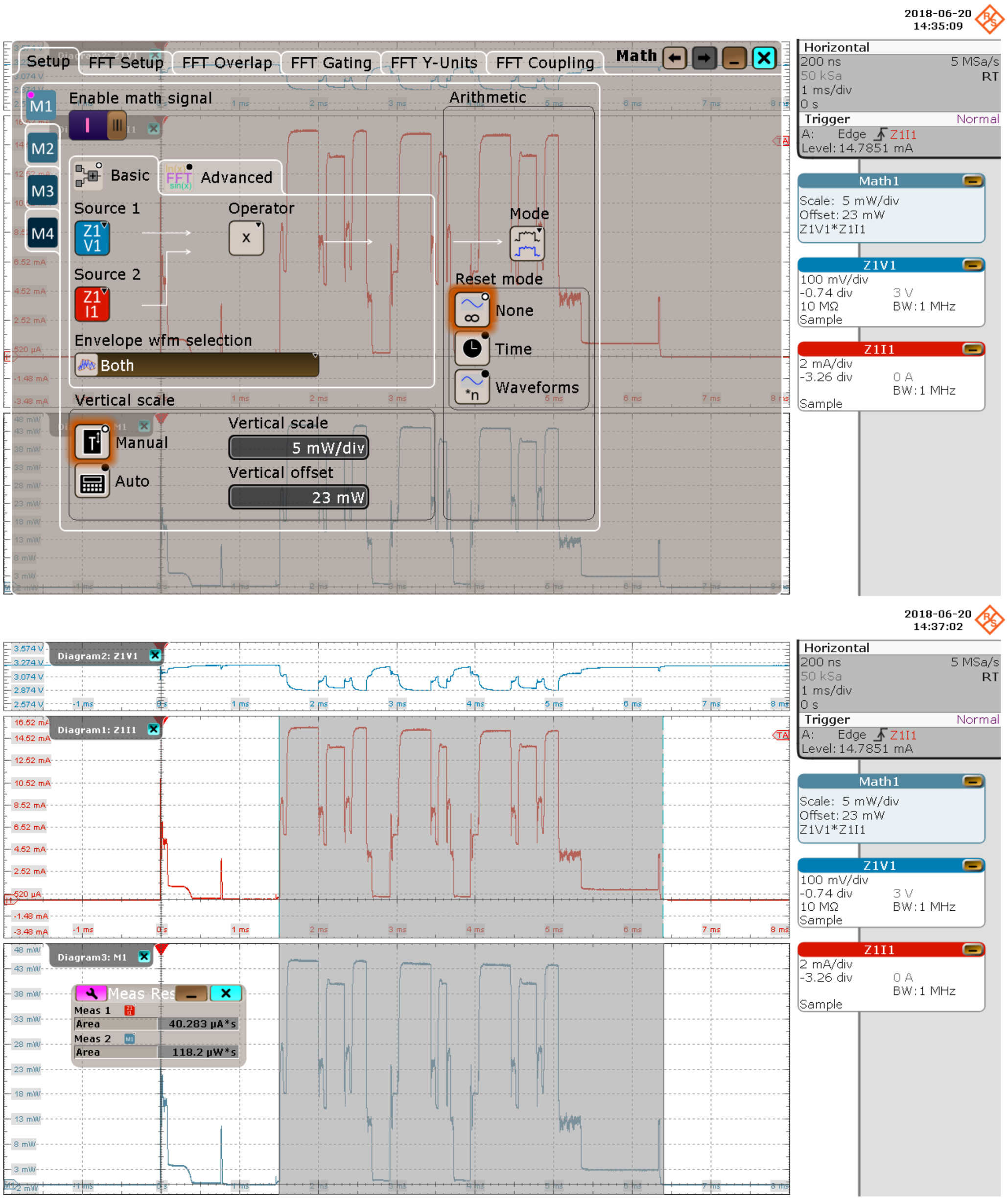

Figure 7 Top: Math mode with multiplication of current and voltage channels. Bottom: Two gated area measurements from power and current equals the energy and charge in three consecutive transmissions from the Bluetooth device.

4.3 Evaluation of dynamic current and power consumption

The high dynamic range of the ZVC also enables measurements when the device switches between its operating modes (cf. Figure 8). The top part shows the voltage at the DUT, followed by the current and the calculated power consumption. Power and current are integrated over the active range (grey area) of the DUT with the “Area” measurement functionality. The bottom graph shows the measured RF signal.

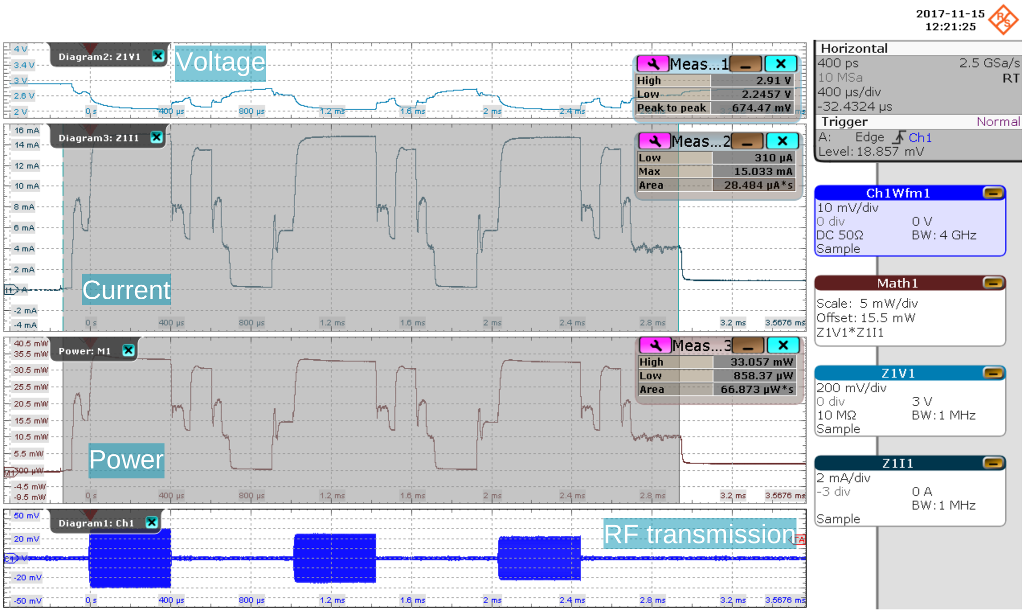

Figure 8 Current and power consumption during device activity determined with gated *Area* measurement functionality on the current and the (mathematical) power channel. The correlated RF signal is also displayed.

The measurement shown in Figure 8 was performed by powering the DUT with a CR2032 button cell and measuring the current with the ZVC’s internal 10 Ω shunt resistor. The burden voltage (shunt plus battery resistance) accounts already for 670 mV (cf. Peak-to-Peak measurement on the top), while the peak current is ~15 mA. Since the battery provides a voltage of about 3 V and the DUT requires a minimum operating voltage of ~2.0 V, this burden voltage is no issue. However, the accuracy of the measurement could be increased by using an external shunt which is not shown here.

4.4 Estimated battery lifetime

The total current consumption of the DUT is achieved by calculating the consumption of the repetitive current profile and extrapolating this result (i.e. current profiling) as shown in the following example. Assumptions:

- Advertise event: Similar to Figure 6 with 40.3 µC in a 4.5 ms time interval.
- Remaining idle duration between advertising event: 95.5 ms with 5 µA current draw, yielding 0.48 µC.
- Every hour the device wakes-up and performs the cycle 33 times.
- In sleep mode, the device draws 2 µA.

The consumed charge is calculated as follows:

$$Q_{100ms} = Q_{advertise} + Q_{idle} = 40.8\ \mu C$$

$$Q_{active} = n \cdot Q_{100ms} = 33 \cdot 40.8\ \mu C = 1.35\ mC$$

$$Q_{sleep} = I_{sleep} \cdot t_{sleep} = 2\ \mu A \cdot (3600\ s - 33 \cdot 100\ ms) = 7.19\ mC$$

$$Q_{1h} = Q_{active} + Q_{sleep} = 8.54\ mC$$

This Q_{1h} pattern would now repeat until the battery runs out of charge, thus dividing the battery charge by the charge of the pattern yields the battery lifetime. In this case, a CR2032 button cell battery with 220 mAh[4] is assumed:

$$n_{life} = \frac{Q_{bat}}{Q_{1h}} = \frac{220mAh}{8.54\ mC} = \frac{220 \cdot 3600\ mC}{8.54\ mC} = 92\ 740$$

$$t_{life} = n_{life} * 1h = 92\ 740\ h \approx 10.59\ a$$

The consumed charge in sleep state (Q_{sleep}) is highly important as shown in the above equations. The active part allocates only ~16% of the total charge consumption and the current in sleep state consumes the majority of charge. Still, in this fictitious example the battery would last more than 10 years.

4.5 Correlating current consumption to hardware and software events

A useful feature of the ZVC in combination with an oscilloscope is the multi-domain analysis capability. The oscilloscope offers advanced analysis but also trigger and decode capabilities. For instance, the oscilloscope could trigger and decode events on an I²C bus and measure the current consumption of the DUT with respect to such events.

Also the FFT function of the oscilloscope[5] is very helpful to understand the impact of RF transmission on power consumption in more detail. In this example, the current in Figure 9 is measured during the transmission of the Bluetooth signal. As can be seen in the figure, the current consumption is at maximum during the RF transmission the Bluetooth device. Using a gated FFT the oscilloscope shows the spectrum on the first and second pulse of the Bluetooth advertising event (cf. Figure 9 and Figure 10).

A cursor on the top of each peak shows the first pulse at 2.4021 GHz while the second pulse exhibits a carrier frequency of 2.4261 GHz, thus the channel hopping difference is 24 MHz.

[4] Note: It may be difficult to draw the maximum amount of charge for which a battery is specified. Often the internal resistance increases strongly at the end of the lifetime of the battery thus reducing the effective charge to e.g. 90% of the specified value in practical applications.

[5] For detailed analysis, the oscilloscope must exhibit enough bandwidth and sample rate to resolve the RF transmission.

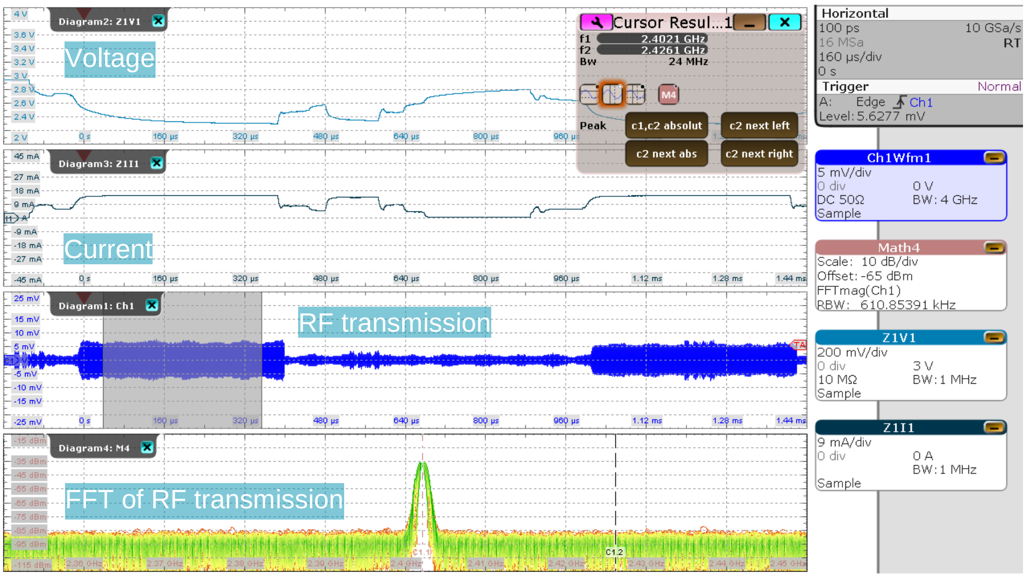

Figure 9 Gated spectrum measurement of Bluetooth frequency and hopping evaluated with near field probe The two consecutive transmissions differ in frequency of 24 MHz (this figure: 2.4021 GHz, next figure: 2.4261 GHz).

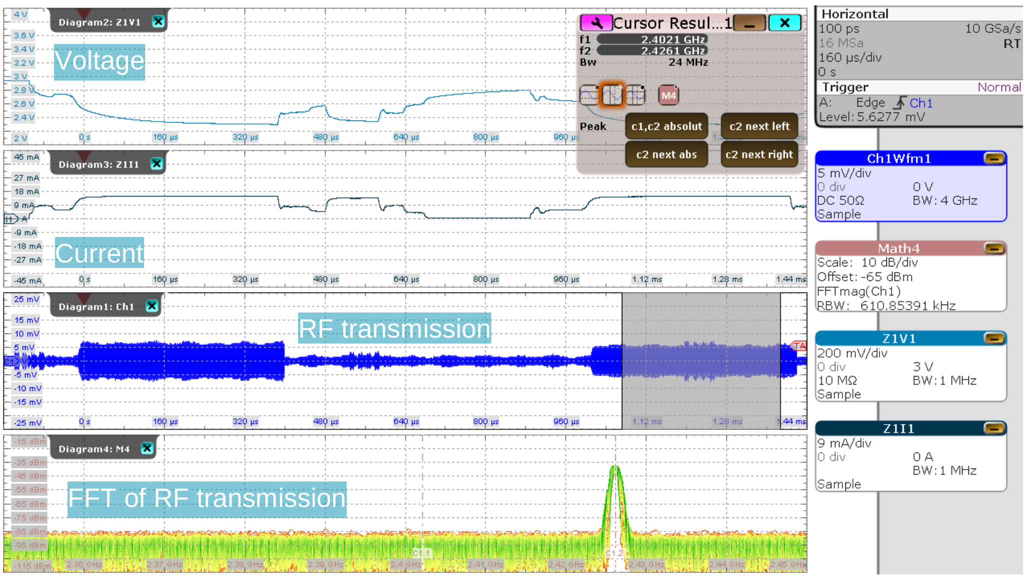

Figure 10 Gated spectrum measurement of Bluetooth frequency and hopping evaluated with near field probe The two consecutive transmissions differ in frequency of 24 MHz (previous figure: 2.4021 GHz, this figure: 2.4261 GHz).

5 Summary

Consumers pay a lot of attention to the battery life of their mobile / IoT device. This parameter is easy to compare and some IoT devices in remote locations often cannot be charged and have to last their whole lifetime with one battery. Therefore optimizing the battery lifetime is key for designing IoT devices. This is done by minimizing its current consumption in all different operation modes (e.g. sleep, transmit, receive).

The ZVC in combination with an oscilloscope offers a solution that provides not only the required high dynamic range for these measurements, it also allows detailed analysis of certain events during operation. The oscilloscope captures these events using its serial trigger and decode capability or via measuring the RF transmission.

As a shunt-based measurement tool, the ZVC exhibits an easy switching of three internal shunts but also offers the use of flexible external shunts to achieve the best match for the application. Shunt-based measurements implicate a burden voltage at the shunt resistor and require careful consideration where to place the resistor inside the DUT circuitry. Regardless of a high side or low side measurement, the battery internal resistance needs to be kept in mind in order to supply sufficient voltage at the DUT level.

Interpreting measurement results of IoT devices is sometimes not trivial and a good approach is to isolate components or have less complex components in the circuit. A good start is always a battery due to its noise performance. A next step would be to use power supplies. If the device is affected by a low pass characteristic then maybe blocking capacitors can be avoided or a lower shunt resistor value be chosen.

Each device and component adds another layer of difficulty but the analysis functions of the oscilloscope, i.e. various measurement and trigger capabilities, Math modes and FFT are an enormous toolkit to look into these effects in detail.

6 Ordering information

Designation	Type	Order number
Oscilloscope RTO		
4 GHz, 20 Gsample/s, 50/200 Msample, 4 channels	R&S®RTO2044	1329.7002.44
Digital Extension Port for R&S®RT-ZVC usage with R&S®RTO oscilloscope, included in R&S®RTO-B1	R&S®RTO-B1E	1333.0738.02
Mixed Signal Option, 400 MHz	R&S®RTO-B1	1326.3558.02
Oscilloscope RTE		
200 MHz, 5 Gsample/s, 10/40 Msample, 4 channels	R&S®RTE1024	1326.2000.24
Digital Extension Port for R&S®RT-ZVCxx usage with R&S®RTE oscilloscope, included in R&S®RTE-B1	R&S®RTE-B1E	1333.0750.02
Mixed Signal Option, 400 MHz, 5 Gsample/s, 16 channels, 100 Msample/channel	R&S®RTE-B1	1326.3570.02
ZVC Multi-Channel Power Probe and additional accessories		
Multi-Channel Power Probe, 2 × 4 voltage/current channels, for R&S®RTO2000/R&S®RTE	R&S®RT-ZVC04	1326.0259.04
Multi-Channel Power Probe, 2 × 2 voltage/current channels, for R&S®RTO2000/R&S®RTE	R&S®RT-ZVC02	1326.0259.02
Multi-Channel Power Probe, 2 × 4 voltage/current channels, for R&S®CMWrun	R&S®RT-ZVC04	1326.0259.24
Multi-Channel Power Probe, 2 × 2 voltage/current channels, for R&S®CMWrun	R&S®RT-ZVC02	1326.0259.22
Extended Cable Set for R&S®RT-ZVC, PCB probing, 1 current and voltage lead, length: 32 cm	R&S®RT-ZA30	1333.1686.02
Extended Cable Set for R&S®RT-ZVC, 4 mm probing, 1 current and voltage lead, length: 32 cm	R&S®RT-ZA31	1333.1692.02
Oscilloscope Interface Cable for R&S®RT-ZVC (included in R&S®RT-ZVC02/-ZVC04, 1326.0259.02/.04)	R&S®RT-ZA33	1333.1770.02
Extended Cable Set for R&S®RT-ZVC, 4 mm probing, 1 current and voltage lead, length: 1 m	R&S®RT-ZA34	1333.1892.02
Extended Cable Set for R&S®RT-ZVC, PCB probing, 1 current and voltage lead, length: 1 m	R&S®RT-ZA35	1333.1905.02
Solder-in Cable Set for R&S®RT-ZVC, 4 current and voltage solder-in cables, solder-in pins	R&S®RT-ZA36	1333.1911.02
Extended Cable Set for R&S®RT-ZVC, BNC connector, 1 current and voltage lead, length: 16 cm	R&S®RT-ZA37	1337.9130.02

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Rohde & Schwarz is an independent group of companies specializing in electronics. It is a leading supplier of solutions in the fields of test and measurement, broadcasting, radiomonitoring and radiolocation, as well as secure communications. Established more than 75 years ago, Rohde & Schwarz has a global presence and a dedicated service network in over 70 countries. Company headquarters are in Munich, Germany.

Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1-888-TEST-RSA (1-888-837-8772)
customer.support@rsa.rohde-schwarz.com

Latin America
+1-410-910-7988
customersupport.la@rohde-schwarz.com

Asia/Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86-800-810-8228 /+86-400-650-5896
customersupport.china@rohde-schwarz.com

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Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | D - 81671 München
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com

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