Battery Life Optimization in IoT devices with the Multi-Channel Power Probe R&S®RT-ZVC02/04(A)

Application Note

Products:

- R&S®RT-ZVC02/04(A)
- R&S®RTP
- R&S®RTO2000
- R&S®RTE1000
- R&S® CMW290

This application note describes Battery Life Measurements with the R&S®RT-ZVC02/04(A) Multi-Channel Probe. The measurements are described mostly with the use of an oscilloscope; however, measurements are also possible with CMWRun and a corresponding communication tester.

Note:

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

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

Application Note

Dr. Andreas Ritter, Markus Reil

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1 Introduction

Battery life is a key consideration for mobile phones, Internet-of-Things (IoT) devices and any other device, which falls under the category of so-called “Wearables”.

Every one of us can relate to the feeling when the smartphone battery is running low and a charging station is nowhere in sight. Consumers pay a lot of attention to the aspect of battery life, because it is such an important criteria and easily to compare between different devices of a certain category.

For these devices with an “anytime and anywhere” expectation, the battery life and therefore energy consumption is perhaps one of the most important aspects for consumers.

In order to keep energy consumption as low as possible, these devices work typically with special sleep modes where power consumption is very low and do only have very short activity phases with normal or high power consumption.

To accurately measure the power consumption, probing solutions are required which measure very small currents in the µA or even nA range at the same time as currents which can go 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). The R&S®RT-ZVC02/04 offers measurement ranges from 4.5 µA up to 10 A and can resolve smallest details in this ranges with its 18-bit ADC. For a full view of the dynamic range, the R&S®RT-ZVC02A/04A[1] offers automatic gain switching, allowing a nearly seamless view on a current over several measurement ranges.

In the following, the R&S®RT-ZVC02/04(A) probing solution is presented as well as typical challenges one can encounter in measuring battery life of low power consumption devices. 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[2]. CMWRun offers long-term acquisition of data and correlation to signaling events. In addition, the battery life is directly estimated in 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 in principle, a universal toolkit for signal investigations.

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[1] R&S®RT-ZVC02A/04A is currently compatible only with CMWRun.

[2] The use of the R&S®RT-ZVC in combination with CMWRun and R&S®CMW500 for IoT power consumption measurements is described in another Application Note: “*IoT Power Consumption Measurement - 1MA281*”. In there, the described setup enables the user 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 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 most of the time in sleep mode and activate it only for very short activity phases. The longer a device can stay in sleep mode, the longer the battery will last. This makes the sleep-mode current, and thus energy consumption during this mode as well as in an activity phase important factors for the achievable battery life.

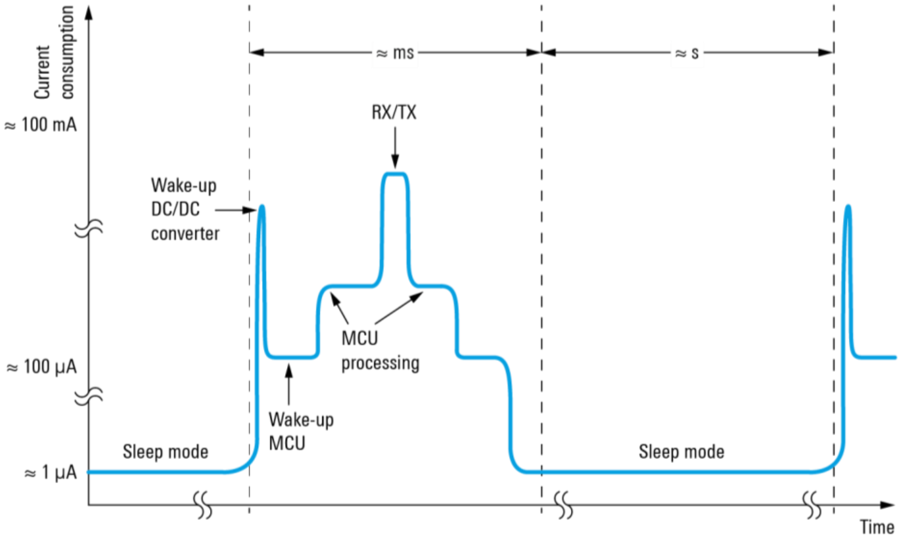

Figure 1 Typical current consumption profile of an IoT module. Long sleep-mode periods with very low current consumption are interrupted by short periods of activity in which the microcontroller unit (MCU) processes data.

Figure 1 shows a typical current consumption profile of an IoT device. The duration of the sleep-mode phases is often in the range of seconds with sleep mode currents in the low µA range and may last often considerably longer. In the activity phase, current can peak to levels as high as 100 mA, but usually there are activity intervals with different current consumption levels.

In order to evaluate battery life, it is important to cover both very low sleep mode currents as well as currents during the activity phase. With the R&S®RT-ZVC02/04 probing solution the range of the R&S®RTE1000, R&S®RTO2000 or R&S®RTP oscilloscope (in the following just named as ZVC, ZVCA, or RTO/RTE/RTP) is extended by each 2x (RT-ZVC02) or each 4x (RT-ZVC04) voltage and shunt based current channels controlled via the MSO[3] interface of the oscilloscope.

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[3] Mixed Signal Option

The ZVC offers a high dynamic range and an 18-bit ADC converter. This dynamic range is effectively increased with the ZVCA due to automatic gain switching. Thus, measurements from the lowest to the highest gain factor can be easily performed.

Typical use case are:

- Detection of software errors. The application in question 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 this state was achieved.
- A further possibility of the former is to perform a full current profiling, i.e. to evaluate the time the device is spending in a certain mode and also measure the current consumption of the various modes (e.g. wake-up, sleep, stand-by, …) when the device is put into these modes.

Examples, which highlight these topics, can found in section 4.1 (ZVC with oscilloscope) and in section 4.2 (ZVCA in combination with CMWRun).

Accurate time and current measurements allow not only optimizing the hardwired electronics but also enables software engineers to further optimize the software code of the device by correlating the measured power to different device activities.

In addition, multiple measurement channels are often required because in complex products different modules of the electronic circuit are activated at defined different times. It is e.g. possible to trigger onto the decoded serial bus data command (e.g. I²C) between the microprocessor unit and the transponder of the device and measure the delay until the RF transmission (cf. Figure 2) of the device starts, or to measure the current consumption in this switch-on period.

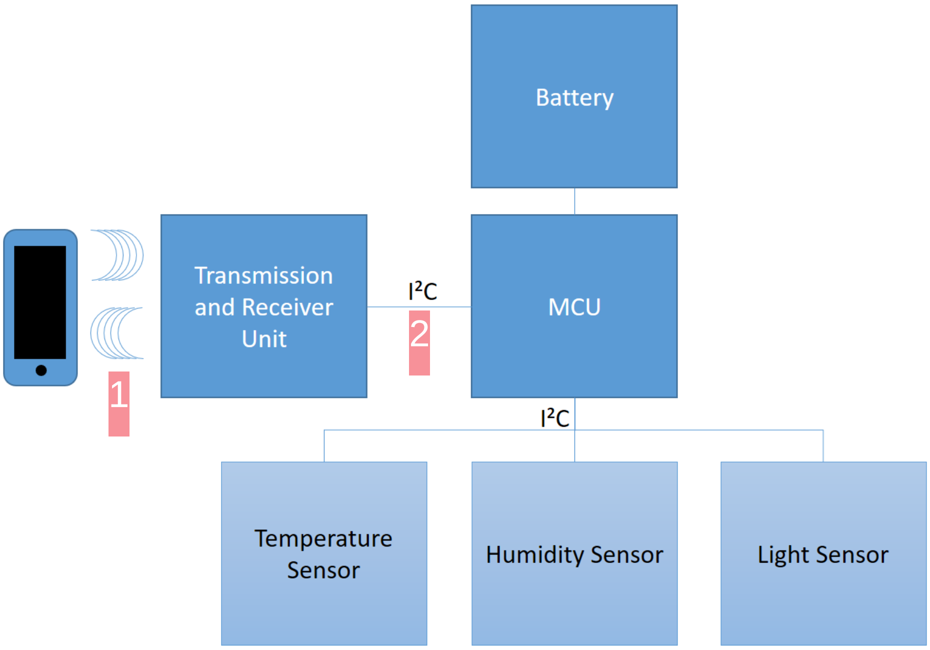

Figure 2 Internal device architecture of a low power DUT with serial buses (here I²C). Near field probes can be used at (1), while serial trigger and decode ability of an oscilloscope becomes handy at (2).

In such a setup, the serial trigger and decode capabilities of an oscilloscope combine precise triggers on signals detected with a near field probe with accurate current measurements.

3 Considerations for current measurements with the RT-ZVC(A) Probing Solution

3.1 Preparing the DUT

Depending on the DUT, the access to key components can vary a lot. For a rather simple current/voltage measurement, the battery compartment of a device allows usually easy access. In addition, for external powered devices (e.g. power supplied via USB cable) adapters come in handy to attach banana plugs in order to probe in between of the supplying cable.

As the ZVC exhibits shunt based current measurements, one needs to consider whether to perform a high-side or low-side measurement with a shunt (cf. section 3.6 for details). An example of measuring a real DUT is given in section 4.1.

The following sections deal with different types of supply voltages for the DUT, considerations when dealing with shunt based measurements, and internal DUT effects such as battery resistance and power control loops.

3.2 Noise and DC accuracy

3.2.1 DC Accuracy

Typically, a measurement exhibits several basic requirements. Amongst them are high accuracy with a sufficient resolution and low noise to resolve smallest details. The ZVC enables high-resolution measurements due to its 18-bit ADC, while an adjustable low pass filter enables even lower noise values.

Range	Resolution	DC Accuracy	Noise	Noise
			(RMS at 1 MHz BW)	*(RMS at 5 kHz BW)*
4.5 µA	38 pA	900.0 pA	2.00 nA	160.0 pA
45.0 µA	380 pA	9.0 nA	6.00 nA	420.0 pA

Table 1 Measured noise at two different bandwidths and two current ranges of the ZVC Multi-Channel Probe. Note that the noise can be below DC accuracy.

The bandwidth of the ZVC current channels can be reduced in 5 kHz steps for selecting the appropriate bandwidth to filter the noise. Table 1 exemplary summarizes the noise at full (1 MHz) and at minimum (5 kHz) bandwidth of the ZVC. As Table 1 shows, the offset error (cf. DC accuracy in data sheet)[4] of the measurement range is in such cases

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[4] Error depending on the selected measurement range; more details can be found in the corresponding data sheet. In addition, the ZVC must be warmed-up for 30 minutes to achieve specified values.

even higher than the noise. This needs to be kept in mind, as a reduction of the bandwidth will not increase the overall accuracy beyond this level.

In addition, this puts also constraints when interpreting the available resolution. At the smallest bandwidth, the resolution is similar to the noise at that measurement range.

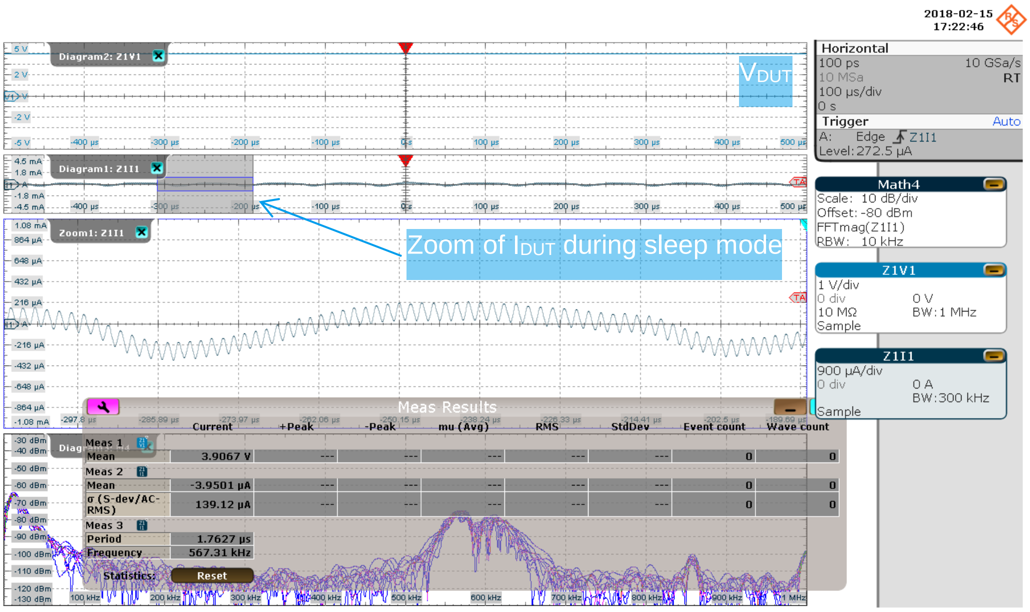
3.2.2 Selecting the right power supply

A stable and noiseless power supply voltage is important when measuring very low currents. The following two examples highlight this requirement.

On-chip DC-DC converter

A typical DUT laboratory setup may consist of the actual DUT, e.g. a low power device with nearly everything contained in one chip. This chip is then connected to a PCB with some power connectors. Power may be transferred via an external power adapter, e.g. $230V_{AC}$ to $12V_{DC}$. A DC-DC regulator is mounted on the board itself for converting the intermediate 12V to a typical voltage of 3.8V for the DUT.

When measuring a sleep current in such a setup, the current may look like as shown in Figure 3. The expected small DC current is highly superimposed by noise.



Horizontal
100 ps 10 GSa/s
10 MSa RT
100 µs/div
0 s
Trigger Auto
A: Edge Z1I1
Level: 272.5 µA

Math4
Scale: 10 dB/div
Offset: -80 dBm
FFTmag(Z1I1)
RBW: 10 kHz

Z1V1
1 V/div
0 div 0 V
10 MΩ BW: 1 MHz
Sample

Z1I1
900 µA/div
0 div 0 A
BW: 300 kHz
Sample

Meas Results

	Current	+Peak	-Peak	mu (Avg)	RMS	StdDev	Event count	Wave count
Meas 1								
Mean	3.9067 V	---	---	---	---	---	0	0
Meas 2								
Mean	-3.9501 µA	---	---	---	---	---	0	0
σ (S-dev/AC-RMS)	139.12 µA	---	---	---	---	---	0	0
Meas 3								
Period	1.7627 µs							
Frequency	567.31 kHz							

Figure 3 Oscillation of approx. 800 $\mu A_{peak\text{-}peak}$. Expected current is ~3µA, however, it is superimposed by oscillations.

A spectrum of this waveform reveals distinct frequencies, e.g. a slow varying 12.5 kHz and a faster oscillation of ~600 kHz. As these frequencies do not originate from the ZVC current probe, the noise must originate from the DUT or the evaluation board itself.

In order to minimize this example the focus is set on the slow varying oscillation. It is isolated using an RTO and a R&S®RT-ZPR20 power rail probe and adjustable low pass filters inside the oscilloscope to limit the bandwidth to isolate the lower 12.5 kHz.

This revealed a very small ripple on the DC supply voltage after the regulator (cf. Figure 4). Such small voltage ripples, i.e. 5mV$_{PP}$ on top of a 3.907 V$_{DC}$, can hardly be seen without exhibiting the correct measurement tools. However, even these small ripples may affect a measurement and show up as oscillations in a (small) current as can be seen in Figure 3.

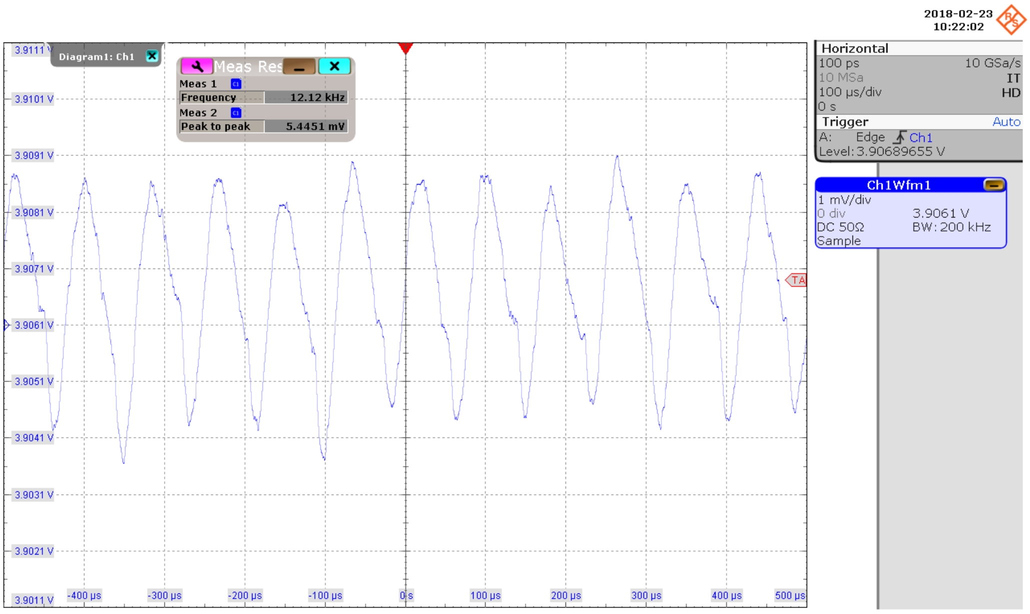


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Diagram1: Ch1

Meas Res

Meas 1 Frequency 12.12 kHz

Meas 2 Peak to peak 5.4451 mV

Horizontal
100 ps 10 GSa/s
10 MSa IT
100 µs/div HD
0 s

Trigger Auto
A: Edge Ch1
Level: 3.90689655 V

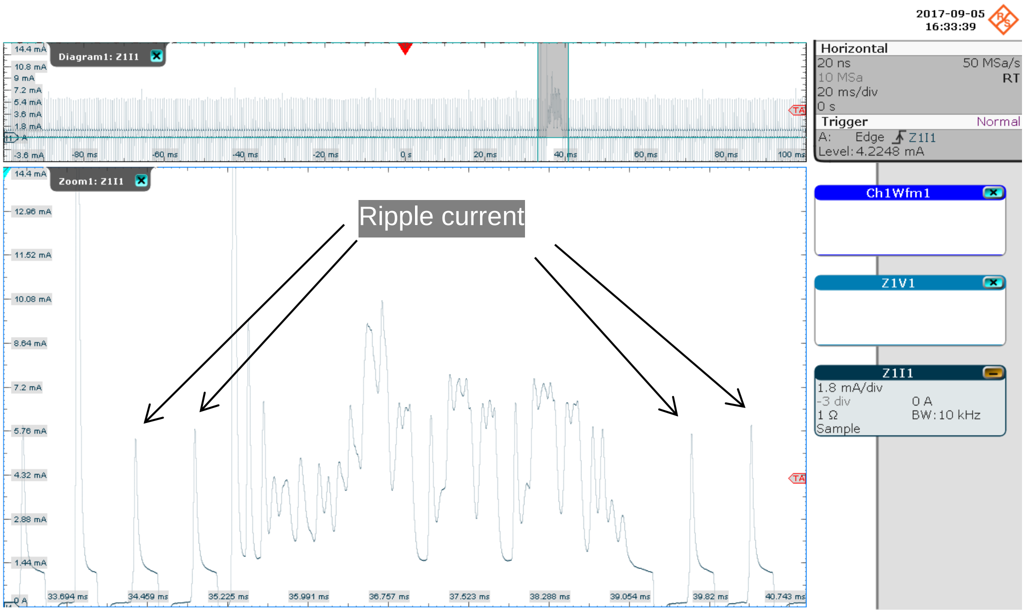
Ch1Wfm1
1 mV/div
0 div 3.9061 V
DC 50Ω BW: 200 kHz
Sample

Figure 4 12.5 kHz oscillation on the supply lines of an evaluation board measured with a dedicated RT-ZPR20 power rail probe. Higher frequency oscillations are filtered out.

It is therefore recommended that for high accurate measurements a battery powered setup be used as this avoids noise on the voltage supply lines. Ideally, evaluation boards already have the possibility to bypass on-board voltage regulators and allow an easy battery access. Good results can also be achieved by using old-fashioned analog low-noise power supply devices and high-performance SMUs with ultra-low noise and fast recovery times.

Switched-mode laboratory power supplies

A problem that can occur in switched-mode power supplies are spikes or ripples on the supply voltage especially when only a marginal current (from the point of view of the power supply) is consumed. That is why one has to evaluate the voltage supply lines when using benchtop power supplies. This is always recommended when observing ripple and other oscillations in current and voltage measurement at the DUT probing point. An example of spikes originating from a benchtop power supply is shown in Figure 5.



Horizontal
20 ns 50 MSa/s
10 MSa RT
20 ms/div
0 s
Trigger Normal
A: Edge Z1I1
Level: 4.2248 mA

Z1I1
1.8 mA/div
-3 div 0 A
1 Ω BW: 10 kHz
Sample

Figure 5 Ripple on small currents introduced by a non-suitable power supply.

3.3 Selection criteria for shunt resistors

With the ZVC as a shunt based measurement device, it is important to consider a suitable value for the shunt resistor to limit the burden voltage but keeping a good signal-to-noise ratio for the measurement.

3.3.1 Internal vs. external shunt resistors

Three different internal shunt resistors are available in the ZVC that can be easily switched by the software (ZVCA offers additionally automatic gain switching):

ZVC	ZVCA
10 mΩ	50 mΩ
10 Ω	200 mΩ
10 kΩ	1 Ω

Another possibility is to select an external shunt resistor and use its value for the current channel. The ZVC acts then as a voltmeter over this resistor. The value of the external resistor can be set in the software and the current is calculated automatically.

Each option, internal vs. external, offers advantages and disadvantages. A short overview is shown in Table 2.

Internal Shunt	External Shunt
3 resistance values integrated and easily switchable for automated testing.	Resistance can be chosen freely. This allows optimizing the shunt with respect to measurement range.
Resistors exhibit very high accuracy and a low temperature coefficient (cf. details in corresponding data sheet).	Resistors with highest accuracy/low temperature coefficient are expensive and not easy to obtain.
Resistors are calibrated in the factory to provide a high absolute accuracy.	A sophisticated calibration or two-resistor-measurement is needed to obtain a comparable accuracy.
User friendly switching of values.	Usually soldered into circuit, no easy exchange.
Not recommended in high current applications (voltage drop at leads).	Recommended for high current applications.

Table 2 Selection criteria for internal vs. external shunt resistors.

The most important aspect for shunt based current measurements is the relationship between shunt resistor R_S and the DUT's resistance R_{DUT}, which should fulfill $R_S \ll R_{DUT}$ for minimizing the burden voltage drop at the additional resistor. Other aspects are power rating, temperature stability, and the accuracy on the nominal value.

It is recommended to use an external shunt resistor for high current applications. An example shall highlight this topic: In high current applications, the internal resistor is set to 10 mΩ. When using such low resistance values it is important to keep the resistance of connectors and leads in mind as the burden voltage might be considerably higher than expected. The shipped AWG20 cable exhibits the length dependent resistance of $\rho(l) = \left(41 + 0.33 \cdot {}^{l}/_{cm}\right) m\Omega$. This adds 87 mΩ in the standard length configuration (l=8cm; $R_{con} = 2 \cdot \rho(8cm)$). Thus, the burden voltage is actually 10x higher than expected (10 mΩ vs. 97 mΩ).

In such a scenario, an external shunt resistor is a better choice as, due to the high input impedance of 10 MΩ of the measuring voltmeter, the contact and transfer resistance is negligible (cf. Figure 6).

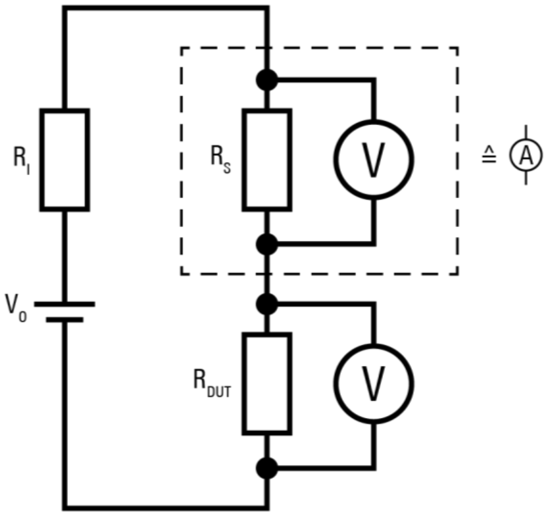


Figure 6 Measurement setup with external shunt resistor R_S. The shunt resistor R_S in combination with a voltmeter acts as the ammeter. The battery exhibits an internal resistance R_I and needs to be taken into account for the total burden voltage.

3.3.2 Selecting a shunt resistance value

In order to perform a good measurement, two contradicting requirements need to be fulfilled:

1. The ratio of ${}^{R_S}/_{R_{DUT}} \ll 1$ to limit the burden voltage; on the other hand,
2. The higher the burden voltage, the higher the signal-to-noise ratio.

An initial hint of the resistance of the DUT when selecting the shunt resistor for the measurement is to apply the ZVC with its internal resistors and determine the active current of the device as this is usually the state where most of the current is consumed. The resistance can then be estimated from this measurement; however, as the DUT usually includes active components, this can only be a hint for the DUT’s resistance.

When deciding for a shunt resistor one can either rely on a rule of thumb (e.g. 1% of R_{DUT}) or calculate the shunt resistor in accordance with the maximum tolerable voltage drop before the DUT itself.

3.4 Internal resistance of batteries and battery capacity

To the aforementioned discussion about choosing the appropriate shunt resistor, one parameter is still missing, i.e. the internal resistor of the power supply R_i. In terms of noise, one of the best power supplies is actually a battery as this provides a clean current and avoids additional effects such as ground loops, noise from mains voltage etc.

However, choosing a battery with a low internal resistance is actually a challenging task by itself. Considering the CR2032 button cell battery from the example in section 4.1. Even though the battery is specified with 220 mAh, a considerable voltage drop is expected to take place beyond ~180 mAh of consumed charge. The internal resistance is quite stable up to this value, changing from 18 Ω to 25 Ω. However, beyond 180 mAh, the internal resistance increases steeply.

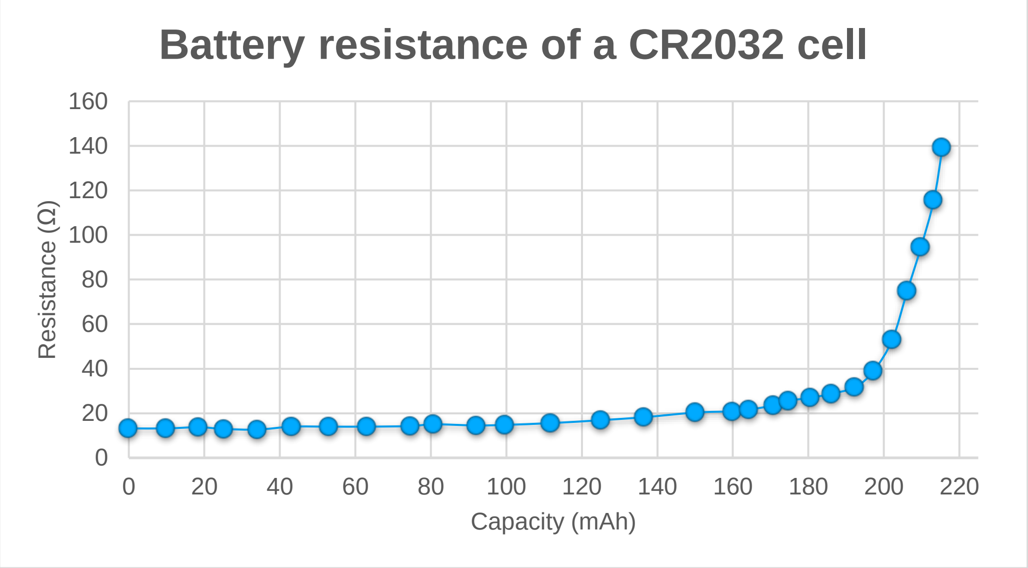


Figure 7 Example of the internal resistance of a button cell battery.

The following example shall highlight the charge dependent resistance of a battery: First of all the battery CR2032 is specified to exhibit ~220 mAh of charge and supplies 3 V. Further, assume that during high activity phase of a processor the circuit draws 15 mA ± 2 mA of current.

This will lead to a voltage drop at the internal resistance of 0.3 V ± 0.04 V during normal battery capacity ($R_i \approx 20\ \Omega$). This poses still no threat if the processor is able to run at 2.0 V. Near the end of the battery life the internal resistance increases steeply and at a consumed charge of 200 mAh the resistance is already 45 Ω. This leads to a burden voltage of ~0.68 V ± 0.09 V. This might seem still be ok, but due to the high amount of produced units in IoT applications a safety margin of 3 standard deviations (≈99.7%) is already close to the limit of 2.0 V ($V_{DUT} = 3.0\ V - (0.68\ V + 3 \cdot 0.09\ V = 2.05\ V$). This example highlights that only 90% of the battery charge can be consumed safely.

In general, when evaluating current on a shunt based measurement the resistance of the power supplies, and especially of batteries, needs to be kept in mind. The burden voltage must not be increased beyond a point as to which the DUT is not working properly anymore.

3.5 Internal DUT effects

Internal power control loops are another aspect when interpreting measurement results. The main task of a power control loop inside a DUT is to deliver a steady power to the device components. This can result in a contra-intuitive effect that when choosing a smaller shunt resistor the consumed current goes down. The equivalent circuit is shown in Figure 8.

The constant power is represented by:

$$P \sim const = V_{DUT} \cdot I = (V_0 - V_{Ri} - V_{RS}) \cdot I$$

Due to the now lower shunt resistor R_S, the burden voltage V_{Rs} at this point is decreased as well leading to a higher voltage at the DUT. In order to deliver a constant power to the device components a smaller current is regulated by the control loop.

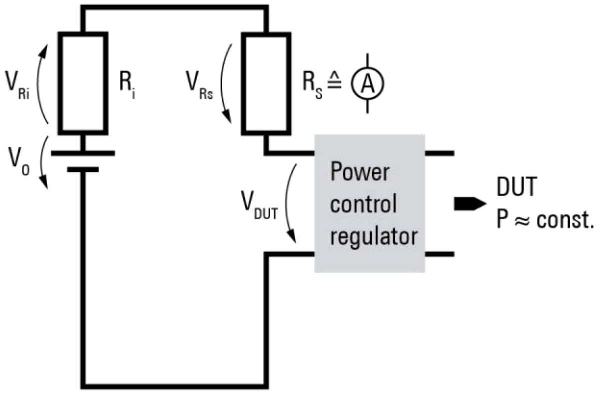


Figure 8 Schematic of a measurement setup with a power regulated DUT.

This effect is opposite to a pure resistive load (cf. e.g. Figure 6). In such a setup, the current would increase as the total resistance is lowered.

3.6 Offset errors due to measurement setup

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. This has the benefit that the DUT experiences a real ground and potentially short-circuit currents to ground inside the DUT can be detected by the probe (cf. Figure 9 for details).

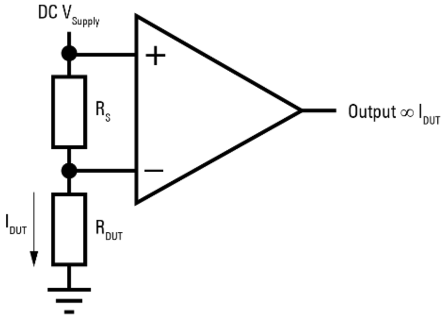


Figure 9 Shunt-base ammeter connected on the supply side of the DUT.

As a drawback, the positive and minus connector at the shunt resistor experience a potentially high common mode voltage. This voltage (and resulting thereof the common mode current) is usually suppressed but a finite level remains. 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 could lead to an effect of "negative current", which seems to charge the battery instead of vice versa. A user-defined subtraction of the common mode current may need to be performed in order to get reliable results.

1. Connect one current cable 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 mode from the current measurements. In CMWRun, the zero offset current can be defined directly in the GUI (cf. section 4.2 for more details)
4. Connect ammeter correctly to the DUT. The DUT is now powered and the ammeter connected.

Another way of connecting the ammeter is on the low side of the DUT (cf. Figure 10). The aforementioned issue of common mode current does not happen in this scenario as one of the ammeter leads are connected to ground. However, the DUT itself does not exhibit a real ground anymore, and 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, and even if this is possible, the resulting connection may exhibit a non-sufficient current cross-section.

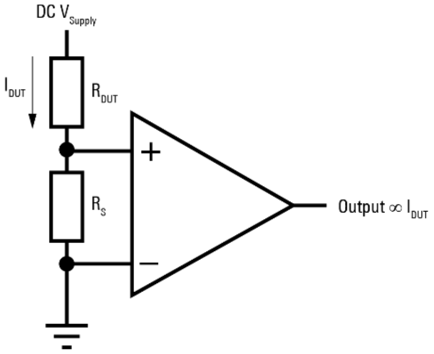


Figure 10 Shunt-base ammeter connected on the ground side of the DUT.

3.7 Capacitive loads

If the resistance of the DUT exhibits a capacitive portion, the resulting waveform may look at first unexpected. However, the waveform is correctly measured as the shunt resistance in combination with the capacitive DUT acts as a low pass filter.

The resulting measurement bandwidth is then given by a combination of the original probe (e.g. ZVC with 1 MHz bandwidth) and the DUT, which now exhibits a certain cut-off frequency. This bandwidth can be estimated using:

$$f_{BWeff} = \frac{1}{\sqrt{\left[\left(\frac{1}{f_{BWprobe}}\right)^2 + \left(\frac{1}{f_{BWDUT}}\right)^2\right]}}$$

A current measurement of a Bluetooth advertising event is used to demonstrate this effect. At first, many capacitors were present on the DUT and the resulting waveform showed the typical charging curves of capacitors. The capacitors were de-soldered to get a “pure” test board and a capacitance of 9.4 µF is now connected via a switch. When the capacitance is switched on, the cut-off frequency of the DUT is given (shunt resistance of 10Ω) by $f_c = \frac{1}{2\pi RC} = 1.69kHz$. The combination of 1 MHz and 1.69 kHz results in a domination of the measurement setup by the DUT’s low pass filter.

The measured current profile without capacitance is shown in Figure 11. The measured charge (via $Q = \int I(t)dt$, i.e. “Area” measurement function used) is averaged over 33 waveforms and results in 59.4 µC.

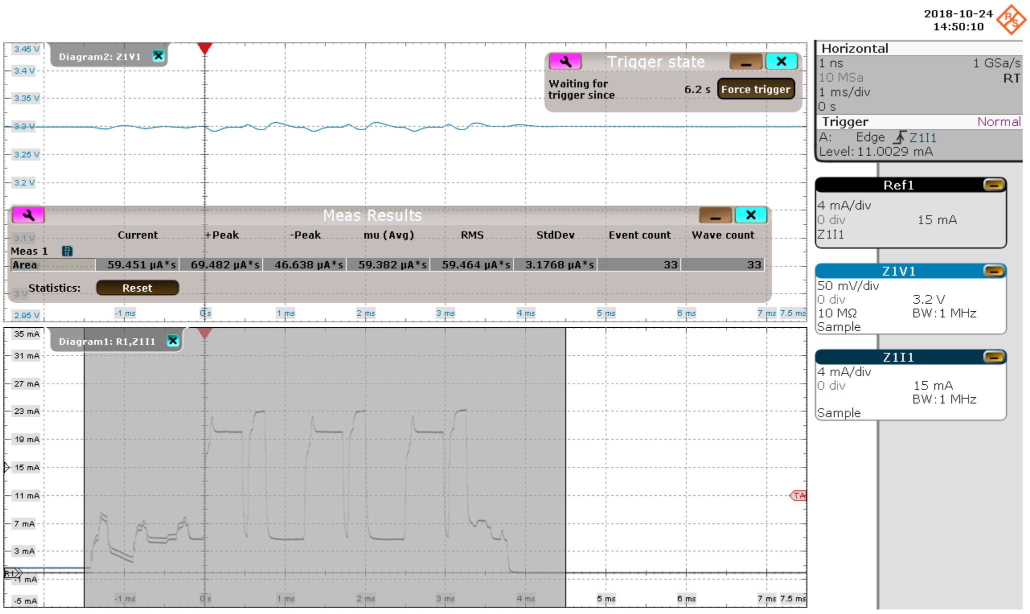


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Diagram2: Z1V1

Trigger state
Waiting for trigger since 6.2 s

Meas Results

	Current	+Peak	-Peak	mu (Avg)	RMS	StdDev	Event count	Wave count
Meas 1								
Area	59.451 µA*s	69.482 µA*s	46.638 µA*s	59.382 µA*s	59.464 µA*s	3.1768 µA*s	33	33

Statistics: Reset

Diagram1: R1,Z1I1

Horizontal
1 ns 1 GSa/s
10 MSa RT
1 ms/div
0 s

Trigger Normal
A: Edge Z1I1
Level: 11.0029 mA

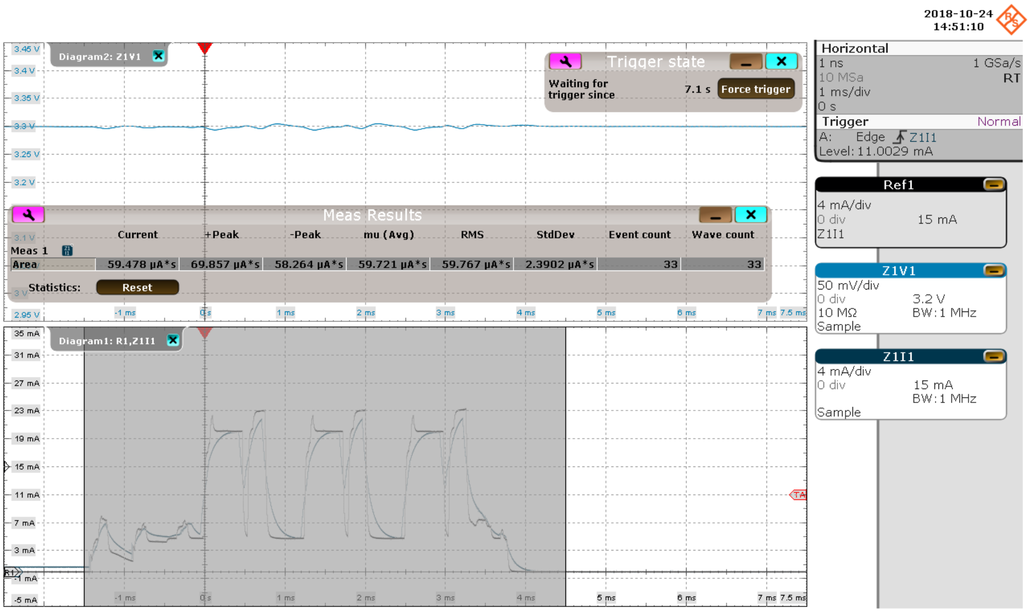
Ref1
4 mA/div
0 div 15 mA
Z1I1

Z1V1
50 mV/div
0 div 3.2 V
10 MΩ BW: 1 MHz
Sample

Z1I1
4 mA/div
0 div 15 mA
BW: 1 MHz
Sample

Figure 11 Bluetooth advertising event with only marginal capacitance present. The current waveform is also stored as a reference waveform.

As a comparison, the capacitance is switched backed, the waveform is shown in Figure 12. The charging characteristic is clearly visible in comparison to a reference waveform from a “pure” advertising event.



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14:51:10

Diagram2: Z1V1

Trigger state
Waiting for trigger since 7.1 s

Meas Results

	Current	+Peak	-Peak	mu (Avg)	RMS	StdDev	Event count	Wave count
Meas 1								
Area	59.478 µA*s	69.857 µA*s	58.264 µA*s	59.721 µA*s	59.767 µA*s	2.3902 µA*s	33	33

Statistics: Reset

Diagram1: R1,Z1I1

Horizontal
1 ns 1 GSa/s
10 MSa RT
1 ms/div
0 s

Trigger Normal
A: Edge Z1I1
Level: 11.0029 mA

Ref1
4 mA/div
0 div 15 mA
Z1I1

Z1V1
50 mV/div
0 div 3.2 V
10 MΩ BW: 1 MHz
Sample

Z1I1
4 mA/div
0 div 15 mA
BW: 1 MHz
Sample

Figure 12 Bluetooth advertising event with 9.4 µF capacitance present.

The now measured charge consumption is 59.7 µC, which differs only by 0.5% from the pure waveform. Due to charge conservation, such a measured waveform might still be used when measuring the lifetime of a battery.

However, as can be seen in the figures, the top current is not as high as in the case in which no capacitance was present. In addition, small but fast rising edges are not visible, thus, also timing information is lost.

It is therefore 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. by switching to an external shunt resistor) to increase the cut-off frequency of the DUT.

4 Verifying Power Consumption: Real-World-Examples

4.1 Current Consumption Measurements with RT-ZVC and Oscilloscope

4.1.1 Preparation of the Device-under-Test

A Bluetooth Low Energy beacon is evaluated. This device is intended as a smart keychain and enables each device, keychain and smartphone, to find each other. The device connects in regular intervals to the coupled phone in order to detect e.g. theft of one device or beeps if via the app on the smartphone a corresponding command is sent.

Typically, battery powered IoT devices can be accessed relatively easy at the point of the battery compartment. The ZVC is shipped with already preconfigured PCB solder-in cables and connectors but these can also be manufactured by the engineer himself. Optionally banana and BNC plug interface are available as well.

The Bluetooth device is powered by a button cell CR2032 with a capacity of ~220 mAh and provided solder-in cables are used to measure voltage and current at the battery outlets (cf. Figure 13). The electric power supply to the Bluetooth device is therefore interrupted and the device is connected to the I_1 and V_1 channels of the ZVC. A common measurement potential (GND) is defined via the black cable. In addition, a near field probe (R&S®HZ-15) is placed in close proximity to the DUT and connected to an analog channel of the oscilloscope.

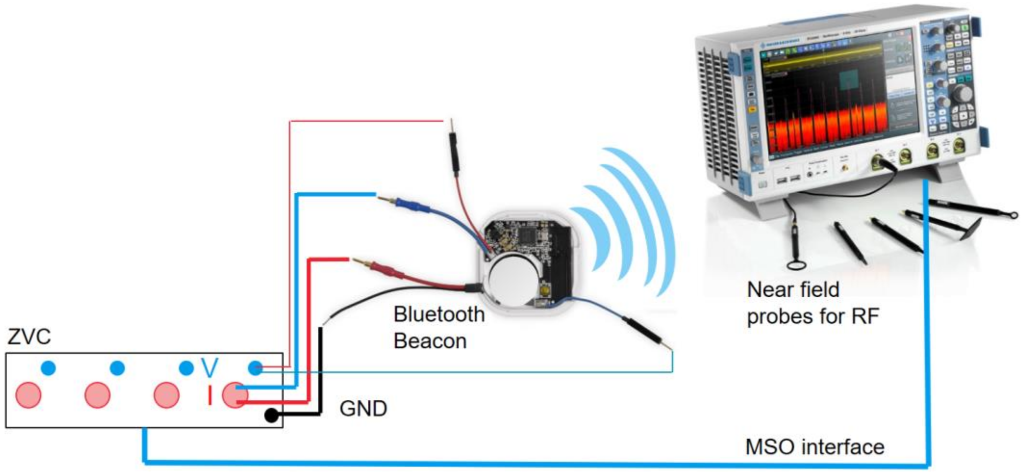

Figure 13 Measurement setup for a Bluetooth Low Energy beacon. The ZVC measures the total current and the voltage at the DUT (incl. GND). The oscilloscope detects the RF transmission on an analog channel and controls the ZVC via the MSO interface.

4.1.2 Software settings

The Multi-Channel Power Probe is connected via the Digital MSO Oscilloscope interface to the oscilloscope[5]. This setup allows in its maximum configuration up to 8 additional voltage and current channels for the oscilloscope by utilizing 2x RT-ZVC04.

The ZVC channels can be enabled in the *Vertical* menu of the oscilloscope from the bottom touch bar, cf. Figure 14. In the following windows, the different channels can be enabled separately as well as defining individual ranges and offsets.

A common bandwidth plus three different decimation modes (*Sample*, *Peak detect*, *High res*) are set for all channels of the ZVC.

Each channel can be independently scaled in vertical direction, as well as applying offset and position.

	State	Scale	Offset
Z1 V1	I	50 mV/div	3.3 V
Z1 V2	○	50 mV/div	0 V
Z1 V3	○	50 mV/div	0 V
Z1 V4	○	50 mV/div	0 V
Z1 I1	I	2 mA/div	8 mA
Z1 I2	○	2 A/div	0 A
Z1 I3	○	2 A/div	0 A
Z1 I4	○	2 A/div	0 A

General
Decimation mode: Sample
Bandwidth: 1 MHz

Z1 I1 State: I
☐ Max Bandwidth
Vertical scale: 2 mA/div
Offset: 8 mA
Bandwidth: 1 MHz
Position: 0 div
Skew: 0 s
Shunt Settings
External Shunt: ○
Internal Shunt Value: 10 Ω ± 45 mA
10 mΩ ± 10 A
10 mΩ ± 4.5 A
10 Ω ± 45 mA
10 Ω ± 4.5 mA
10 kΩ ± 45 µA
10 kΩ ± 4.5 µA

Figure 14 ZVC setup within the oscilloscope software.

Hint: For fast update rates on the scope it is recommended to limit the sample rate to 5 MSa/s as this is the inherent sample rate of the ZVC. Higher sample rates (e.g. due to analog scope channels being present) lead to an interpolation calculation of ZVC channels. This calculation is decreasing the oscilloscope’s performance.

4.1.3 Measurements

The measured signals are in general voltage and current from which other required quantities can be derived. Power can be easily calculated using the math mode via multiplying the current and voltage channel. The consumed energy can be further determined by using the “Area” measurement on the power (math) channel. Another useful quantity is the drawn charge from the battery capacity, which can be calculated similar as the energy (cf. Figure 15).

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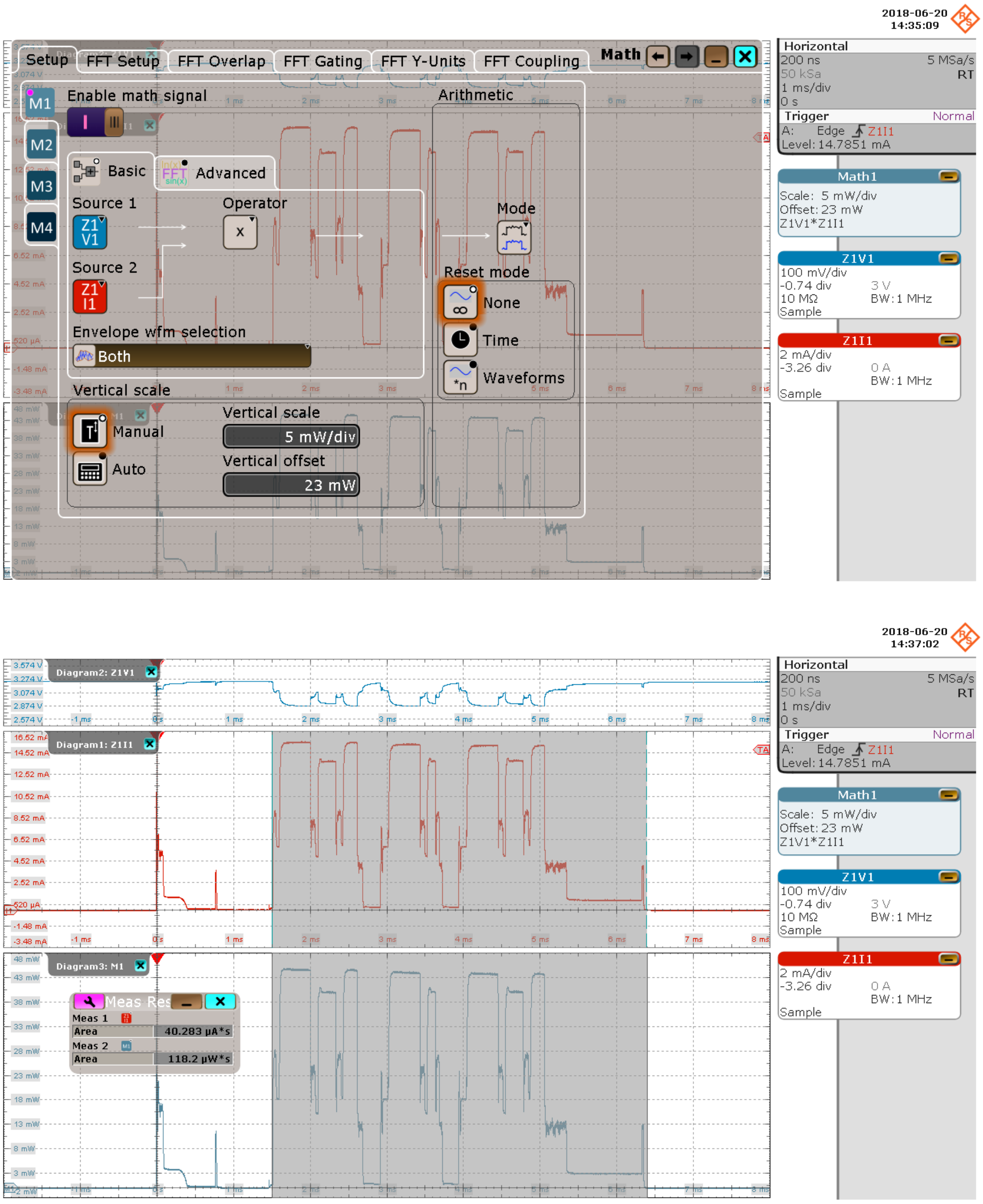
[5] For use with RTE/RTO/RTP oscilloscopes, additionally, the RTx-B1 Mixed Signal Option/RTx-B1E Digital Extension Port is required.



2018-06-20
14:35:09

Enable math signal
Source 1: Z1 V1
Operator: x
Source 2: Z1 I1
Mode
Reset mode: None
Time
Waveforms
Envelope wfm selection: Both
Vertical scale: Manual
Auto
Vertical scale: 5 mW/div
Vertical offset: 23 mW

Horizontal
200 ns 5 MSa/s
50 kSa RT
1 ms/div
0 s
Trigger Normal
A: Edge Z1I1
Level: 14.7851 mA

Math1
Scale: 5 mW/div
Offset: 23 mW
Z1V1*Z1I1

Z1V1
100 mV/div
-0.74 div 3 V
10 MΩ BW: 1 MHz
Sample

Z1I1
2 mA/div
-3.26 div 0 A
BW: 1 MHz
Sample

2018-06-20
14:37:02

Meas 1
Area 40.283 µA*s
Meas 2
Area 118.2 µW*s

Figure 15 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.

4.1.3.1 Current consumption in static operating modes

Evaluating the exact current respective power consumption is one of the first tasks when looking into the operating modes of a DUT. This includes e.g. consumption in sleep but also in transmitting and receiving mode. In order to achieve reliable measurement results the device should be put into the desired operating mode by the developer and the respective current can be measured.

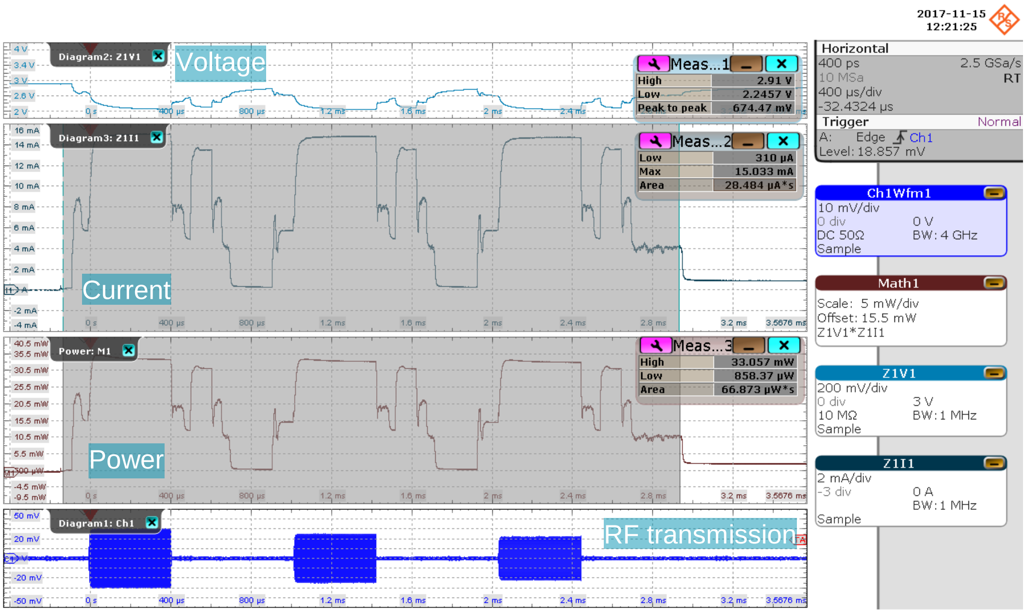
As a common example, modern DC/DC converters in IoT devices achieve sleep currents in the sub-µA range. The ZVC can use its high resolution in combination with the low-pass filter to achieve minimal noise and evaluate this state.

4.1.3.2 Evaluation of dynamic current and power consumption

The high dynamic range of the ZVC allows also for measurements when the device switches the various operating modes by itself[6].

Such a measurement is shown in Figure 16 where the internal shunt resistors have been used and a measurement with external shunt resistor is shown in Figure 17.

The top graph shows the voltage at the DUT, followed by the current and the calculated power. The bottom graph shows the measured RF signal. Power and current are integrated over the active range of the DUT with the "Area" measurement functionality.



Meas...1

High	2.91 V
Low	2.2457 V
Peak to peak	674.47 mV

Meas...2

Low	310 µA
Max	15.033 mA
Area	28.484 µA*s

Meas...3

High	33.057 mW
Low	858.37 µW
Area	66.873 µW*s

Horizontal
400 ps 2.5 GSa/s
10 MSa RT
400 µs/div
-32.4324 µs

Trigger Normal
A: Edge Ch1
Level: 18.857 mV

Ch1Wfm1
10 mV/div
0 div 0 V
DC 50Ω BW: 4 GHz
Sample

Math1
Scale: 5 mW/div
Offset: 15.5 mW
Z1V1*Z1I1

Z1V1
200 mV/div
0 div 3 V
10 MΩ BW: 1 MHz
Sample

Z1I1
2 mA/div
-3 div 0 A
BW: 1 MHz
Sample

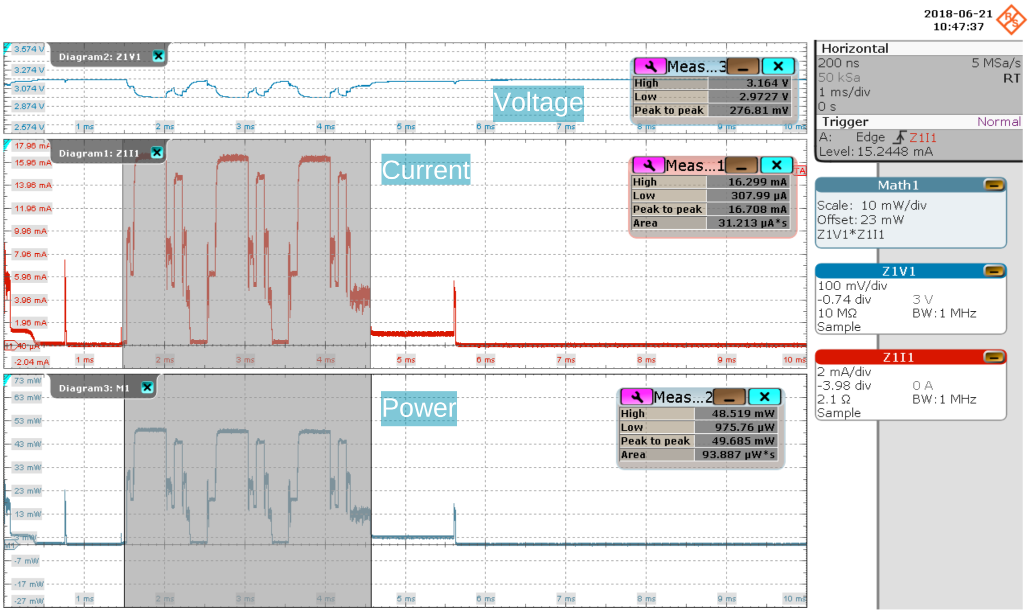
Figure 16 Power usage and current consumption during device activity determined with gated *Area* measurement functionality on the current and the (mathematical) power channel.

The measurement shown in Figure 16 was performed by powering the DUT with a CR2032 button cell and evaluating the current with the ZVC's internal 10 Ω shunt resistor. The burden voltage (shunt plus battery resistance) accounts already for 670 mV, while the peak current is ~15 mA.

---

[6] The R&S®RT-ZVCA offers automatic gain switching, thus the probe gives the communicating CMWRun software the best selection for the current in question and switches through its amplification stages if e.g. the DUT awakes from sleep current and switches into an active state. Thus, the overall measurement resolution is effectively increased with the R&S®RT-ZVCA (currently only compatible with CMWRun).

Figure 17 shows the same DUT and measurement as above, however a 1 Ω external shunt resistor was used. When using small resistance values also leads and connectors (e.g. clamps) need to be taken into account. In this example, a total resistance of 2.1 Ω is put into the calculation of the RTO. As a result, the burden voltage is dropped significantly from ~670 mV towards 280 mV, however, the battery is still strong enough to supply the DUT's regulation circuits with the 10 Ω shunt, and thus the consumed current is changed only marginally.



Meas...3

High	3.164 V
Low	2.9727 V
Peak to peak	276.81 mV

Meas...1

High	16.299 mA
Low	307.99 µA
Peak to peak	16.708 mA
Area	31.213 µA*s

Meas...2

High	48.519 mW
Low	975.76 µW
Peak to peak	49.685 mW
Area	93.887 µW*s

Horizontal
200 ns 5 MSa/s
50 kSa RT
1 ms/div
0 s

Trigger Normal
A: Edge Z1I1
Level: 15.2448 mA

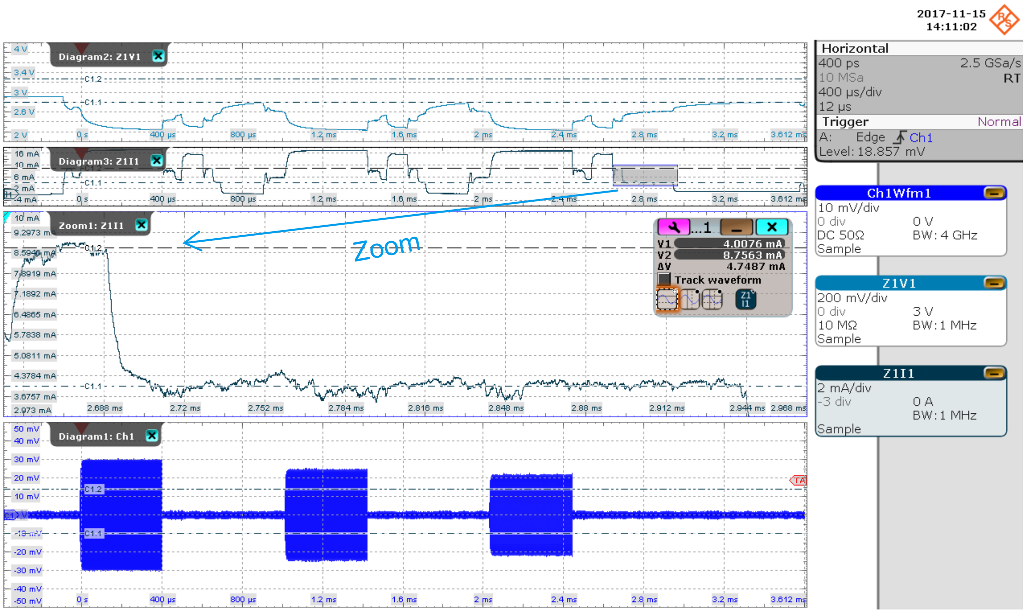
Math1
Scale: 10 mW/div
Offset: 23 mW
Z1V1*Z1I1

Z1V1
100 mV/div
-0.74 div 3 V
10 MΩ BW: 1 MHz
Sample

Z1I1
2 mA/div
-3.98 div 0 A
2.1 Ω BW: 1 MHz
Sample

Figure 17 Current measurement with an external (1 Ω) resistor. From top to bottom, the graphs show DUT voltage, current, and calculated power.

The ZVC enables further detailed current measurements, which can be used best with the zoom functionality to enhance the region of interest (cf. Figure 18) or set the device in a defined state and select the resolution of the ZVC accordingly as suggested in section 4.1.3.1.



2017-11-15
14:11:02

Horizontal
400 ps 2.5 GSa/s
10 MSa RT
400 µs/div
12 µs

Trigger Normal
A: Edge Ch1
Level: 18.857 mV

Ch1Wfm1
10 mV/div
0 div 0 V
DC 50Ω BW: 4 GHz
Sample

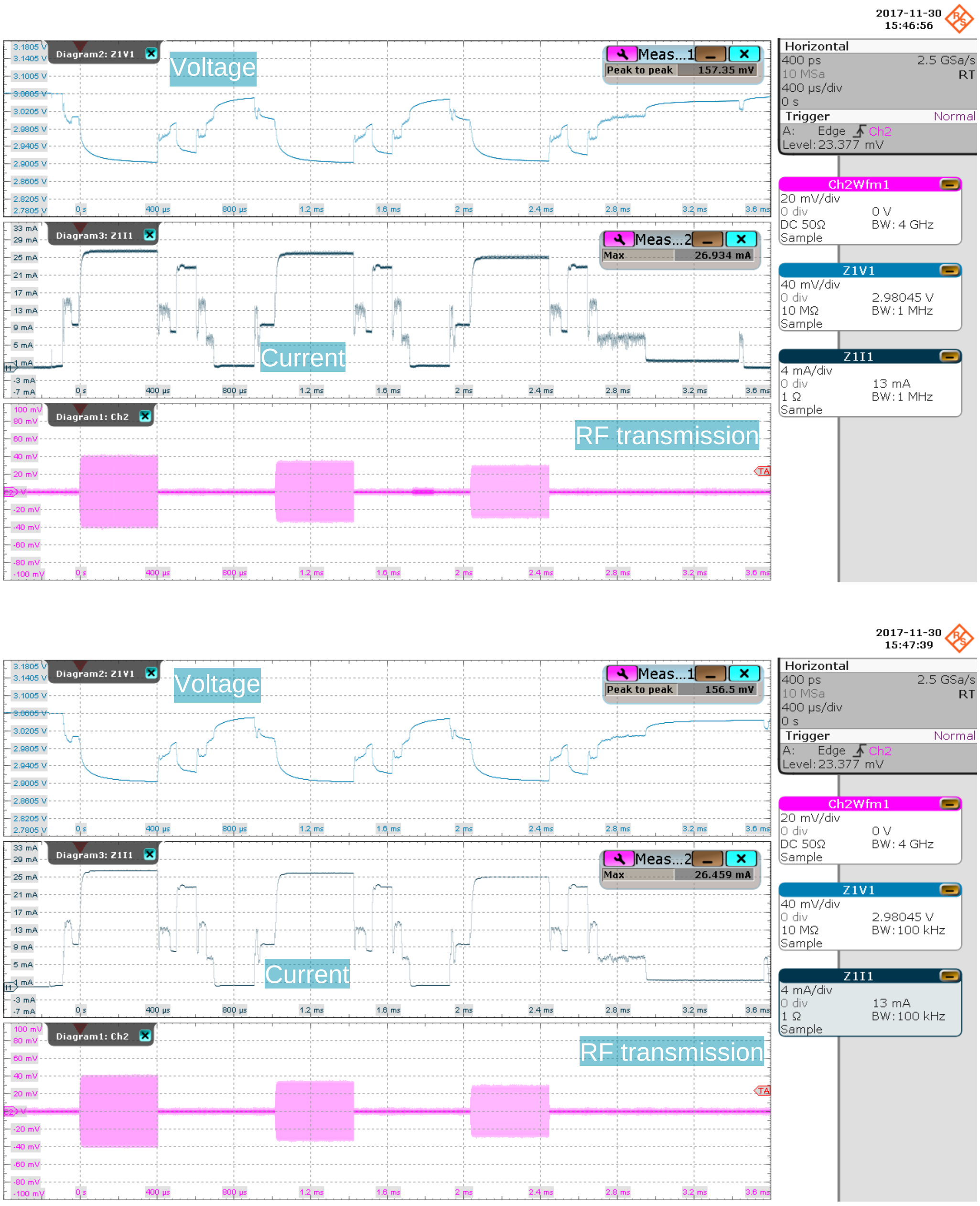
Z1V1
200 mV/div
0 div 3 V
10 MΩ BW: 1 MHz
Sample

Z1I1
2 mA/div
-3 div 0 A
BW: 1 MHz
Sample

V1 4.0076 mA
V2 8.7563 mA
ΔV 4.7487 mA
Track waveform

Figure 18 Zoom functionality in combination with cursors enables device state correlation.

The zoom functionality can reveal smallest variations of the current, therefore it might be desirable to reduce the noise of the current measurement. This can be easily done via limiting the bandwidth in the software. Figure 19 shows a comparison between 1 MHz and 100 kHz bandwidth. The reduced bandwidth curve shows considerably less noise.



2017-11-30
15:46:56

Meas...1
Peak to peak 157.35 mV

Meas...2
Max 26.934 mA

Horizontal
400 ps 2.5 GSa/s
10 MSa RT
400 µs/div
0 s

Trigger Normal
A: Edge Ch2
Level: 23.377 mV

Ch2Wfm1
20 mV/div
0 div 0 V
DC 50Ω BW: 4 GHz
Sample

Z1V1
40 mV/div
0 div 2.98045 V
10 MΩ BW: 1 MHz
Sample

Z1I1
4 mA/div
0 div 13 mA
1 Ω BW: 1 MHz
Sample

2017-11-30
15:47:39

Meas...1
Peak to peak 156.5 mV

Meas...2
Max 26.459 mA

Horizontal
400 ps 2.5 GSa/s
10 MSa RT
400 µs/div
0 s

Trigger Normal
A: Edge Ch2
Level: 23.377 mV

Ch2Wfm1
20 mV/div
0 div 0 V
DC 50Ω BW: 4 GHz
Sample

Z1V1
40 mV/div
0 div 2.98045 V
10 MΩ BW: 100 kHz
Sample

Z1I1
4 mA/div
0 div 13 mA
1 Ω BW: 100 kHz
Sample

Figure 19 Comparison between 1 MHz (top) and 100 kHz bandwidth (bottom). The reduced bandwidth limits noise in the current measurement.

4.1.4 Estimated lifetime

The total charge consumption can be measured by the CMWRun software directly. However, in combination of the ZVC with an oscilloscope the total current consumption must be estimated by calculating the consumption of the repetitive current profile and extrapolating this result (i.e. current profiling). The following fictitious example illustrates the procedure:

Assumptions:

- Advertise event as in Figure 15, i.e. 40.3 µC in a 4.5 ms time interval.
- Remaining idle duration to be 95.5 ms between advertising; drawing 5 µA in this period, yielding 0.48 µC.
- Every hour the device wakes-up, performing 33x times the above cycle. In sleep mode, the device draws 2 µA.

The consumption is straightforward:

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

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

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

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

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 lifetime. In this case here, a CR2032 button cell battery with 220 mAh lasts (see also restrictions on available battery charge in section 3.4):

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

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

The current consumption in sleep state is highly important as can be seen 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.

4.1.4.1 Correlation of current consumption to hardware and software events

A big advantage of the ZVC in combination with an oscilloscope is the possibility of multi-domain analysis. The oscilloscope offers advanced analysis but also trigger and decode capabilities. E.g., one could trigger and decode for events on an I²C bus and evaluate the current consumption of the DUT with respect to such events.

Another possibility is to utilize the FFT functionality of the oscilloscope[7] to understand the RF transmission in more detail. In this example, the current is evaluated during the

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

transmission of the Bluetooth signal. As can be seen in Figure 19 the current consumption is at maximum during the RF transmission the Bluetooth device. A gated FFT is used to isolate the FFT on the first and second pulse of the Bluetooth advertising event (cf. Figure 20). As can be seen from Figure 20 the first pulse is transmitted at 2.4021 GHz while the second pulse exhibits a carrier frequency of 2.4261 GHz, thus the channel hopping difference is 24 MHz.

Cursor Resul...1
f1 2.4021 GHz
f2 2.4261 GHz
Bw 24 MHz

Horizontal
100 ps 10 GSa/s
16 MSa RT
160 µs/div
0 s
Trigger Normal
A: Edge Ch1
Level: 5.6277 mV

Ch1Wfm1
5 mV/div
0 div 0 V
DC 50Ω BW: 4 GHz
Sample

Math4
Scale: 10 dB/div
Offset: -65 dBm
FFTmag(Ch1)
RBW: 610.85391 kHz

Z1V1
200 mV/div
0 div 3 V
10 MΩ BW: 1 MHz
Sample

Z1I1
9 mA/div
0 div 0 A
BW: 1 MHz
Sample

Figure 20 Gated spectrum measurement of Bluetooth frequency and hopping evaluated with near field probe The two consecutive transmissions differ in frequency of 24 MHz (top: 2.4021 GHz, bottom: 2.4261 GHz).

4.2 Battery Life Measurements with RT-ZVCA and CMWRun

4.2.1 Preparation of the Device-under-Test

In this section, an off-the-shelf NB-IoT device is evaluated. As the focus of NB-IoT devices lies on very low power consumption, the power save mode (PSM) is a critical feature of IoT devices. When reliable battery life forecasts are required, it does not suffice to simply measure the PSM current only. As such, the setup presented hereafter allows to accurately measure a large number of complete PSM cycles during a long-term test session. The challenge in such a setup is the large dynamic range required by the power probe as sleep mode currents may be as low as few microamperes while the device draws several hundred milliamperes during the wake-up process. The RT-ZVC power probe in the auto ranging variant ZVC02A/04A is ideally suited for this task, as this probe can cover the whole current range while still providing accurate readings.

A 3.8 V lithium-ion battery powers the NB-IoT device. The DUT was modified in such a way, that current and voltage measurements could be performed as close to the chip as possible in order to obtain meaningful results. Provided cables are used to measure voltage and current at jumper pins on the DUT board (cf. Figure 13). The electric power supply to the IoT device is therefore interrupted and the device is connected to the I_1 and V_1 channels of the ZVC02/04A. A common measurement potential (GND) is established via the black cable.

The DUT communicates with an R&S® CMW290 radio communication tester, which acts as base station emulator and configures the NB-IoT device to enter PSM after a certain idle time.

The auto-ranging variant RT-ZVCA is controlled via the test automation software CMWRun, which will be described in the next chapter.

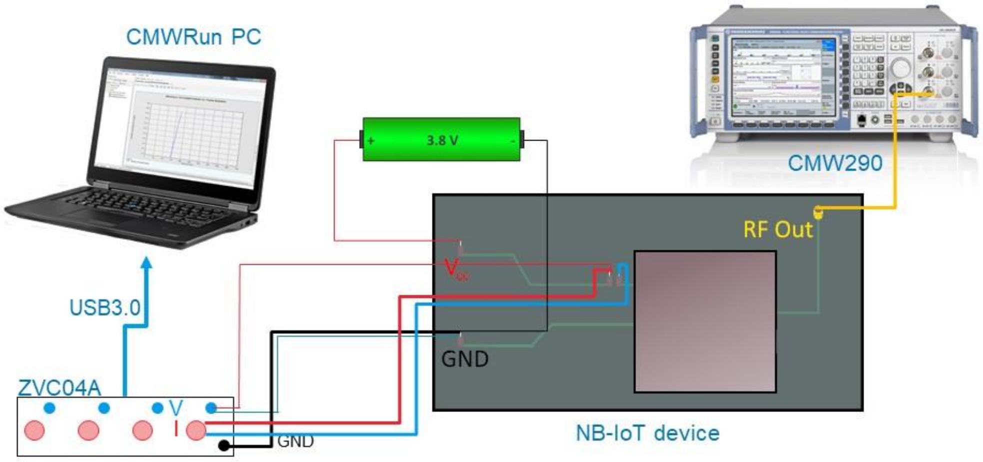


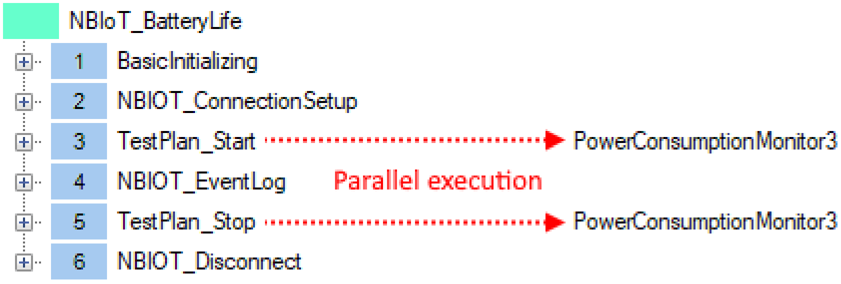
Figure 21 Measurement setup for a NB-IoT device. The ZVC variant A measures the total current and the voltage at the DUT (incl. GND) during multiple complete PSM cycles.

4.2.2 Software settings

This section shows the creation and configuration of a test plan for NB-IoT battery life measurements in CMWRun.

4.2.2.1 Test plan structure

Figure 22 shows a typical CMWRun test plan for battery life testing. Step 1 resets the R&S® CMW radio communication tester in order to obtain reproducible results. After the DUT connection to the test instrument has been established in step 2, a power measurement is started in parallel to the current test plan in step 3. The event log in step 4 ensures that relevant events are logged in parallel to the measurement.



NBIoT_BatteryLife

1 BasicInitializing

2 NBIOT_ConnectionSetup

3 TestPlan_Start

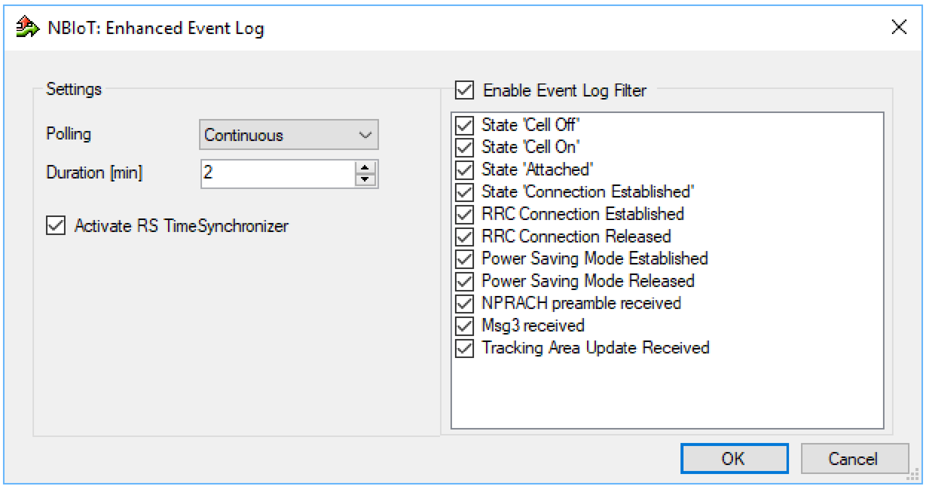
4 NBIOT_EventLog

5 TestPlan_Stop

6 NBIOT_Disconnect

Figure 22 CMWRun test plan for NB-IoT battery life testing.

All events that can be logged in the measurement report are shown in Figure 23. The duration of the power consumption measurement is also set in this configuration window, as the PowerConsumptionMonitor3 is stopped in the test plan in step 5 after the event log has ended. The RS TimeSynchronizer setting uses a small client software on the CMW radio communication tester in order to get more accurate IP-based readings.



Polling: Continuous

Duration [min]: 2

☑ Activate RS TimeSynchronizer

☑ Enable Event Log Filter

☑ State 'Cell Off'
☑ State 'Cell On'
☑ State 'Attached'
☑ State 'Connection Established'
☑ RRC Connection Established
☑ RRC Connection Released
☑ Power Saving Mode Established
☑ Power Saving Mode Released
☑ NPRACH preamble received
☑ Msg3 received
☑ Tracking Area Update Received

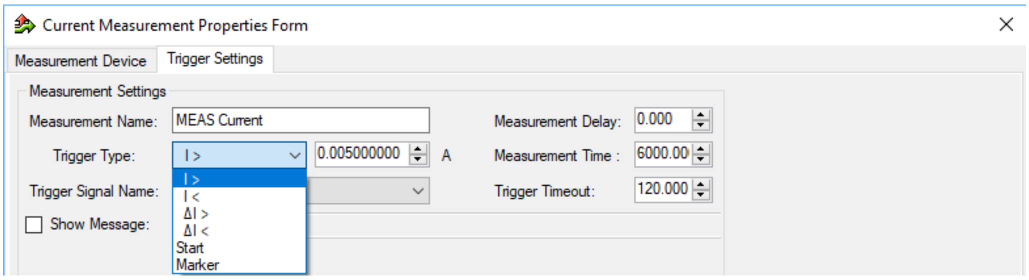
Figure 23 CMWRun event log configuration.

4.2.2.2 Test plan configuration

Regarding the measurement itself, CMWRun in conjunction with the RT-ZVC02/04A offers two different options that differ in terms of procedure and reporting. This depends on the test case started in step 3 in Figure 22.

The first option is to perform a triggered measurement using the test case “PowerMeasurement3”. This test offers various trigger options, including current and specific markers. Figure 24 shows the trigger settings for this test case, which additionally offers a limit check for further evaluation of the results.

The second option is to use the test case “PowerConsumptionMonitor3” which offers detailed graphs of all measured quantities including all markers configured in Figure 23.



Measurement Name: MEAS Current
Trigger Type: I > 0.005000000 A
Trigger Signal Name:
☐ Show Message:
Measurement Delay: 0.000
Measurement Time : 6000.00
Trigger Timeout: 120.000

Figure 24 Trigger settings of PowerMeasurement3.

The results of both cases are shown in chapter 4.2.3.1 and 4.2.3.2 respectively.

Figure 25 shows the configuration screen of the current measurement when using the four channel auto-ranging probe RT-ZVC04A. This window is identical for both options introduced at the beginning of this section.

The elements in ① allow to select the sample rate. When averaging is selected as measurement function, the device’s 5 MSa/s are averaged in such a way that from 10 Sa/s up to 50 kSa/s are logged. As the test may run for a long time, it is important to know how much data has to be stored, which is given by the data volume per minute.

The display settings in ② configure the axes for the result graph.

It is further possible through ③ to display various electric measurements, which are derived from the current and voltage measurements. The battery life result does for example integrate the measured current consumption over the whole runtime and can thus estimate the battery life if the corresponding battery capacity is known.

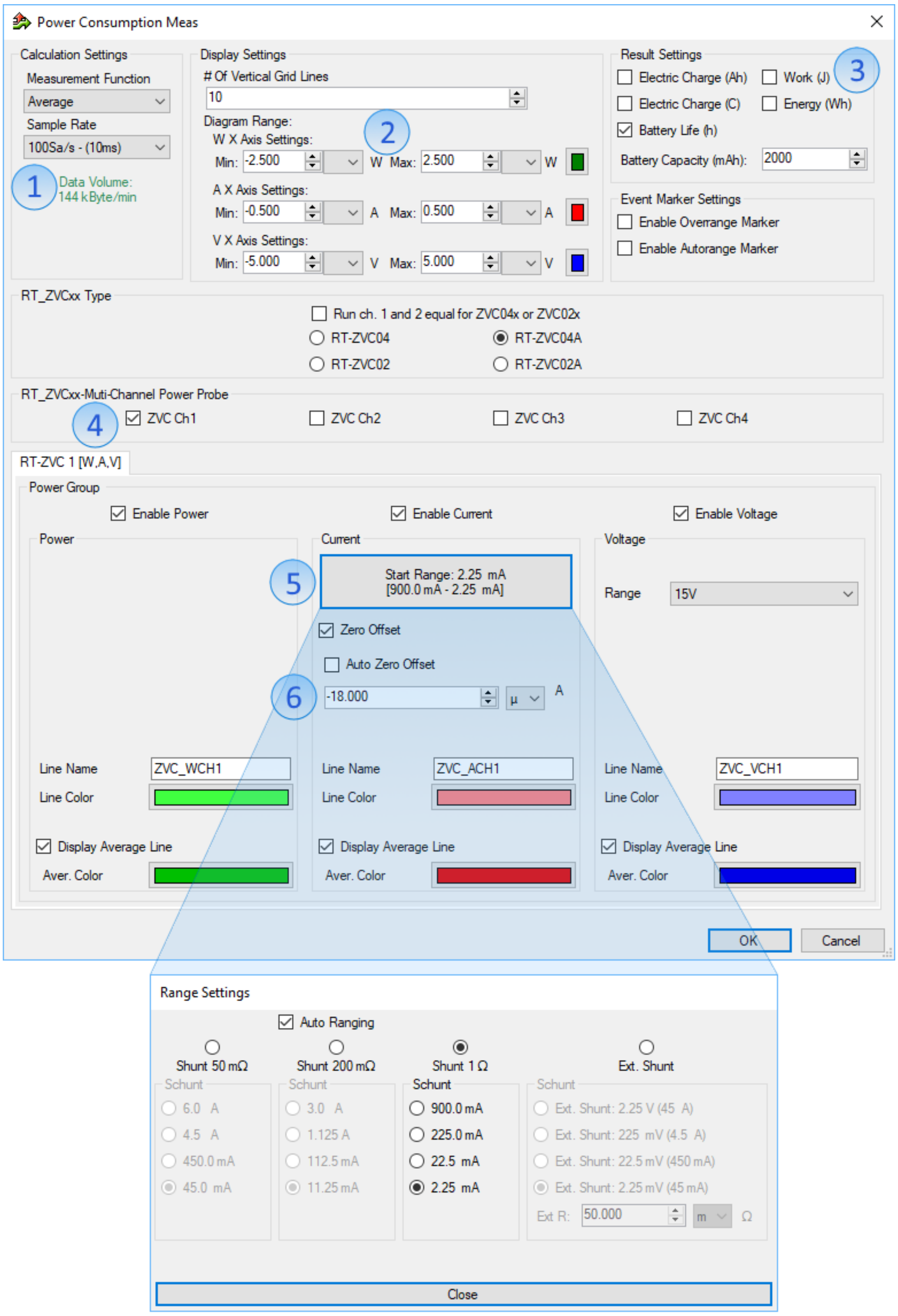
The number of channels used for the measurement is defined in ④. This setting does greatly impact the expected data volume from ①.

The button ⑤ brings up the shunt and auto-ranging settings. The configuration dialog shows the measurement ranges supported per shunt. Using the example of the 1 Ω shunt, it can be seen that this configuration allows a measurement range from 2.25 mA up to 900 mA. The RT-ZVC02/04A digitally switches the measurement ranges through different amplification factors, which means that there is no switching of shunts.

Chapter 3.6 showed that when measuring very small currents, it is important to consider inevitable offset errors. The configuration element ⑥ allows the definition of a static offset in order to compensate these effects. The approach for acquiring this offset described in chapter 3.6 does also apply when CMWRun is used in conjunction with the RT-ZVC02/04A. The only difference is that the offset value in step 2. is measured using CMWRun.

There are two ways how to measure the zero offset in this setup. The “Auto Zero Offset” function prompts the user to perform steps 1. and 2. of chapter 3.6. and automatically applies the measured zero offset. The measured offset is also included in the measurement report for use in future test executions.

Alternatively, this can be done manually by starting a current measurement in CMWRun after modification of the setup according to steps 1. and 2. in chapter 3.6 and noting the offset value. In this case, the result (in the example shown in Figure 24, the measured offset is -18 µA) has to be manually set as zero offset in the GUI.



Power Consumption Meas

Calculation Settings
Measurement Function: Average
Sample Rate: 100Sa/s - (10ms)
Data Volume: 144 kByte/min

Display Settings
Of Vertical Grid Lines: 10
Diagram Range:
W X Axis Settings: Min: -2.500 W Max: 2.500 W
A X Axis Settings: Min: -0.500 A Max: 0.500 A
V X Axis Settings: Min: -5.000 V Max: 5.000 V

Result Settings
☐ Electric Charge (Ah) ☐ Work (J)
☐ Electric Charge (C) ☐ Energy (Wh)
☑ Battery Life (h)
Battery Capacity (mAh): 2000

Event Marker Settings
☐ Enable Overrange Marker
☐ Enable Autorange Marker

RT_ZVCxx Type
☐ Run ch. 1 and 2 equal for ZVC04x or ZVC02x
○ RT-ZVC04 ● RT-ZVC04A
○ RT-ZVC02 ○ RT-ZVC02A

RT_ZVCxx-Muti-Channel Power Probe
☑ ZVC Ch1 ☐ ZVC Ch2 ☐ ZVC Ch3 ☐ ZVC Ch4

RT-ZVC 1 [W,A,V]
Power Group
☑ Enable Power ☑ Enable Current ☑ Enable Voltage

Power
Line Name: ZVC_WCH1
Line Color
☑ Display Average Line
Aver. Color

Current
Start Range: 2.25 mA [900.0 mA - 2.25 mA]
☑ Zero Offset
☐ Auto Zero Offset
-18.000 µ A
Line Name: ZVC_ACH1
Line Color
☑ Display Average Line
Aver. Color

Voltage
Range: 15V
Line Name: ZVC_VCH1
Line Color
☑ Display Average Line
Aver. Color

Range Settings
☑ Auto Ranging
○ Shunt 50 mΩ ○ Shunt 200 mΩ ● Shunt 1 Ω ○ Ext. Shunt

Schunt	Schunt	Schunt	Schunt
○ 6.0 A	○ 3.0 A	○ 900.0 mA	○ Ext. Shunt: 2.25 V (45 A)
○ 4.5 A	○ 1.125 A	○ 225.0 mA	○ Ext. Shunt: 225 mV (4.5 A)
○ 450.0 mA	○ 112.5 mA	○ 22.5 mA	○ Ext. Shunt: 22.5 mV (450 mA)
● 45.0 mA	● 11.25 mA	● 2.25 mA	● Ext. Shunt: 2.25 mV (45 mA)
			Ext R: 50.000 m Ω

Figure 25 Configuration of the measurement in CMWRun.

4.2.3 Measurements

The goal of the setup consisting of an RT-ZVC02/04A and CMWRun is to measure the current consumption of an NB-IoT device over many PSM cycles in order to estimate the expected battery life of the tested device. NB-IoT devices typically use power save mode cycles in order to achieve a minimal power consumption. These cycles start with a short active time at the beginning of which the RRC (Radio Resource Control) connection is established. This is followed by a DRX (discontinuous reception) phase, in which the device can still be paged but the RRC connection has been released. Finally, the device enters PSM, which means that the transceiver is switched off. The whole cycle is shown in Figure 26, which also hints at the large difference concerning the current consumption, which lies in the order of magnitudes.

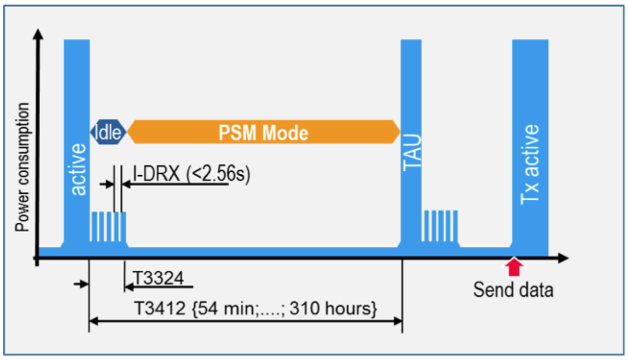
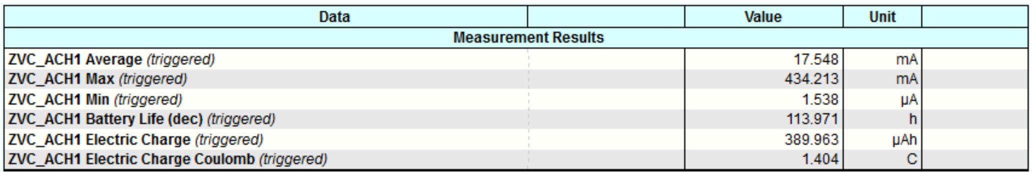


Figure 26 PSM cycle after phases of idle states DRX and TAU (Tracking Area Update).

4.2.3.1 Triggered measurements

The previous section introduced the possibility of triggered measurements with CMWRun and the ZVC using the *PowerMeasurement3* test plan. The measurement report provides information like average, maximum and minimum current consumption as well as the battery life estimate as shown in Figure 27. The device tested in this example would last about 114 h in this use case if powered by a 2000 mAh battery. The power save mode cycle is a lot longer in real life networks in order to achieve a battery life of up to 10 years with a similar battery.



Data		Value	Unit	
Measurement Results				
ZVC_ACH1 Average *(triggered)*		17.548	mA	
ZVC_ACH1 Max *(triggered)*		434.213	mA	
ZVC_ACH1 Min *(triggered)*		1.538	µA	
ZVC_ACH1 Battery Life (dec) *(triggered)*		113.971	h	
ZVC_ACH1 Electric Charge *(triggered)*		389.963	µAh	
ZVC_ACH1 Electric Charge Coulomb *(triggered)*		1.404	C	

Figure 27 Measurement report excerpt of a battery life measurement.

The measurement report contains additionally the current consumption over time as shown in Figure 28. In this case, the entry of the device in the PSM triggered the measurement.

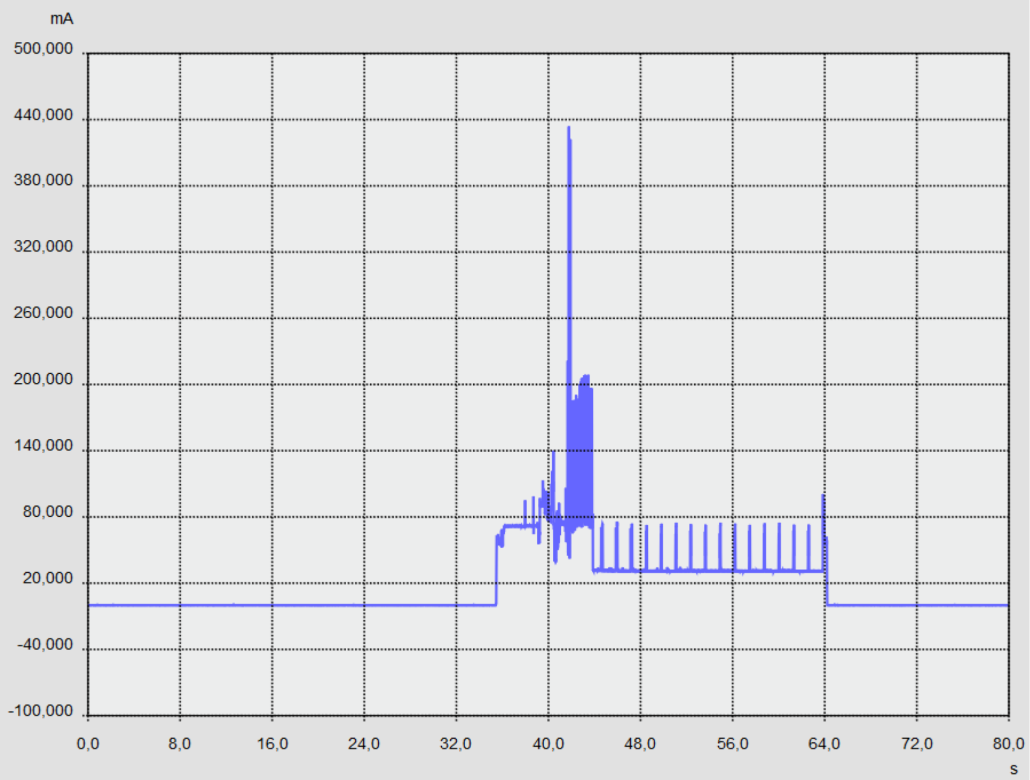
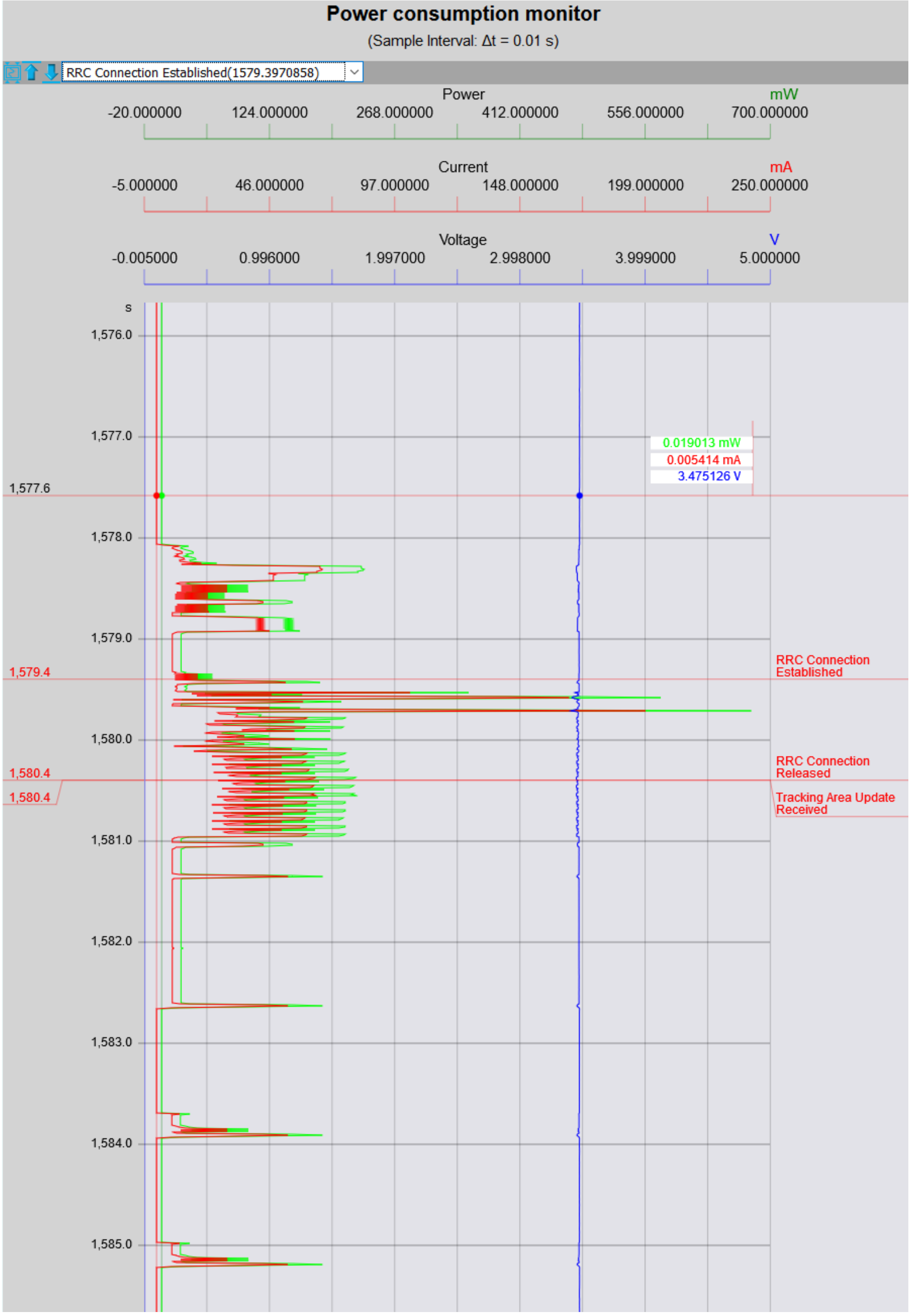


Figure 28 Triggered CMWRun measurement.

4.2.3.2 Detailed event measurements

In case that precise information about the power consumption in arbitrary points during the measurement is required, CMWRun offers a detailed measurement report when the test case *PowerConsumptionMonitor3* is used as described in chapter 4.2.2.2.

All events that occur during runtime of the measurement are logged with the correct time stamp. This enables the user to select an event of interest and directly jump to this point in time. The excerpt of the measurement report in Figure 29 shows the wake up process of the DUT from PSM followed by the active phase and DRX cycles. As the measurement was already running for a long time, this point in time was conveniently selected by choosing the *RRC connection established* event through the dropdown menu in the upper left corner. The PSM current consumption was measured at 5.4 µA using the sliding marker for precision readings.



Power consumption monitor

(Sample Interval: Δt = 0.01 s)

RRC Connection Established(1579.3970858)

Figure 29 Detailed measurement report including event markers.

5 Summary

Consumers pay a lot of attention to the battery life of their mobile - or to use the more generic term – IoT device. This parameter is easy to compare and some IoT devices in remote locations often do not have the ability at all to be charged and have to last their whole lifetime with one battery. Evaluating this parameter is key in designing IoT devices.

The ZVC in combination with an oscilloscope offers a solution, which copes with the high dynamic range of IoT devices and allows for detailed analysis of certain events. The oscilloscope can capture these events utilizing e.g. 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 external shunts, which can be chosen to achieve a best match to the application in question. Shunt based measurements have the drawback of burden voltage at the shunt resistor and one needs to take care where to place the resistor with respect to the DUT. Regardless of a high side or low side measurement, i.e. where the shunt resistor is placed, the battery 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. E.g., a good start is always a battery due to its noise performance. A next step would be to use power supplies. However, as shown in previous sections, power supplies may lead to undesired effects such as oscillations or spikes in the measurement data.

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[8]		
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
Multi-Channel Power Probe with Autoranging, 2 × 4 voltage/current channels, for R&S®CMWrun	R&S®RT-ZVC04A	1326.0259.34
Multi-Channel Power Probe with Autoranging, 2 × 2 voltage/current channels, for R&S®CMWrun	R&S®RT-ZVC02A	1326.0259.32

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[8] The user manual of the ZVC holds detailed information about connector types; Document ID 1326.2139.02 – 02

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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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