Extending 2.4 GHz ZigBee Short Range Radio Performance with Skyworks Front-End Modules

Keywords:

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RF Indoor Propagation
Wireless RF System Range

Abstract:

The SKY65336 and SKY65337 ZigBee front-end modules (FEMs) can greatly enhance the performance of a ZigBee radio solution when integrated with any ZigBee low power reference design. Both devices can transmit up to 100 times more power than a typical 0 dBm low power ZigBee radio transmitter and can reduce the level of unwanted spurious emissions to be compliant with the main regulatory standards without the use of external components such as filters. Ember's EM250 with Skyworks' FEM reference design [1] shows a good example of the complete subsystem.

The SKY65336 also integrates a low noise amplifier (LNA) that enhances the sensitivity of a ZigBee receiver by several dB, a key factor that extends the receiver range. The SKY65336 can also be used to implement high data rate solutions that require high signal-to-noise ratios (SNRs). This note describes the benefits of using the SKY65336 and SKY65337 FEMs in ZigBee radio systems and details how the devices can contribute to tremendously extending the ZigBee wireless range and throughput.

1. Transmit Power Improvement

The SKY65336 and SKY65337 FEMs incorporate a highly efficient power amplifier (PA) in the transmit path that can deliver up to +20 dBm at the antenna port (see Figure 1). Up to this high power level, both modules which also provide harmonic filters guarantee a level of harmonics lower than –44 dBm, which eliminates the need for additional filters in the transmit path to be compliant with regulatory standards (Table 1 summarizes the limits for each standard). This facilitates RF design efficiency, and reduces the bill of materials (BOM) count and cost as demonstrated in [1].

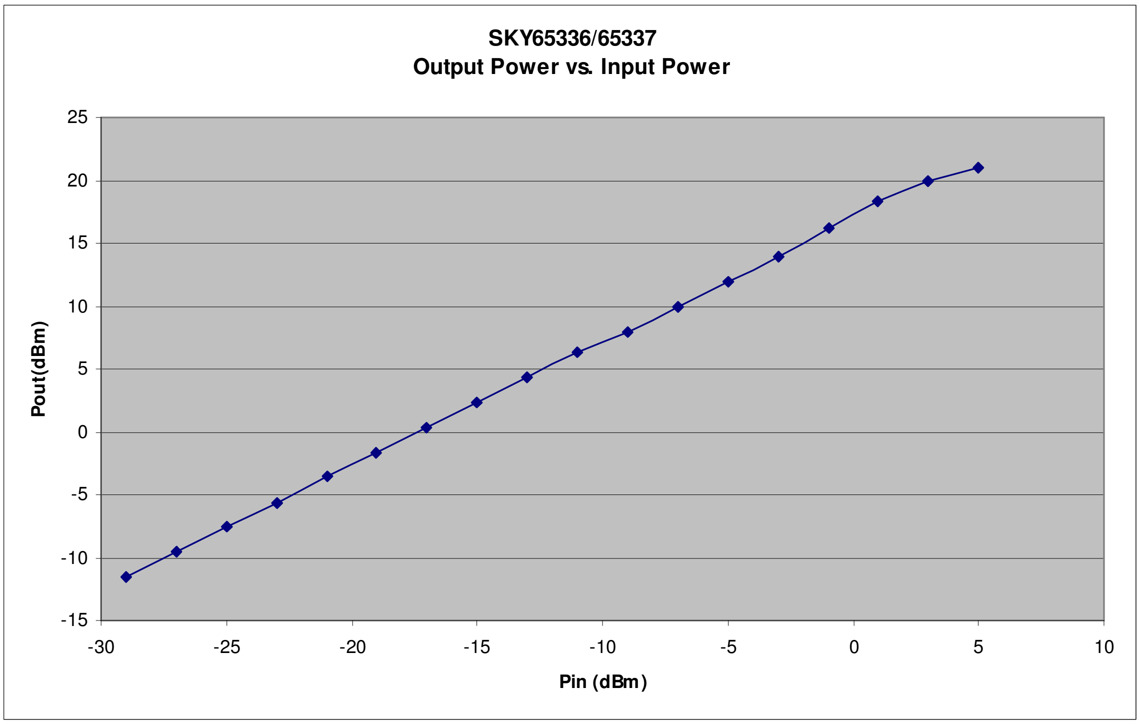

Figure 1 Output Power vs. Input Power

Table 1: Conducted Spurious Emission Limits

Standard	Effective Isotropically Radiated Power (dBm/MHz)
FCC 15.247	-41.2
EN 300 328	-30
ARIB STD-T66	-26.02

2. Receiver Sensitivity Enhancement

Sensitivity of a Receiver:

The sensitivity of a receiver is the minimum level of the input signal that it is able to receive and decode successfully with a given error rate. This sensitivity depends on two main factors:

- The SNR at the receiver output that is necessary to ensure the target error rate. The SNR is a function of the energy per bit to the noise density ratio (Eb/No), the date rate (R), and the receive bandwidth (B):

$$SNR = \frac{E_b}{N_0} \cdot \frac{R}{B} \quad \textbf{Equation 1}$$

- The noise figure (NF) of the system, which describes the ability of the system to process a small signal noise-free. The NF is calculated according to the following equation:

$$NoiseFigure = \frac{SNR_{in}}{SNR_{out}} = \frac{S_{in}/N_{in}}{S_{out}/N_{out}} \quad \textbf{Equation 2}$$

The minimum sensitivity (measured in dBm) is calculated as:

$$Sensitivity = NoiseFigure + SNR_{out} + N_{in} \quad \textbf{Equation 3}$$

If

$$N_{in} = 10.\log(kTB)$$

Where: k = Boltzman's Constant = 1.38 × 10–23 Joules/Kelvin
T = absolute temperature = 298 °K
B = noise bandwidth

Then

$$N_{in} = -174 + 10\log(B)\ dBm$$

And

$$Sensitivity = -174 + 10\log B + NoiseFigure + SNR_{out}\ (dBm) \quad \textbf{Equation 4}$$

Where: SNRout = Minimum SNR that guarantees the target error rate.

The IEEE Std 802.15.4^{TM}-2003 [2] sets the requirements for the –85 dBm one percent packet error ratio (PER) minimum sensitivity. The 2.4 GHz receiver link uses offset quadrature phase-shift keying (O-QPSK) modulation with direct sequence spreading spectrum (DSSS) techniques. The main benefit of DSSS systems is to provide substantial immunity to narrow band interference because the signal energy is spread over a wide bandwidth. Beyond the IEEE Std 802.15.4^{TM}-2003, using different spreading factors (e.g., 8, 4, 2, or 1) can also provide an efficient way to achieve a multi-user configurable data rate system.

Figure 2 shows an example of PER (20 octets) curves for a O-QPSK signal for different data rates. The spreading gain is demonstrated in this Figure by showing that the highest spread signal (250 kbit/sec data rate with a spreading factor of 8 as used in ZigBee system) for a given PER requires the smallest SNR.

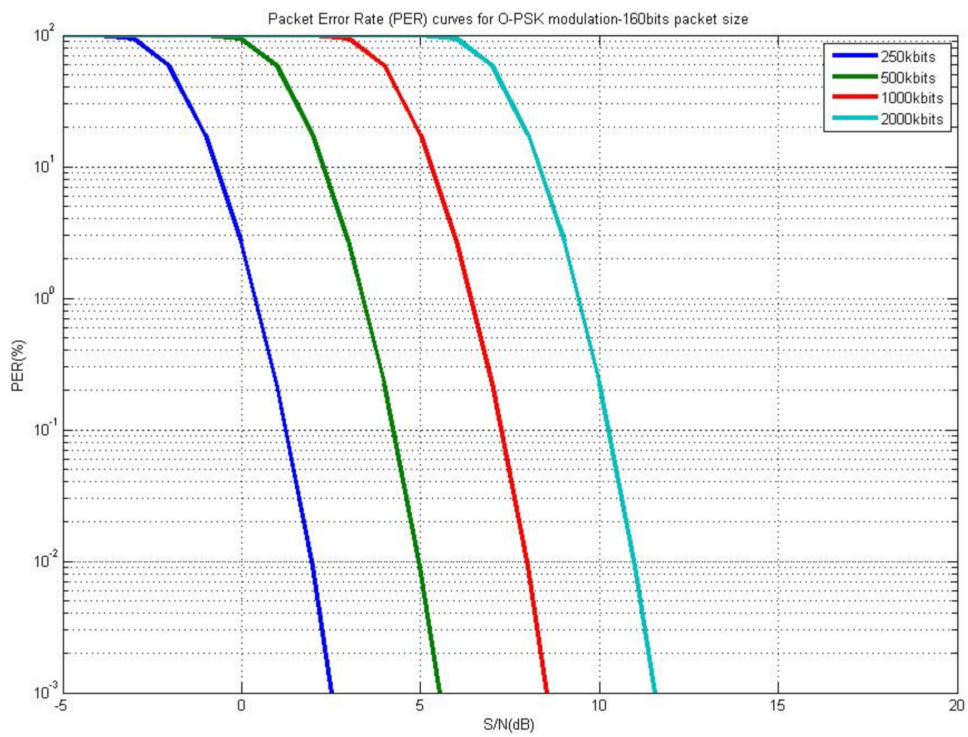

Figure 2: PER curves for O-QPSK Modulation vs. SNR and Data Rate

Various ZigBee-compliant transceivers are available with reported sensitivities for 250 kbit/sec ranges from –97 to –101 dBm. For the same data rate, Ember in their Application Note 5059 [3] suggests that for an actual ZigBee receiver, the minimum SNR is 3 dB and the receive bandwidth is 1.1MHz. Typical sensitivity data for the different data rates are calculated according to Equation 4 and summarized in Table 2.

Table 2: Typical Receiver Sensitivity Performance

Data Rate	SNR(Note 1) (dB)	Sensitivity (dBm)	NF (dB)
250kbits/s	3	-99dBm	11.5
500kbits/s	6	-96dBm	11.5
1000kbits/s	9	-93dBm	11.5
2000kbits/s	12	-90dBm	11.5

Note 1: SNR for higher data rates are calculated from SNR at 250kbits/s and spreading gain reduction

Improving Sensitivity with the SKY65336

Equation 4 shows that reducing the system NF improves sensitivity. The cascaded NF of a complex system can be derived from the standalone block level NF and gain as follows (Friis Formula):

$$NF_{Total} = NF_1 + \sum_i \frac{NF_i - 1}{G_{i-1}} \quad \textbf{Equation 5}$$

The SKY65336 incorporates an LNA in its receive path along with the front-end transmit/receive switch and output RF balun. The device provides a NF of 2.5 dB with a gain of 10.5 dB. Assuming the ZigBee transceiver (without the off chip RF balun and harmonics filter) NF is 9.5 dB, the cascaded NF is 4 dB compared to the original value of 11.5 dB. Table 3 summarizes the sensitivity of the receiver calculated using Equations 4 and 5. Note that for all data rates, the sensitivity improvement is greater than 7 dB.

Table 3: Sensitivity Comparison Table between Transceiver Standalone and with the SKY65336 FEM

Data Rate	Sensitivity No FEM	Sensitivity with SKY65336
250kbits/s	-99dBm	-106.5dBm
500kbits/s	-96dBm	-103.5dBm
1000kbits/s	-93dBm	-100.5Bm
2000kbits/s	-90dBm	-97.5dBm

3. Range Extension with the SKY65336/337

RF Signal Propagation Attenuation

Signal propagating from the source or transmitter to the receiver can be attenuated by several different factors:

1. Free space attenuation (the signal "spreads" in space).
2. Signal absorption or shadowing (the signal passes through solid objects like walls or floors).
3. Multipath fading (the signal reflects, refracts, or scatters).

Free space attenuation can be calculated according to the following equation:

$$L_{FreeSpace}(dB) = -(20\log d(m) + 20\log f(MHz) - 27.5)$$ **Equation 6**

Where: $L_{FreeSpace}$ = Free space attenuation in dB
d = Distance in meters
f = Frequency in MHz

In the case of a ZigBee frequency of 2.45 GHz, Equation 6 becomes:

$$L_{FreeSpace\_2450MHz}(dB) = -(20\log d(m) + 40.3)$$ **Equation 7**

Note that Annex E of ref[2] suggests a different free-space attenuation formula for 802.15.4-compliant systems:

$$L_{FreeSpace\_2450MHz}(dB) = -(33\log \frac{d(m)}{8} + 58.5)$$ **Equation 8**

Attenuation for signal absorption and multi-path fading are usually derived from Equation 7 with the addition of some empirical factors [4]:

$$L_{2450MHz}(dB) = -(10 * \gamma * \log d(m) + L_{FreeSpace\_2450MHz}(1m) + L_{Absoption})$$ **Equation 9**

Where γ = the propagation loss exponent
$L_{Absoption}$ = Attenuation (in dB) of the signal passing through walls, doors, floors etc.

Examples of indoor wall absorption [5] indicate that γ equals 4 and $L_{Absorption}$ equals 10 dB. Using these values, Equation 9 becomes:

$$L_{2450MHz\_indoor}(dB) = -(40\log d(m) + 50.3) \quad \textbf{Equation 10}$$

Comparing Equation 8 and 10 indicates that a ZigBee RF subsystem range is greatly reduced when operating indoors. For example, at 20 meters away from the source, the transmit signal is reduced by more than 100 dB indoors compared to only 72 dB for outdoor free space loss.

Comparing ZigBee System Ranges

The range of the RF system is defined as the maximum distance between the signal source or transmitter and the receiver. Range depends on three factors:

1. Effective transmit power
2. Propagation path loss
3. Minimum sensitivity of the receiver as defined in Equations 1 through 4

The effective transmit power is the power transmitted by the source in the direction of the receiver. Effective transmit power is derived from adding the transmit antenna gain (*Gt*) to the total transmit power (*Pt*). Similarly, receiver antenna gain (*Gr*) and receiver power (*Pr*) can be derived from the following equation:

$$P_r = P_t + G_r + G_t + L \quad \textbf{Equation 11}$$

Where: *Pr* = Receiver power in dBm
Pt = Transmitter power in dBm
Gr = Receiver antenna gain in dB
Gt = Transmitter antenna gain in dB
L =Attenuation at 2450 MHz in dB

Assuming the antenna gain are 0dB for the transmitter and the receiver, the receive power is then given by

$$P_r = P_t - (33\log\frac{d(m)}{8} + 58.5) \quad \textbf{Equation 12}$$

for free-space propagation conditions, and by:

$$P_r = P_t - (40\log_{10} d(m) + 50.3) \quad \textbf{Equation 13}$$

for indoor propagation conditions.

Examples of receive power for two different systems are shown in Figure 3 for free-space propagation conditions. A similar example is shown in Figure 4 for indoor propagation conditions. In both cases, the range is derived from the intersection of the minimum sensitivity level, as calculated in Table 3, and the receive signal strength measured at the receiver input.
Table 4 lists the range for a ZigBee transceiver and the improved ranges by adding the SKY65337 or SKY65336 FEM to the system. The optimum performance is achieved with the SKY65336 because of the improved sensitivity of the receiver.

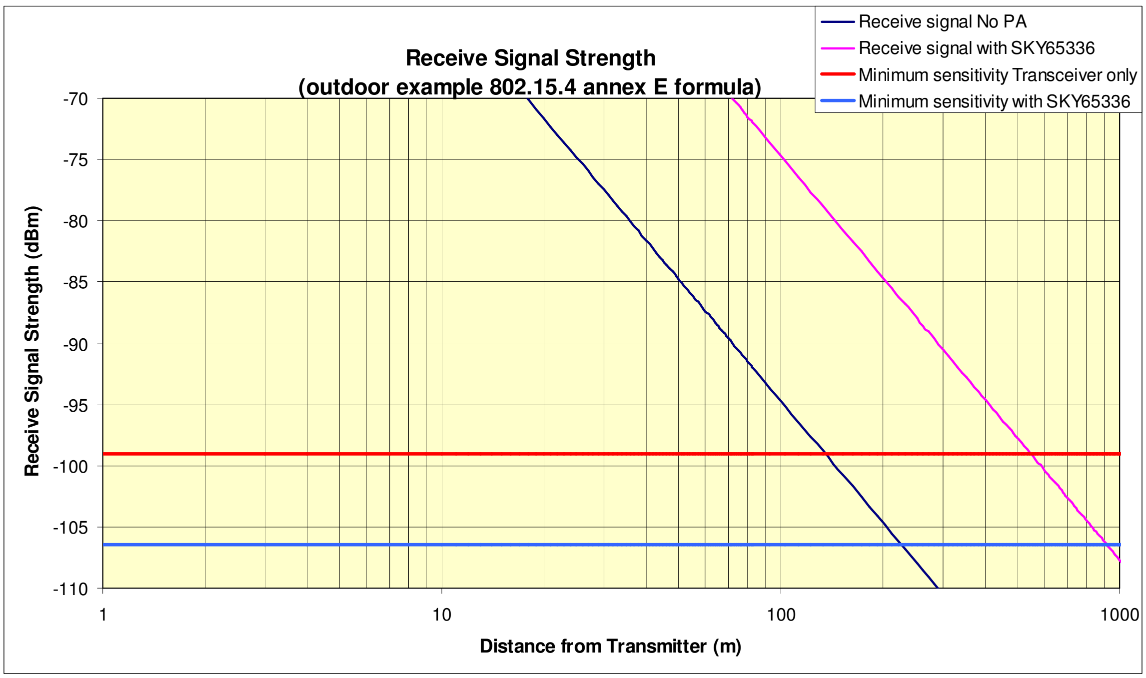

Figure 3: Received Signal Strength at the Receiver Node versus Distance between Transmitter and Receiver for Low Power 0dBm and High Power 20dBm Transmitters (Free-Space Propagation Conditions)

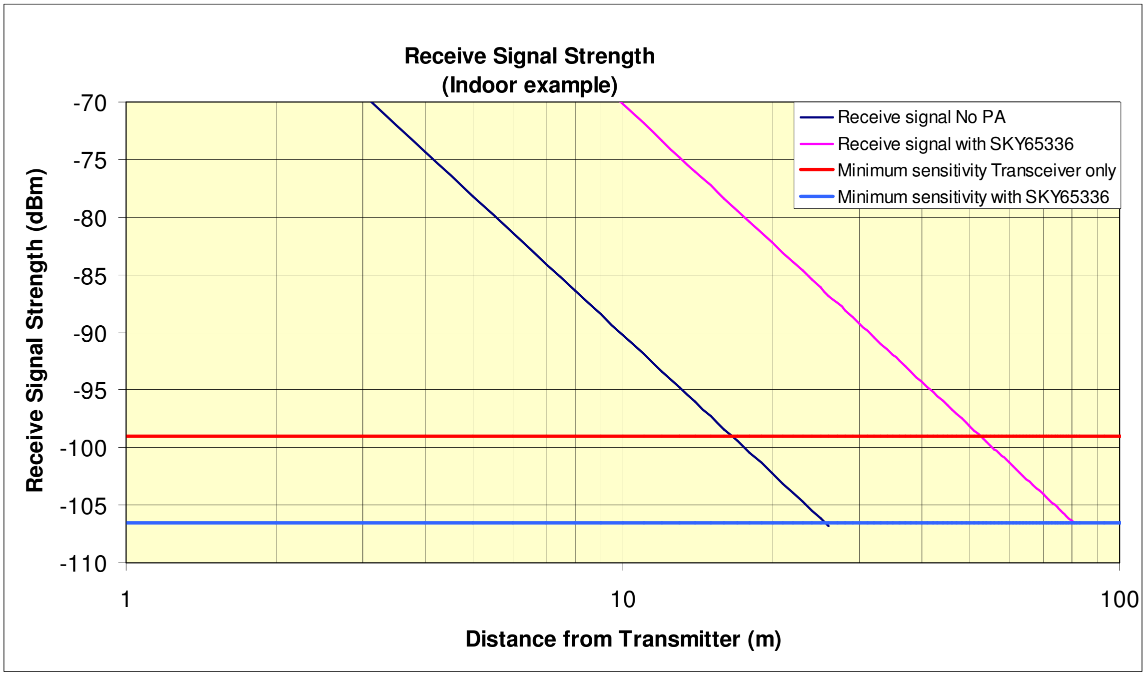

Figure 4: Received Signal Strength at the Receiver Node versus Distance between Transmitter and Receiver for Low Power 0dBm and High Power 20dBm Transmitters (Indoor Propagation Conditions)

Table 4: Comparison of Wireless Ranges for Transceiver only and with the SKY65336/SKY65337 FEMs

System	Free-Space Range (m)	Indoor Range (m)
Transceiver only	133	16
Transceiver with the SKY65337	543	53
Transceiver with the SKY65336	923	81

4. Conclusion

The SKY65336 and SKY65337 are easy to integrate, highly efficient ZigBee FEMs. Both devices provide a natural, low-cost solution to improve ZigBee wireless network performance whether extending coverage or increasing the available data rate. For further information, please refer to the SKY65336 and SKY65337 data sheets ([6], [7]) and Ember's EM250 reference hardware design [1].

References

[1] Ember EM250 with Skyworks - Front End Module Reference Design. http://ember.com/zip/REF_DES_SKY65336_SKY65337.zip

[2] IEEE Std 802.15.4^{TM}-2003, Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs).

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[5] RF Propagation Basics White Paper, Sputnik, Inc., April 2004.

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[7] 200940D the SKY65337 datasheet