Extending Battery Life of Wireless IoT Devices

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Introduction

Wireless IoT devices are becoming increasingly more prevalent. For example, wearable devices are often used for remote monitoring and logging vital signs to assist in the detection and treatment of diseases and medical anomalies. Wireless body sensors upload vitals via an internet hub or personal server such as the owner's smart phone. To continuously monitor and upload vital data, wireless wearable devices need to maintain long-term connectivity to the cloud. Key to continued rapid growth of wearable devices is reduced device size, longer battery life and ubiquity of smart phones that use Bluetooth Low Energy (BLE) to connect to these devices.

Wearable monitoring devices are designed to collect and compress data (metadata), send it to the cloud via internet hub devices in short bursts, and then go to sleep to conserve power. Battery life depends in part on the power consumption of the wireless radio and interface protocol deployed in the design.

Designers of wearable sensor devices choose BLE low power wireless communication standards architect to satisfy the demands of short-range wireless applications. Using a few passive components, any of these transceivers can be interfaced to a low-cost microcontroller via UART, SPI or USB and can fit a small footprint ideally suited for monitoring human vital signs or other sensing applications.

Which Wireless Standard has the Lowest Power?

Independent studies comparing the top three wireless standards have shown that BLE has the lowest power consumption in a cyclic sleep scenario typical of a network of wireless body sensors [1],[2]. The cyclic sleep scenario is a typical use case for these battery powered devices wherein the device core is shut down for a pre-set time called “sleep time” typically in the range of 2 to 10 seconds and “woken” when it needs to transmit vitals during a short burst lasting a few milliseconds. This translates to a low duty cycle activity scenario which leads to lower average power consumption as illustrated in Figure 1.

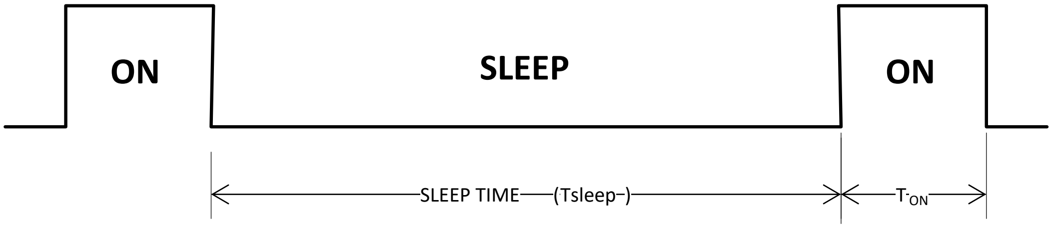


Figure 1: Cyclic sleep activity scenario; Average power is directly proportional to duty cycle (Ton/Tsleep)

In one experiment, average power consumption was measured across various sleep intervals on three wireless modules [1]. The results of the power consumed across the various RF modules shown in Figure 2, indicate that the BLE protocol consumes the least amount of power compared to ANT and ZigBee irrespective of sleep intervals. The data also shows power consumption scales inversely with sleep interval across all three RF standards in a cyclic sleep activity scenario.

Given the ubiquity of the smart phone and its native support for Bluetooth 5.3 and higher, BLE is ideally suited for wearable devices. In specific environments, where smart phone use is prohibited, the use of a BLE-to-Internet bridge may be used as an alternative.

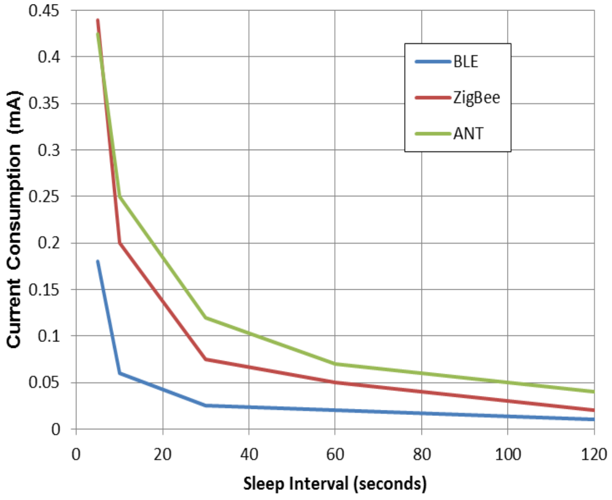


Figure 2: Average current consumption of the three wireless standards vs. sleep interval

BLE in an IoT Device

A typical wireless IoT device comprises a low power BLE SoC interfacing to biometric sensors with a RF front-end as shown in Figure 3.

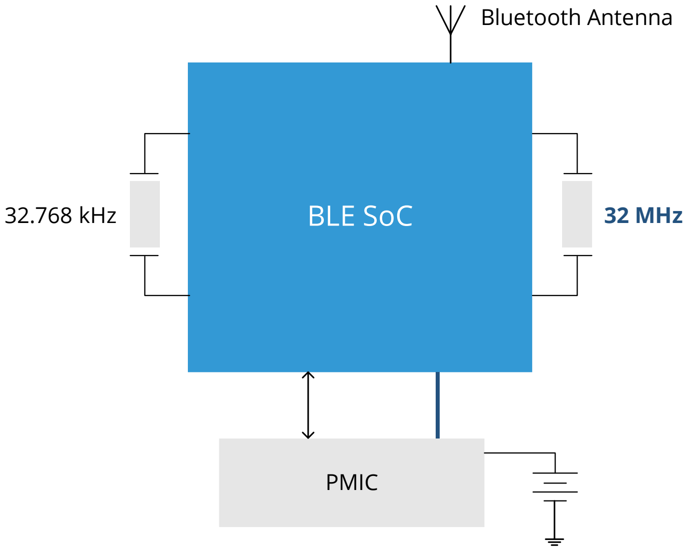


Figure 3: Simplified block diagram of an IoT device using a BLE SoC with MHz and 32 kHz crystals

The low power BLE SoC runs off the following clock sources:

- MHz crystal resonator (32 MHz is the most common): used for clocking BLE SoC device while in actives modes (RX, TX)
- 32.768 kHz crystal resonator: used for real-time clock (RTC), watch-dog timer and sleep clock. Frequency Stability is typically 200 ppm for -40°C to 85°C.

Empirical measurements have shown power consumption of a BLE device is inversely proportional to the time it spends in the "sleep" state, and the sleep clock accuracy (SCA) of the 32 kHz clock used to time this "sleep" state has a direct impact on the battery life of the device. To understand this, let's briefly review how a BLE Peripheral (wearable device) and a "paired" BLE Central (internet hub or smart phone) establish a connection event. A scope capture of the dynamic I_{DD} timing of a BLE Peripheral is representative of the connection event timing profile of a BLE device as shown in Figure 4.

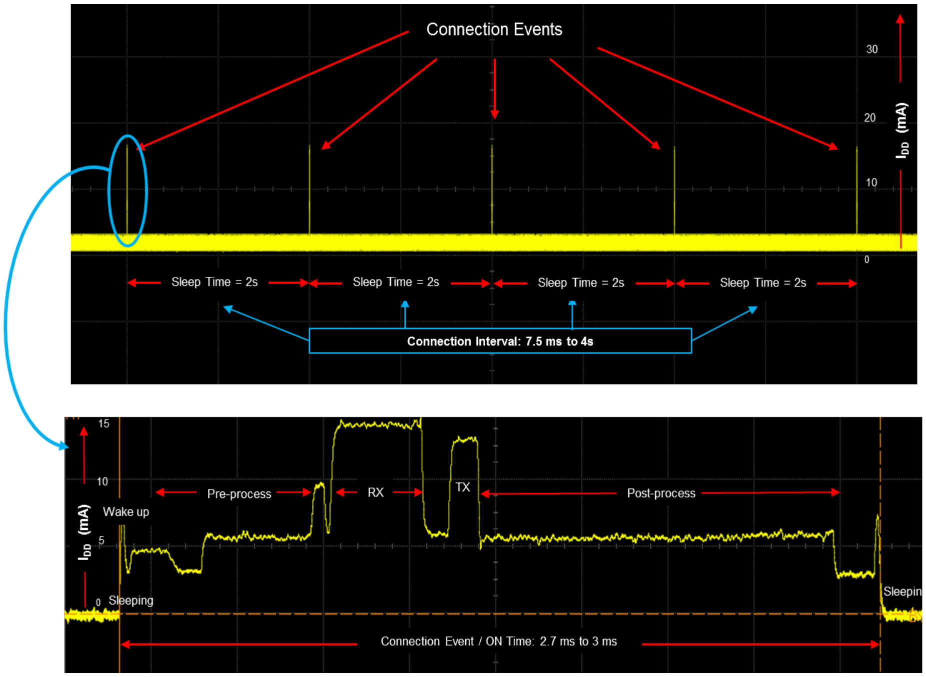


Figure 4: Connection event Timing Profile of a BLE SoC with I_{DD} current scope measurements

Note that the BLE standard calls out “sleep time” by the term “connection interval”; range: 7.5 ms to 4s.

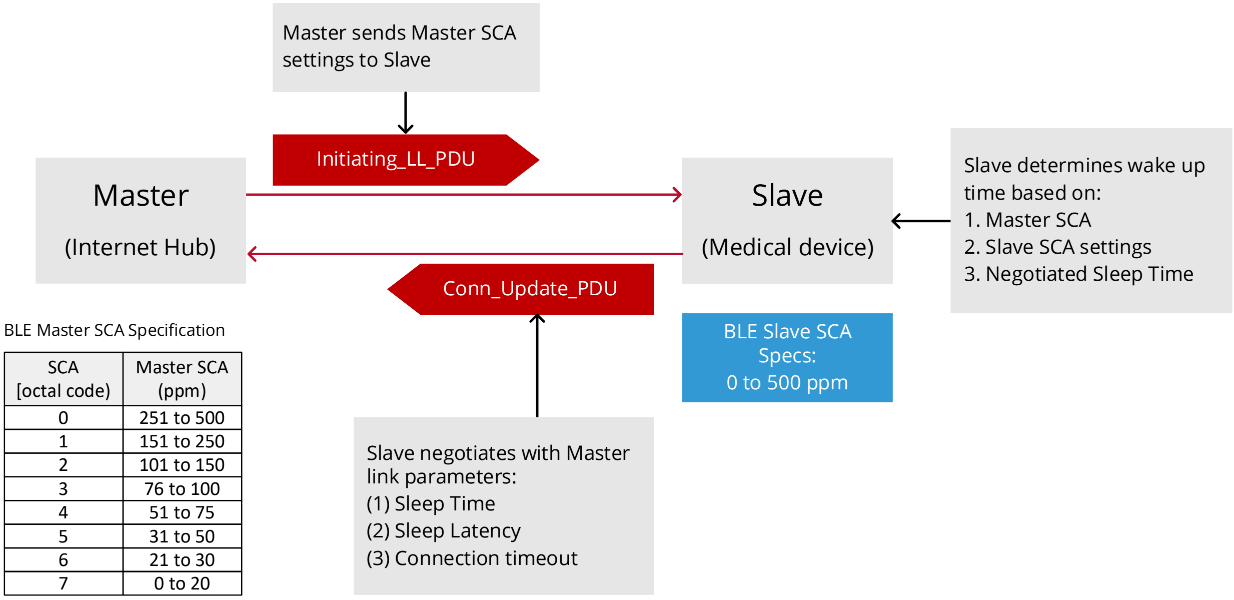
The connection event is the “ON” time during which certain functional blocks of the device wake up and stay active for short periods in the range from 0.08 ms to 1.3 ms as shown in the zoomed scope snapshot in Figure 4.

The following link parameters are negotiated by the BLE Peripheral with BLE Central during every connection event:

- Connection interval (sleep time)
- Sleep latency
- Supervisory timeout

A sleep latency value of N (N < 500) extends the sleep time by N connection intervals. Example: connection interval = 2 s and sleep latency = 5 extends the sleep time to 2 x 5 = 10 seconds. The link parameter, supervisory timeout, is used by the Central to terminate the connection if a “paired” Peripheral does not respond within an agreed upon period range: 100 ms to 32s.

To further understand the impact of the 32 kHz sleep clock accuracy (SCA) let’s review the link-layer (LL) messages exchanged between a “paired” Central and Peripheral device while establishing a connection event as illustrated in Figure 5.



BLE Master SCA Specification

SCA [octal code]	Master SCA (ppm)
0	251 to 500
1	151 to 250
2	101 to 150
3	76 to 100
4	51 to 75
5	31 to 50
6	21 to 30
7	0 to 20

Figure 5: BLE Central/Peripheral handshake for link parameters while establishing a connection event

During every connection event, the Central sleep clock accuracy (Central SCA) is communicated to the Peripheral. The Peripheral determines when to wake up during consecutive connection events based on a combination of the following:

- Last negotiated connection interval
- Central SCA
- Its own sleep clock accuracy (Peripheral SCA)

Due to inaccuracies of the sleep clocks involved, there’s a certain level of uncertainty in the time when the Peripheral wakes up from sleep to listen to packets from the Central. Due to this uncertainty, the Peripheral wakes up and starts listening (receiver turned ON) earlier – a process called “window widening”. As per the Bluetooth 5.3 specification volume 6, this window widening or early turn on time, ΔT is given by the following formula:

$$\Delta T = \text{windowWidening} = ((\text{CentralSCA} + \text{PeripheralSCA})/1000000)*(\text{last connection interval}))$$

Where:

- Central SCA is sleep accuracy of the Central 32 kHz sleep clock in ppm
- Peripherals SCA is sleep accuracy of the Peripheral 32 kHz sleep clock in ppm
- Last connection interval is the last successful established connection interval in seconds

This window Widening or early turn on time, ΔT due to sleep clock inaccuracies is illustrated in Figure 6.

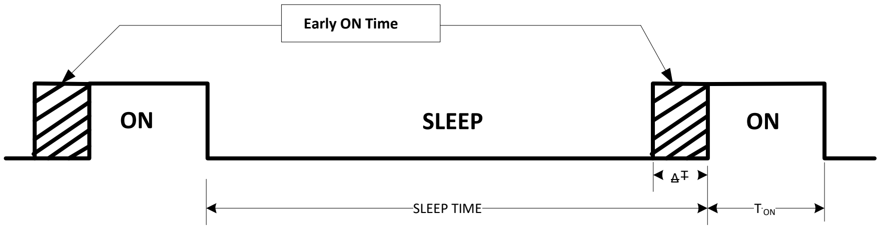


Figure 6: Connection event profile due to sleep clock inaccuracies

This “window widening” directly translates to the width widening of the Peripheral RX window shown in Figure 6. To quantify the RX window width across various SCA settings, we measured the current profile of a BLE Peripheral in a test setup (see Figure 7) like the one referenced in the TI BLE Application Note [3].

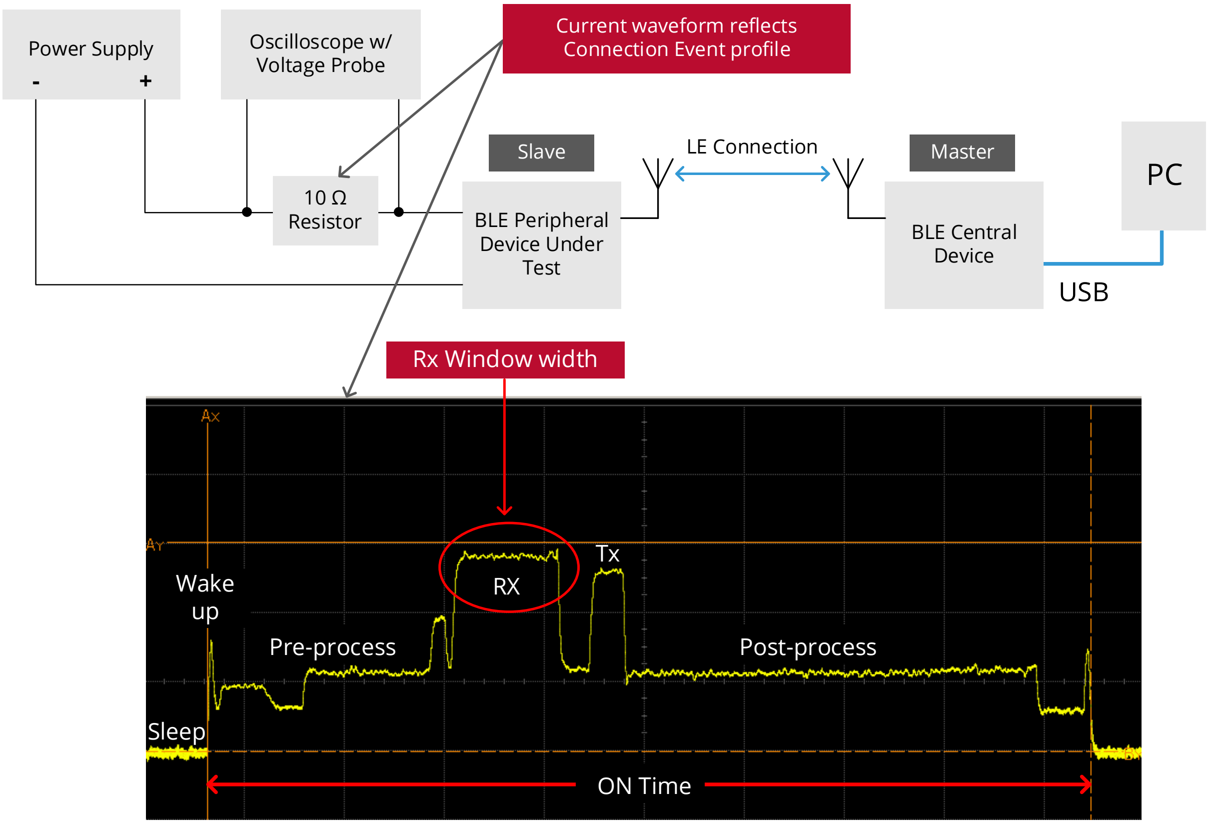


Figure 7: Measuring RX Window width on a BLE Peripheral with varying sleep clock accuracy.

The link parameters programmed into the Peripheral:

- Connection interval = 2s
- Latency = 0
- Supervisory timeout = 32s

The 32 kHz crystal on the BLE Peripheral was replaced with a high accuracy 32 kHz 5 ppm TCXO (SiT1552 from SiTime); Peripheral SCA = 5 ppm. A vendor provided GUI was used on the host PC to sweep the Central SCA values: 20 to 500 ppm in eight steps. For each Central SCA setting, the RX width during a connection event (ON time) was measured.

Table 1: Impact of sleep clock accuracy (SCA) on the width of Peripheral RX window

CentralSCA 3-bit Field	PeripheralSCA (ppm)	CentralSCA + PeripheralSCA (ppm)	RX Width µs	Link Integrity with 32 kHz TCXO (5 ppm)	Link Integrity with 32 kHz Crystal (200 ppm)
7 (20 ppm max)	5	25	227	Good	Time-out

The RX width measurements listed in Table 1 correlate with the equation for window widening – width increases proportionately as the combined SCAs.

Extending Battery Life

Due to the use of a BLE SoC which turns on during short bursts of a few milliseconds, most of the system power during ON time is dictated by the BLE RF front-end in a wireless medical device. As explained earlier, 32 kHz sleep clock inaccuracies cause the BLE radio receiver (RX) to turn on earlier and stay on longer to avoid missing packets from the Central thereby increasing the power penalty.

Sleep Interval Sleep Clock Accuracy	2 Seconds	20 Seconds	50 Seconds
	Early ON Time		
5 ppm	0.01 ms	0.1 ms	0.25 ms
50 ppm	0.10 ms	1.0 ms	2.5 ms
70 ppm	0.14 ms	1.4 ms	3.5 ms
200 ppm	0.40 ms	4.0 ms	10.0 ms

- T_{ON} = 3 ms (typical)
- For 5 ppm sleep clock (SCA = 5) and 20 seconds sleep time, $\Delta T1 = 0.1$ ms
- For 200 ppm sleep clock (SCA = 200) and 20 seconds sleep time, $\Delta T2 = 4.0$ ms

The average system current consumption follows the formula below:

$$I_{AVG} = (T_{sleep} * I_{sleep} + (T_{ON} + \Delta T) * I_{active}) / (T_{sleep} + T_{ON} + \Delta T)$$

Figure 8 compares the average system current consumption for a traditional 200 ppm stability Xtal, a more expensive 100 ppm stability Xtal and SiT1552 (5 ppm 32 kHz TCXO). As the plots demonstrate, the system current consumption is lower when the sleep interval is longer, but in all cases both Xtal solutions consume higher power than SiT1552. Battery life is inversely related to the average system current consumption. Therefore, SiT1552 delivers a longer battery life than both Xtal solutions for all sleep intervals. For instance, for a sleep interval of 50 seconds, the SiT1552 can achieve a battery life 1.46 times longer than using a traditional 200 ppm Xtal and 1.17 times longer than an expensive 100 ppm Xtal.

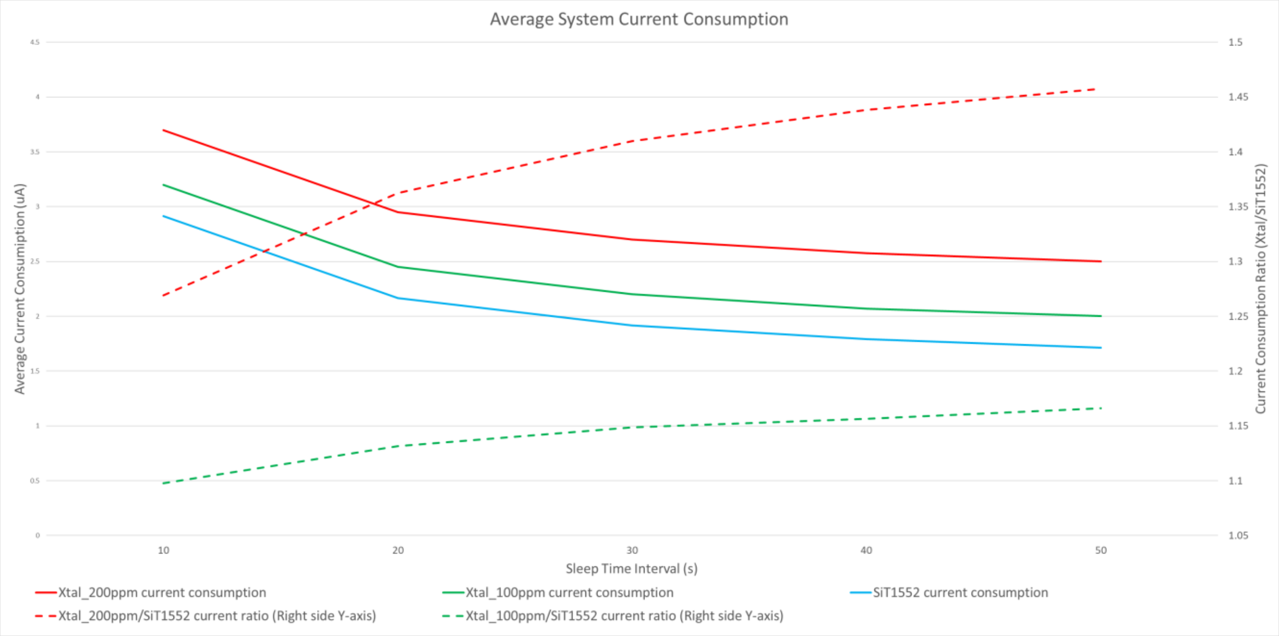


Figure 8: System current consumption among Xtal 200 ppm, Xtal 100 ppm and SiT1552 TCXO

Power Optimized IoT Devices

Designers of wearable devices now have an alternative higher accuracy 32 kHz sleep clock to accurately wake up after extended sleep times with optimized radio RX window widths. SiTime's MEMS based 32.768 kHz TCXOs (SiT1552, SiT1566, SiT1568 and SiT1580) are alternatives to the 200 ppm 32 kHz crystal-based sleep clock sources used in past designs [4]. They have ±5 ppm frequency stability across -40° to 85°C, and come in a small CSP package (1.5 x 0.8 mm), consuming 25% less PCB area than the smallest mainstream crystal resonator (1.6 x 1.0 mm). An optimized version of the wearable device architecture using the SiT1552, SiT1566, SiT1568 and SiT1580 TCXO is shown in Figure 9.

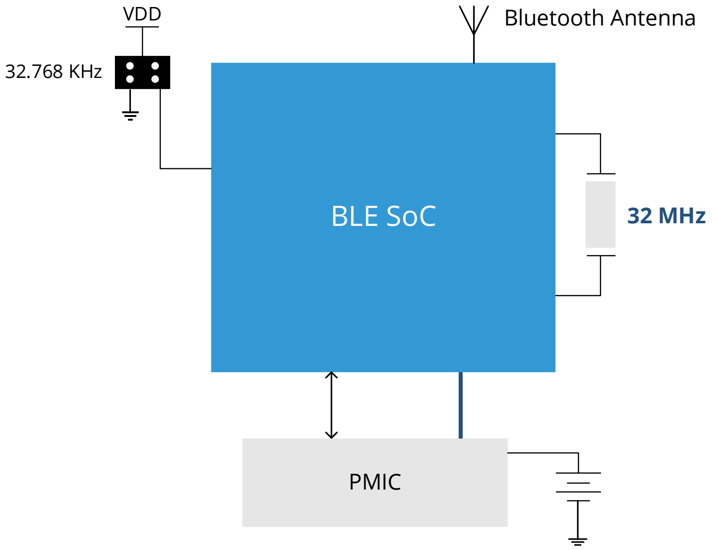


Figure 9: Optimized system architecture of a BLE SoC using SiT1552 TCXO instead of traditional 32 kHz crystal

Using a SiT1552, SiT1566, SiT1568 or SiT1580 TCXO instead of the BLE SoC sleep clock 32 kHz crystal enables system designers to leverage compression and transmit vitals in short bursts only when requested while keeping the device in its lowest power sleep state for extended periods, thus potentially achieving up to 1.45x the battery life.

References

[1] A. Dementeyev, S. Hodges, S. Taylor and J. Smith, "Power Consumption Analysis of Bluetooth Low Energy, ZigBee, and ANT Sensor Nodes in Cyclic Sleep Scenario," in *IWIS*, Austin, 2013.

[2] R. Tabishi, M. B. Adel and F. G. A. Taouti, "A Comparative Analysis of BLE and 6LoWPAN for U-healthcare Applications," IEE GCC, Quatar, 2013.

[3] Texas Instruments, CC2652R: Power consumption and latency estimation when transmitting multiple packets, April 2024

[4] SiTime Corp, Datasheet
- SiT1552 Datasheet
- SiT1566 Datasheet
- SiT1568 Datasheet
- SiT1580 Datasheet

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