Accuracy of Power Prediction Models in ZigBee Sensor Networks Applied in Grass Environment

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***Abstract*—Wireless Sensor Networks (WSNs) have become an area of great interest due to their usage in a wide range of applications. A preliminary study concerning the viability of a WSN introduced in the environment is recommended, considering that this type of network is applied with several variables that influence the operation of the network. Those variables directly affect the network performance metrics such as the Received Signal Strength Indicator (RSSI). The present paper provides a study about the application of a WSN on a specific environment to practice sports, in which the RSSI metric was used to study the link quality. The study uses several power prediction models, and the results were compared with real measurements in order to identify the best prediction model in this particular environment.**

Keywords–Wireless Sensor; RSSI; Sports environment; Real measurements.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have became a very interesting research topic in the last few years. The recent advances in microelectromechanical systems technologies, wireless communications, and digital electronics have enabled the development of low-cost sensor nodes, that are capable of communicating with each other over short distances. Small nodes consist of a few components: a radio part for spreading data, a sensor part for sensing environment phenomena, a processing unit and a power supply. The potential application of wireless technologies has also been recognized by the Institute of Electrical and Electronics Engineers (IEEE), which set up a standardization group 802.15.4 for designing a new physical layer for low-data rate communications combined with positioning capabilities [1].

WSNs came into the spotlight during the past years due to the advances in wireless communications, such as new information technologies and electronic attributes developed for those technologies [2]. It is even possible to affirm that WSNs are a quite promising technology of this generation since they have a great utility because of their implementation in industrial control systems. Other advantages to be mentioned are their low cost and multi-functional sensors that perform surveillance functions and day-to-day activities control.

It is because of their versatility that WSNs have generated increasing interest in the past few years [3]. In the last two decades, surveys indicate that the wireless systems will be capable of extending even more the application fields. There are applications such as in health care, home automation and automation in general. A relevant topic observed while researching wireless systems, was the characterization of how the radio signals range varies according to indoor and outdoor environments because of the conditions on some ambient factors, that can immediately make a transmission harder to be done, due to interferences [4].

The main goal of this research is to perform a study in addition to the works presented by [5] and [6], in which the authors conducted a performance analysis of ZigBee devices in each environment. This work uses the same space so that, from the results presented in [5] and [6] the performances can be compared with power prediction models, and, thus, estimate the accuracy of the proposed model. This application has importance because of the existence of different places, such as for sporting events, which makes necessary the use of resources to provide improvements, such as water, in environments where this type of WSN is widely used.

This paper is organized as follows: Section II shows fundamental concepts in ZigBee and RSSI. Section III shows the related works and Section IV shows the importance of power prediction in networks. In Section V the mechanisms of Radio Frequency (RF) Propagation are shown. Section VI shows the Propagation Models used in this paper. In Section VII the Statistical Methods used to analyze the measurements are explored. Section VIII shows the Methodology of Experiments and finally, Section IX shows the results and conclusion about this work.

II. ZIGBEE TECHNOLOGY AND RSSI

The ZigBee technology is an option to supply a space in WSN's network architecture. This technology has advantages compared of other communications protocols, such as Wi-Fi [7] and Bluetooth [8]. ZigBee technology has a protocol which supports mesh, star and tree networks, creating more than one path possible between transmitter and receiver.

Thus, an information packet that can not be transmitted through one path can find another path that may deliver it. This works in a similar way with the routing table which is created by a router, making possible the delivery of a packet.

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ZigBee operates in three frequency bands: 868 MHz in Europe, 915 MHz in the USA and 2.4 GHz in the rest of the world. It bases on IEEE's 802.15.4 protocol to implement the Physical (PHY) and Media Access Control (MAC) layers from the OSI model. Other layers are defined by *ZigBee Alliance* [9]. In many applications, and in the ZigBee Technology the performance is measured by the RSSI metric.

Received Signal Strength Indicator (RSSI) is used as a measurement system to estimate the transmission quality between two nodes based on their relative distance. RSSI is implemented under IEEE 802.11 Standard [10]. This method uses relative distance to estimate the transmitted signal quality by comparing the received signal with probability distributions and location measurements based on the statistic analysis method [11]. On RSSI, its importance is due to the severity of fading effects on wireless communications, causing their existence to directly affect the performance of wireless communications systems [6], [12], [13], [14]. Most 802.11 radio modules support RSSI, which means it is possible to calculate received power to each received packet. The power or energy of a signal travelling between two nodes is a signal parameter that contains information related to the distance between those nodes. This parameter can be used together with path-loss and shadowing model for distance estimation [1].

III. RELATED WORKS

Various papers have been published with the purpose of investigating the effects on the propagation of radio signals in the *ZigBee* devices. Jafer et al. [15] have investigated the effects caused by external factors on the RF signals. Specifically, they have analysed the RF activity outdoors for 24 hours in order to investigate the influence of time on the RSSI measurements and therefore to estimate the difference between day and night measurements. The effects of the communication were aleatory and erratic because people might have been passing through the area. The effects of internal factors on RSSI measurements have also been analyzed, such as the effect of polarization antenna between the transmitter and the receiver [16], or the effect of the conception of hardware devices [17]. Pellegrini et al. [18] perform a RF propagation analysis using collected RSSI values.

IV. IMPORTANCE OF PROPAGATION PREDICTION

Before implementing the designs and confirming the planning of wireless communication systems, accurate propagation characteristics of the environment should be noted. Propagation prediction usually provides two types of parameters corresponding to the large-scale path loss and small-scale fading statistics. The path loss information is vital to determine the coverage of a base-station (BS) placement and also in optimizing it. The small-scale parameters usually provide statistical information on local field variations and this, in turn, leads to the calculation of important parameters that helps improve receiver (Rx) designs and combat the multipath fading. Without propagation predictions, these parameter estimations can only be obtained by field measurements which are time consuming and expensive [19].

V. RADIO FREQUENCY PROPAGATION

With the increasing capacity of mobile communications, the size of a cell is becoming continuously smaller: from macrocell to microcell, and then to picocell. The service for environments includes both outdoor and indoor areas.

When propagation is considered in an outdoor environment, three different areas catch our attention: urban, suburban, and rural areas. In those cases, the terrain profile of the particular area needs to be considered. The terrain profile may vary from a simple, curved Earth to a highly mountainous region. The presence of trees, buildings, moving cars, and other obstacles must also be taken into account. The direct path, reflections from the ground and buildings, and diffraction from the comers and buildings' rooftops are the main contributors to the total field generated at a receiver, due to radio-wave propagation.

Reflection, diffraction, and scattering are the three basic propagation mechanisms that impact propagation in mobile communication systems [20] which will be briefly explained below.

A. *Reflection*

Reflection occurs when a propagating electromagnetic wave impinges upon an object that has very large dimensions compared to the wavelength of the propagating wave. It occurs from the surface of the ground, from walls, and from furniture. And when it does, the wave may also be partially refracted.

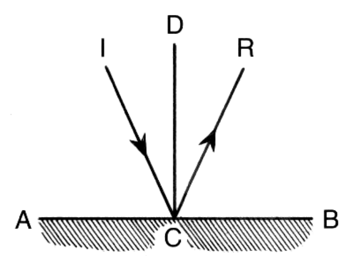

Figure 1. Reflection.

The coefficients of reflection and refraction are functions of the material properties of the medium, and generally depend on the wave polarization, the angle of incidence, and the frequency of the propagating wave [20]. These effects are shown in Fig. 1.

B. *Diffraction*

Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp edges, (Fig. 2).

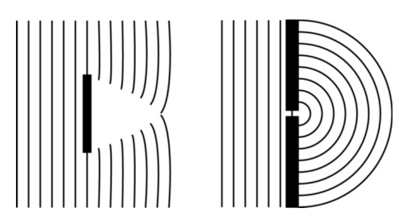

Figure 2. Diffraction.

The waves produced by the obstructing surface are present throughout space and even behind the obstacle, giving rise to

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the bending of waves around the obstacle, even when a line of sight (LOS) path does not exist between the transmitter and receiver. At high frequencies, diffraction - like reflection - depends on the geometry of the object, as well as on the amplitude, phase, and polarization of the incident wave at the point of diffraction [20]. These effects are shown in Fig. 2.

C. Scattering

Scattering occurs when the medium through which the wave propagates, consists in objects with dimensions that are small compared to the wavelength, and also where the volume number of obstacles per unit is large. Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel.

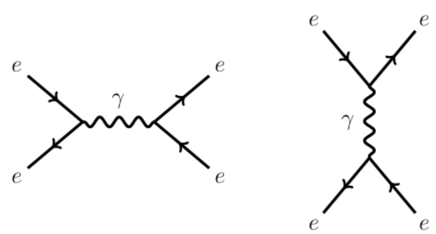

Figure 3. Scattering.

In practice, foliage, street signs, lampposts, and stairs within buildings can induce scattering in mobile-communication systems. A sound recognition on the physical details of the objects can be used to accurately predict the scattered signal strength [20]. These effects are shown in Fig. 3.

VI. PROPAGATION MODELS

Propagation models are fundamental tools for designing and deploying any wireless communication system including WSNs. The models are closely related to the system working environment and characteristics. In general, propagation models are methods and algorithms used to predict the signal strength level along with the description of the signal level variability. Its main purpose is to predict the distortion and attenuation of the RF signal that will reach the receiver [21].

Currently there are many mathematical models with the purpose of predicting the average strength of the wireless signal transmission between two network devices. These models are useful in estimating the radio area of coverage of a transmitter and they are called propagation models, featuring the signal strength when there is a separation between transmitter and receiver. The PL_{dB} represents the losses of the model, **d** represents the distance, **f** represents the frequency, and the λ is a wavelength and all losses from these models are given in **dBm**.

A. Free Space Model

This model determines the power at the receiver in meters of transmitting power, the gain of the antennas and the distance between sender and receiver. They are not contemplated in the model losses that may occur, due to the propagation environment and the coverage area of an antenna that could be irregular. The satellite communication, as there is line of sight between transmitter and receiver, can be used as propagation model. The attenuation (path loss) for the Free Space model is defined by equation (1).

$$PL_{dB} = -10 * log(\frac{G_t * G_r * \lambda^2}{(4 * \Pi)^2 * d^2}) \tag{1}$$

Where G_t and G_r represents the transmitter gain and receiver gain.

B. Log-Distance Model

Defined in [22] and [23], Log-Distance model considers that the average received power decreases logarithmically with distance from the transmitter. This model is characterized by the (2) equation.

$$PL_{dB} = PL(d_0) + 10 * n * log(\frac{d}{d_0}) \tag{2}$$

Table I shows the values for the coefficients (n).

TABLE I. N EXPONENTS.

Environment	Path loss exponent (n)
Free space	2
Urban area	2.7 to 3.5
Shadowed urban	3 to 5
Obstructed in building	4 to 6

C. Shadowing Adapted Model

Adapted models are implemented from the classic models by adjusting (adaptation) their coefficients relation to field measurement by the minimum mean square error technique. The main advantage of this approach is the fact that it ”encapsulates” some model input parameters, thus avoiding problems related to bad dimensioning, which can lead to considerable errors of prediction. It is defined in [24] by equation (3).

$$PL_{dB} = -10 * \beta * log(d) + 9 \tag{3}$$

Where β is a path loss exponent of the environment.

D. Tewari, Swarup and Roy Model

This model is defined in [25]. This model was developed based on measurements performed in the forest of India, which resembles in some attributes, the Amazon rainforest [25], and it is defined by equation (4).

$$\begin{aligned} PL_{dB} = 88 + 20 * log(f_{MHz}) + 40 * log(d_{Km}) - \\ 20 * log[H_t(m) * H_r(m)] + L_f(dB) \end{aligned} \tag{4}$$

Where H_t represents transmitter height, H_r represents receiver height and L_f represents environmental losses defined in [25].

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E. Weissberger Model

For empirical models, it was found that the model developed by Weissberger estimate the excess of attenuation produced by vegetation, which is a model of interest when providing for the existence of foliage, and to make prediction for small stretches [26]. The loss model is given by equations (5) and (6).

Case $d \leq 14m$:

$$PL_{dB} = 0.45 * f^{0.284} * d \tag{5}$$

Case $14m \leq d \leq 400m$:

$$PL_{dB} = 0.45 * f^{0.284} * d^{0.588} \tag{6}$$

Where d represents distance and f represents frequency.

F. ITU-R Model

The International Telecommunication Union Recommendations (ITU-R) Model, defined in [27], is given by equation (7).

$$PL_{dB} = 0.2 * f^{0.3} * d^{0.6} \tag{7}$$

G. COST 235 Model

Defined by [28], this model is given by equations (8) and (9).

$$PL_{dB} = 15.6 * f^{-0.009} * d^{0.26} - With\ leaf \tag{8}$$

$$PL_{dB} = 15.6 * f^{-0.2} * d^{0.5} - Without\ leaf \tag{9}$$

H. RIM Model

RIM (Radio Irregularity Model) is a model developed purposefully for wireless sensor networks. In isotropic models of radio coverage, the received power is obtained by equation (10).

$$P_r = P_t - PL + F \tag{10}$$

Where P_r represents received power, P_t represents transmitted power, PL represents the path losses and F represents component of fading. This model is defined by [29] and as the literature already mentions, the radio coverage is not a perfect circle in real environments [23], neither it resembles a circle. The RIM model is based on this irregularity. To symbolize the irregularity of the radio coverage model, the parameter DOI (Degree of Irregularity), was introduced in the RIM model. Fig. 4 shows this irregularity of behavior in the propagation.

It is possible to observe that the bigger by the image irregularity of the radio coverage is, the higher the DOI value parameter. The description of the DOI calculation irregularity is given by equation (11).

$$PR = PE - (PL_{DOI} * K_i) + F, \tag{11}$$

where:

- PL_{DOI} = *Path Loss* with DOI adjustment;
- F = Component of *fading*.
- K_i = Coefficient representing the difference in losses *path loss* in different directions, where $K_i = 1, case(i = 0)$, i.e., the angle being the angle 0 is analyzed, in reference to line of sight;
- i = Coefficient of i-nth degree.

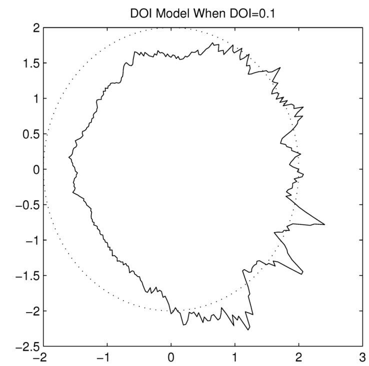

Figure 4. Irregularity coefficient in the radio coverage.

VII. Used Statistical Methods

The results obtained have undergone a process of statistical analysis for validating data. Such reliability is based on the methods that follow.

A. Mean Square Error (MSE)

In practical terms, the Mean Square Error (MSE) equals the sum of the variance and tendentiousness square estimator. An estimator is used to deduce the value of an unknown parameter in the statistical model. The estimating of MSE is expressed by (12).

$$MSE = \frac{\sum_{t=1}^{n} e_t^2}{n}, \tag{12}$$

where:

- e_t: error caused by the difference between sample and predicted value;
- n: number of periods.

B. Mean Absolute Percentage Error (MAPE)

The average absolute percentage error calculation estimates how exact is the actual value with the estimated one, in percentage. Such a connection is expressed by (13).

$$MAPE = \frac{\sum_{t=1}^{n} \left| \frac{(A_t - P_t)}{A_t} * 100 \right|}{n}, \tag{13}$$

where:

- A_t: real value in t period;
- P_t: prediction in t period.

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VIII. Methodology of Experiments

The methodology adopted during the assembly from a RSSI measurer and subsequent measurements with it were made under the following step's schedule.

- First Step: The used device had a direct-access terminal on a specific pin to read the RSSI. A PWM (Pulse Width Modulation) modulated signal was read in the pin. This signal was treated as an analogical output but it is, as a matter of fact, a digital output that generates an alternating signal (*low* and *high* digital levels), where the data is codified in how long the pin's output stands on a digital level.

- Second Step: Compatibility tests were performed between the used Arduino Uno R3 platform and the XBee modules and basic trigger circuits with the modules, in order to verify whether there was correct communication maintenance between the devices. At this stage, the prototypes were assembled in assembly boards. Other electronic components were also added to the project, such as a 16×2 LCD (Liquid Crystal Display) display for showing the reading values, and components responsible for maintaining and feeding the display, among other devices.

- Third Step: At this stage, the source-code executed by the prototype was written. The source-code development used an open-source programming framework for microcontrollers, called *Wiring*, that includes several on-the-box applications allowing an easy development of various input-output operations. That is one of the reasons whereby it is the standard development language for Arduino projects. The analogical pin (the one who provides the RSSI value) was read through the *pulseInt()* function, made for occasions like this one. This function reads a *high* or *low* pulse on the pin and then returns to its duration in milliseconds. Thus, it measures the PWM pulses length.

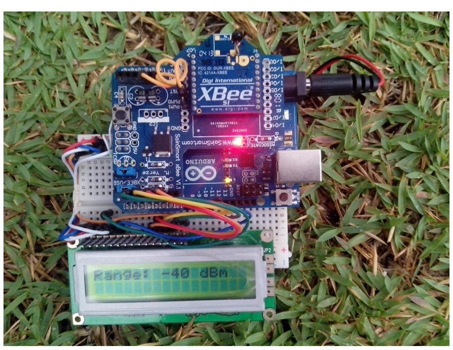

Figure 5. Receiving device standing on the ground, during first measurement.

The code executed by the micro-controller responsible for the reading function can be found in the following code, and Fig. 5 shows the prototype.

```
int dur = pulseInt (A1,LOW,200);
float val = analogRead(A1);
int rssi=(dur+50)*(-1);
```

- Fourth Step: The measurements were made on an outdoor sports field, Fig. 6. The transmitter was fixed and the receiver was taken to increasingly longer distances from the transmitter. Two tests were made: on the first, both devices were on ground level. Starting with one meter distance, the transmitter's signal strength on the receiver was measured. The distance was increased up to the point where there was no connection. This test was performed on a sunny day, in the afternoon, with low wind, temperatures between 28 and 31 Celsius degrees, and air humidity at 65%.

Figure 6. Place of measurements.

- Fifth Step: At this stage we did the analyzes of samples collected from the comparison variables of the models used and the real measurements.

IX. Results and Conclusions

From the conclusion of the data analysis, which was the last stage of the work methodology, we obtained satisfactory results that were expected for the work proposed. Fig. 7 shows the curve obtained from the real RSSI values versus power prediction curves for each propagation model.

The calculations of Mean Square Error (MSE) and Mean Absolute Percentual Error (MAPE) were used as statistical methods to measure the approximation of the actual measurement with the proposed models. The results are described in Table II.

TABLE II. TABLE OF RESULTS.

Model	MSE	MAPE
Log-Distance n =2	218.810050	17.019827
Log-Distance n=3	399.298599	24.947916
Log-Distance n=4	1319.050187	45.931788
Log-Distance Shadowing	67.151034	9.985123
Free Space (Friis)	184.344305	19.477650
RIM-DOI	252.340084	16.715468
Weissberger d<14	**44.966762**	6.869068
Weissberger d>14	395.457018	22.606341
Tewari, Swarup e Roy	1855.379165	57.330225
ITU-R	635.934654	30.098993
COST 235 With leaf	144.596843	**5.358066**
COST 235 Without leaf	550.381070	27.301250

The deployment of a WSN in sports environment requires the study of signal propagation in order to find the best way of positioning sensor nodes, and the power of prediction of RSSI

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values is very important to building this network. This work contributes to the deployment of WSNs in the region of the Campina Grande - Paraíba in order to optimize the usage of resources, such as water and electricity, considering that those sports environments require a lot of water.

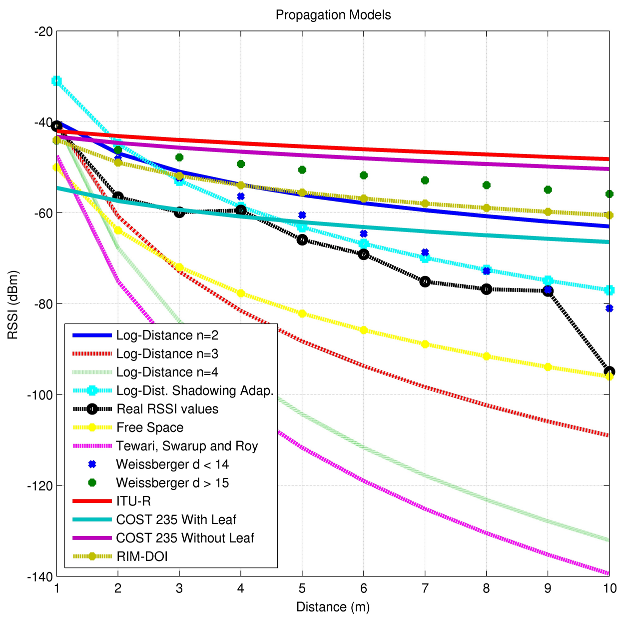

Figure 7. Used Models and Real RSSI Values.

From the analysis of the propagation models to power prediction, we conclude that the Weissberger Model $d < 14$ and COST 235 with leaf are the best way to model the power prediction in that area, but other models also had good results. The major contribution to the research was the use of a technology, such as ZigBee, applied to the monitoring of sports practicing areas. That was the main objective of this research, which was effectively reached.

The requirement of the experiments stands in the verification of the viability of applying ZigBee in that specific type of environment, since to our knowledge, was not done in literature so far. In addition, it was possible to perform an experiment to test the effectiveness of an external RSSI meter, which can be used visually and externally.

For this work, we chose to study only the transmission range of the sensors in sports environments. In future work, we intend to study the impact of climate on those measurements, arranging the schedules for data collection on different days with different climate and temperatures.

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