System Design Considerations for a ZigBee RF Receiver with regard to Coexistence with Wireless Devices in the 2.4GHz ISM-band

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Abstract

At the present time the task of designing a highly integrated *ZigBee* radio frequency (RF) receiver with an excellent coexistence performance is still very demanding and challenging. This paper presents a number of system issues and design considerations for a *ZigBee* RF receiver, namely IEEE 802.15.4, for coexistence with wireless devices in the 2.4-GHz ISM-band. With regard to IEEE 802.15.4, the paper analyzes receiver performance requirements for; system noise figure (NF), system third-order intercept point (system-IIP3), local oscillator phase noise and selectivity. Based on some assumptions, the paper illustrates the relationship between minimum detectable signal (MDS) and various situations that involve the effects of electromagnetic interference generated by other wireless devices. We infer the necessity of much more stringent specification requirements than the published standard for various wireless communication field environments

Keywords: Design consideration, RF receiver, ZigBee, coexistence, electromagnetic interference, wireless communications

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1. Introduction

Recently, the desire for wireless connectivity has resulted in exponential growth in wireless communications. In particular, wireless sensor networks are a potential wireless network application for future wireless connectivity systems. Wireless sensor networks are an emerging research area with potential applications in environmental monitoring, surveillance, military, health and security. Such a network consists of group nodes called sensor nodes, each having one or more sensors, an embedded processor and a low power radio. Typically, these nodes are linked by a wireless medium to perform distributed sensing tasks [1].

In recent years, the concept of a standardized low rate wireless personnel area network (LR-WPANs), namely ZigBee, has emerged. Impelled by the need to enable inexpensive wireless sensor network applications, in December, 2000, Task Group 4 under the IEEE 802 Working Group 15 was formed. The goals of Task Group 4 are to begin the development of a LR-WPAN standard IEEE 802.15.4 and provide a standard that has the characteristics; ultra-low complexity, low-cost and extremely low power for wireless connectivity among inexpensive, fixed, portable and moving devices [2].

In the 2.4 GHz industrial, scientific and medical (ISM) band, LR-WPAN devices are intended to operate with other IEEE 802 wireless devices such as IEEE 802.11b (WLAN) and IEEE 802.15.1 (Bluetooth). The IEEE 802.15.4 and IEEE 802.11b standards support complimentary applications; e.g., IEEE 802.15.4 devices are used to support a wireless sensor array within a home or industrial complex. They could be collocated with IEEE 802.11b devices in order to provide WLAN support. Wireless devices based on these three standards are likely to be collocated and therefore their ability to coexist needs to be evaluated [3][4][5][6][7][8][9].

The system performance of the major specifications required by the IEEE 802.15.4 physical layer is greatly degraded by interference generated by wireless devices in the ISM-band. Thus, an analysis of the electromagnetic interference environment based on distance may be required to solve coexistence problems.

Section 2 of this paper presents the analysis and simulation of RF receiver requirements, considering the coexistence problems between IEEE 802.15.4 and IEEE 802.11b/802.15.1. Discussion of the key results of this paper is presented in Section 3. Conclusions are presented in Section 4.

2. Analysis of RF Receiver Requirements, Considering Device Coexistence

The IEEE standard specification for part 15.4 specifies that “the Packet Error Rate (PER) shall not exceed 1%” at the receiver sensitivity level [10].

The first step for receiver-design is to establish the signal to noise ratio (SNR) required for the input of a digital baseband demodulator in order to obtain the required-PER. This is because the SNR determines the noise figure requirement of the RF front-end. Generally, this minimum SNR is determined by an E_b/N_0 and processing gain with frequency de-spreading process. Although a power control algorithm may be properly executed, E_b/N_0 can’t be accurately determined because of variations of data-rate in service applications and the distance between an access point (AP) and a mobile station. Thus, the minimum SNR having a *baseband-margin* of a few dB is used for these variations as a design margin. The second step is to determine the SNR consisting of a desired signal, and various noises generated by various wireless devices in the 2.4 GHz ISM-band, at the input of the RF receiver. When these various noise components are adequately considered, the *system noise figure* can be determined [11][12][13][14]. With an interferer profile, the important specifications such as *phase noise* of a local oscillator, *system-IIP*$_3$ and *channel selectivity* are determined in a real RF receiver system.

2.1 Overview of physical layer of LR-WPANs

With the direct sequence spread spectrum (DSSS) technique, LR-WPAN is intended to support two physical layer options. Both physical layers utilize the same basic packet structure for low duty cycle and low power operation. Between both physical layers, the 2.4 GHz specifies operation in the 2.4 GHz ISM-band with nearly worldwide availability. This band distances from 2.4 to 2.483 GHz and offers 16 channels with a channel spacing of 5 MHz, operating at a raw data rate of 250 kb/s, using the offset quadrature phase shift key (OQPSK) modulation technique. With 90 degree constellation transition shift, the OQPSK modulation method is more power-efficient than QPSK modulation. This requires less linear power amplification for low power consumption. The IEEE 802.15.4 standard specifies a receiver sensitivity of -85 dBm for the 2.4 GHz band. The standard specifies a transmit power capability of 1 mW, although it can vary within governmental regulatory bounds. The physical layer uses a common packet structure enabling the definition of a common medium access control interface. The physical layer protocol data unit (PPDU) contains a preamble, a packet length, a start of packet delimiter, and a payload field. The 32 bit preamble is designed for acquisition of symbol and chip timing.

2.2 Derivations of RF receiver specification from standard

The data in LR-WPAN are coded into the carrier with direct sequence spread spectrum (DSSS), an inherently robust wireless communication technique improving multi-path performance and receiver sensitivity through signal processing gain (PG). This PG decreases the minimum-SNR (SNR_{min}) required by a digital baseband demodulator for the achievement of a desired bit error rate (BER). The SNR_{min} can be described by (1) [11][12]

$$SNR_{min}\ [dB] = E_b/N_0 - PG + BB\_margin. \tag{1}$$

The PG can be defined as the ratio of chip rate to data rate and implies the spectrum-despreading gain of a digital baseband demodulator. E_b/N_0 can be defined as the ratio of traffic channel bit energy to noise density. Though the power can be exactly controlled, E_b/N_0 is varied by the power control deviation and affected by multi-path fading, data rate, communication distance and interference generated by other devices. With these effects and baseband implementation loss, a baseband demodulator margin (BB_margin) is defined. In this paper, the BB_margin will be set at +2 dB. The required noise figure ($NF_{required}$) incurring a BB_margin is shown in (2) [11][12]

$$\begin{aligned} NF_{required}\ [dB] &= SNR_{in} - SNR_{out} \\ &= (P_{signal} - KTB) - (E_b/N_0 - PG + BB\_margin). \end{aligned} \tag{2}$$

P_{signal} represents the desired-signal power injected into the antenna and KTB is the thermal noise power with respect to bandwidth. For example, when a PG is used with a data rate of 250 kbps, the $NF_{required}$ becomes +23 dB with a P_{signal} of -85 dBm, KTB of -111 dBm, E_b/N_0 of 10 dB, PG of +9 dB, and BB_margin of +2 dB.

Generally, the *system-IIP*$_3$ can be derived from the inter-modulation distortion (IMD) test condition suggested in any standard specification. This performance parameter indicates the extent of the distortion of an RF/analog-path due to strong interference generated by other users. The IEEE Standard for Part 15.4 [4] doesn't include the interferer's state, so the assumed distribution of receiver noise power for LR-WPAN is shown in **Fig. 1**. The major noise components inducing the SNR-degradation of a receiver consist of a normal-noise component (P_{nomal_noise}) and a distortion-noise component ($P_{distortion\_noise}$) generated by other systems. The assumed noise power distribution is; P_{nomal_noise}: 50%, $P_{distortion\_noise}$: 50% of P_{accept_noise}. As shown in **Fig. 1**, P_{nomal_noise} consists of; thermal noise power ($P_{thermal}$) and $P_{system\text{-}NF}$ associated with a system noise figure from RF/analog blocks. And, the $P_{distortion\_noise}$ consists of ; P_{IMD}: from inter-modulation effects, $P_{MOD\text{-}block}$: from modulated-blocking effects, $P_{CW\text{-}blocking}$: CW-blocking effects, P_{LO}: reciprocal-mixing effects originating from interferers. The assumed distortion noise power distribution is; P_{IMD}: 15%, $P_{MOD\text{-}block}$: 15%, $P_{CW\text{-}blocking}$: 15%, P_{LO}: 5% of P_{accept_noise} of power, as shown in **Fig. 1** [5]. The acceptable noise power (P_{accept_noise}) for a receiver is [11][12]

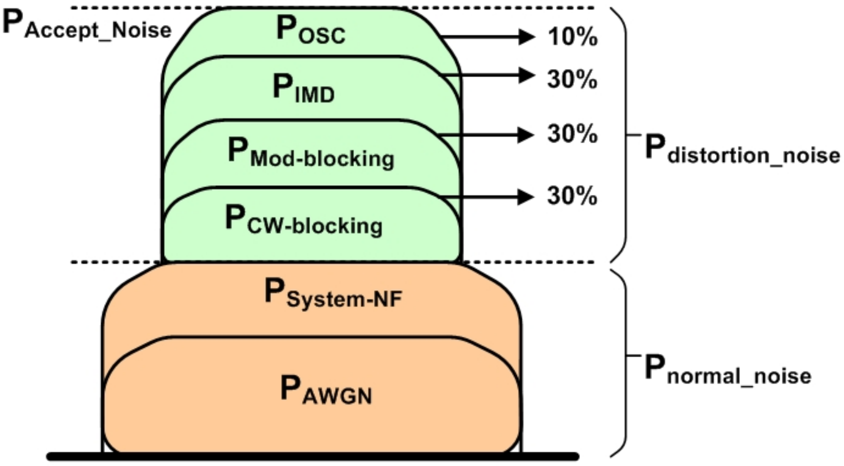

Fig.1. Assumption about distribution of receiver noise power for LR.

$$\begin{aligned} P_{accept\_noise}\,[dBm] &= P_{normal\_noise} + P_{distortion\_noise} \\ &= P_{signal} - SNR_{out} \\ (SNR_{out}\,[dB] &= E_b/N_0 - PG + BB\_margin). \end{aligned} \tag{3}$$

From equation (3), assuming a P_{signal} of -82 dBm and a SNR_{min} of +1 dB, the P_{accept_noise} will be accepted for -83 dBm, with a P_{nomal_noise} of -86 dBm and a $P_{distortion\_noise}$ of -86 dBm, respectively. In this paper, since the P_{IMD} and P_{LO} are assumed to be 15 and 5 % of P_{accept_noise}, respectively, as shown in **Fig. 1**, the P_{IMD} can be accepted for -91 dBm and the P_{LO} for -96 dBm. The $system\text{-}IIP_3$ required by a receiver is [11][12]

$$system\text{-}IIP_3\,[dBm] = P_{signal} + 0.5(P_{signal} - P_{IMD}). \tag{4}$$

Assuming the IMD test scenario with a P_{signal} of -82 dBm and a P_{IMD} of -52 dBm, the $system\text{-}IIP_3$ must berequired is-34 dBm (@10M/20MHz). The phase noise required by a local oscillator (*LO*) is shown by (5) [11][12]

$$PN_{LO}\,[dBc/Hz] = P_{LO} - P_{signal} - 10\log(BW) \tag{5}$$

Assuming an IMD and a blocking test scenario with a $P_{blocker}$ of -52 dBm, the PN_{LO} required must be: -87 dBc/Hz (@1MHz).

The selectivity of a receiver for in-band and out-of-band rejection will be determined by the attenuation performance of the RF/IF/baseband filters. In these specifications, the adjacent-alternate channel rejection (AACR) is defined by the relative attenuation of the adjacent-channel power and the alternate channel power. The *Selectivity* required by a receiver at 5/10 MHz-offsets frequency is [11][12]

$$\begin{gathered} Selectivity\ [dBc]\ (@5MHz) \geq P_{blocker} - P_{accept\_noise} \\ :Adjacent\ channel \\ Selectivity\ [dBc]\ (@10MHz) \geq P_{blocker} - P_{accept\_noise} \\ :Alternate\ channel. \end{gathered} \tag{6}$$

Assuming the test scenario with power of blockers of -82 and -52 dBm, the selectivity required is: +1 and +31 dBc (@ 5/10MHz), respectively.

2.2 RF receiver requirements with regard to coexistence

In the physical layer standard specification of IEEE 802.15.4, channel-selection methods are introduced with channel clear assessment and energy detection / link quality indication. With strong interferers, the channel link through these methods is not available, so it should wait for the current channel or move into other channels. In these situations, the addition of more devices using the 2.4 GHz ISM-band will lead to a lower probability of link-success. Thus, in this paper, we will identify more practical specifications for the physical RF path to increase the probability of link-success under coexistence circumstances.

Unfortunately, the interference profiles can’t be precisely specified in the 2.4 GHz unlicensed frequency band, which has many types of wireless communications. In fact, possible strong blockers will considerably degrade the performance of a RF-receiver system. Thus, a system budget is required, which contains specifications of the performance parameters of a receiver with respect to strong interferers.

The communication block-diagram of a LR-WPAN relative to interferers generated by various communication systems in the 2.4 GHz ISM-band is shown in **Fig. 2**. In this figure, the receiver of FFD1 only wants to communicate with the transmitter of RFD2. However, it simultaneously receives transmitters’ signals from a UE1 and a UE4 of an NT2-network (IEEE 802.11b) and an NT3-network (IEEE 802.15.1), respectively. In this case, the FFD1 receives undesired blockers’ signals; P_{b1} and P_{b2} based on distance d_1 and d_2, respectively. For example, with a worst-case field environment such as a very short distance, i.e., one meter, and maximum transmission power allowed, the sensitivity of the receiver is rapidly degraded because of inter-modulation distortion products and reciprocal mixing products generated by strong interferers.

The SNR-degradation of a receiver incurring IMD and reciprocal mixing effects from interferers is shown in **Fig. 3**. To reduce the SNR-degradation from strong interferers, there are two solutions. One method is to decrease the distortion-noise components included in a desired-in-channel, by the reduction of the interferers’ signal power. Using the transmitter’s power control algorithm of another communication standard, this is the most efficient method. However, this is not a good solution because of problems beyond the scope of our standard (IEEE802.15.4) category. The other method is to increase the requirements of the receiver performance parameters. In this paper, we will identify the major parameters of receiver performance: *system-IIP*$_3$, *PN*$_{LO}$, and *selectivity*, taking into consideration worst-case interference environments.

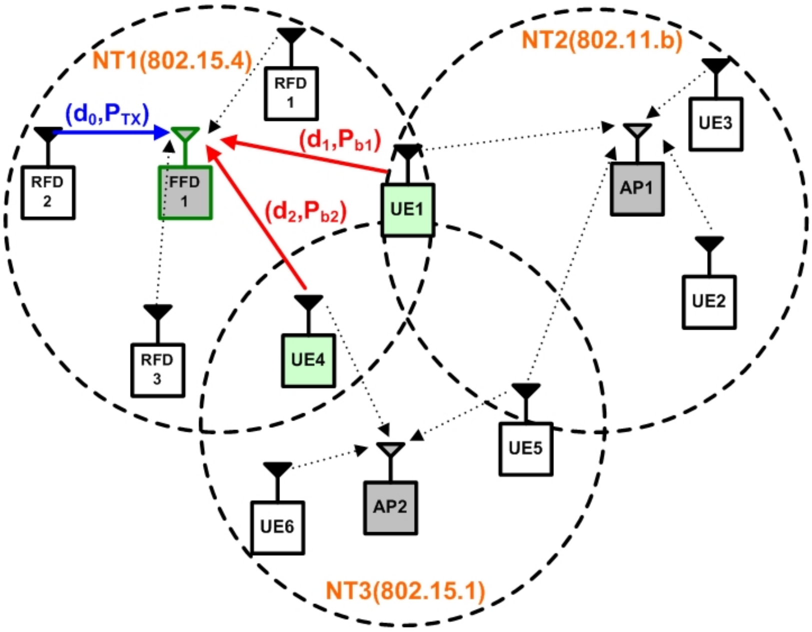

Fig.2. Communication block-diagram of LR-WPAN against interferers generated by various communication systems in the 2.4 GHz ISM-band.

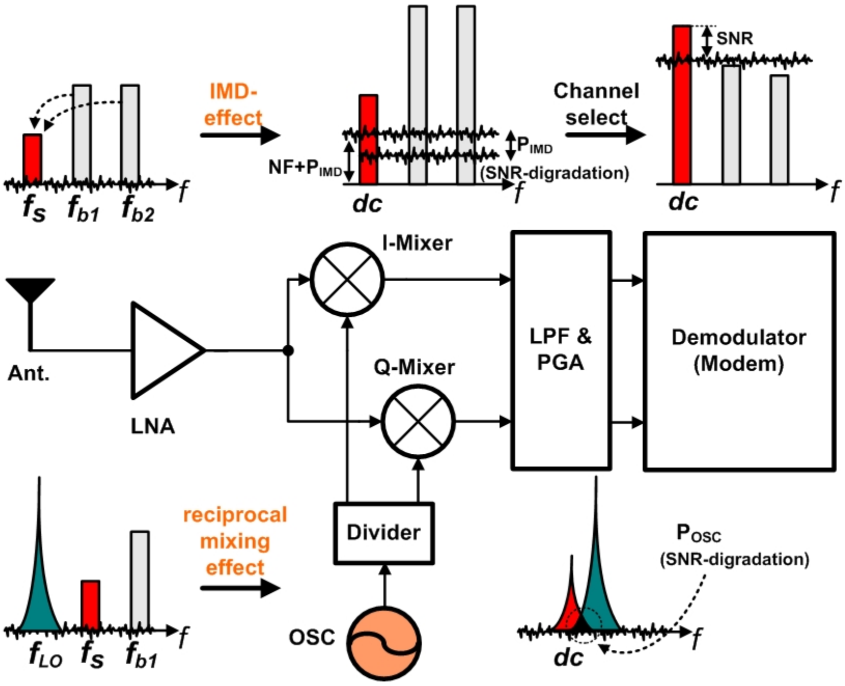

Fig. 3. SNR-degradation of a receiver containing inter-modulation dist-ortion (IMD) and reciprocal mixing effects by interferers.

The receiver sensitivity with regard to *system-*IIP_3 and the strength of blockers is

$$
\begin{aligned}
&Sensitivity\ [dBm] = NF + 10\log(KTB + P_{IMD}) + SNR_{demod} \\
&[where,\ P_{IMD}\ [dBm] = 3\sum_{n=1}^{k}(P_{b\_n}) - 2IIP_3,\ (k=1,2,\cdots), \\
&SNR_{demod}\ [dB] = SNR_{min} = E_b/N_0 - PG + BB\_margin, \\
&P_{b\_n}\ [dBm] = P_{b\_n\_max.} - 20\log(4\pi \cdot d \cdot f/c)].
\end{aligned}
\tag{7}
$$

Here, the *system-*IIP_3 is related to the linearity performance of the receiver. The P_{IMD} can be expressed by *system-*IIP_3 and a summation of blockers generated by IEEE 802.11b and IEEE 802.15.1 stations. The P_{b_n} represents all blocker signals coming into the antenna input-port of desired RF-receiver; $P_{b\_n\_max}$ is the maximum blocker signal powers of various wireless devices; *KTB* is thermal noise power with respect to bandwidth (*BW*); SNR_{demod} is a minimum SNR required for a digital baseband modem; *f* is the frequency [Hz]; *c* is the velocity of light [meter/sec], and *d* is a physical distance between a desired IEEE 802.15.4 station and a position of a blocker [meters]. Under any channel environment, the signal power of a blocker is exponentially decreased through a path-loss which is dependent on distance. Thus, the path-loss can be calculated by an air channel model fitted to real world environments.

However, in this paper, it is calculated under the assumption of the general free space channel condition for a simple computation. Indeed, the air channel model issue having a high accuracy is not a focus in this paper. The relationship between sensitivity and distance based on *system-*IIP_3 is shown in **Fig. 4**.

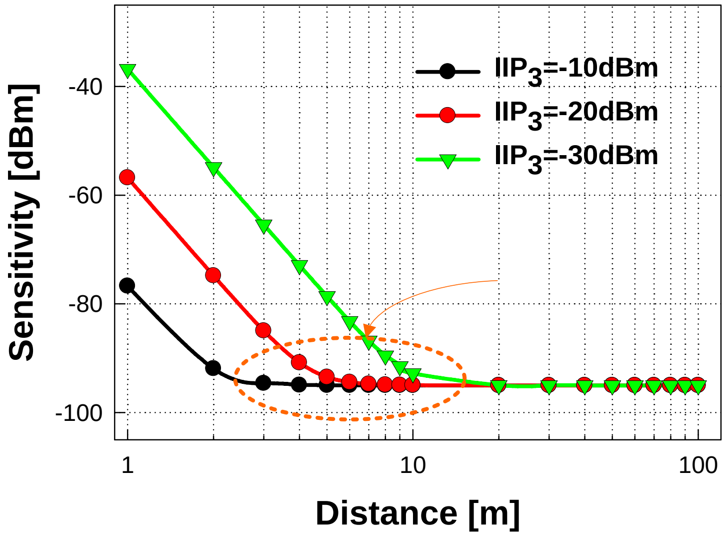

Fig.4. Sensitivity vs. distance, based on various system-IIP_3.

The blockers used in this analysis are generated by various wireless communication devices: IEEE 802.11b and 802.15.1. In this graph, there is degradation of receiver sensitivity because of the increasing strength of the blocker signal power with decreasing distance. Also, we see the loss of sensitivity associated with lowering the *system-*IIP_3. In particular, in the case of a less than ten-meter distance, we can see the drastic degradation of sensitivity. So, note that the *system-IIP$_3$* must be more than -10 dBm to guarantee a receiver sensitivity of -95 dBm relative to strong interferers at short distances. The receiver sensitivity dependence on phase noise of the local oscillator and the strength of blockers is given by

$$\begin{gathered} Sensitivity\ [dBm] = NF + 10\log(KTB + P_{LO}) + SNR_{demod} \\ [where,\ P_{LO}\ [dBm] = \sum_{n=1}^{k} (P_{b\_n}) - PN_{LO} + 10\log(BW),\ \ (k=1,2,\cdots), \\ P_{b\_n}\ [dBm] = P_{b\_n\_max.} - 20\log(4\pi \cdot d \cdot f/c)]. \end{gathered} \tag{8}$$

Here, the PN_{LO} is related to the spectral purity performance of the local oscillator. The PLO is expressed by a LO-phase noise and a summation of maximum blockers generated by IEEE 802.11b and IEEE 802.15.1 stations. Also, the frequency bandwidth (*BW*) of IEEE 802.15.4 is 2 MHz. The relationship between sensitivity and distance based on a LO-phase-noise is shown in **Fig. 5**.

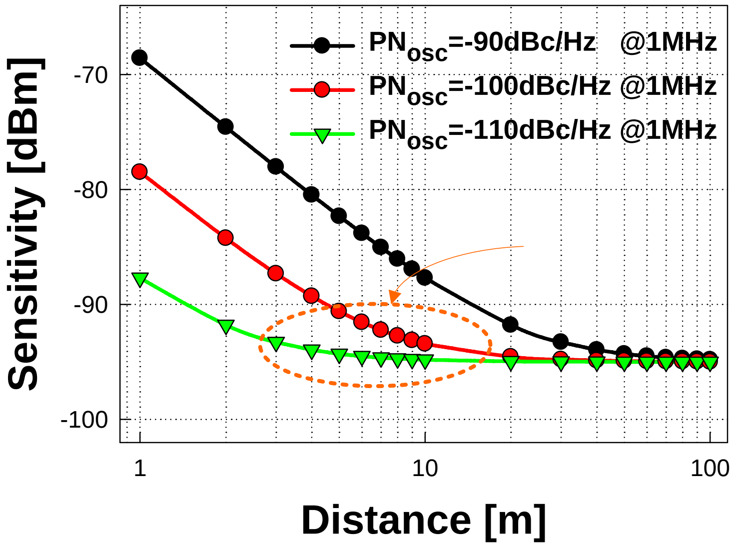

Fig.5. Sensitivity vs. distance based on various LO phase-noise.

The blockers used in this analysis are generated by other wireless communication systems: IEEE 802.11b and 802.15.1. In this graph, we can see the degradation of receiver sensitivity with the increasing strength of the blocker signal power due to decreasing distance. Also, we see the loss of sensitivity associated with an increase in the phase noise of the LO. In particular, in the case of a less than ten-meter distance, we can see the rapid degradation of sensitivity. Note a PN_{LO} must be less than -110 dBc at a 1 MHz-offset frequency for a guarantee of a receiver sensitivity of -95 dBm relative to strong interferers at very short distance.

The relationship between sensitivity and distance based on a *system-IIP$_3$* and a PN_{LO} is shown in **Fig. 6**. The blockers used in this analysis are generated by other wireless communication systems: IEEE 802.11b and 802.15.1. In this graph, note that sensitivity is much more affected by interferes generated by an 802.11b system than from an 802.15.1.

This is because of higher transmitter output power than 802.15.4 under the FCCI and ETSI regulations.

The *selectivity* for the in/out of-band channel selection must be determined for the specification of RF/IF/baseband filters. The selectivity of a receiver relative to blockers generated by other wireless communication system is shown (9). In this equation, we can see that the selectivity of receiver is decided by a signal power of blockers.

$$\begin{gathered} Selectivity\ [dBc] = P_{b\_n\_max.} - (MDS - SNR_{demod}), \\ (SNR_{demod}\ [dB] = E_b/N_0 - PG + BB\_margin). \end{gathered} \tag{9}$$

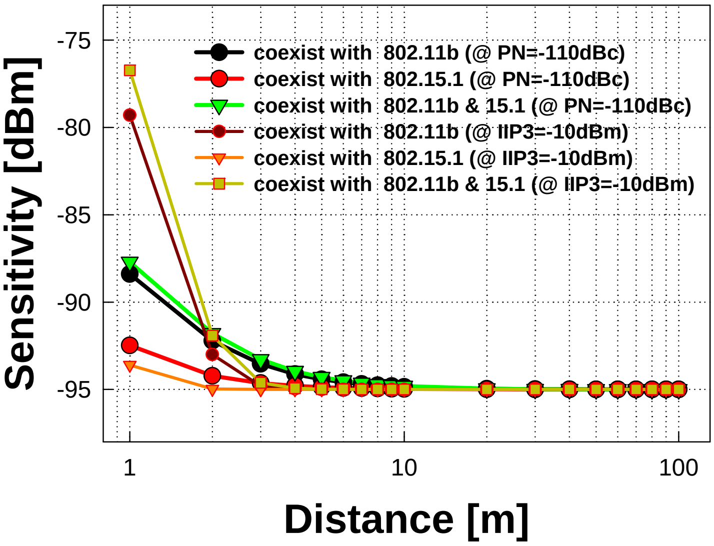

Fig.6. Sensitivity vs. distance under coexistence circumstances.

The MDS represents the minimum detectable signal and SNRdemod describes a SNR required from a digital baseband-demodulator. The relationship between selectivity and distance under coexistence circumstances is shown in **Fig. 7**. For the 802.15.4 standard condition, the solid and dotted lines show the selectivity of a receiver at a 5 and 10 MHz frequency offset, respectively. The other lines show various selectivity values based on distance, in the case of a coexistence situation with one or more 2.4 GHz standards. In particular, in the case of less than twenty-meters of distance, we can see a hard requirement of selectivity. Note, the receiver selectivity is required to be more than +50 dBc relative to strong interferers at a very short distance.

The relationship between a battery lifetime, receiver sensitivity, TX output power and *NF* is shown in (10)

$$\begin{gathered} P_{TX.Output} \propto 10\log(I_{PA}\cdot V) \propto NF \propto Sensitivity^{-1}, \\ Battery\ lifetime\ [h] \propto \frac{\text{Battery capacity [mAh]}}{\text{I}_{\text{ON}}\ \text{[mA]}\cdot\text{duty cycle}}, \\ [where,\ I_{ON} = kI_{TX.ON} + (1-k)I_{RX.ON},\ I_{TX.ON} = I_{PA} + I_{other\text{-}TX.blocker}, \\ k = a\ living\ weighting\ factor]. \end{gathered} \tag{10}$$

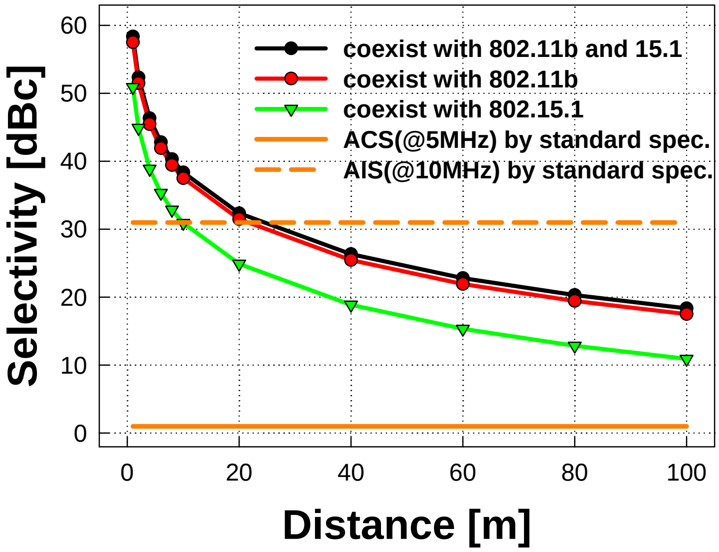

Fig.7. Selectivity vs. distance under coexistence circumstances.

Here, $P_{TX.OUTPUT}$ is proportional to power amplifier current (I_{PA}) and NF, but inversely proportional to sensitivity. The battery lifetime is related to battery capacity, duty-cycle and turn-on current (I_{ON}). Regardless of a living-weighting factor (k), the I_{ON} consists of the summation of transmitter on-current ($I_{TX.ON}$) and receiver on-current ($IRX.ON$). Also, the $I_{TX.ON}$ consists of an I_{PA} and the current of the transmitter at other stages($I_{other\text{-}TX.blocker}$). For a desired $P_{TX.Output}$, the battery lifetime can be increased by reducing I_{PA} and I_{ON}. The relationship between battery lifetime, receiver sensitivity, $P_{TX.Output}$ and NF is shown in **Fig. 8**.

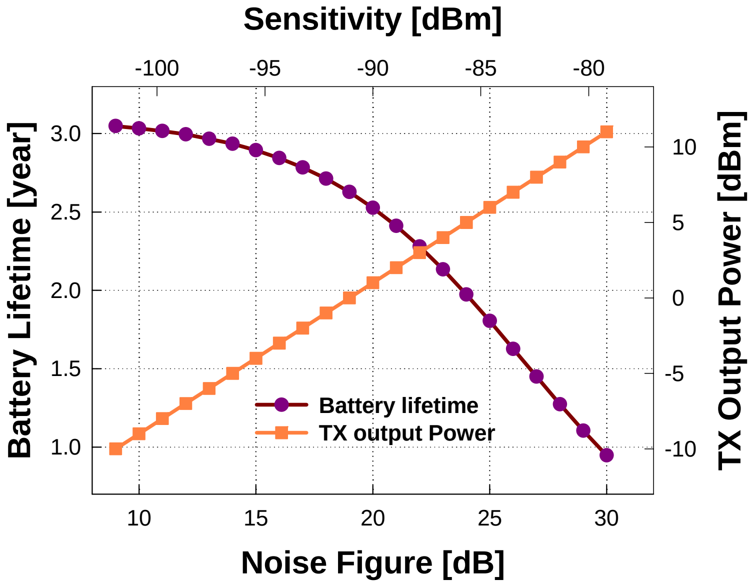

Fig. 8. Relationship between battery lifetime / TX output power and noise figure / sensitivity.

3. Discussion

The LR-WPAN system (or IEEE 802.15.4, *ZigBee*) will be a core-IP for future wireless connectivity systems. This system is in great demand for wireless communication modules satisfying low-cost, low-power consumption and ultra small size. Therefore, it is expected that the unlicensed 2.4 GHz worldwide ISM frequency band will be used worldwide. The minimum requirements of the physical layer component of LR-WPAN must be less demanding than that of other wireless communication standards because of the low-cost, low power consumption and ultra-small size requirements.

However, under real environments where various wireless devices coexist, the minimum requirement of the physical layer of LR-WPAN should be more stringent than the published standard. Of course, the IEEE 802.15 TG2 group has been researching algorithm-oriented solutions for coexistence problems, but these have many constraints in real-world operations. Thus, we suggest much more stringent specification requirements than the published standard, through increasing RF functionality in terms of major system performance parameters such as *sensitivity*, *selectivity*, *NF*, *system-*IIP_3 and *LO phase noise*. The RF system-parameters for LR-WPAN are shown in **Table 1**.

Table 1. RF-system parameters for LR-WPAN.

Requirements	Standard Spec. (IEEE802.15.4)	Reasonable Spec. (This paper)
NF / Sensitivity [dB/dBm]	+25 / -85	+14 / -95
IIP3 [dBm]	-32.4	-10.8
LO-Phase noise [dBc/Hz, @ 1MHz]	-87	-110
Selectivity [dBc, @5MHz]	+1	+52
Selectivity [dBc, @10MHz]	+31	+58

In this paper, for -95 dBm of minimum sensitivity, the required NF must be 14 dB. The required *system-*IIP_3 must bemore than -10 dBm, for a receiver sensitivity of -95 dBm, relative to strong interferers at a very short distance. The LO phase noise must be more than -110 dBc, at a 1 MHz-offset frequency, for a receiver sensitivity of -95 dBm, relative to strong interferers. It must be more than +50 dBc of the receiver *selectivity,* relative to strong interferers at very short distance. A LR-WPAN having these stringent specifications can be implemented with manufacturing technology for sub-micron semiconductors and integrated circuit techniques.

4. Conclusion

The desire for wireless connectivity has resulted in exponential growth in wireless communication. In particular, wireless sensor networks are a potential wireless network application for future wireless connectivity systems. Therefore, the design of a highly integrated ZigBee^{TM} radio frequency (RF) receiver with an excellent coexistence performance is still very demanding and challenging.

This paper presented a number of system issues and design considerations for an RF receiver for *ZigBee*, namely IEEE 802.15.4, with regard to coexistence with wireless devices in a 2.4-GHz ISM-band. With regard to the IEEE 802.15.4 standard specification, we provided analysis of receiver performance requirements incurring NF, system-IIP3, LO phase noise and selectivity. In addition, we illustrated the relationship between the sensitivity of a receiver in various situations with respect to interferers generated by other wireless communication devices, based on distance. We inferred the necessity of much more stringent specification requirements than the published standard for various wireless communication field environments. In further work we aim to adopt various channel models to enhance the accuracy of the required specification of IEEE 802.15.4 standard under coexistence circumstances, for the 2.4 GHz worldwide ISM frequency band.

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