RF Front-End Modules Boost Wireless Performance

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Not all front-end solutions for Bluetooth® Low Energy, Wi-Fi, or Zigbee applications are created equal. That is the inescapable conclusion of some tests comparing popular system-on-chip (SoC) platforms with and without Skyworks Solutions front-end modules (FEMs).

Tests examined output power versus transmit (TX) current, data rate versus range (for high and low data rates), and current consumption per bit.

Before we get into the test results, let's provide some background on the components used. The main characteristics of the FEMs reviewed are listed in Table 1.

For example, the SKY66112 is a 2.4 GHz, fully-integrated radio frequency (RF) FEM designed to support Zigbee, Thread and next-generation Bluetooth 5.x wireless networking protocols. For starters, the SKY66112 high RF output power is well-suited to the new Bluetooth 5.x standards for enhanced connection range. This is important since the standard has emerged with 4x range, 2x speed, and 8x broadcasting message capacity when compared to the previous version, increasing functionality for the Internet of Things (IoT).

This particular FEM produces as much as 40x the RF output power of the SoC radio alone (+21 dBm versus +4 dBm). It can increase receive (RX) sensitivity up to 6 dB, approximately doubling the receive range of a typical IoT device. It also handles RF input power levels up to +15 dBm, allowing the receiver to function in the presence of high-power, co-located Wi-Fi access points, which is likely to be a common scenario in IoT environments.

The SKY66112 integrates all transmit and receive functions in a module measuring only 3.5 × 3.0 × 0.96 mm. In addition, it reduces total system current (Icc) by as much as 38% when compared to an SoC alone delivering the same transmit output power.

Similarly, the devices in Table 1 are high-performance, fully integrated RF FEMs designed for Zigbee, Thread and Bluetooth smart applications such as smart thermostats, in-home appliances, beacons, gateways, sensors, and wearable devices. Designed for ease of use and maximum flexibility, the devices provide an integrated inter-stage matching and harmonic filter and digital controls compatible with 1.6 V to 3.6 V complementary metal oxide semiconductor (CMOS) levels.

The RF blocks operate over a wide supply voltage range from 1.8 V to 3.6 V that allows the FEMs to be used in battery powered applications over a wide spectrum of the battery discharge curve.

In addition, the FEMs can support Bluetooth functions with Enhanced Data Rate (EDR), which is important because it differentiates these FEMs from most other products on the market.

	SKY66111	SKY66112	SKY66113	SKY66403	SKY66404	SKY66405	SKY66407	SKY66408	SKY66409	Units
TX power	6 to 13	21/16/13	SoC - 1 dB (bypass)	21/16/13	13/17	13	11.5	-0.7 to 21	13 to 15 (EDR:10.5)	dBm
TX current	10 at 10 dBm	90 at 20 dBm	25 (μA)	97 at 20 dBm	42 at 17 dBm	16 at 13dBm	13 at 11.5 dBm	115 at 21 dBm	13 at 10 dBm	mA
RX noise figure (NF)	0.9 (bypass)	2	2	2	2.5	2	1 (bypass)	2.5	2.5	dB
RX current	25 (μA)	4	4	4	3.5	3.5	4	9	1.5	mA
Sleep current	<1	<1	<1	<1	<1	<1	<1	<3	<1	μA
Dual antenna support	No	Yes	No	Yes	Yes	No	No	Yes	No	
Bluetooth EDR support	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Supply voltage	1.8-5	1.8-3.6	1.7-3.6	1.8-3.6	1.7-3.6	1.7-3.6	1.7-3.6	1.7-3.6	1.8-3.6	V
Size	3.3 x 3	3.5 x 3	2.4 x 2.4	3.5 x 3	3.5 x 3	1.9 x 1.9	1.2 x 1.2	3 x 3	1.25 x 1.7	mm

Table 1. Skyworks Front End Modules for Bluetooth and Zigbee Applications

Low Energy Application SoCs for Bluetooth Applications

Most low energy devices today are SoCs. Their current consumption profile has a large effect on end product lifetimes.

The tests conducted pair SoC platforms that perform baseband functions, analog-to-digital conversion, and overall subsystem control with and without Skyworks FEMs. The examples used include some of the most popular options for Bluetooth Low Energy and Zigbee functionality from leading manufacturers (Table 2). Although details on the SoCs are, by agreement, excluded from this discussion, we would be remiss not to mention that the Skyworks FEMs are designed into reference designs with products from (alphabetically) Dialog Semiconductor, Nordic Semiconductor, NXP, Semtech, Silicon Labs, and Texas Instruments, among others.

Zigbee: Current Versus Output Power and Receive Sensitivity

For Zigbee applications, and even with a high-power (+20 dBm) SoC, Skyworks FEMs provide compelling advantages in transmit current, receive sensitivity and dual antenna capability. SoC 4 (Table 2) has an onboard high-current DC-DC converter that can be used to supply its own radio as well as external loads. The DC-DC converter was used to power the FEM for one of the Pout versus Icc tests.

To conduct the tests, the evaluation board for SoC 4 was connected to the evaluation boards for the SKY66112 and SKY66113 FEMs. The SoC antenna connector output was connected to the RFIN port on the FEM.

For TX Pout versus Icc measurements, the SoC was placed in a continuous modulated transmit state. The system (SoC + FEM) Icc was measured and compared versus the SoC alone.

For receive sensitivity measurements, the SoC was placed in a shielded box. The input signal power was swept while recording the Packet Error Rate. The experiment was repeated with the combined SoC and FEM. Figures 1, 2, and 3 illustrate the test results associated with SoC 4, SKY66112, and SKY66113.

	Bluetooth Low Energy Applications			Zigbee Applications	
Parameters	**SoC 1**	**SoC 2**	**SoC 3**	**SoC 4**	**Units**
TX power	3.5	-1	0	19.5	dBm
TX current	16	4.8	5.9	133	mA
RX sensitivity	-93	-92.5	-94	-101	dBm
RX current	13	5.1	5.8	9.8	mA

Table 2. SoCs used in the lab tests.
The selection includes some of the most popular options from leading vendors.

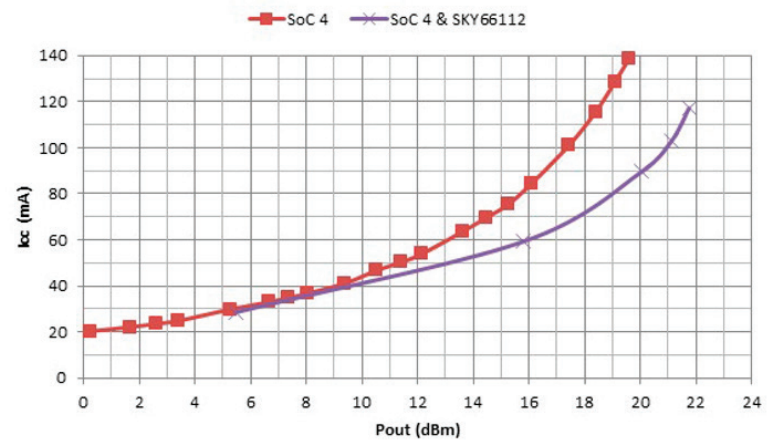

Figure 1. Pout vs. Icc for SoC Only vs. SoC and FEM

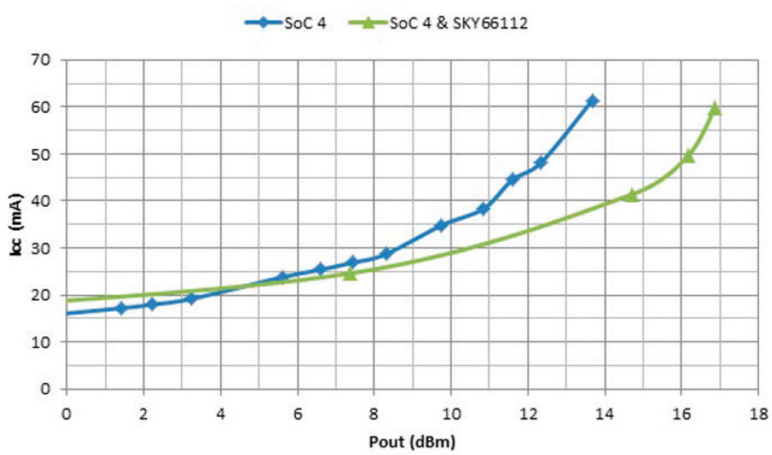

Figure 2. Pout vs. Icc with DC-DC Enabled

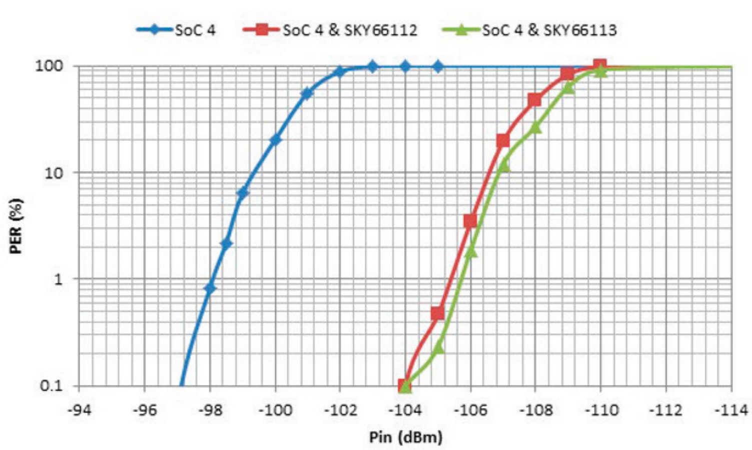

Figure 3. PER vs. RX Power for SoC only vs. SoC and FEM

Range Advantage

To determine the range improvement provided by combining an SoC with an FEM, custom printed circuit boards (PCBs) were designed integrating SoC 2 with the SKY66111 FEM and SoC 3 with the SKY66112 FEM. The SoC 1 development kit and the two custom PCBs were used as transmitters in this range test. They were configured to continuously transmit Bluetooth Low Energy packets.

A standard USB dongle for Bluetooth Low Energy applications based on SoC 2 was used as the receiver for the range test. The Received Signal Strength Indicator (RSSI) measurement from the dongle was continuously monitored as the distance from the transmitter was increased.

Three sets of range tests were conducted:

1. An outdoor environment (busy covered parking garage) with transmitter inside a car,
2. An indoor office environment with line-of-sight (LoS), and,
3. An indoor office environment, non-line-of-sight (through metal cubicle walls).

RSSI at the receiver was measured and plotted versus distance from the transmitter for the three boards.

Taking a step back, RSSI is a measurement of how well a device can hear a signal. It is a value that is useful to determine if you have enough signal to get a good wireless connection. RSSI varies greatly between chipsets, which is why RSSI is a relative index and not an absolute value. But you can infer that the higher the RSSI, the better the signal. RSSI and dBm are different units of measurement, but both represent the same thing–signal strength. The difference is that RSSI is a relative index, while dBm is an absolute number representing power levels in milli-Watts (mW).

Figures 4, 5, and 6 show test results for Current vs. Output power and RX sensitivity in Zigbee applications. The results are stated in dBm, and the superior performance of SoC 3 and SKY66112 and SoC 2 and SKY66111 compared to SoC 1 alone is evident.

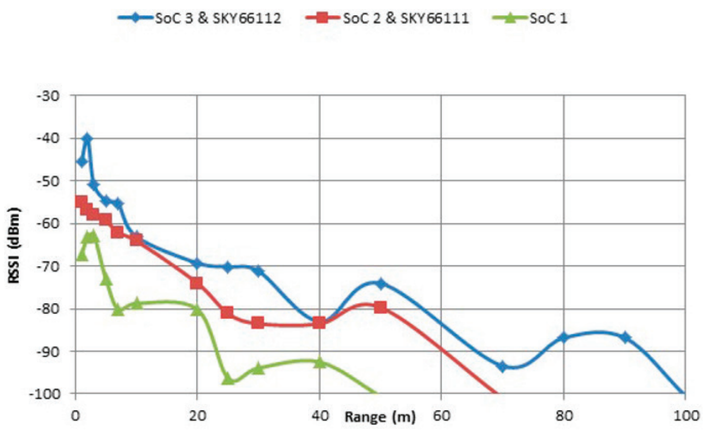

Figure 4. Range vs. RSSI, Parking Garage

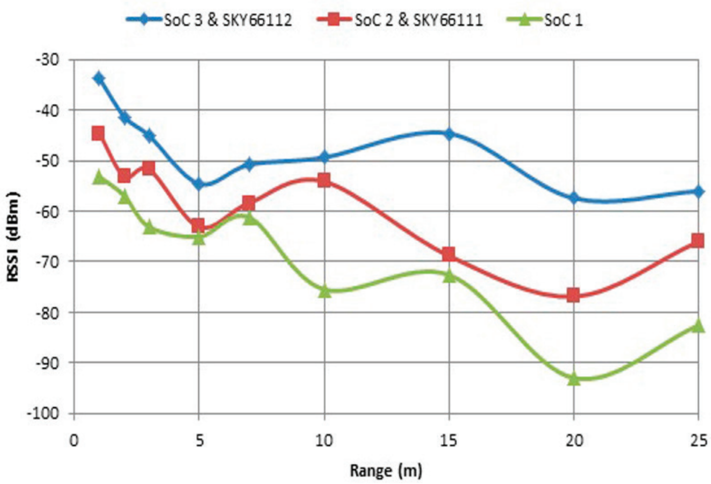

Figure 5. Range vs. RSSI, Indoor with LoS

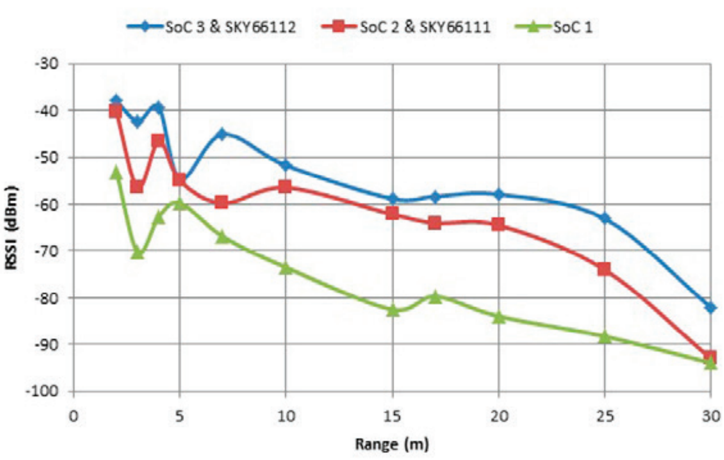

Figure 6. Range vs. RSSI, Indoor non-LoS

Transmit Output Power Versus Current Test

Battery life is a key aspect of user experience in battery-operated, handheld/mobile devices. Since more often than not current consumption is the deciding factor to procure design wins, it is given priority by designers. Power consumption for the device can vary widely depending on the use of on-chip resources. Therefore, to determine consumption, you must understand the components of the device in use and the usage patterns for those components.

It is also important to recognize that software components used (operating system, user interface customizations, and driver optimizations) can also have a significant impact on power consumption of a specific device.

Chipset low energy current consumption is affected by four factors:

1. The power output of the device—the higher the output power, the more current is required. Some low energy radios consume 20 mA or more when transmitting.

2. The amount of data sent—larger packets require the radio to stay on the air longer, drawing more current.

3. The selected low energy advertising interval—low energy connectable advertising packets (adverts) are broadcast at a configurable constant rate. Each packet may contain up to 20 bytes of useful payload and requires up to 376 µs of radio on-time to send.

4. The processor (typically an ARM Cortex-M0, M3 or M4)—the different layers of the low energy stack all require certain amounts of processing in order to remain connected and comply with protocol specifications. A microcontroller unit (MCU) takes time to perform this processing, and, during this time, current is consumed by the device. The processor can draw several mA when running.

To quantify battery life and compare power consumption differences between different FEMs and SoC chipsets, a custom PCB was designed integrating SoC 1 with the SKY66111 FEM. The custom PCB was compared with the standard SoC 1 development kit. The SoC was then placed in a continuous modulated transmit state. Conducted output power from the SoC was swept in software and measured using an RF power meter (Figure 7).

Concurrently, the system (SoC 1 by itself versus SoC 1 and SKY66111 together) Icc was measured using a precision digital multimeter to take measurements and using the formula:

$$\textit{Power} = \textit{voltage} \times \textit{current}$$

Test results show that compared to using a bare SoC, the SKY66111 FEM offers the choice of 15% current savings or an 8 dB boost in output power.

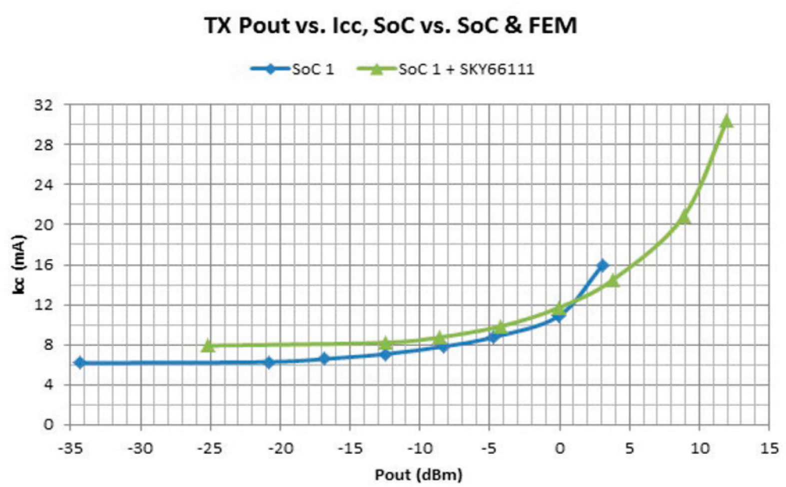

Figure 7. Transmission Power vs. Total System Current

Data Rate Versus Range Test

Two different data rates versus range tests were run: a high data rate test with a 20 ms connection interval and a low data rate test with a 1,000 ms connection interval. In each test, the peripheral or slave device sent a 20-second transmission to the master. After the test, the total data transferred and the total charge consumed were both measured.

As seen in Figures 8 and 9, data rate drops with increasing range in both the low rate and the high rate tests. The SoC 2 and SKY66111 combination, however, demonstrates superior performance in both cases, particularly beyond 50 m where SoC 2 operating alone drops off precipitously.

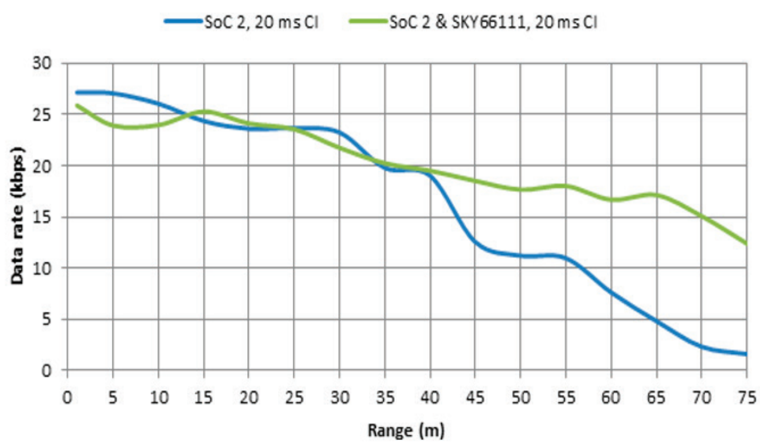

Figure 8. Data Rate vs. Range, High Data Rate

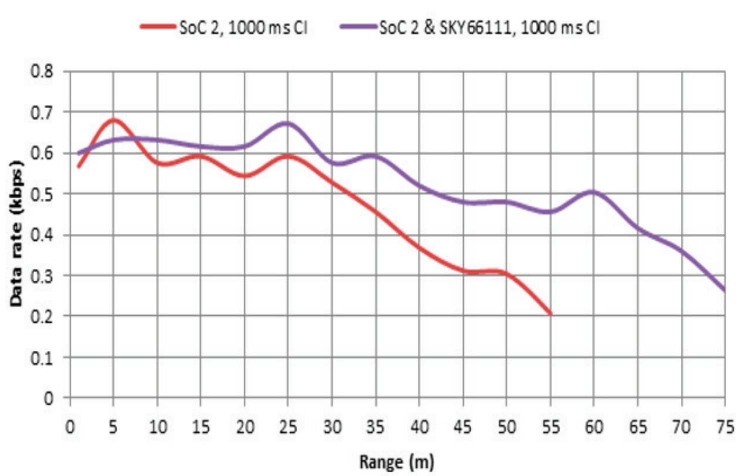

Figure 9. Data Rate vs. Range, Low Data Rate

Charge per Byte Measurements

Another test studied how much charge was used per bit transmitted and received, and what could actually be saved when using these FEM devices. A custom PCB was designed integrating an SoC (designated SoC 2) with the SKY66111 FEM. Table 3 presents the comparative specifications of the SoC alone and the SoC plus SKY66111 in static testing.

Two low energy links were tested in an indoor, non-line-of-sight (office) environment. RF propagation conditions were stated as “poor” as there was reflection from metal cubicles and walls and Wi-Fi and cellular signals were present. One link used boards with only SoC 2. The other used the custom PCB with SoC 2 and SKY66111.

The 3x higher transmit current shown in Table 3 is not as big of a disadvantage as might be assumed. Even in very high throughput systems, a device is transmitting only for a small percentage of the total time. Low energy devices spend most of their lives in sleep mode, so most battery drain occurs during sleep mode.

Parameters	SoC	SoC and SKY66111	Unit	Type
TX power	-1	9	dBm	Typical
TX continuous current	4.8	14	mA	Typical
RX sensitivity	-92.5	-91	dBm	Typical
RX continuous current	5.1	5.1	mA	Typical
Sleep current	1.2	1.4	µA	Typical

Table 3. Comparative Specifications of the two PCBs During Static Testing

For the test, the peripheral or slave device sent a 20-second transmission to the master. Then, the total data transferred and the total charge consumed were both measured. It is not intuitive at first glance, but under certain circumstances, using the SKY66111 can actually improve battery life.

As Figures 10 and 11 show, beyond a certain transmission range, the SoC 2 and SKY66111 combination becomes more efficient in terms of battery charge used to send a given amount of data. Notice the increase in charge per byte of the SoC 2 acting without the SKY66111 as range increases.

In examining the results, it is important to remember that when a low energy device sends a packet in the connected state, it waits for a response from the receiving end before sending the next packet. If it cannot "hear" the response due to poor channel conditions, it will wait for the next connection interval to attempt retransmission. Lower data rates or a high number of retransmission attempts lead to increased battery usage per byte of data sent.

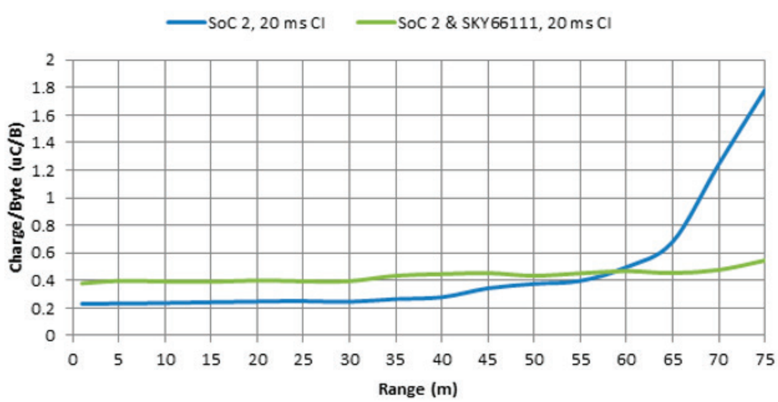

Figure 10. Charge per Byte vs. Range, High Data Rate

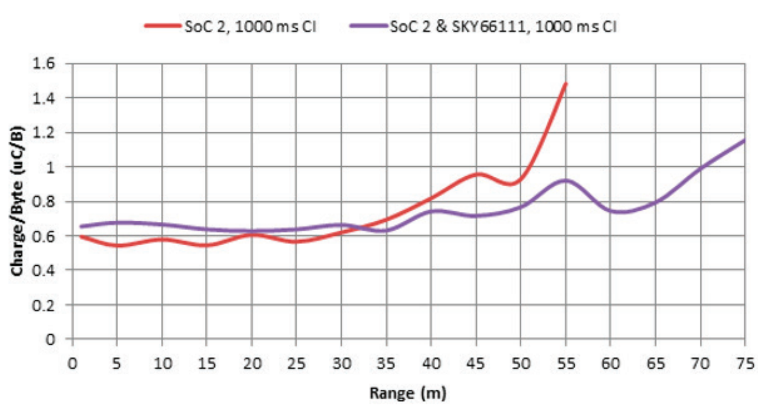

Figure 11. Charge per Byte vs. Range, Low Data Rate

Conclusions

As the tests demonstrate, when paired with SoC platforms, Skyworks front end modules deliver an efficient wireless solution. Pairing a Skyworks FEM with a low energy SoC can improve battery life for a given power efficiency or increase range due to higher output power and sensitivity. Even as the Internet of Things expands affecting the way people and businesses manage information and their environments, the Skyworks FEM product portfolio continues to meet the needs of major markets, such as automotive, industrial, and the connected home (see Table 4 listing design win areas).

Applications/Features	Application Category
Bluetooth Low Energy Application Modules	Internet of Things (IoT)
Door locks	Connected home
Earbuds	Wearables
Home assistants	Connected home
IoT Hubs	Connected home
Motion detectors	Connected home
Multi sensors	Connected home
Smart watches	Wearables
Thermostats	Connected home

Table 4. Skyworks Front End Modules for Bluetooth Application Design Wins

Skyworks | Nasdaq: SWKS | skyworksinc.com | sales@skyworksinc.com

USA: 949-231-3000 | Asia: 886-2-2735 0399 | Europe: 33 (0)1 43548540