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PROPAGATION ANALYSIS AND DEPLOYMENT OF A WIRELESS SENSOR NETWORK IN A FOREST

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Abstract—A complete study for the deployment of a wireless sensor network in a forest based on ZigBee is presented in this paper. First, due to the lack of propagation models for peer to peer networks in forests, propagation experiments were carried out to determine the propagation model.

This model was then used for planning and deploying an actual wireless sensor network. The performance of the network was compared with the expected theoretical behavior to extract some conclusions that are presented in the paper.

Finally, some general conclusions, as an estimation of the minimum number of routers necessary to cover a given area, are extracted from the experiments and presented in the paper.

1. INTRODUCTION

Wireless sensor network applications are nowadays in an exponential growing. Initially, these wireless networks were oriented for indoor use, as home automation and industrial control [1] or medical applications [2]. But its use has been extended to other applications that were not considered at the beginning: outdoor networks and, particularly, sensor/actuator networks in rural areas and forests. The research results provided by this work consider this later environment.

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The forest considered corresponds to a wet area with Atlantic climate, and it was conformed essentially by pine trees. Within this forest, propagation experiments have been conducted in order to analyse the behaviour of such a special radio channel at a frequency band that is assigned to wireless networks.

Propagation studies in rural environments and forests have to take into account the presence of vegetation in the propagation channel. Although there are several research works related to propagation at such condition [3, 4] and even the International Telecommunication Union-Radiocommunication Sector (ITU-R) recommendation P.833.6 [5], most of them are focused on classical master-slave (or base station to mobile terminal) configuration, where the base has a prominent height over the coverage area.

However, the proposed sensor application is intended to be deployed in terms of peer to peer collaborative networks where there is no predominant location. And there is a lack in the scientific knowledge for such configuration [6]. There are a lot of studies focused on the attenuation induced by the tree canopies [7, 8] and on wind effects [9, 10], but this peer to peer configuration is mainly affected by the tree trunks.

Some previous work related to the deployment of a wireless sensor network (WSN) in a forest has been checked. Similar technologies have been previously used to deploy WSN [12]. An application to analyse the forest fire propagation is shown in [13], but no study was done regarding the propagation conditions in these wooded environments. The interest of the use of WSN in the forest fire propagation analysis is also highlighted in [11].

In the related literature, there are some propagation analyses in the VHF band within forests [14–16] and some indoor [17] and outdoor propagation studies in the UHF band within vegetated environments [18]. But the size of the future WSN will increase substantially in order to cover bigger outdoor areas, so, the need of a simpler propagation model is increasing.

The final objective of our study is to assess the performance limits, the coverage and best network configuration in the forest considered. The technology selected for this aim was ZigBee. Low power consumption, small size of the devices together with their low cost are the main characteristics that this technology is the best choice for this objective.

The initial experiments were performed by means of separate transmitter and receiver. The receiver was moved along different radials. These radials began at the transmitter location, and they went along a straight line moving away from it. Each radial contains various tens of trees of different sizes where the receiver was placed to get the measurements. The receiver was placed at each tree along the radial. Around each tree, four received power measurement points were considered including both illuminated and shadowed sides of the trunk. The number of trees in the propagation path and their diameters were carefully registered. The data were analysed by means of an experimental power decay fit with distance.

Results were used for planning and deploying an actual wireless network. Before the deployment, the maximum distance between the coordinator and routers or end-devices and between routers and end-devices must be estimated in order to optimize the number of devices assuring the network performance.

The ZigBee network deployed consisted of:

- A network coordinator, which is the master of the network and was located in a place with electric power supply.
- Several routers, whose principal function is to route packets from end-devices to the network coordinator. They were placed on the tree trunks.
- End-devices, which periodically transmit the sensor information, such as air temperature, humidity, light intensity level and all variables people want, to the router which had been previously connected to. These devices were located on the tree trunks. The wireless network was deployed according to the plan, and several performance measurements were taken to check these previously done estimations.

Section 1 begins with a description of the environment under study and the equipment used during the measurement campaign. Section 2 explains how we have carried out the measurements. Section 3 presents results individually for each one of the scenarios considered, and a general propagation equation will be calculated for each environment in order to estimate the range coverage of each device. Furthermore, the attenuation induced by the number of trees in the radio propagation path will be estimated. From the results in Section 4, some conclusions that could help future deployments will be extracted. Finally, an estimation of the minimum number of routers necessary to cover a fixed area is computed.

2. MEASUREMENTS

An extensive measurement campaign has been designed and carried out to determine the effect of the mature wet forest in the radio link quality. In particular, the objective of this campaign was to obtain the parameters P_0 and n, which, according to Eq. (1), define the attenuation at a distance d.

$$P = P_0 d^{-n} \tag{1}$$

In Eq. (1), P_0 is the reference power at 1 meter from the transmitter; d is the distance in meters between transmitter and receiver; n is the factor that determines the power decay rate with the distance.

The knowledge of these parameters is necessary for planning the deployment of the ZigBee Network in the forest.

2.1. Environment under Study

These measurements were carried out in a mature wet forest near the campus of the University of Vigo. The forest was composed basically of pine trees from the specie *Pinus pinaster*. These trees usually have height from 20 to 35 m. The canopy only occupies the last 20% of the total height. The tree canopies are irregular, open and present only on the top of the tree trunks. Due to this tree shape and antenna heights, the radio propagation path is going to be under the influence of the tree trunks but not under their canopies. The tree density of this forest has been estimated as 0.03 pine trees per square meter.

The environment under study is shown in Figure 1, where the building and tower within the forest constitute a cellular mobile phone base station. This station has been used to get power supply for the transmitter during part of the propagation measurements and, for the network coordinator, in the network deployment experiments. In the future, it would be also used to send data gathered by the sensor network to a remote center.

Measurements were made in summer, and the time period was between 10 AM to 7 PM. The selection of this time schedule does not appear to have any influence on the measurement campaigns due to the stable conditions in terms of moisture and temperature that our Atlantic climate usually has.

2.2. Measurement Equipment and Setup

The measurement equipment used in the present campaign consisted of separated radio transmitter and receiver topology. Two different configurations were considered:

The first scenario emulates the radio link between the coordinator of the ZigBee Network and its sons (routers and end-devices). This first scenario was named "master-slave". The transmission segment was based on a Signal Generator (Rohde Schwarz SMR-40), which fed an omnidirectional antenna Electro-Metrics EM6865 via a low-loss coaxial cable. The transmitter was placed at a height of 3.5 m in a fixed location of the base station enclosure. The frequency of the transmitted tone was 2.45 GHz, and its power was +18 dBm. This first scenario is depicted in Figure 2.

The second scenario emulates the radio link between routers, and between routers and end-devices, in a "peer to peer" scheme. The transmission system was based on a tailor-made portable signal generator, which fed the EM6865 antenna via a low-loss coaxial cable. This transmitter was placed at a height of 1.5 m on a tripod close to a tree labeled as "transmitter tree". The frequency of the transmitted tone was the same, but in this case, its power was +12 dBm. In this case, two possible configurations have been studied: the transmitter in front of or behind the transmitter tree, taking as reference the direction of movement. The second scenario is depicted in Figure 3.

In this second scenario, both the receiver and transmitter were located at 1.5 meter high from the floor. This height was chosen because one of the objectives of a deployment could be the outdoor location of animals, as cows or horses, and their height seems to be around 1.5 meters. Furthermore, when a high number of devices is needed, the simplicity to deploy the network appears to be quite important. This height is probably not the best choice if we are looking for the optimum propagation conditions, because of the effects of the ground surface, but a trade-off between propagation conditions and deployment facilities is necessary.

The receiver (the same for both configurations) consisted of a Spectrum Analyzer (Rohde Schwarz FSH-6) that acquired the RF signals by another omnidirectional antenna Electro-Metrics EM6865. The antenna was fixed on the top of a tripod at 1.5 meters high, which made easier the displacements around the trees, as shown in Figures 1 and 2. This receiver system was moved to different trees along the radials described below.

Figure 1. Environment under study.

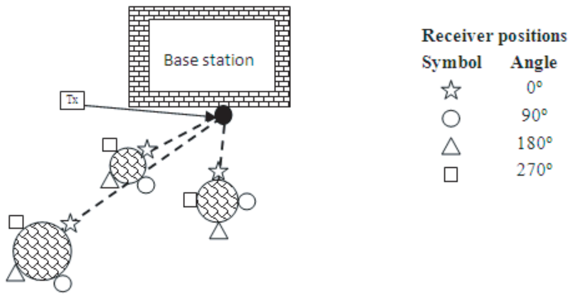
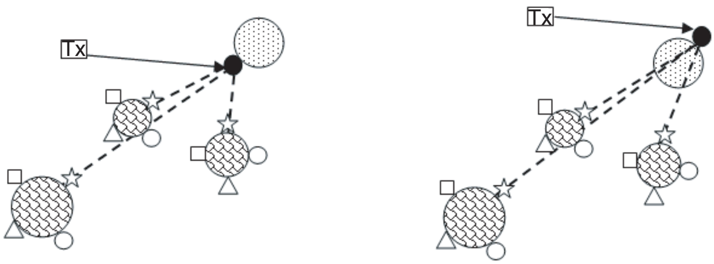


Figure 2. Example of a measurement in “master-slave” scenario.



(a) (b)

Figure 3. Examples of a measurement in “peer to peer” scenario. (a) Transmitter in front of the tree (LoS). (b) Transmitter behind the tree (OLoS).

Four power measurements have been made around each tree, as shown in Figure 2 and Figure 3. The position denoted as “0°” was the closest position from the tree under measurement to the transmitter. The other three positions were identified with the angle between them and the 0° position. See Figure 2 and its legend for more details. Solid black circle represents the transmitter location, and dashed lines show the shortest path between the tree under study and the transmitter. Tiled circles are the trees under study, and the dotted one is the “transmitter tree,” where the transmitter was placed during the “peer to peer” measurements.

In peer to peer scenario (Figure 3), data collected when the transmitter was in front of the tree trunk (a) is defined as Line of Sight (LoS), even though there was not a line of sight between transmitter and receiver at all four receiving locations. When the transmitter is behind the tree, the situation is defined as the Obstructed Line of Sight (OLoS).

In order to average temporal power variations, up to 301 power samples were obtained for each position around the tree trunk.

The results of these measurements allow the analysis of the attenuation as a function of the distance between transmitter and receiver, and the study of the attenuation induced by the number of trees between the transmitter and the receiver.

2.3. Measurement Procedure

The measurements were made according to the following procedure, which has been divided into three steps: the definition of radials, the installation of transmitter and the measurements themselves.

The first step was the definition of several radials along the forest. For Scenario I, three radials have been defined (shown as solid line in Figure 1), and four have been defined for Scenario II (shown as dashed line in Figure 1). The geometry and distribution of these radials are shown in Figure 4 and Figure 5. In both figures, the solid black circle is the transmitter, and the circumferences depict the trees along the radials included in the study. The radii of these circumferences are proportional to the actual radius of each tree trunk. The position of other trees off the radials is not shown. The squared block represents the Base Station in both figures.

The azimuth and distance to the transmitter and radius were collected for each pine tree. The three radials involved in master-slave scenario were numbered as shown in Figure 4, from R_1 to R_3.

For the peer to peer scenario, as shown in Figure 5, four radials were labeled as R_4, R_5, R_6 and R_7. The transmitter tree, represented by a solid black circle, is the coordinate origin of each graph, and it was chosen so that three or four radials of at least 50 meters could be defined around it (see Figure 6(b)).

Some characteristics of both scenarios are summarized in Table 1. "Number of trees" is the total number of trees considered for the study in each radial.

Table 1. Properties defining both scenarios.

Scenario	Master-slave			Peer to peer			
Radial	R_1	R_2	R_3	R_4	R_5	R_6	R_7
Number of trees	18	48	23	30	27	20	20
Mean tree radius (cm)	13.9	15.3	18.7	20.4	15.4	16.0	14.7
Mean tree azimuth (°) referred to north	104	68	355	151	58	314	246

The second step was to place the transmitter in an appropriate position. Figure 6(a), for master-slave scenario, and Figure 6(b), for peer to peer one, show the selected locations.

Once these steps were carried out, we started the measurements as described in Figure 2 and Figure 3 along the radials represented in Figure 4 and Figure 5.

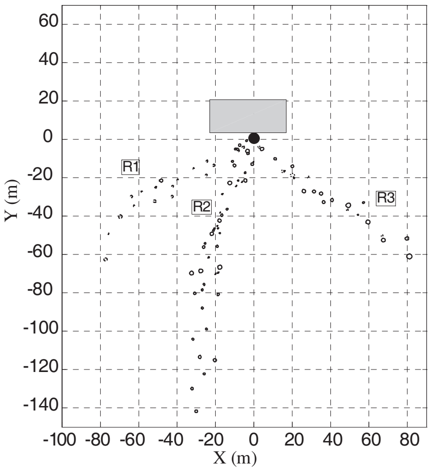


Figure 4. Geometry of the three radials in master-slave scenario.

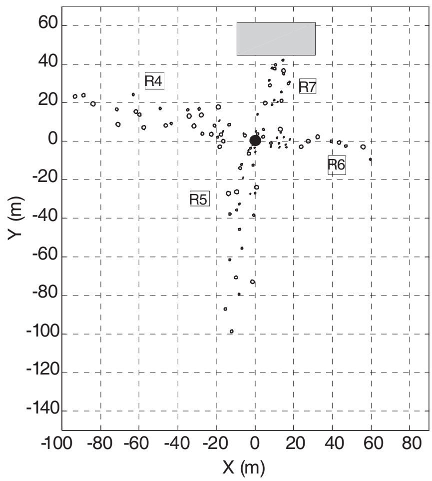


Figure 5. Geometry of the four radials in scenario II.

(a)

(b)

Figure 6. Transmitter location detail. (a) Master-slave scenario. (b) Peer to peer scenario.

3. MEASUREMENT RESULTS AND ANALYSIS

A large amount of data was gathered during the measurement campaign. Measurements were collected around more than 180 trees. Up to 1204 power samples were recorded and analyzed for each tree. In total, more than 220 thousand samples were recorded.

Two different scenarios were considered. For the first one, two distinct effects have been identified out of the analysis of the measured data: power variation versus distance between transmitter and receiver, which can be modeled by means of a log-distance regression, and the influence of the receiver tree trunk in the received power (depending on that receiver is located in front of or behind the tree trunk), which can be observed by comparing the received power at 0°, 90° and 270° versus the power measured at 180°.

For the second scenario the influence of the transmitter tree stem (Transmitter in LoS or OLoS) in the received power has also been considered.

Even though we have used different transmitted powers in both scenarios, all data presented in the following sections have been referenced to a virtual transmitted power of 0 dBm. Moreover, the correction of cable attenuation and antenna gains used in our campaign has been included in these data, and the corrected values are shown in Table 2.

Table 2. Attenuation parameters.

Scenario	Master-slave	Peer to peer
Transmitter cable	2.00	0.21
Receiver cable	0.21	0.21
Antenna	1.46	1.46

3.1. Master-slave Scenario: Power Decay with Distance

As explained before, this first scenario emulates the communication between the ZigBee Coordinator and routers or end-devices directly linked. This scenario is made up of three radials whose distribution is represented in Figure 4. The power variation with the distance shows how the received power falls down as we move away from the transmitter. This study provides the first coverage limits of the wireless sensor network for a given signal to noise ratio.

Relation in (1) is made linear into (2), where powers are in dBm and distances are in meters, in order to compute the log-distance regression.

$$P\,(\mathrm{dBm}) = P_0\,(\mathrm{dBm}) - 10 \cdot n \cdot \log(d\,(\mathrm{m})) \tag{2}$$

Parameters P_0 and n in (2) have been obtained for each one of the three radials at this first scenario. They have been computed separately for each reception angle around the receiver tree stem. All the values of the parameters P_0 and n obtained for each reception angle at any radial are summarized in Table 3. The error parameters represent an estimation of the standard deviation of the linear fit residuals and give an estimation of the error of the model.

Table 3. Parameters N and P_0 obtained for each reception angle of each radial separately.

	Master-slave scenario								
	Radial 1			Radial 2			Radial 3		
R_x Angle	P_0 (dBm)	n	Error (dB)	P_0 (dBm)	n	Error (dB)	P_0 (dBm)	n	Error (dB)
0°	−23.2	3.60	4.46	−23.2	3.66	5.43	−28.5	3.05	4.39
90°	−35.1	2.98	6.24	−21.7	3.73	6.34	−33.9	2.54	3.68
180°	−49.2	2.48	4.81	−46.1	2.62	4.74	−48.3	2.47	4.94
270°	−30.0	3.16	6.89	−26.8	3.52	5.91	−24.6	3.32	5.96

Observing the values ain Table 3, the rate of decay with distance, n, appears to be larger than the convened value for open environments, typically 2. This indicates the additional attenuation probably due to the forest.

An example of the regressions that have been computed is shown in Figure 7. Black points represent the mean power measured at this tree position (in this case 0°) in each tree at any radial (in this case radial R_2). The solid line shows the regression estimated in this case. The horizontal axis represents the distance (in meters) between transmitter and receiver, and the vertical axis shows the received power in dBm.

The regression lines obtained for each reception angle of radial R_2 is shown in Figure 8. Solid, dashed and dashed-dot lines represent the regressions obtained for the receiver located at 0°, 90° and 270° respectively. Dotted line corresponds to 180°. This figure seems to clearly show that data from angles of 0°, 90° and 270° are very similar, and 180° is slightly different. The numeric data of this figure is in Table 3. This is because of the attenuation introduced by the tree trunk of the receiver tree. Due to these differences, front and rear data have been studied separately.

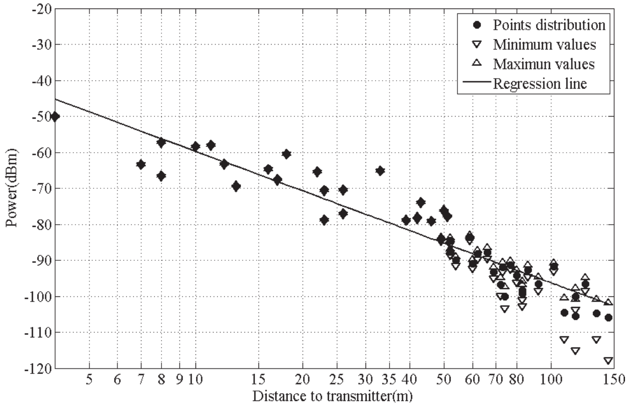


Figure 7. Regression of the received power in radial 2 at receiver angle of 0° around each tree.

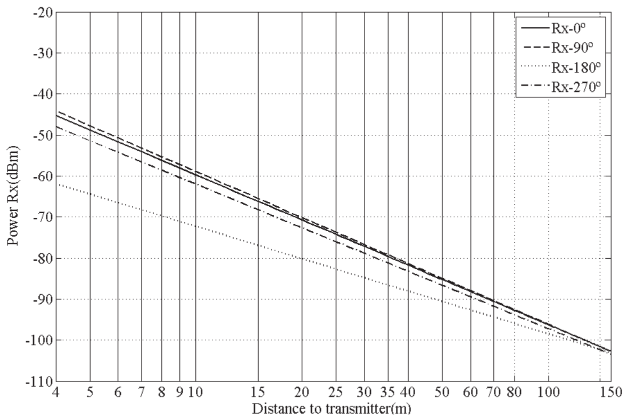


Figure 8. Regressions for radial 2. Receiver located at 0°, 90°, 180° and 270° around receiver tree stem.

After reviewing data from Table 3, the power received at 0°, 90° and 270° (front angles) has been labeled as "front data" and the power received at 180° as "rear data". The difference between rear and front data is depicted in Figure 2.

The objective of this first study is to get a general propagation expression for the master-slave scenario. General parameters (P_0, n, and error) of front (rear) angles can be obtained by collecting front (rear) data of the three radials at Table 4. The general propagation parameters for master-slave scenario are presented in Table 4.

Table 4. General parameters master-slave scenario.

Receiver location	P_0 (dBm)	n	Error (dB)
Front	−25.9	3.43	6.04
Rear	−47.2	2.56	4.61

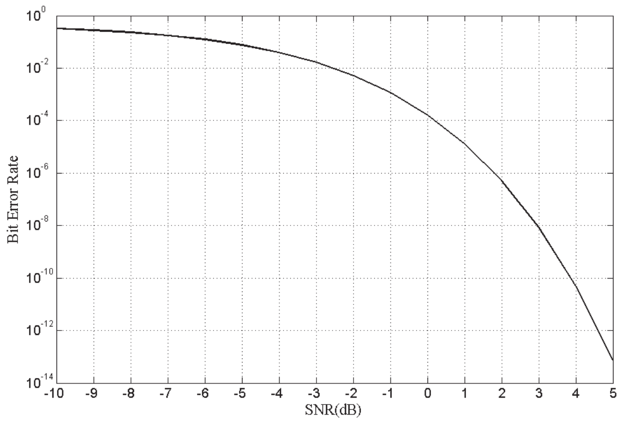


Figure 9. SNR vs. BER for IEEE 802.15.4.

Then, two general equations for the propagation in Scenario I could be written: one for the receiver located in front angles (3) and the other for the rear angle (4).

$$P\,(\text{dBm}) = -25.9 - 34.3 \cdot \log(d\,(\text{m})) \qquad (3)$$

$$P\,(\text{dBm}) = -47.2 - 25.6 \cdot \log(d\,(\text{m})) \qquad (4)$$

From (3) and (4), the coverage distance can be estimated if P is known. P is calculated from the required SNR and the noise power necessary to obtain a predefined Bit Error Rate (BER) or Packet Error Rate (PER):

- Noise power: We have assumed that the noise power in the 5MHz bandwidth ZigBee channel is −85 dBm. This is the value measured using a Rohde-Schwarz FSH-6 portable spectrum analyzer at a central frequency of 2.45 GHz [19]. Other values would have to be used if network devices with different noise factors are used.
- SNR: The average frame length for IEEE 802.15.4 is 22 bytes [20]. If a PER of 2% is desired, a BER $< 1.14 \cdot 10^{-4}$ would be needed. According to Figure 9 the required Sound to Noise Ratio (SNR) would be approximately 0 dB.

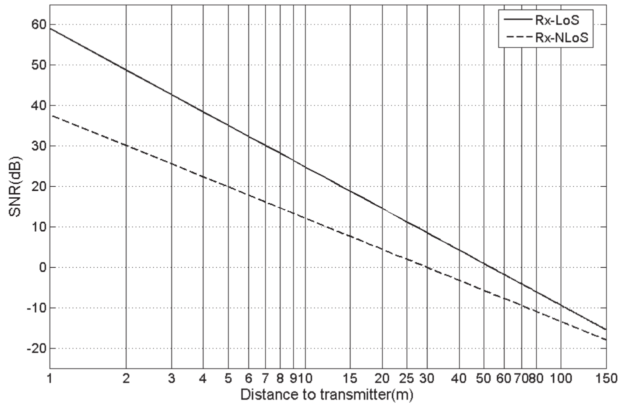


Figure 10. SNR vs. distance to transmitter for a ZigBee device in Scenario I.

The SNR versus distance between transmitter and receiver for master slave scenario is depicted in Figure 10.

Radius is between 50–55 m when the receiver is located at front angles, and around 30 m if the receiver is behind the tree trunk.

The estimated range of coverage (Figure 10) is lower than the one from [21], where for LoS situation the path loss exponent is 2.6. This value provides a range of coverage of around 150 m. However that value for the path loss exponent does not appear to be estimated for a master-slave scenario. Furthermore, that value is obtained from Wi-Fi measurements, where the channel bandwidth is 22 MHz, and the deployed network is based on ZigBee technology with a channel bandwidth of 5 MHz. This large difference in LoS situation could be due to the discrepancies on the heights of transmitter and receiver, the various antenna model, or even the diversity in the propagation models that have been fitted to the measured data. Anyway, the OLoS path loss exponent values are very similar in both cases. This fact could be explained because the propagation channel appears to be less affected by the antenna model or the heights of transmitter and receiver, when dealing with OLoS conditions than LoS. Both results are shown in Figure 11.

3.2. Peer to Peer Scenario: Power Decay with Distance

This second scenario emulates the communication between ZigBee routers and between routers and end-devices, all fitted on its respective tree trunk. This scenario is made up of four radials whose distribution is represented in Figure 5.

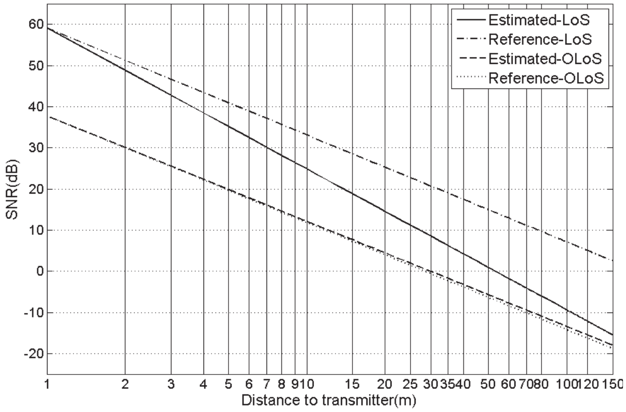


Figure 11. Comparison between estimated data and data from [21].

In this case, there are two different situations due to the possible locations of the transmitter (See Figure 3):

- Transmitter located in front of the tree stem, named as "Tx LoS" location.
- Transmitter located behind the tree stem, called "Tx OLoS" situation.

The results are presented separately for each one of the possible situations of the transmitter.

As in the first scenario, parameters P_0 and n of (2) have been computed for the four radials of this second scenario. They have been obtained separately for each reception angle around the receiver tree stem.

As in Section 3.1 "front data" and "rear data" were defined (see Figure 3). As in the first scenario, results for parameters n and P_0 for front data and rear data are very similar for the four radials. Again, the main objective is to get a general propagation expression for the scenario II when the transmitter is placed ahead of the tree stem (Tx LoS) and behind it (TX OLoS). With the processed data, general parameters (P_0, n, and error) for front and rear received angles can be obtained.

The general propagation parameters for the peer to peer scenario are presented in Table 5.

Two general equations can be computed for the propagation in peer to peer scenario when transmitter is located in LoS position: one for the receiver located in front angles (5), and the other for the rear angle (6). For the Tx in OLoS situation the equations are (7) and (8).

$$P\,(\text{dBm}) = -44.4\,\text{dBm} - 25.5 \cdot \log(d\,(\text{m})) \quad (5)$$
$$P\,(\text{dBm}) = -60.7\,\text{dBm} - 20.4 \cdot \log(d\,(\text{m})) \quad (6)$$
$$P\,(\text{dBm}) = -69.3\,\text{dBm} - 14.2 \cdot \log(d\,(\text{m})) \quad (7)$$
$$P\,(\text{dBm}) = -72.5\,\text{dBm} - 16.3 \cdot \log(d\,(\text{m})) \quad (8)$$

Figure 12 has been obtained using the same values calculated in Table 3 for BER, SNR and noise power. This figure shows the Signal to Noise Ratio versus distance between transmitter and receiver for the peer to peer scenario.

When the transmitter is in LoS location the radius of coverage to get an SNR of 0 dB is around 40 m with the receiver located at front angles and around 16 m if the receiver is behind the tree trunk. If the transmitter is behind the tree trunk, these radii are 13 and 6 meters respectively. Furthermore, the symmetric situations of "Tx OLoS-Rx Front" and "Tx LoS-Rx Rear" have very similar range values for an SNR of 0 dB and lower, as can be seen in Figure 12. This symmetric situation is shown in Figures 3(a) and (b).

Table 5. General parameters of peer to peer scenario.

	Transmitter Location					
	LoS			OLoS		
Receiver location	P_0 (dBm)	n	Error (dB)	P_0 (dBm)	n	Error (dB)
Front	−44.4	2.55	7.29	−69.3	1.42	6.50
Rear	−60.7	2.04	6.67	−72.5	1.63	6.14

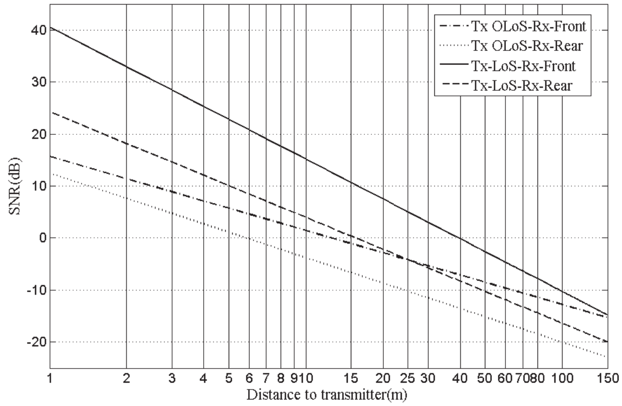


Figure 12. SNR vs. distance to transmitter for a ZigBee device in the peer to peer scenario.

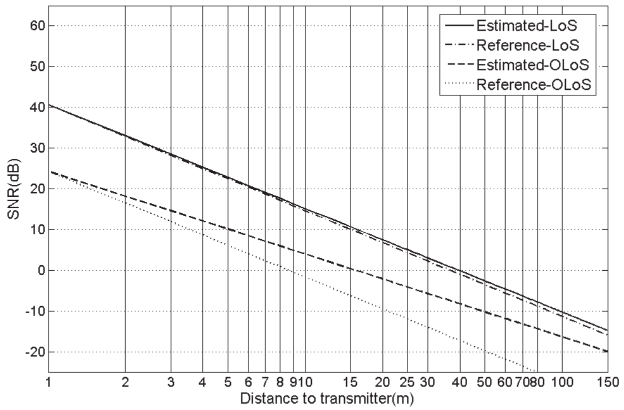


Figure 13. Comparison between estimated data and data from [21].

The Tx-LoS Rx-Front and Rx-Rear values with the LoS and OLoS values from [21] are compared in Figure 13. In this case, the LoS value matches that in [21] but the OLoS one does not.

3.3. Attenuation Caused by the Number of the Intermediate Trees

The number of tree trunks between transmitter and receiver probably will cause the same effect, as in other environments where the number of obstructions causes attenuation in the received signal [21].

The main aim is to determine a general equation for the attenuation caused by k tree trunks in the radio path. This attenuation is estimated by subtracting free space path loss at a distance d from the measured received power at the same distance. Due to the path length and large number of trees, radial R_2 of the master-slave scenario was chosen for this study. The regression of the attenuation caused by the intermediate tree trunks inside the radio path is shown in Figure 14.

A general equation can be computed with the fitting values obtained. Eq. (9) indicates that the mean attenuation produced by a tree trunk is around 1.52 dB, with an estimation error of 5.87 dB.

$$L(k)\,(\mathrm{dB}) = -0.0397 - 1.52 \cdot k \tag{9}$$

Although the attenuation grows with the number of intermediate trees, as shown in Figure 14, this equation may not be used for estimating the coverage range. This is because of the subjectivity and the uncertainty in estimating the number of intermediate trees, especially for the big variance in the attenuation values for the same

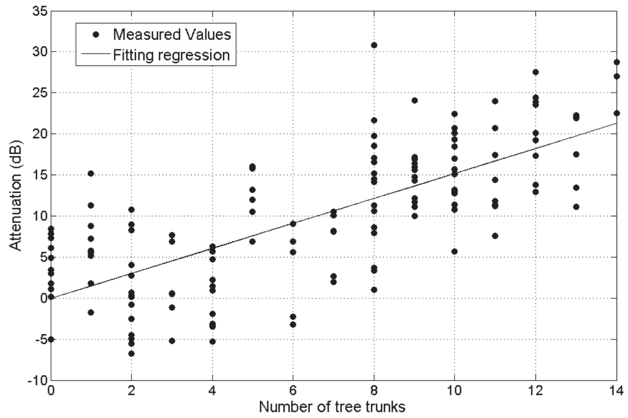


Figure 14. Attenuation caused by the number of intermediate tree trunks.

number of intermediate trees, reaching up to 30 dB for 8 tree stems. In other words, the tendency appears to be qualitatively clear, but equation is not quantitatively reliable.

3.4. Results Summary

Table 6 shows the mean range of coverage for each one of the situations that have been previously studied. Values presented as "Master-slave scenario," corresponds to the interface between the coordinator of the ZigBee network (C) and a router (R) or an end-device (ED). Data presented as "Peer to peer scenario" are from the interface between any router and an end-device or another router.

Table 6. Summary of radii of coverage.

Scenario	Transmitter location	Mean range coverage (m)	
		Receiver at front	Receiver at rear
Master-slave	LoS	50/55	30
Peer to peer	LoS	40	16
	OLoS	13	6

4. ANALYSIS AND DEPLOYMENT OF A WIRELESS SENSOR NETWORK

4.1. Deployment of a Wireless Sensor Network

One of the most important restrictions in ZigBee technology is the maximum depth of the network. The maximum value of 5 for this parameter means that the maximum number of routers along any path between an end-device and the coordinator is four. As this number is so low, and the larger coverage is looked for, more distance between routers is intended to be reached using high gain external antennas. As a general rule, a device always tries to connect the network through the router (or the coordinator directly) which is at minor number of hops to the coordinator.

A ZigBee network has been deployed to check the values obtained in the previous sections. This wireless network has been developed with devices based on CC2430 chip. Coordinator, routers and end-devices have been designed in the same way. The only difference is that the design of the coordinator and router includes an external SMA-connector, to allow the connection of an external high gain antenna.

The CC2430 is a System on Chip solution that combines the performance of the CC2420 RF transceiver with an enhanced 8051 Master Control Unit (MCU) [22]. Furthermore, end-devices are equipped with an external temperature sensor and a light sensor.

Data from Table 5 suggest that too many devices are going to be required to cover a small area, mainly when the devices are in OLoS situation. Omnidirectional antennas with gain larger than 0 dBi were connected to routers and the coordinator trying to improve the coverage.

Type, Equivalent Isotropically Radiated Power (EIRP) and vertical beamwidth of each antenna are shown in Table 7.

The use of these high gain antennas should increase the cost per device because of the high cost of both the SMA connector and the antennas. Due to this increment in cost per device, only the coordinator and routers will carry on these antennas. End-devices will install an integrated antenna with a gain of 0 dBi.

Table 7. Characteristics of the antennas used.

Device	Type	Model	EIRP	3 dB Vertical beamwidth
Coordinator	Dipole	WAI-100B	10 dBm	30°
Router	Dipole	DWL50AT	5 dBm	60°
End-device	Integrated	Inverted F	0 dBm	—

Then, if routers and coordinator antennas are well pointed (according to radiation patterns) the improvement in the links could be, for instance:

- Up to 15 dB in the interface involving the coordinator and any router, (C-R).
- Up to 10 dB in the interface between routers. (R-R).

Figures 10 to 12 could help to determine the new radius of coverage for each scenario and interface. These data, which include the antenna gains, are shown in Table 8. An error margin of 3 dB would be considered for each router or coordinator antenna (3 dB beamwidth) associated to their orientation. The mean range corresponding to the mean power plus the antennas gain are given in Table 8.

Table 8. Summary of radius of coverage with high gain antennas.

Scenario-Tx Location	Interface	Gain (dB)	Coverage range (m)	
			Receiver at front	Receiver at rear
			Mean	Mean
I-LoS	C-R	9	95	65
	C-ED	7	85	55
II-LoS	R-R	4	55	25
	R-ED	2	45	20
II-OLoS	R-R	4	25	10
	R-ED	2	15	8

With the aid of data in Figure 4 and Figure 5, and the new estimated radius of coverage, the wireless sensor network can be deployed within the forest. The mean range coverage value will be considered for each interface to deploy the network. By this way, if the actual received power is lower than this mean, due to the estimation error, we can offset it with the antenna gains.

The diagram of the deployment that has been carried out is shown in Figure 15. The coordinator of the network is located near the base station, and it is represented by a square. Routers (Ri) are presented as crosses, and the circles are the end-devices (EDi). Routers and end-devices were located on the surface of the tree trunks. White lines represent the link between one device and its father.

The image of a router and an end-device, both added to a tree trunk, are shown, respectively, in Figures 16(a) and (b). According to characteristics from the Table 6, the router has an external dipole antenna, and the end-device has an integrated one.

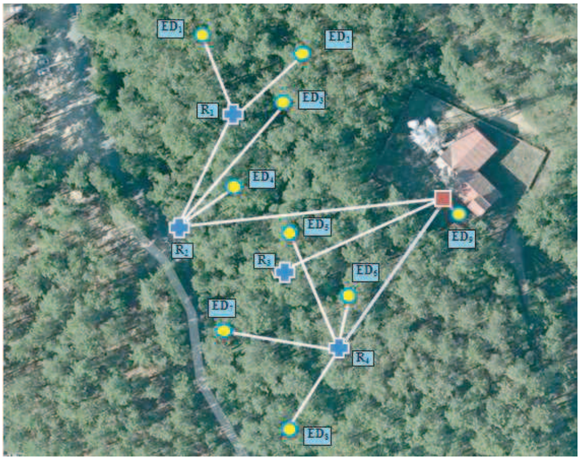


Figure 15. Network diagram.

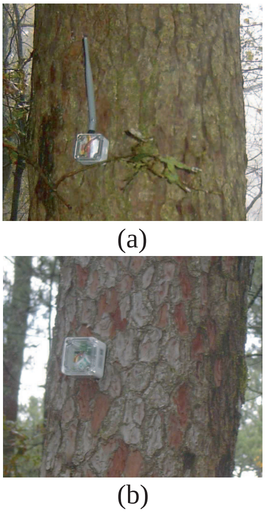


Figure 16. Detail of (a) a router and (b) an end-device.

4.2. Network Performance

End-devices are going to be polled for their sensor values (temperature and light) every 30 seconds in order to check the correct operation of the network. Furthermore, in the same report they will include the parameter LQI (Link Quality Indicator) of the link established with their father, following router towards coordinator: 0 is the lowest value for the LQI (worst link quality), and 255 is the highest. This indicator gives us the link quality based on RSSI and PER measurements. As the routers do not execute any sensor function, they only send a report every minute. This report includes the LQI of the link with its father.

4.3. Results

Once the network was deployed, it would collect data for 18 hours. The father of each device, the mean estimated range in meters for each link, and the measured path length are indicated in Table 9. Last column shows the average Link Quality Indicator for each link.

All values presented in this table for path length are below mean ranges estimated for LoS locations. The only link that exceeds the mean estimation is that established between router 2 and end-device 3. But the mean LQI for this link (2) is very close to the lowest value (0), so it is near the limit.

Table 9. Maximum estimated and real path length for each link.

Device	Father	Mean estimated (m)		Actual Path length (m)	LQI
		R_x front	R_x rear		
R_1	R_2	55	25	41	7.33
R_2	Coord.	95	65	90	5.50
R_3	Coord.	95	65	52	26.7
R_4	Coord.	95	65	43	0
ED1	R_1	45	20	22.5	4.35
ED2	R_1	45	20	34	15.6
ED3	R_2	45	20	48	2.00
ED4	R_2	45	20	23	14.0
ED5	$R_4\backslash R_2$	45	20	35\34	4.28
ED6	R_4	45	20	15	75.0
ED7	R_4	45	20	26	42.0
ED8	R_4	45	20	23.5	4.79
ED9	Coord.	85	55	1.5	64.0

The link involving R_4 and the coordinator has the minimum LQI value, with only 43 meters of path length. This appears to be caused by a wrong orientation of the router antenna.

In general, if the measured path length is close or below the mean estimated range for OLoS receiver location, the mean LQI value is quite high, which confirms the validity of the previous calculations.

4.4. Recommendations for Future Deployments

After the tests are carried out during the test network deployment, the following recommendations for future deployments can be presented:

The coordinator should be in a clear zone, with the major line of sight to all the area to be covered. Thus, the range coverage will be the largest possible. Furthermore, the height of the coordinator should be similar to the rest of the devices. Thus, its elevation radiation pattern appears to be optimally used to get the major range coverage.

Routers should be located always in line of sight with the following one and the predecessor. That is, the tree stem in which the routers are located should not be blocking the line of sight to those devices which the router links.

End-devices should be located according to the mean range of coverage estimated in Table 8. When installing the end-devices, care should be taken in assuring the LoS condition, because large differences have been detected between LoS and OLoS links, and the performance of the connection could be degraded. An approximation of the range of coverage of the link between a router and an end-device is represented in Figure 17. We have considered the 180 degrees from the front side as LoS, and the other 180 degrees as OLoS. The distance values come from the mean values of Table 8.

The terrain slope appears to have meaningfully influence the received power. We have to take care with it while we are planning the network.

Rain events might affect links connecting the elements of the WSN, but due to the short distances between them (usually less than 150 meters) this effect is almost negligible (usually below 0.0013 dB according to [23]).

4.5. Estimation of the Number of Routers Needed Depending on the Area to Be Covered

Based on estimated data from Tables 7 and 9, the maximum depth of 5, the recommendations from "D" and Figure 17, an estimation of the number of routers that would be necessary to cover any area could be made. As an example, an area of 30,000 m^2, near main campus of the University of Vigo, has been selected.

The polygon from Figure 18 delimits the area to be covered. In this figure, only routers (crosses) and the coordinator (square) are shown. The coverage areas of routers are represented as semi-transparent surfaces with the shape drawn in Figure 17.

The coordinator has two estimated coverage areas:

- The smallest one limits the places where an end-device will be able to connect directly to the coordinator (radius 55 m).
- The biggest one represents the limit for routers (radius 65 m).

Both areas are presented as red circles.

End-devices could be located in any point of the area printed in blue or red. These values (OLoS from Table 7) are going to be used because these first links are the most important of the network. If one of these links falls down, all devices depending on it will fall down too.

Solid white lines represent the main path between each router and the coordinator. Dashed ones indicate possible alternative routes for the packets when the main route falls down. (This feature is not implemented yet by the devices used in this study).

Finally, as shown in Figure 18, up to ten routers and a coordinator are needed to cover this pine forest. That is, one router per each 3,000 m^2 approximately.

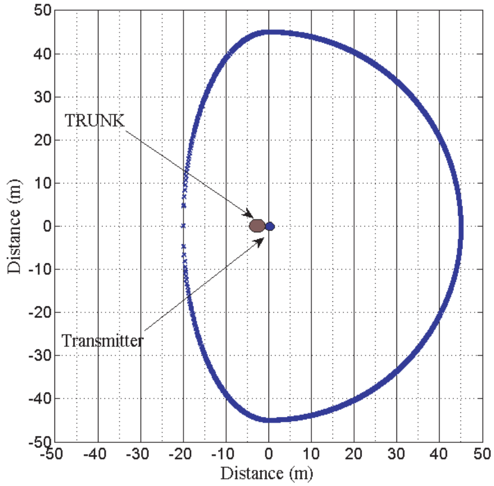


Figure 17. Approximation of a router range coverage.

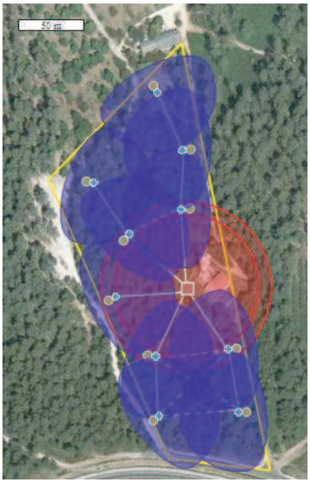


Figure 18. Estimation of the number of routers to cover an area of 30,000 m^2.

5. CONCLUSION

An extensive power measurement campaign has been carried out along two different scenarios. A general propagation model has been computed both for the peer to peer scenario and for the master to slave one. Initial ranges of coverage have been estimated, and some improvements for ZigBee devices have been proposed in order to extend these ranges.

An actual ZigBee network has been deployed, and the proposed improvements were checked. Some recommendations have been proposed in order to reach the best performance in wireless networks deployed in forests. Finally, the mean number of ZigBee routers necessary to cover an area has been computed, obtaining one router per each 3,000 square meter.

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