RF Front-end Modules
Boost Wireless Performance

Table of Contents

Not all Bluetooth® Low Energy (BLE), Wi-Fi or ZigBee® solutions are created equal. That is the inescapable conclusion of some recent tests comparing popular system-on-chip (SoC) platforms with and without Skyworks Solutions' front-end modules (FEMs). The tests examined output power versus transmit 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 wireless networking protocols. For starters, the SKY66112's high RF output power is well-suited to the new Bluetooth 5 standard's enhanced connection range. This is important since Bluetooth 5 has emerged with 4x range, 2x speed and 8x broadcasting message capacity when compared to the older version, increasing the functionality of Bluetooth for the Internet of Things (IoT).

This particular FEM has been shown to produce as much as 40x the RF output power of the SoC radio alone (+20 dBm versus +4 dBm). It can increase receive sensitivity up to 6 dB, approximately doubling the receive range of a typical IoT device. It also handles RF input power

	SKY66111	SKY66112	SKY66113	SKY66403	Unit
TX power	10	20	SoC - 1	20	dBm
TX current	10	90	25 (µA)	97	mA
RX sensitivity	SoC + 1	SoC - 5	SoC - 6	SoC - 5	dBm
RX current	25 (µA)	4	4	4	mA
Sleep current	<1	<1	<1	<1	µA
Dual antenna support	No	Yes	No	Yes	
Bluetooth® EDR support	Yes	No	Yes	Yes	

Table 1. Skyworks' Bluetooth® and ZigBee® FEMs.
When discussing RX sensitivity, "SoC - 5 dB" means the SoC and FEM combination can receive signals up to 5 dB weaker than the SoC alone.

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, as we will see shortly, 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 SKY66403 and SKY66113 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 SKY66111, SKY66113 and SKY66403 can support Bluetooth with Enhanced Data Rate (EDR), which is important to note because it differentiates these FEMs from most other products on the market.

Bluetooth® Low Energy (BLE) SoCs

Most BLE devices today are SoCs. Their current consumption profile has a large effect on the end product's lifetime. The tests we will be discussing will 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 BLE and ZigBee from leading vendors (Table 2). Although the specific SoCs are, by agreement, excluded from this discussion, we would be remiss not to mention that the

Skyworks FEMs have been designed into reference designs with products from (alphabetically) Dialog Semiconductor, Nordic Semiconductor, NXP, Silicon Labs and Texas Instruments, among others.

ZigBee®: Current Versus Output Power and Receive (RX) 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 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's antenna connector output was connected to the RFIN port on the FEM.

For transmit (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 power of the input signal was swept while recording the Packet Error Rate. The experiment was repeated with the combined SoC and FEM.

	SoC 1	SoC 2	SoC 3	SoC 4	Unit
Protocol	BLE	BLE	BLE	ZigBee®	
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.

Range Advantage

To determine the range improvement provided by combining an SoC with a 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 BLE packets.

A standard USB BLE dongle 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 in:

1. an outdoor environment (busy covered parking garage) with transmitter inside a car,

2. an indoor office environment with line-of-sight, and

3. an indoor office environment, non-line-of-sight (through metal cube walls).

RSSI at the receiver was measured and plotted versus distance from the transmitter for the three boards. The results are shown in Figures 1, 2 and 3.

Taking a step back, RSSI is a measurement of how well your device can hear a signal. It's a value that is useful for determining 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 value is, the better the signal is.

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 mW. The test results presented in Figures 1 through 3 all 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.
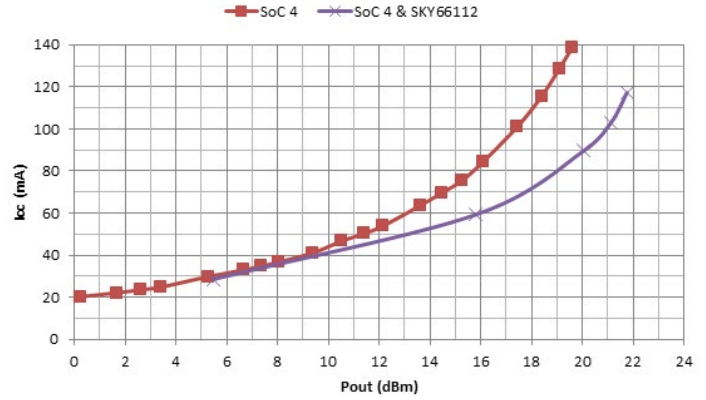

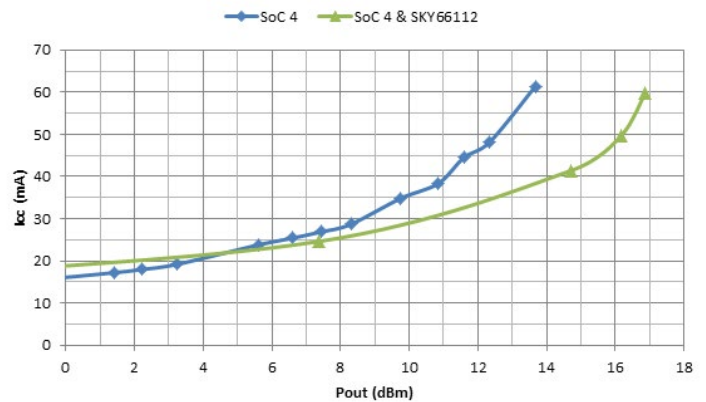**Figure 1. Pout vs. Icc for SoC Only vs. SoC and FEM**
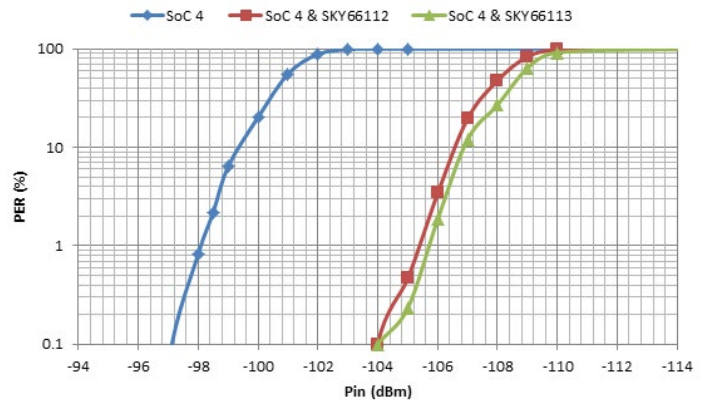

Figure 2. Pout vs. Icc with DC-DC Enabled

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

Figures 1,2 and 3. For ZigBee® applications: current vs. output power and Rx sensitivity

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 and user interface customizations, driver optimizations) can also have a significant impact on power usage of a specific device.

Current consumption of BLE chipsets is affected by four factors:

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

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

3. The selected BLE advertising interval—BLE 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 BLE stack all require certain amounts of processing in order to remain connected and comply with the protocol's specifications. An 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 4).

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 use the simple formula: *power = voltage x 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.
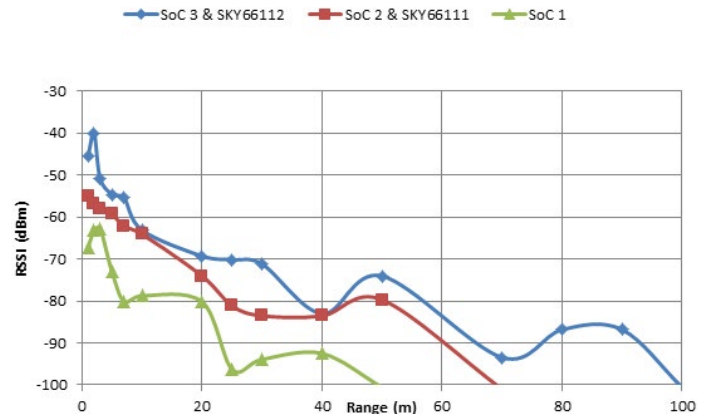
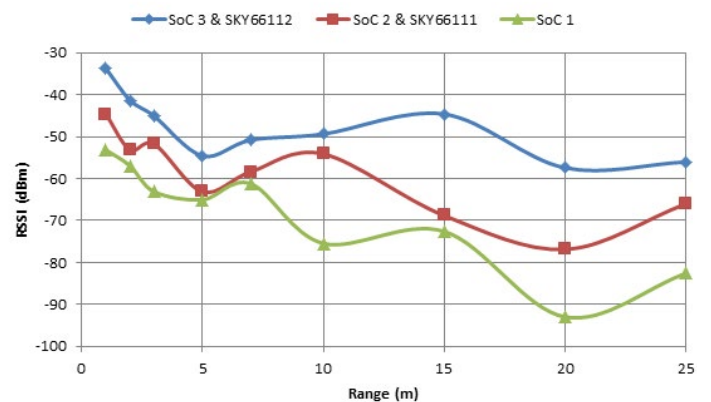

Figure 4. Range vs. RSSI, Parking Garage
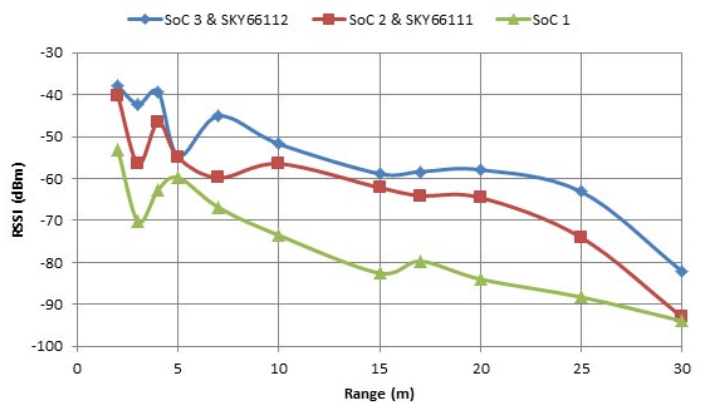

Figure 5. Range vs. RSSI, Indoor with LoS

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

Data Rate Versus Range Test

Two different data rate 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 5 and 6, 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.

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 BLE 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 BLE 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 BLE device is transmitting only for a small percentage of the total time. BLE devices spend most of their lives in sleep mode, so most battery drain comes from sleep mode.

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's not intuitive at first glance, but under certain circumstances,
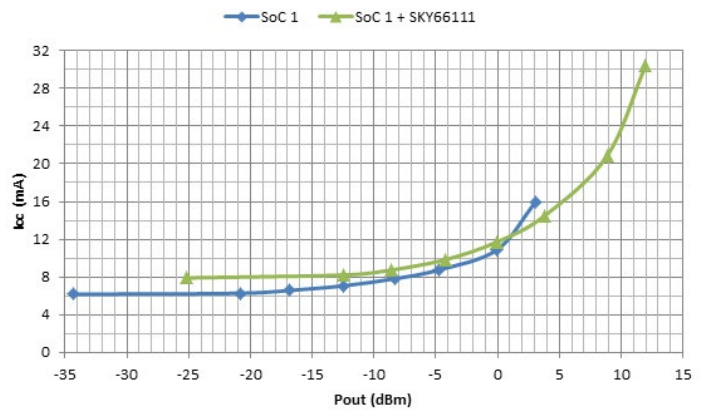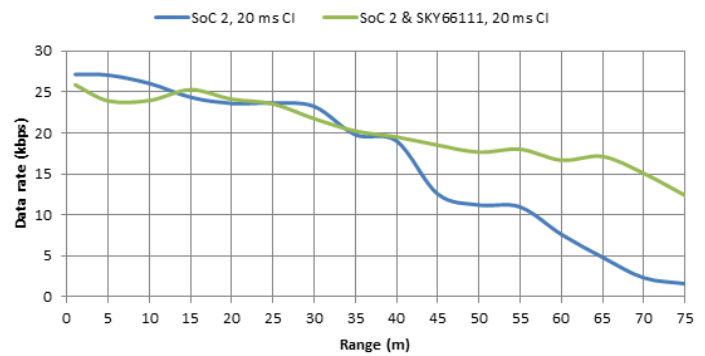

Figure 7. Transmission power vs. total system current.

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

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

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

Table 3. Comparative specifications of the two PCBs during static testing.

using the SKY66111 can actually improve battery life. As Figures 7 and 8 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 BLE device sends a packet in the connected state, it will wait 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 rate or a high number of retransmission attempts leads to increased battery charge usage per byte of data sent.
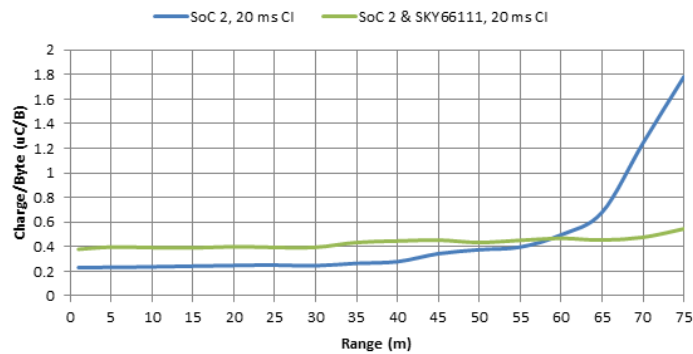

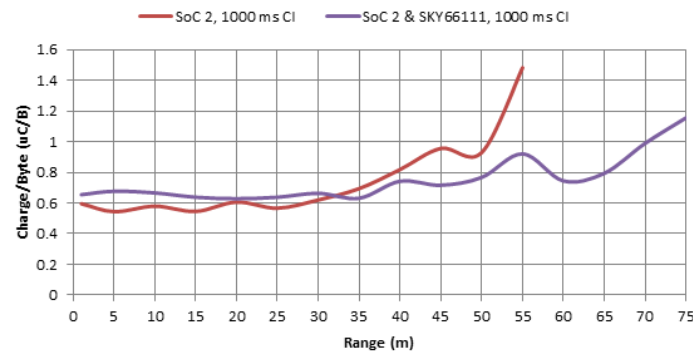
Figure 10. Charge per Byte vs. Range, High Data Rate

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

Conclusion

As the tests demonstrate, when paired with SoC platforms, Skyworks' FEM devices deliver an efficient wireless solution. Pairing a FEM with a BLE SoC can improve battery life given higher 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, Skyworks' FEM product portfolio is continuing to meet the needs of major markets, such as automotive, industrial and the connected home (see Table 4 listing recent design wins).

Product	Segment
Home assistants	Connected home
Thermostat	Connected home
BLE module	Internet of Things (IoT)
HUB	Connected home
Multi sensor	Connected home
Door locks	Connected home
Multi sensor	Connected home
Motion detector	Connected home
Thermostat	Connected home
IoT Hub 2	Connected home
Thermostat	Connected home

Table 4. SKY66112, SKY66113 and SKY66114 design wins.

Author and Contact Information

Stefan Fulga (stefan.fulga@skyworksinc.com)

Owen Taggart (owen.taggart@skyworksinc.com)

For more information about our solutions, please visit us at www.skyworksinc.com