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A STUDY OF RF LINK AND COVERAGE IN ZIGBEE

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ABSTRACT

To implement a ZigBee network, wave propagation models are necessary to determine propagation characteristics for installation of these short-range networks of industrial, scientific, and medical (ISM) applications but also consumer electronics and smart home appliances. Most applications are deployed indoor, so a very large variety of situations will be met. Using propagations models for indoor environment, the distances between nodes for a reliable RF link, using standard ZigBee devices were determined.

Keywords: ZigBee; RF link; WSN networks; antenna; propagation; coverage area

I. INTRODUCTION

The proliferation of mobile computing devices including laptops, personal digital assistants (PDAs), and wearable computers has created an enormous demand for wireless personal area networks (WPANs).

In classical WPANs, interaction is mostly between humans and machines. A large number of new short-range wireless applications have to support interaction between machines, reading sensors or controlling actuators at remote nodes. These networks are classified as sensor actuator networks (WSN). Wireless networks for industrial control and sensing, above all, must be reliable, adaptable, and scalable.

Majority of domain analysis are indicating that the IEEE 802.15.4 standard and ZigBee wireless network technology are the best solution for the implementation of a wide range of low cost, low power and reliable control and monitoring applications within the private home and industrial environment.

II. OVERVIEW OF ZIGBEE/IEEE 802.15.4

The *ZigBee/IEEE 802.15.4* protocol, the newly introduced *WPAN* standard was approved and published in 2003 and modified in 2006/2007. It defines the characteristics of the physical layer and the MAC layer of this *Low-Rate Wireless Personal Area Networks* (*WPANs*). In this section, a brief description of the characteristics for these two layers is presented

A. *The ZIGBEE/IEEE 802.15.4 Physical Layer*

As with any other wireless communication technology, the main functions of the physical layer are to define radio communication link (*RF link*) spreading, de-spreading, modulation and demodulation of the signal.

At the physical layer (*PHY*), *ZigBee* operates in the *ISM* band within three different frequency bands. There is a single channel between *868.0* and *868.6MHz* (Europe), *Ch 0*, 10 channels between *902.0* and *928.0MHz* (USA), *Ch 1-10*, and 16 channels between *2.4* and *2.4835GHz* (worldwide), *Ch 11-26*. *ZigBee* uses *DSSS* as a spreading technique.

The *2.4GHz* band uses *OQPSK* technique for chip modulation. Each 4-bit symbol is mapped into a *32* chip *PN* sequence. In the *915MHz* and *868MHz* bands each one-bit symbol is mapped into a *15* chip *PN* sequence, and uses the Binary Phase Shift Keying (*BPSK*) technique for modulation. The physical layer of the stated frequency bands uses the same common frame structure.

B. *The ZigBee/IEEE 802.15.4 MAC Layer*

The *MAC* layer controls the access to the communication channel. It provides flow control through acknowledgments and retransmissions. It is also responsible for data validation, synchronization and providing services to the upper layers. The *ZigBee* standard defines two types of devices, a full-function device (*FFD*) and a reduced function device (*RFD*).

The *FFD* can operate in three different modes:

- a personal area network (*PAN*) coordinator, called ZigBee Coordinator (*ZC*) in *ZigBee WSN*. One and only one required for each ZigBee network. Initiates network formation and acts as *802.15.4 2003 PAN* coordinator (*FFD*). May act as router once network is formed.
- ZigBee Router (*ZR*) is an optional network component. May be associated with *ZC* or with previously associated *ZR*. *Acts as 802.15.4/2003* coordinator (*FFD*) and participates in multihop routing of messages.
- The *RFD* is intended for very simple applications that do not require the transfer of

large amounts of data and need minimal resources called also *ZigBee End Device* (*ZED*). This is optional network component and shall not allow association and shall not participate in routing.

Depending on the application requirements, *ZigBee* devices might operate either in a star topology or mesh topology or a cluster tree topology.

The main application domains are: Home Automation; Industrial Automation; Remote Metering Automotive Networks; Interactive Toys, Active RFID/ asset tracking, Medical and recently Consumer Electronics Remote Controls.

There are three types of data transfer mechanisms between *ZigBee* devices: from a coordinator to a device, from a device to a coordinator and between two peer devices.

There are used two channel access mechanisms:

- Non-beacon network, a simple, traditional multiple access system used in simple peer and near-peer networks, using standard *ALOHA CSMA-CA* communications and with positive acknowledgement for successfully received packets;
- Beacon-enabled network using superframe structure, network coordinator transmits beacons at predetermined intervals.

III. PHY- RF LIMITS AND REGULATIONS

The *ZigBee* devices are elements of radio communication systems, specific rules and limitations should be accomplished. The *PHY* layer of *ZigBee/IEEE 802.15.4* comply with *FCC* regulations *47CFR15* (USA) and *ERC/REC 70-03* (EU) regarding *ISM* band. This standard specifies operation in the unlicensed *2.4GHz*, *915MHz* and *868MHz ISM* bands. The center frequency of these channels is defined as follows:

f_C = 868.3 in MHz, for $k = 0$;

f_C = 906 + 2 (k – 1) in MHz, for k = 1, 2, …, 10;

f_C = 2405 + 5 (k – 11) in MHz, for k = 11, 12, …, 26, where k is the channel number.

Thus *2400–2483.5MHz* is the only worldwide allocation of spectrum for unlicensed usage without any limitations on applications and transmitted duty cycle. It provides up to *1W* transmit power in spread spectrum modes in the United States, up to *100mW* (*25mW* for *868.3MHz* band) in EU (*ETSI EN 300 328*). Allowed transmit power is up to *1W*, delivered at the antenna port, with a maximum antenna gain up to *6dBi*. If antenna gain is greater than *6dBi*, then transmit power must be reduced by an amount equal to the decibel measure of how much the antenna gain exceeds *6dBi*. However, for *2400MHz* fixed point-to-point operations, the transmit power need only be reduced by *1dB* for every *3dB* that antenna gain exceeds *6 dBi*. Based on these regulatory opportunities, *2400–2483.5 MHz* has been selected as the primary *IEEE 802.15.4* band.

A transmitter shall be capable of transmitting at least *–3dBm*. Although *IEEE 802.15.4* equipment is generally envisioned to operate with a maximum transmit power of approximately *0dBm*, the international community generally allows a minimum of *+10dBm* in the *2400MHz* band. Devices should transmit lower power when possible, in order to reduce interference to other devices and systems.

The maximum transmit power is limited by local regulatory bodies. The lowest value of transmit power is interpreted as less than or equal to *–32dBm*.

For a *Packet Error Rate* (*PER*) < 1%, a compliant device shall be capable of achieving a *sensitivity* (*RS*) of *–85dBm* or better (2.4 GHz), or *–92dBm* or better (868/915 MHz). The receiver maximum input level is the maximum power level of the desired signal present at the input of the receiver for which the error rate criterion (*PER< 1%*) is met. A receiver shall have a receiver maximum input level greater than or equal to *–20dBm*. Other *PHY* parameters like modulation, out-of-band spurious emission, packet structure, etc. are not implied in this analysis.

IV. RF LINK IN ZIGBEE NETWORKS

ZigBee networks are large *WSN* networks (large number of devices and large coverage area) that can be formed autonomously and that will operate very reliably for years without any operator intervention.

The promoters of this system maintain that *ZigBee* networks are easy to deploy, is no need of frequency planning and mesh and tree networking protocol provides redundant paths. The designers and implementers of platforms and products must have in their mind that the link between two members of the *ZigBee* network is a *RF link* and this interface should be a reliable one and need a careful evaluation.

The peer to peer *RF link* is the elementary communication link produced between two nodes of the *ZigBee* network and like in all wireless communication process the elements involved are: transmitters, receivers, antennas and the propagation.

For a correct setting of a *ZigBee* network, an evaluation of the level of the received signal for each node of the network is mandatory.

The system behavior depends on d – the distance between antennas and on λ – the wavelength of radiated signal. The transmitter and the receiver involved in the process should be placed in *Far Field Region* named also *Fraunhofer* zone. The border of this region can be calculated using the formula:

$$R_{FF} = 2D^2/\lambda \quad (1)$$

D – the length of antenna and λ – the wavelength of radiated signal. For distances larger than R_{FF}, the radiation pattern is independent on the distance; we are in the far field region. The distance between transmitter and receiver antennas will be in this region.

The values of *D*, the length of half-wave dipoles and quarter-wave monopoles, in free space and on a PCB are ranging from *170mm* to *50mm* (868/915Mhz bands) and from *60mm* in free space, *25mm* PCB to *7mm*, chip antenna (2.4 GHz band) [14].

The *Far Field Regions* are ranging from *1.5cm* to *17cm* for *868/915MHz* band and *1mm* to *6cm* for *2.4GHz* band. *All ZigBee network nodes can be considered working in radiating region.*

Nodes in wireless sensor networks exchange information through transceivers. The nodes transmitters (*Tx*) and receivers (*Rx*) will be establish a reliable radio connection only if the power of the signal received by (*Rx*) is higher than the *sensitivity* threshold. The signal between the transmitter (*Tx*) and the receiver (*Rx*) is subject to propagation phenomena and due to obstacles in his way, an attenuation of the signal power is produced.

The path loss *PL* is the difference (in *dB*) between the transmitted power and the received power and represent signal level attenuation caused by free space propagation, reflection, diffraction and scattering.

For peer to peer nodes, the free-space power that the receiver's antenna receives P_R, separated from a transmitting antenna by a distance *d*, for the ideal situation of line of sight propagation (*LOS*), the *Friis* free-space equation defines:

$$P_R = P_T\, G_T\, G_R\, (\lambda/4\pi d)^2 \qquad (2)$$

P_T is the transmitted power; $P_R(d)$ is the received power and is a function of the transmit-receive separation, *d*; G_T is the transmitter-antenna gain; G_R is the receiver-antenna gain; *d* is the distance between the transmitter and the receiver in meters; and λ is the wavelength in meters.

From (2), when the antennas are assumed to have unity gain, we can deduce the path loss as the transmitted power divided by the received power:

$$PL(dB) = 10 \log P_T/P_R = 20\log f(\text{MHz}) + 20\log d - 28 \qquad (3)$$

This path-loss formula applies only to ideal scenarios, with clear lines of sight and only for initial estimates. Propagation models use the close-in distance d_0, often determined empirically, as the received- power reference point (Fig. 1).

The received power, $P_R(d)$, can be calculated at any distance *greater than* the received-power reference point with reference to $P_R(d_0)$, whose value you predict from equation (2). The reference distance for practical systems operating at *1 ÷ 2GHz* is *1m* for indoor environments and *100m* for outdoor environments.

$$P_R(d) = P_R(d_0) + 20\log(d/d_0) \qquad (4)$$

For *ZigBee* networks it's important to know the maximum reliable data-transmission range. This wireless-system range directly depends on the *LB* - link-budget parameter:

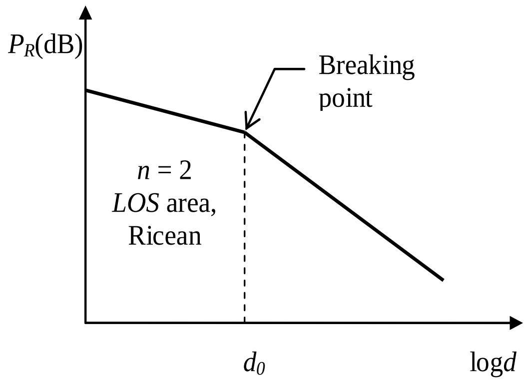

***Fig. 1**. Close-in distance*

$$LB = P_T + G_T + G_R - RS \qquad (5)$$

LB is the link budget in decibels, P_T is the transmitted power in decibels referred to milliwatts or watts, G_T is the transmitter-antenna gain in decibels, G_R is the receiver-antenna gain in decibels, and *RS* is the receiver sensitivity.

Sensitivity is the minimum RF signal that the system can detect with an acceptable *SNR* (signal-to-noise ratio). If the total path loss *PL* between the transmitter and the intended receiver is greater than the link budget *LB*, loss of data ensues, and communications cannot take place.

The condition for a reliable *RF link* is:

$$LB > PL \qquad (6)$$

Therefore, it's important for designers developing end systems to accurately characterize the path loss and compare it with the link budget to obtain an initial estimation of the range.

The calculated versus measured results demonstrate the limitations of the free-space model. *The link margin* is defined as the margin in *dB* above the receiver sensitivity level required to ensure reliable radio connection between the transmitter and receiver. In optimum conditions (antennas are perfectly aligned, no multi-path or reflections exists, and there are no losses) the necessary link margin would be *0dB*. In real world conditions, the link margins *LM are typically in the range of 15 to 25dB*.

In realistic *WSN* propagation models, free-space model does not apply. Propagation models are used extensively for conducting feasibility studies and during initial deployment. These models can be broadly categorized into three types: empirical, deterministic and stochastic. Empirical models are those based on observations and measurements alone. The deterministic models make use of the laws governing electromagnetic wave propagation to determine the received signal power at a particular location. Stochastic models, on the other hand, model the environment as a series of random variables.

The phenomena which influence radio wave propagation can generally be described by four basic mechanisms: reflection, penetration, diffraction, and scattering. For the practical prediction of propagation in a real environment these mechanisms must be described by approximations.

In both, indoor and outdoor environments, the average large scale path loss for an arbitrary Transmitter-Receiver (*T-R*) separation is expressed as a function of distance by using a path loss exponent, *n* [9]. This value of *n* depends on the specific propagation environment, i.e., type of construction material, architecture, and location within a building. Lowering the value of *n* lowers the signal loss. The values of *n* range from *1.2* (Waveguide effect) to *8* [2]. For example, in free space, *n* is equal to *2*, and when obstructions are present, *n* will have a larger value.

Random shadowing effects occurring over a large number of measurement locations which have the same *T-R* separation, but different levels of clutter on the propagation path, is referred to as *Log-Normal Distribution* [9]. This phenomenon is referred to as *log-normal shadowing*. Variations in environmental clutter at different locations having the same *T-R* separation is not accounted for by the log-distance path loss model alone. This leads to measured signals which are vastly different than the average value predicted by using the log-distance path loss model. To account for these variations, the average path loss $PL(d)$ for a transmitter and receiver with separation *d* becomes:

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n\log(d/d_0) + X_\sigma \quad (7)$$

where X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ. For example: In building LOS ($n=1.6\div1.8$), Obstructed in Building ($n=4\div6$), Obstructed in Factories ($n=2\div3$).

Most of *ZigBee* applications are indoors, having a microcell ($d_0\approx1\div10$m) or a pico-cell size. The micro-cellular propagation channel typically is Ricean: it contains a dominant direct component, with an amplitude determined by path loss, a set of early reflected waves.

Indoor channels may be classified as either *Line-of-sight* (*LOS*) or *Obstructed* (*OBS*), with varying degrees of clutter. The indoor propagation channel differs considerably from the outdoor one. Calculating path loss for an indoor environment is difficult because of the variety of physical barriers and materials within the indoor structure; one cannot exactly predict the loss of signal energy. Obstacles such as walls, ceilings and furniture, usually block the path between receiver and transmitter. Depending on the building construction and layout, the signal usually propagates along corridors and into other open areas. In some cases, transmitted signals may have a *Line-of-Site* (*LOS*) to the receiver. In most cases a *Non-Line-Of-Sight* (*NLOS*) conditions i.e., the signal path is obstructed (*OBS)*. The indoor channel is not stationary both in space and in time domains. The motion of people and equipment around the low-level portable antennas cause temporal variations in the indoor channel statistics, Ricean Fading for the stationary receivers.

Furthermore, the indoor channel is characterized by higher path losses and sharper changes in the mean signal level, as compared to the mobile channel. Multipath occurs when there is more than one path available for radio signal propagation. The reflection, diffraction and scattering phenomena cause additional radio propagation paths to the direct *LOS* path between the transmitter and receiver. There is not a unified theoretical model for path loss and fading effects prediction in indoor communications.

The propagation inside a building is influenced by: layout of the building, construction materials, building type (sports arena, residential home, factory, etc). The values for *n* and X_σ where measured for following buiding types: Residential homes in suburban areas; Residential homes in urban areas; Traditional office buildings with fixed walls (hard partitions); Open plan buildings with movable wall panels (soft partitions); Factory buildings; Grocery stores; Retail stores; Sport arenas [9].

In building, path loss factors are: Partition losses (same floor); Partition losses between floors; Signal Penetration into Buildings.

There are two kind of partition at the same floor: Hard partions (the walls of the rooms); Soft partitions (moveable partitions that does not span to the ceiling). The path loss depends on the type of the partitions.

There are situation when *RF link* is established between a outside and an inside node. *RF* signals can penetrate from outside transmitter to the inside of buildings. However the siganls are attenuated, the path loss during penetration has been found to be a function of: frequency of the signal (penetration loss decreases with increasing frequency) and the height of the building (penetration loss decreases with the height of the building up-to some certain height).

For the calculation of path loss, there are indoor propagation models including a lot of enumerated losses: Partition Losses – Same Floor; Partition Losses – Different Floor, Log-distance path loss model, Ericsson Multiple Breakpoint Model, Attenuation Factor Model.

A. Attenuation Factor Model

This model includes effect of building type and variations caused by obstacles, reduces standard deviation for path loss from σ ≈13dB to σ ≈ 4dB.

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n_{SF}\log(d/d_0) + FAF + \sum_{=1}^{m} PAF \quad (8)$$

where n_{SF} = exponent value for same floor measurement (must be accurate); *FAF* = floor attenuation factor for different floor; *PAF* = partition

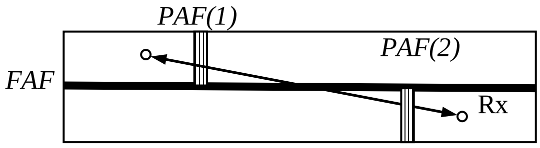

Fig. 2. *Primary ray tracing*

attenuation factor for obstruction encountered by *primary ray tracing* (single ray drawn between *Tx* and *Rx*) (Fig. 2).

For multiple floors, *FAF* can be replaced with n_{MF} - exponent for multiple floor loss:

$$PL(d) = PL(d_0) + 10 n_{MF} \log(d/d_0) + \sum_{=1}^{m} PAF \qquad (9)$$

In Table 1 are presented Path Loss exponents and Standard Deviations for typical building. There are two kind of partition at the same floor: hard partitions (the walls of the rooms) and soft partitions (moveable partitions that does not span to the ceiling). The path loss depends on the type of the partitions.

Average signal loss measurements, for *915MHz*, reported by various researches for some common building material are: *26dB* (all metal), *20.4dB* (aluminim siding), *3.9dB* (concrete block wall). An average values of *1.4dB* for soft partition and *2.4dB* for hard partition should be considered [13]. Penetration loss decreases with increasing frequency, a reduction by *85%* can be estimatated at *2.4GHz*.

TABLE 1. Path Loss exponents and Standard Deviations.

Location	***n***	**X_σ (dB)**
same floor	2.76	12.9
through 1 floor	4.19	5.1
through 2 floor	5.04	6.5
through 3 floor	5.22	6.7

B. Coverage in ZigBee

The coverage is defined as the percentage of area within a cell that has received power above a given minimum power, the distance between two sensors in the case of ideally distributed nodes. A circular coverage area with radius *R=d* should be considered. For this estimations, the link budget *LB* is improved considering the *link margin LM* (a mean value of *20dB*).

$$PL(\mathrm{d}) = LB - LM \qquad (10)$$

Using *log-normal shadowing model* the distance *d* will be calculated, for various link budget scenarios:

$$d = 10\exp 1/10n[PL(d) - \mathrm{PL}(d_0) \pm X_\sigma] + \log d_0 \qquad (11)$$

If the devices are stationary, the effects of X_σ can be ignored [10]. The value of *n* does not vary much with frequency and depends on the surroundings and the building type.

$$d = 10\exp 1/10n[PL(d) - \mathrm{PL}(d_0)] + \log d_0 \qquad (12)$$

For multiple floors, the distance *d* the following formula should be used:

$$d = 10\exp 1/10n_{MF}[PL(d) - \mathrm{PL}(d_0) - \sum_{=1}^{m} PAF] + \log d_0 \qquad (13)$$

The distance *d* between nodes can be also calculated using the channel model, based on IEEE Standard 802.11 as adapted by IEEE Standard 802.15.2™-2003 and IEEE Standard 802.15.3-2003 [7]:

$$d = 10\ \exp(P_T - P_R - 40.2)/20 \quad \text{for } d < 8\text{m} \qquad (14)$$

$$d = 10\ \exp(P_T - P_R - 58.5)/33 \quad \text{for } d > 8\text{m} \qquad (15)$$

Using these formulas, different scenarios were used to calculate and compare the limit of a reliable distance *d* between nodes. Some results are summarized in the Table 2 and Table 3.

TABLE 2 *(d_0=1m, P_R= −92/ −85dBm, LM =20dBm)*

f MHz	***P_T*** dBm	**LOS Bld** *d*(*m*)	**OBS Fact** *d*(*m*)	**OBS Bld** *d*(*m*)	**IEEE** *d*(*m*)
n		**1.8**	**2.4**	**4**	
868	0	195.22	52.23	10.73	82.84
868	-3	133.00	39.17	9.03	67.19
868	10	701.60	136.32	19.09	166.45
915	0	184.11	49.98	10.45	82.84
915	-3	125.44	37.48	8.80	67.19
915	10	661.67	130.46	18.59	166.45
2450	0	25.17	11.24	4.27	8.88
2450	-3	17.15	8.43	3.59	50.83
2450	10	90.47	29.33	7.59	41.23

For a closer comparison with *IEEE* channel model, d_0 was modified to *8m*. This value is not very appropriate for indoor propagation.

TABLE 3 *(d_0 = 8m, P_R = −92/−85dBm, LM = 20dBm)*

f MHz	***P_T*** dBm	**LOS Bld** *d*(*m*)	**OBS Fact** *d*(*m*)	**OBSBld** *d*(*m*)	**IEEE** *d*(*m*)

n		**1.8**	**2.4**	**4**	
868	0	154.95	73.86	30.36	82.84
868	-3	105.57	55.39	25.54	67.19
868	10	556.86	192.79	53.99	166.45
915	0	146.13	70.69	29.57	82.84
915	-3	99.56	53.01	24.88	67.19
915	10	525.17	184.50	52.58	166.45
2450	0	19.98	15.89	12.08	8.88
2450	-3	13.61	11.92	10.16	50.83
2450	10	71.80	41.48	21.48	41.23

The results for multiple floor building are presented in Table 4. For each upper floor, hard/soft partitions were increased by one. The values listed in Table 1 were used for these calculations.

TABLE 4 *($P_T = 0dBm$, $P_R = -92/-85dBm$, $LM=20dBm$)*

f MHz	**SF + PAF** *d*(*m*)	**1 Fl + 2 PAF** *d*(*m*)	**2 Fl + 3 PAF** *d*(*m*)	**3 Fl + 4 PAF** *d*(*m*)	**IEEE** *d*(*m*)
d_0 =1m, hard partitions					
868	25.52	7.4	4.73	4.04	82.84
915	24.56	7.22	4.64	3.96	82.84
2450	7.29	3.43	2.61	2.38	8.88
d_0 = 1m, soft partitions					
868	26.39	7.74	5.00	4.33	82.84
915	25.40	7.54	4.9	4.24	82.84
2450	7.42	3.5	2.68	2.46	8.88

Conclusions

The future success of *WSN* is related to the condition to have a reliable *RF link* between the nodes composing the network. The analysis and evaluation of these aspects for *ZigBee* networks, especially for indoor applications, reveal a huge diversity of situations.

An accurate prediction of *RF* coverage of the network is very difficult to realize. Using different models of propagation for indoor environment, for the values imposed by *IEEE 802.15.4/Zigbee* standards, the limits of reliable *RF link* were calculated.

The channel model recommended by *IEEE 802.15.4* is less accurate for indoor *RF link*.

The link margin *LM* of 20*dB* was used for determinations of *d*, the distance between two nodes. Due to various and random shadowing effects, for the X_σ - zero-mean Gaussian distributed random variable with standard deviation σ, a value of about *7dB* for *868/915MHZ* band and *14dB* for *2.4GHz* band were considered. For these values, the variation of distance *d* is about *50%*.

The link margin *LM* of *20dB* ensures a reliable *RF link* for almost all scenarios. The multiple floor analysis reveals that a standard *Tx* output power of *0dbm* can ensure a reliable link for only two floors and if the output power is increased to *10dBm* the link is secure only for three floors.

Values reported for P_R, by most of *ZigBee* devices producers, are better than standard values with *10÷18dBm* (2.4 GHz) and with *15dBm* (868/914 MHz). Using these values, the range will be increased two or three times towards the standard devices. There are *Tx* devices capable to deliver an output power $P_T = 20dBm$ (2.4 GHz) so the distance *d* should be increased three to four times towards the standard values used in Table 4.

Using the standard value for maximum *Rx* input power, *-20dBm*, the minimum distance between two standard devices (*Tx=10dBm*) of ≈ 1m was founded.

The value reported for this parameter by some producers is *+5dBm*, so the devices can be placed closer, eventually in the same case with others wireless devices.

This estimation of *RF link* in ZigBee networks is an important step to set a design procedure for deployment of this type of WSN network.

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