

Low Power Considerations for ZigBee Applications Operated by Coin Cell Batteries

by: **Karel Povalac and Peter Ligertwood**
Freescale Applications

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1 Introduction

This document describes the use of coin cell batteries for low power ZigBee connectivity applications. Implementation of an application operated by a coin cell battery brings with it many constraints, especially when peak currents can attain relatively high values of the order of 30 mA during radio reception and transmission. The coin cell battery used for testing was the very popular CR2032, which is often used for small/low power applications. It is well known the CR2032 is able to support operating loads of a few mA. Furthermore, small linear currents are sufficiently well specified by the battery manufacturer data sheets. However, the use case involving high transient peak currents is not well described in terms of the effect on battery lifetime. This application note covers practical experiments with ZigBee wireless applications running on Freescale's MC1323x integrated radio platform, powered by a coin cell battery.

The application was configured to periodically transmit bursts of data, and consequently the battery was stressed by the high peak current drawn. A series of tests were made to investigate the use of a coin cell battery power supply for ZigBee radio applications. Results are presented and a feasibility analysis is made concerning the use case. This analysis could equally be applied to other types of low power wireless connectivity, for example BLE (Bluetooth Low Energy), where similar peak/transient demands are made on the battery.

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2 MC1323x overview

The MC1323x was used during the tests outlined in [Experimental results](#). The MC1323x family is Freescale's low-cost/high-performance System-on-Chip (SoC) platform for the IEEE® 802.15.4 standard, incorporating a complete low-power 2.4 GHz radio frequency transceiver with Tx/Rx switch, an 8-bit HCS08 CPU, and a functional set of MCU peripherals integrated into a 48-pin LGA package. This family of products is targeted for wireless RF remote control and other cost-sensitive applications, ranging from home TV and entertainment systems, such as ZigBee BeeStack Consumer (RF4CE), to low-cost, low-power, IEEE 802.15.4 and ZigBee end device nodes. The MC1323x is a highly integrated solution, with very low power operation.

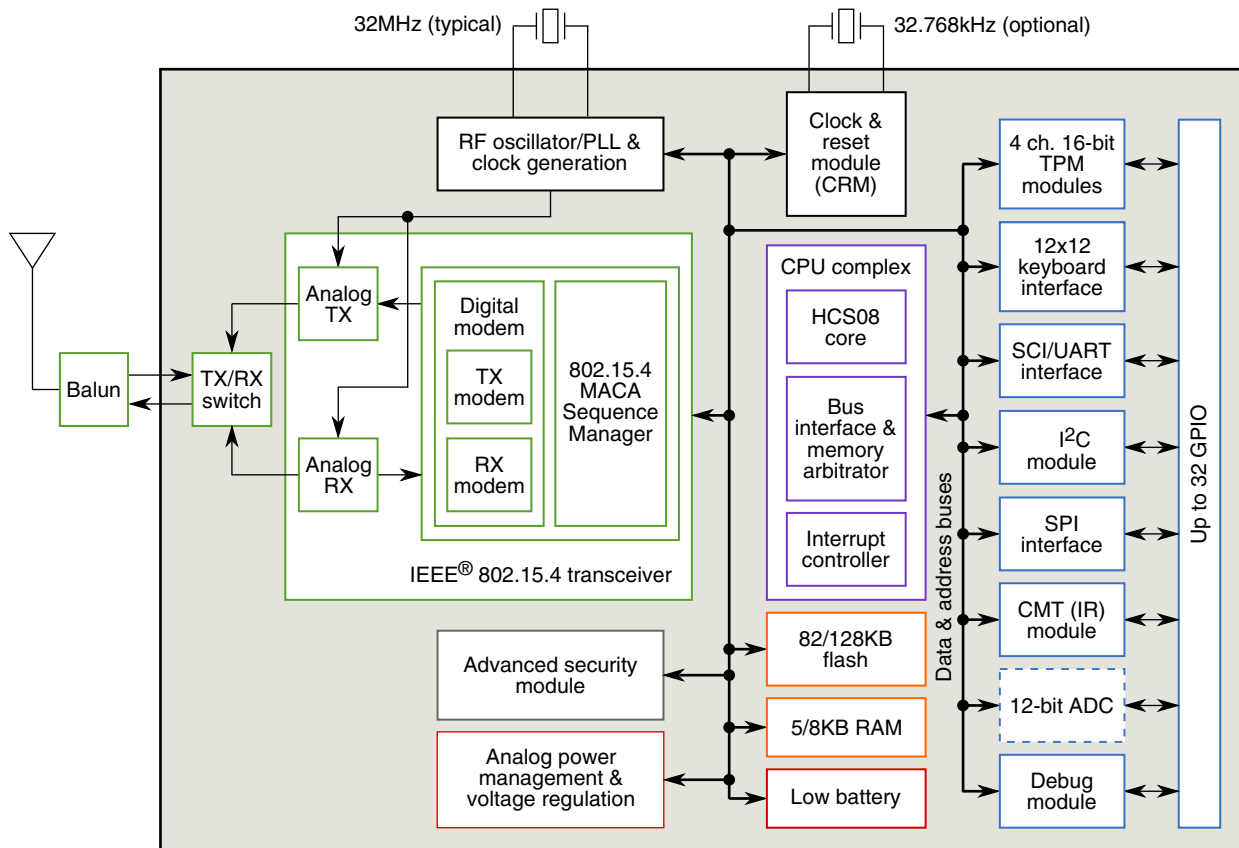


Figure 1. MC13237 block diagram

The MC1323x contains an RF transceiver which is an 802.15.4 Standard – 2006 compliant radio that operates in the 2.4 GHz ISM frequency band. The transceiver includes:

- Low-noise amplifier
- 1 mW nominal output power amplifier (PA)
- Internal voltage controlled oscillator (VCO)
- Integrated transmit/receive switch
- On-board power supply regulation
- Full spread-spectrum encoding and decoding

The on-chip CPU is based on the Freescale HCS08 family of microcontroller units (MCU) and has up to 128 KB of flash memory with up to 8 KB of RAM. The onboard MCU peripheral set has been defined to support the targeted applications. A dedicated DMA block transfers packet data between RAM and the transceiver to off-load the CPU and allow higher efficiency and increased performance.

2.1 Feature summary

- MCU Features
 - Integrated HC9S08 8-bit up to 32 MHz
 - Memory
 - MC13237: 128 KB flash memory and 8 KB RAM
 - MC13233: 82 KB flash memory and 5 KB RAM
 - Peripherals
 - SCI
 - SPI
 - I²C
 - Up to 12×12 KBI
 - Carrier-modulated timer (IR)
 - Up to 32 general purpose input/output ports (GPIO)
 - 12-bit ADC (on MC13237)
- Radio Features
 - Programmable transmit from –30 dBm to +2 dBm
 - Receive sensitivity of –94 dBm
 - <31 mA receive and 27 mA transmit with radio and MCU
 - 802.15.4 compliant 2.4 GHz RF transceiver
 - Auto-trim feature for crystal accuracy
 - Integrated transmit/receive switch
- General Features
 - Power supply range: 1.8–3.4 V
 - AES 128-bit hardware encryption/decryption
 - 7 mm × 7 mm 48-pin LGA
 - Operating temperature range: –40 °C to 85 °C

2.2 MC1323x operating modes

Freescale's MC1323x is a highly integrated solution, with very low power consumption modes. The best power saving options are possible in STOP3 (450 nA) and STOP2 (300 nA) modes. Low power STOP3 mode was especially used during the battery tests.

Table 1. Supply current characteristics

Characteristics	Symbol	Minimum	Type	Maximum	Unit
STOP2	S2IDD	—	0.29	1	μA
STOP3	S3IDD	—	0.45	—	μA
LPWAIT (Low Power Wait)	LPWIDD	0.5	0.56	0.62	mA
LPRUN (Low Power Run)	LPRIDD	0.53	0.76	0.85	mA
RUN	RUNIDD	4.0	4.7	4.9	mA
TX	TXIDD	21.3	26.6	28.2	mA
RX	RXIDD	26.8	34.2	35.0	mA

Typical radio and MCU power consumption specified values are presented in [Table 1](#). (For more information, see items 1 and 2 in [References](#).) These values were used for the battery lifetime calculations which follow. It is evident from the table that the most stressful situation for the battery is when transmitting and receiving bursts of data.

2.3 MC1323x low power modes

A summary of MC1323x operating modes is described below. There are a number of different operating modes for this device. (For more information, see item 2 in [References](#).)

- STOP modes — System clocks are stopped and voltage regulator is in standby.
 - STOP2 — Partial power down of internal circuits, RAM content is retained; I/O states are held.
 - STOP3 — All internal circuits are powered for fast recovery (32 MHz oscillator on-off optional).
- LPRun mode — CPU clock is set to 500 kHz and peripheral clocks (bus clock) to 250 kHz. The internal voltage regulator is in standby.
- Wait mode — CPU shuts down to conserve power. System clocks are running and full regulation is maintained.
- LPWait mode — CPU shuts down to conserve power; peripheral clocks are restricted to 250 kHz and the internal voltage regulator is in standby.
- Run mode — CPU clocks can run at full speed and the internal supply is fully regulated.

2.4 1323x-IPB Small form factor reference design

1323x-IPB reference design boards were used extensively during the tests described in [Experimental results](#). The 1323x-IPB module is a complete IEEE 802.15.4/ZigBee wireless node reference design. (For more information, see item 4 in [References](#).) The printed circuit board (PCB) has a very small form factor and employs a printed “F” antenna with a layout using two metal layers. A single 802.15.4 device (the MC1323x) is the only IC and the required RF circuitry is minimal. A single I/O and power port connector provides:

- Separate serial I²C bus
- SPI bus
- UART interfaces
- Four keyboard interrupts (KBI)
- Up to four GPIOs
- Power connection

An on-board 3.3 V LDO voltage regulator is also included.

Freescall provides the 1323x-IPB as a complete reference design with circuit schematic, bill of materials (BOM), and layout database. This reference design can be used as is or can be adapted for small footprint boards.

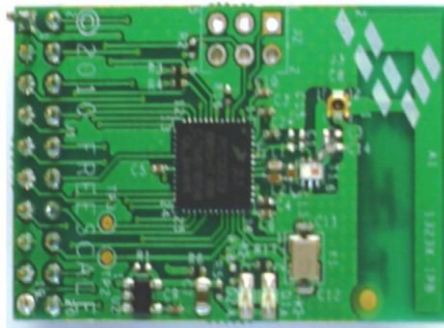


Figure 2. IPB 2-layer reference board with MC13233

3 Coin cell battery considerations

The CR2032 lithium battery is nominally rated at 3 V, with a total capacity around 220 mAh based on continuous current demand. These batteries are designed for low continuous standard load current. Furthermore, they have high source impedance, and cannot sustain high loads. In order to be able to support transient peak loads a parallel so-called super-cap, or large value reservoir capacitor, was employed to, in effect, absorb the transient currents. A summary of the CR2032 parameters is provided in [Table 2](#). (For more information see item 3 in [References](#).) Some of the manufacturers state the pulsed capacity at around 180 mAh.

Table 2. Lithium coin cell battery CR2032 specification

Characteristics	Value
Nominal voltage	3.0 V
Nominal capacity	220 mAh
Standard load current	0.2 mA
Internal resistance	10–40 Ω

It is clear from the table that this type of cell is intended for low/continuous current supply operation, and that a high peak transient current regime will adversely affect battery performance and lifetime. The load current which was used for test purposes was determined mainly by the MC1323x specification parameters. The large reservoir capacitor placed in parallel with the cell was effectively used to maintain the coin cell battery voltage during brief peak current demand phases.

4 Battery lifetime estimation

A preliminary estimate of the battery lifetime is presented below, and is based on average load current over time. It is used to illustrate the difference between the theoretical average estimation and the practical measurement resulting from pulsed discharging of the battery. To simplify matters, the table considers only Sleep (STOP3) and TX/RX current loads.

[Table 3](#) shows the average battery lifetime calculation for a repeated channel scanning procedure. A nominal battery capacity of 200 mAh has been used for estimation.

Table 3. Battery lifetime calculation (repeated channel scan procedure)

Repeated channel scan procedure each 1 s		
—	Sleep (STOP3)	RX/TX
Current consumption [mA]	0.001	30
Duration [ms]	968	32
Total time (24 hours) [s]	83635	2765
Integration during 24 h (Current in time) [mAs]	83.64	82944
Integration over 24 h (Current in time) [mAh]	0.02322	23.04
Able to run [days]	8.68	
Theoretical number of transmissions	749,245	

Battery lifetime estimation

Battery lifetime calculation for data transmission is displayed in [Table 4](#). A nominal battery capacity of 200 mAh has been used for estimation.

Table 4. Battery lifetime calculation (repeated data transmission procedure)

—	Repeated data transmission each 1 s		Repeated data transmission each 0.5 s	
—	Sleep (STOP3)	RX/TX	Sleep (STOP3)	RX/TX
Current consumption [mA]	0.001	30	0.001	30
Duration [ms]	995	5	495	5
Total Time (24 hours) [s]	85968	432	85536	864
Integration during 24 h (Current in time) [mAs]	85.968	12960	85.536	25920
Integration over 24 h (Current in time) [mAh]	0.02388	3.6	0.02376	7.2
Able to run [days]	55.19		27.69	
Theoretical number of transmissions	4,768,370		4,784,210	

Both tables above were derived by means of a battery calculator spreadsheet for the CR2032 lithium battery, based on the tested models. As may be seen from the illustration, the results are dominated by the pulse discharging (transmission RX/TX), in which the tested application spends relatively little time. The longer periods of sleep mode have comparatively little effect on the overall lifetime. In practice a real scenario would consist of a combination of channel scan and data Rx/Tx phases.

4.1 Peak current considerations

The impact of pulsed loads on the CR2032 coin cell was tested by using a specific duty cycle, based on typical 802.15.4 MAC operations. The intention was to investigate possible implementation for ZigBee Personal Area Networks (PANs). The results may be equally applied to other lower power radio interfaces, for example ZigBee-RF4CE and Bluetooth Low Energy. Typical load current profiles are seen during different phases of operation, such as sleep, pre-processing, transmit, and receive. [Figure 3](#) illustrates the typical current consumption profile.

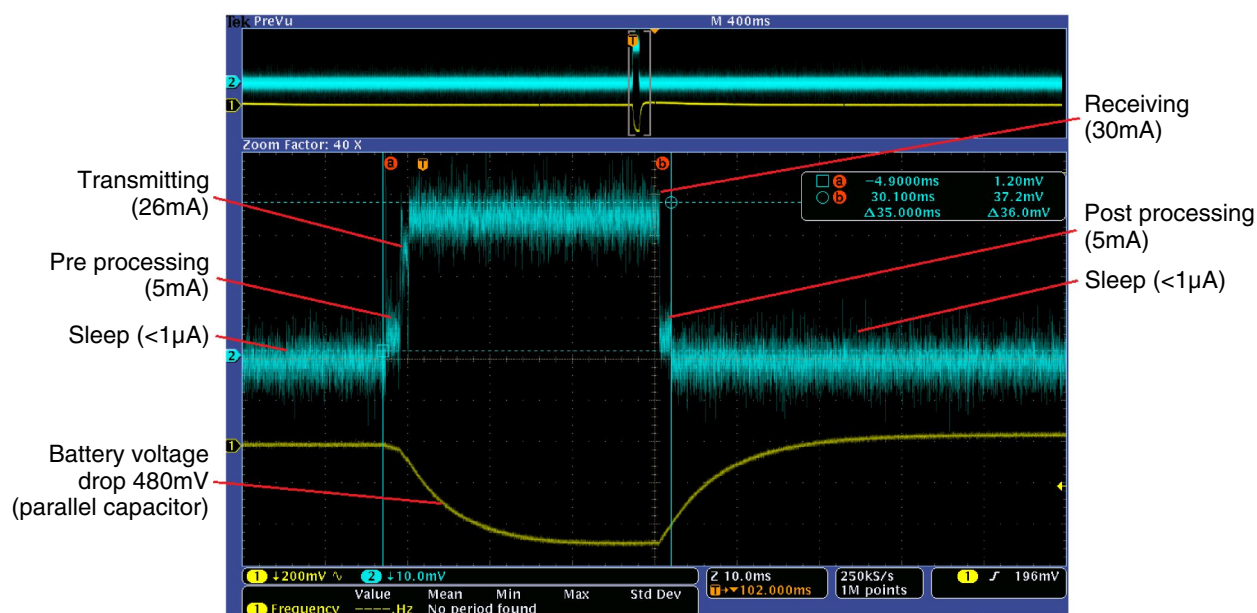


Figure 3. Current load characteristics with battery voltage drop (with parallel capacitor)

This situation corresponds to the case when the device is performing a channel scan. The device sends a beacon and waits for the beacon acknowledge from a coordinator. The shortest time during which the receiver can be on is defined by the ZigBee specification as a scan duration parameter. The receiver waiting procedure takes 31 ms. The application then goes into sleep mode, prior to scanning the next channel. Up to 16 channels, as defined by the 802.15.4 specification, may need to be scanned in this way.

The yellow curve denotes the battery voltage drop with the parallel capacitor, from which it is clear the capacitor becomes fully discharged. The amount of voltage drop corresponds to the internal resistance of the coin cell battery. The actual value of the internal resistance can provide valuable information about the condition of the battery. Manufacturer's data sheets indicate values in the range of 10 to 40 Ω . The situation in Figure 3 shows the value of the internal reference as 16 Ω (voltage drop 480 mV with actual current 30 mA). Internal resistance rapidly increases as the battery becomes fully discharged.

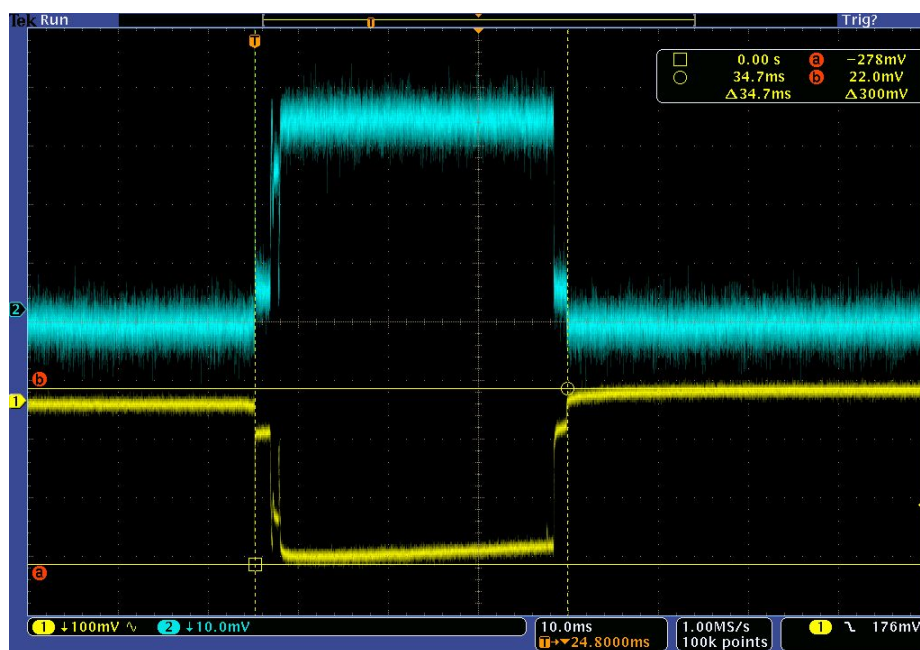


Figure 4. Current load characteristics with battery voltage drop (without parallel capacitor)

Voltage drop without parallel capacitor is shown in Figure 4, using the same beacon request scenario. (In this case the tested battery was brand new, which explains why the value of the voltage drop (300 mV) is smaller.)

Another experiment covers the situation when the transmitting and receiving window is shorter (5 ms) with the same current load. This corresponds to the situation when the ZigBee End Device needs to transmit (for example) 100 bytes of data. In this case the parallel reservoir capacitor is not fully discharged during the data transmission, as was the case in the previous scenario.

4.2 Parallel capacitor calculation

In this section, we provide an example calculation of how the parallel capacitor is able to maintain output voltage while under stress by the peak load current. A typical 802.15.4 MAC level interaction is used to illustrate the case.

To determine the drop in supply voltage from the capacitor:

$$\Delta u = \frac{1}{c} \times i \times \Delta t$$

Where: $C = 470 \mu\text{F}$, $i = 30 \text{ mA}$, $\Delta t = 35 \text{ ms}$.

The resulting voltage drop would be:

$$\Delta u = (1\,470e - 6) \times 30e - 3 \times 35e - 3 = 2.23V$$

Looking at it another way, it is possible to determine how long the capacitor can hold up before the voltage collapses to a point where the MCU would be forced to reset.

$$\Delta t = (C \times \Delta u) / i$$

Where Δu is assumed to be 1.2 V; nominal supply is 3 V and minimum voltage for the MC1323x is 1.8 V, as given in the specification.

Therefore

$$\Delta T = (470e - 6 \times 1.2) / 30e - 3 = 18.8 \text{ms}$$

This demonstrates that use of a large reservoir capacitor can support typical 802.15.4 MAC interactions. If multiple interactions are required, then it is necessary for the device to go to standby mode for a recovery period. The reservoir capacitor can easily support the battery during the non-continuous short data transmission process, for example, 5 ms bursts. However in the longer term, the transmissions will definitely cause the battery voltage level to drop, as determined by the internal battery resistance, which increases as the battery nears the end of its life. The choice of capacitor value is ultimately dependent on the demands of the application.

Another factor to take into account is capacitor leakage current, which can also decrease battery lifetime. The capacitor leakage current can continuously discharge the battery and depends on factors such as the capacitor value, the nominal voltage rating, and the production process technology used.

5 Experimental results

Several test scenarios were considered in order to obtain a realistic expectation of the battery lifetime, for the peak transient current use case. Practical measurements were required to be able to assess whether or not the coin cell could withstand the anticipated discharge characteristics. The sections below illustrate the practical measurement results.

5.1 Measurement setup

A small firmware application was developed for test purposes for the MC1323x device, and was assembled onto the small IPB development board designed for use in low-power applications. The measurement setup is shown in Figure 5. The large reservoir capacitor was placed in parallel with the CR2032 and a 1 Ω series resistor used to monitor the behavior of the supply current.

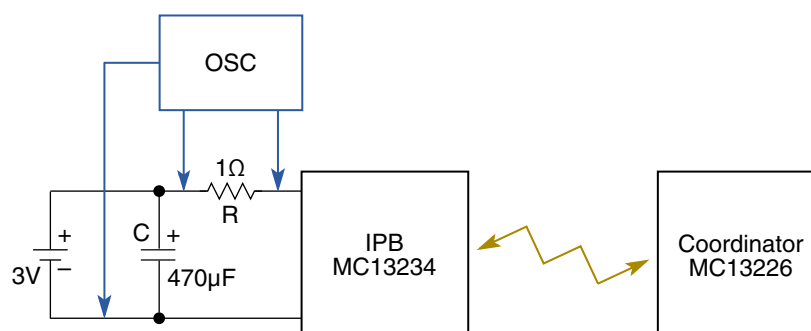


Figure 5. Block diagram of the measurement scenario

The firmware application was used to set transmit beacon or data packet to defined time intervals. The end device application goes into the deep sleep mode for the rest of the time. The coordinator was set up to respond with a MAC acknowledge only. Capturing the over-the-air communication gave a value for the number of transmits during the test. The data packet also provided the same information by incrementing the value of packet the timestamp. Beacon tests were examined with, and without, the parallel reservoir capacitor being present.

5.2 Measured results

Table 5 describes the practical measurement results. The scenarios tested were designed to emulate practical conditions which can occur in operational ZigBee networks. For example, the active scan procedure is designed to transmit a beacon signal and wait for an acknowledge. The shortest waiting time is defined by the ZigBee specification (IEEE 802.15.4) as 31 ms. (Hence the power supply must provide ~30 mA for this 32 ms period.) The receiver must be kept enabled throughout this period. The active scan procedure occurs when the ZigBee node tries to find a coordinator (or router) on the 16 possible

Experimental results

frequency channels defined in 802.15.4. Another test was made with repeated data transmissions of 100 bytes at intervals of 1.0 and 0.5 seconds. The default transmitter power level for this test was set to -1 dBm. The measurement results show two different scenarios: repeated beacon scans and repeated data transmissions.

Table 5. Measurement results

—	Number of TX/RX [–]	Corresponds to theoretical battery capacity [mAh]	Battery capacity utilization [%]	TX/RX duration [ms]
Repeated scan procedure at 1 s intervals	543,685	145	72.5	32
Repeated scan procedure without parallel cap at 1 s intervals	498,990	133	66.5	32
Data transmission (1 s)	3,055,015	154	77	5
Data transmission (0.5 s)	2,228,022	111	55.5	5

The theoretical capacity is given by the integration of load current in time. The beacon scan phase is approximately six times more demanding than the basic data transmission. The tests were made over a number of days with these settings. The table also emphasizes how the battery capacity is diminished by heavy current demands.

Results also indicate that a longer battery recovery time between each data transmission leads to better overall utilization of the battery capacity. In effect, the battery needs time to recover following each discharge episode. Data transmission at 0.5 s intervals has the smallest theoretical battery capacity usage. The repeated scan procedure without the parallel capacitor indicates a lower battery capacity utilization than the same case with the reservoir capacitor.

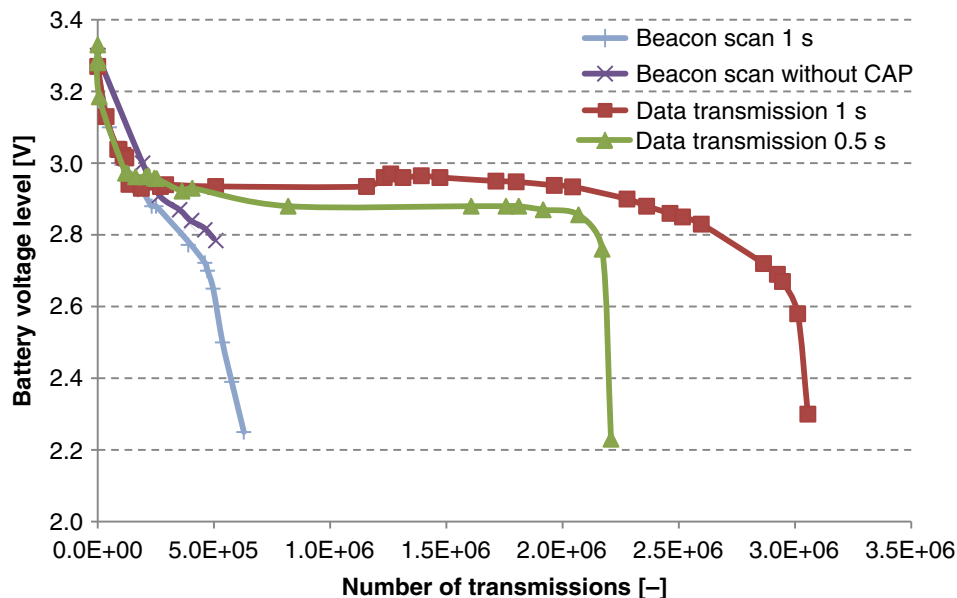


Figure 6. Battery voltage level varying with the number of transmissions

The results are portrayed graphically in [Figure 6](#), showing battery voltage level varying with the number of data transmissions. The voltage level was measured during the sleep period of the device. Four scenarios were evaluated:

1. Repeated scan procedure with parallel capacitor
 - The capacitor supported the battery voltage level during the load current. The IPB board went into reset when the voltage level decreased below 2.3 V.

2. Repeated scan procedure without parallel capacitor
 - When the battery voltage level fell under 2.8 V, the voltage drop had a large impact (increasing the value of internal resistance) and caused the reset of the device (1.8 V limit).
3. Data transmission of 100 bytes at 1 s intervals with the parallel capacitor
 - This test case had the best results overall, with respect to the battery capacity utilization. The board went into reset when the voltage level dropped below 2.3 V.
4. Data transmission of 100 bytes at 0.5 s intervals with the parallel capacitor
 - This scenario indicates the lowest battery utilization, probably caused by the reduced recovery time.

These experimental measurements provide a clear picture of how the coin cell behaves under pulsed discharge conditions. Preliminary optimistic estimates given by integration of load current in time were compared with the actual measured results. The best case result of battery utilization (77 %) was found to be that for data transmission at 1 s intervals. The nominal capacity of 200 mAh as specified by battery manufacturers corresponds to the 100 % level.

The value of voltage drop corresponds to the state of actual internal resistance. Practical tests demonstrate the voltage dropped during the period under observation, from approximately 120 mV to 1100 mV. The use of the parallel capacitor significantly affects the rate at which the internal resistance increases.

5.3 Mitigation techniques and best practices

In the foregoing sections it was shown how a Freescale RF transceiver node (MC1323x) could be powered from a CR2032 coin cell for use with typical ZigBee radio operations. Based on actual laboratory measurements made, it is possible to infer a number of recommendations on how to obtain the best possible usage from the battery.

- A good indication of the state of the battery can be seen via the measure of internal battery resistance. This has a direct correspondence to the voltage difference across the battery terminals, between loaded and unloaded conditions. It is proportional to the remaining battery capacity and, as was seen, increases rapidly as the battery nears the end of life.
- Coin cells work best with more constant, lower current demand, than with high peak transient currents. Battery capacity is significantly reduced by this type of usage.
- Use of a large value reservoir capacitor can help to absorb the transient peaks and hence protect the battery and help maintain mAh capacity.
- When selecting a reservoir capacitor, a low leakage value is very important.
- Short peak current transients, followed by long recovery times, are better for a coin cell battery. For example, channel scan for 30 ms @ 30 mA, followed by 0.5 to 1.0 seconds in Stop mode, will allow ample time for the battery to recover.
- Close attention needs to be paid to the MCU firmware configuration when in Stop mode, to avoid any possibility of floating pins. All ports not in use must be grounded to avoid this situation.

6 References

1. Freescale document MC1323x, "MC1323x Low Cost SoC Remote Control Platform for the 2.4 GHz IEEE® 802.15.4 Standard"
2. Freescale document MC1323xRM, *MC1323x ZigBee™- Compliant Platform 2.4 GHz Low Power Transceiver for the IEEE® 802.15.4 Standard plus Microcontroller Reference Manual*
3. Energizer CR2032 battery data sheet
4. Freescale document 1323xIPBRM, *1323x-IPB Reference Design Reference Manual*, Rev. 1.0

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Japan:

Freescale Semiconductor Japan Ltd.
Headquarters
ARCO Tower 15F
1-8-1, Shimo-Meguro, Meguro-ku,
Tokyo 153-0064
Japan
0120 191014 or +81 3 5437 9125
support.japan@freescale.com

Asia/Pacific:

Freescale Semiconductor China Ltd.
Exchange Building 23F
No. 118 Jianguo Road
Chaoyang District
Beijing 100022
China
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