Analysis of Topological Impact on Wireless Channel Performance of Intelligent Street Lighting System

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Abstract. *In this work, an analysis of the physical radio channel propagation for the deployment of a wireless sensor network for intelligent street lighting is presented based on an in house implemented deterministic 3D ray launching code. Simulation as well as measurement results from a deployed wireless sensor network, based on ZigBee motes for an intelligent street light control system confirm the topological and morphological dependence of the considered scenario, given to diffraction and scattering from the street lights in which the sensor are located. Received power levels as well as performance metrics given by Packet Error Ratio values are presented in order to validate radioplanning estimations. The results can be applied to the optimal radioplanning of the wireless systems prior to deployment phase, in order to achieve maximum system performance while minimizing power consumption.*

Keywords

3D ray launching, wireless sensor network, intelligent street lighting, channel performance.

1. Introduction

The industry of street light control systems has been growing during the last years due to the increasing interest towards green and efficient use of electrical energy. The improvement of the present street lighting system is one of the major challenges at the moment for saving energy consumption. In the past, the basic principle consisted of a very simple on/off switching mechanism, without any ways of transfer control commands. Nowadays, intelligent control systems offering remote supervision have strongly contributed to increase street lighting efficiency. These systems are based in a central control system which receives information of intelligent lamp posts in order to simplify management and maintenance issues [1-8]. Some of them use the power lines for data transmission (PLC) [9], [10] while others use wireless communication [11-13]. There also exist several intelligent streetlight energy management solutions such as Smart Street Lighting [14], Illumi Wave [15], Street Light Control (SLC) [16] or iiLuix [17], which permit remote control and management of widely distributed streetlights from a central management system. In [18] a wireless retrofitting of lamps is proposed in which self-location capability is exploited. Another solution based on IEEE 802.15.4 network is proposed in [19] focused on the implementation on low-cost nodes, featuring reduced memory resources. Nevertheless, the evaluated systems [11], [19], [20] based on wireless communications, provide general solutions which do not take into account the particularities of the specific scenario in which the complete system must be deployed. The novelty of our proposal relies on the design of an intelligent system to perform street lighting with the aim of minimizing energy consumption as well as maintenance costs. This is achieved by implementing a customized solution, considering the specific scenario where the intelligent system will be deployed. Radio channel performance analysis in outdoor scenarios is not a trivial issue and heavily depends of the complexity of the environment, being the fundamental degradation due to multipath components, but also other phenomenon like reflection, refraction and scattering [21]. In addition, the consideration of the specific scenario, where wireless sensor network will be deployed, is very relevant and impacts on the optimization of the distribution of wireless sensors to achieve a more efficient network coverage and consumption. Traditionally, empirical based models and simplified deterministic methods were employed for initial coverage estimation (i.e., COST 231, Walfish-Bertoni, Okumura Hata, etc.) [22]. These methods exhibit lower computational complexity on expense of reduced accuracy, usually requiring measurement based calibration in order to give an adequate fit of the results, obtained by regression methods. On the other hand, deterministic methods are based on numerical approaches to the resolution of Maxwell's equations, such as ray launching and ray tracing (based on geometrical approximations) [23] or full wave simulation techniques (MoM, FDTD, FITD, etc.). These methods are precise, but are time consuming to inherent computational complexity. As a midpoint, methods based on geometrical optics, for radio planning calculations with strong diffractive elements, offer a reasonable trade-off between precision and required calculation time [24-26].

In this article, an analysis of the radio propagation channel for the deployment of a wireless sensor network for intelligent street lighting has been performed with the aid of an in-house 3D ray launching algorithm. The morphology of the scenario clearly influences the overall system performance, as stated by simulation as well as measurement results from deployed wireless sensors. The estimations can be useful in the radioplanning process prior to the wireless sensor network deployment phase of the street lighting system. The paper is structured in the following way: Section 2 is devoted to presenting the implemented simulation technique and the results for the given scenario under analysis; Section 3 shows the measurement results for RF signal propagation estimation as well as for a deployed wireless sensor network, while Section 4 presents the conclusions.

2. Simulation Technique and Results

As stated in the introduction, a 3D Ray Launching algorithm has been used to assess the radio propagation channel in the considered scenario. The algorithm has been implemented in house, based on MatLab programming environment. Different applications of this algorithm can be found in the literature, like interference analysis [27], electromagnetic dosimetry evaluation in wireless systems [28] or the analysis of wireless propagation in complex indoor environments [29-32]. The 3D Ray Tracing tool is based on geometrical optics (GO) and geometrical theory of diffraction (GTD). The rays considered in GO are only direct, reflected, and refracted rays. Because of this, abrupt transitions areas may occur, corresponding to the boundaries of the regions where these rays exist. To complement the GO theory, the diffracted rays are introduced with the GTD and its uniform extension, the Uniform GTD (UTD). The purpose of these rays is to remove the field discontinuities and to introduce proper field corrections, especially in the zero-field regions predicted by GO. The principle of the ray launching method is to consider a bundle of transmitted rays that may or may not reach the receiver. The number of rays considered and the distance from the transmitter to the receiver location determines the available spatial resolution and, hence, the accuracy of the model. A finite sample of the possible directions of the propagation from the transmitter is chosen and a ray is launched for each such direction. If a ray hits an object, then a reflecting ray and a refracting ray are generated. If a ray hits a wedge, then a family of diffracting rays is generated, as depicted in Fig. 1.

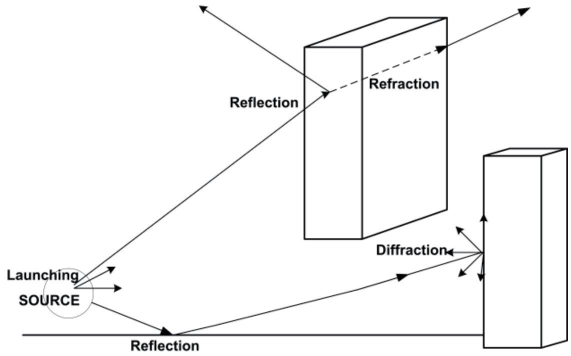


Fig. 1. Principle of operation of the 3D ray launching method implemented in-house to perform indoor coverage analysis.

Rays are launched from the transmitter at an elevation angle θ and with an azimuth angle Φ, as defined in the usual coordinate system. Antenna patterns are incorporated to include the effects of antenna beam width in both azimuth and elevation. Parameters such as frequency of operation, number of multipath reflections, separation angle between rays, and cuboids dimension are introduced. The material properties for all the elements within the scenario are also taking into account, given the dielectric constant and permittivity at the frequency range of operation of the system under analysis. A plane electromagnetic wave falling to the planar interface between two regular semi-infinite media 1 and 2 gives rise to two plane waves: reflected and transmitted (or refracted). According to the Snell's law [33], the reflection coefficient $R^{\perp}$ and transmission coefficient $T^{\perp}$ are calculated by

$$T^{\perp} = \frac{E_t^{\perp}}{E_i^{\perp}} = \frac{2\eta_2 \cos(\Psi_i)}{\eta_2 \cos(\Psi_i) + \eta_1 \cos(\Psi_t)} \quad , \tag{1}$$

$$R^{\perp} = \frac{E_r^{\perp}}{E_i^{\perp}} = \frac{\eta_2 \cos(\Psi_i) - \eta_1 \cos(\Psi_t)}{\eta_2 \cos(\Psi_i) + \eta_1 \cos(\Psi_t)} \tag{2}$$

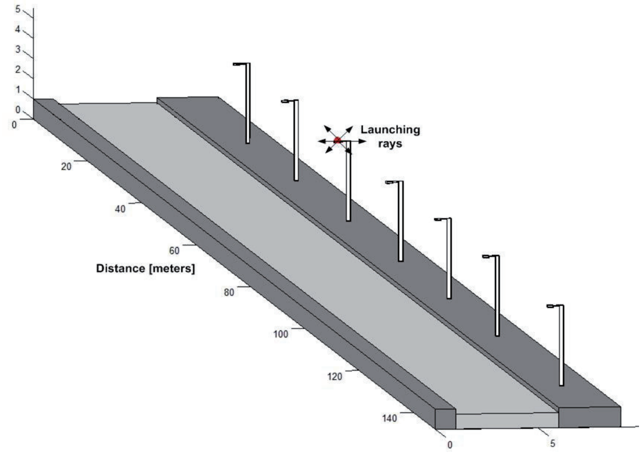
where $\eta_1 = 120\pi/\sqrt{\varepsilon_{r1}}$, $\eta_2 = 120\pi/\sqrt{\varepsilon_{r2}}$ and Ψ_i Ψ_r and Ψ_t are the incident, reflected and transmitted angles respectively. For the parallel (or magnetic) polarization the magnetic field vector of the incident wave is perpendicular to the plane of incidence. Then, the reflection and transmission coefficients $R^{\parallel}$ and $T^{\parallel}$ can be calculated by

$$R^{\parallel} = \frac{E_r^{\parallel}}{E_i^{\parallel}} = \frac{\eta_1 \cos(\Psi_i) - \eta_2 \cos(\Psi_t)}{\eta_1 \cos(\Psi_i) + \eta_2 \cos(\Psi_t)} \quad , \tag{3}$$

$$T^{\parallel} = \frac{E_t^{\parallel}}{E_i^{\parallel}} = \frac{2\eta_2 \cos(\Psi_i)}{\eta_1 \cos(\Psi_i) + \eta_2 \cos(\Psi_t)} \quad . \tag{4}$$

Once the parameters of transmission T and reflection R are calculated, and the angle of incidence Ψ_i and Ψ_t, the new angles (θ_r, Φ_r) of the reflected wave and (θ_t, Φ_t) of the transmitted wave can be calculated. Simulations and measurements have been made in a street section of Areta Street, which is situated in the center of Llodio (Spain). The selected street consists in a stretch two-way road with seven streetlights evenly distributed along the street on one side of the road. The real and schematic scenario is shown in Fig. 2a and Fig. 2b respectively.

(a)



(b)

Fig. 2. Scenario under consideration: (a) Real scenario. (b) Schematic scenario.

The transmitter antenna is fixed at the top of the third streetlight as depicted in Fig. 2b with a red circle for the transmitter. Material parameters have been taken into account given their conductivity and their dielectric constant. Tab. 1 shows the parameters used in the simulation. These parameters have been chosen taking into account a commitment between results accuracy and computational time of the simulation. All the elements within the considered scenario have been taken into account, like the metallic structure of the streetlights and the concrete of the floor. Tab. 2 shows the material properties used in the simulation model [34-35].

Frequency	2.3GHz / 868MHz
Cuboids resolution	1m
Vertical plane angle resolution Δθ	0.2º
Horizontal plane angle resolution Δφ	0.2º
Reflections	5
Transmitter Power	0dBm

Tab. 1. Parameters in the Ray Launching simulation.

Parameters	Air	Aluminum	Concrete
Permittivity (ε_r)	1	4.5	5.87
Conductivity (σ) [S/m]	0	$4*10^7$	0.083

Tab. 2. Material properties in the Ray Launching simulation.

Fig. 3 and Fig. 4 show bidimensional received power plots obtained by means of in-house 3D ray launching algorithm. The height of the considered bidimensional planes is 4 meters, for operating frequencies of 2.3 GHz and 868 MHz, respectively. It can be seen that the selection of the frequency plays an important role in the characterization of the radio propagation channel. The topology as well as the morphology of the specific scenario has a relevant role in the assessment of the radio propagation channel. The estimation of received power along X-distance for different heights in the considered scenario have been depicted in Fig. 5 for 2.3 GHz frequency, and for a fixed value of the Y axis, which correspond with 5 cm distance from the front of the streetlight. A great variability is observed in the received power estimation with distance, fundamentally due to fast fading, a direct cause of multipath propagation, which is a key factor in this particular case of metallic environment around the streetlights.

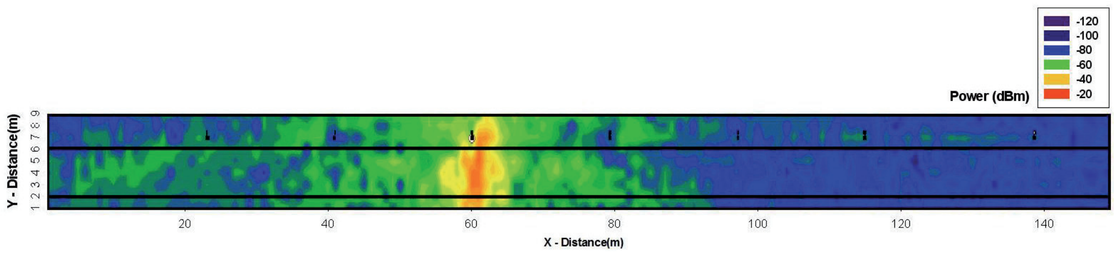


Fig. 3. Received power for 2.3 GHz frequency for 4 m high.

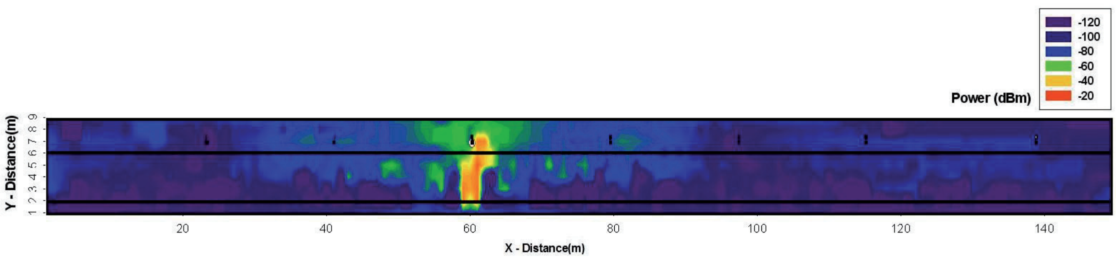


Fig. 4. Received power for 868 MHz frequency for 4m high.

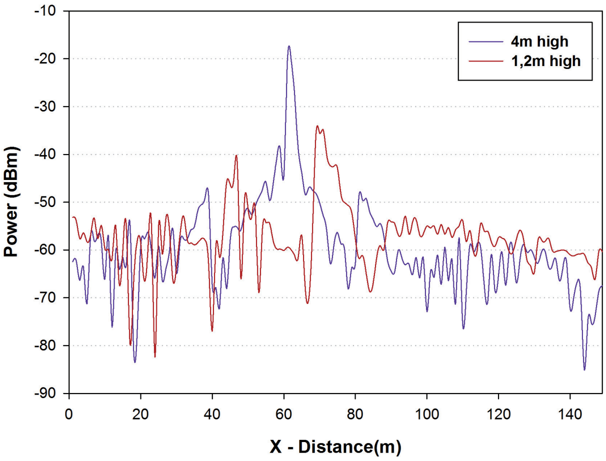


Fig. 5. Radials of received power for different heights for 2.3 GHz frequency.

As stated before, the multipath propagation is a fundamental propagation phenomenon in this type of environment, which is characterized by time dispersion of the signal. It is also important to consider the frequency dispersion due to time variations of the received amplitude. To illustrate the relevance in this specific propagation channel, the power delay profile for a specific location within the scenario has been predicted and is shown in Fig. 6. As it can be seen, there is a large number of echoes in the scenario in a time span of approximately 5 to 600 ns, corresponding to distances from 1.5 to 180 m, which is coherent with the considered scenario and the frequency of operation used in the system.

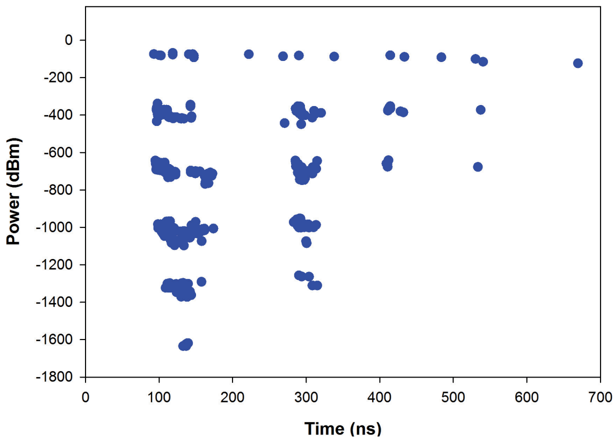


Fig. 6. Power-Delay Profile at a given cuboid, located at the point (29.4 m, 7.5 m, 4 m) in the scenario, for 2.3 GHz frequency.

3. Measurement Results

To validate previous predictions, measurements in the real scenario of Areta Street in the city of Llodio have been performed. The objective is to characterize the different effects of electromagnetic propagation within the scenario and validate the simulations stated in the previous section.

Fig. 7. View of the transmitter antenna magnetically mounted on the top of the streetlight.

A signal generator, a spectrum analyzer, and a set of antennas (used as a transmitter and a receiver) for the 2.3 GHz and 868 MHz frequencies have been used. The transmitter antenna has been located at the top of the third streetlight, with a transmission power of -10 dBm, as shown in Fig. 7. The signal generator is a network analyzer Agilent N1996A configured with a minimum sweep frequency to obtain a single-frequency pulse at the output. The spectrum analyzer is an Agilent N9912 FieldFox. A set of antennas has been used for 2.3 GHz (Model ECOM5-2400 from RS) and for 868 MHz (model FLEXI-SMA90-868 from RFSolutions).

Fig. 8 shows the considered point for the transmitter and the points of measurement along the street. The transmitter is fixed four meters high, and the receiver at the different points is fixed 1.20 meters high.

Fig. 9 and Fig. 10 show the comparison between simulation and measurements for both frequencies (2.3 GHz and 868 MHz) for the different measurement

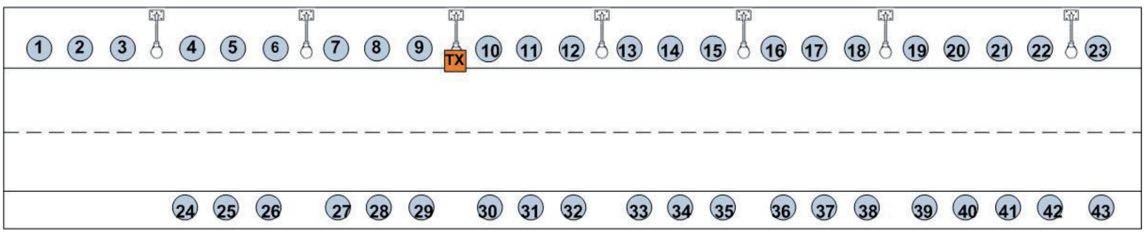


Fig. 8. Measurement points within the considered scenario.

points shown in Fig. 8. They exhibit good agreement with a mean error of 1.6dB for 2.3 GHz frequency, and 3.5 dB for 868 MHz frequency. The differences are mainly due to fast fading, which is the most relevant effect in this type of scenario that occurs due to multipath components which are very significant. Other simplifications that may contribute to the difference between the measured and the simulated values include the effects of scattering from vegetation, which has not been taking into account. An important effect that is worth noting is propagation losses when deployed sensors are within the average height of pedestrian or moving vehicles, a typical case when RF presence detection is employed. In this case, human body losses due to absorption as well as scattering effect and potential Doppler shift (although in principle small due to inherent velocity limitations for persons and vehicles in an urban area) must be considered. This has not been the case under study in this work, due to the requirement of transmission support at the height of the illuminating elements, but is indeed interesting for future work.

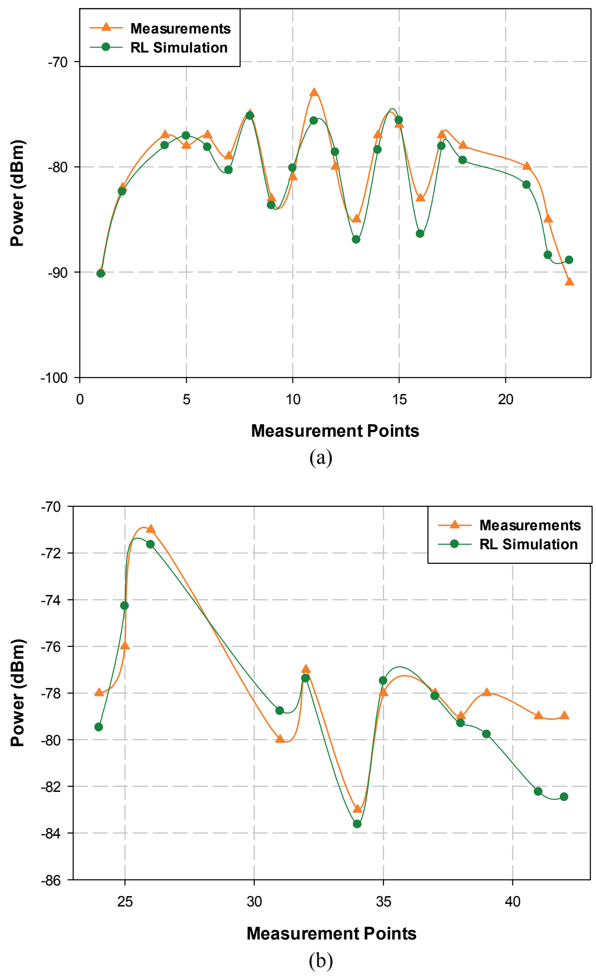


Fig. 9. Comparison of simulation versus measurements for 2.3 GHz frequency: (a) Measurement points 1 to 23. (b) Measurement points 24 to 43.

We have implemented and deployed a wireless sensor network (WSN) of seven Waspmote IEE 802.15.4 nodes [36] located on the streetlights of the scenario depicted in Fig. 8. The initiator node (#1) is placed on the top of the streetlight located between measurement points 3 and 4, while node #7 is placed on the top of the streetlight located between measurement points 22 and 23. Nodes, which are deployed following a chain, communicate at 2.4 GHz with a transmission power of 1 mW. Node #*i* receives a message from node #(*i*-1) and then sends another message to node #(*i*+1), from node #1 to node #7. The initiator node communicates with node #2 following a transmission period of 100 milliseconds. The gateway node, which is located 1.20 meters from the curb, collects the information provided by node #7 (last node of the chain). Finally, the gateway is connected to a laptop that stores the received trace.

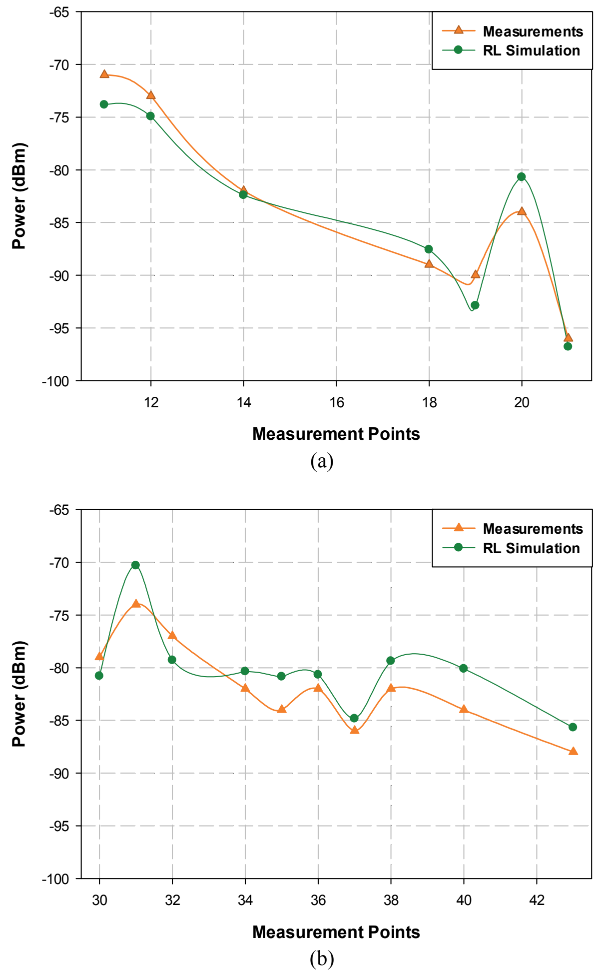


Fig. 10. Comparison of simulation versus measurements for 868 MHz frequency: (a) Measurement points 10 to 23. (b) Measurement points 30 to 43.

Tab. 3 summarizes the received signal strength indication (RSSI) by node, where the average value ranges between -62 and -58 dBs, with a standard deviation ranging between 0.46 and 0.52 dBs. The similar values obtained for the mode and the median of the RSSI distribution show the stability and consistency of the values obtained, which is corroborated by the low values of the standard deviation (0.6043 dB for the worst case). The values obtained are low enough from the maximum sensitivity (-92 dBm) of the devices, so nodes could be located considerably far away.

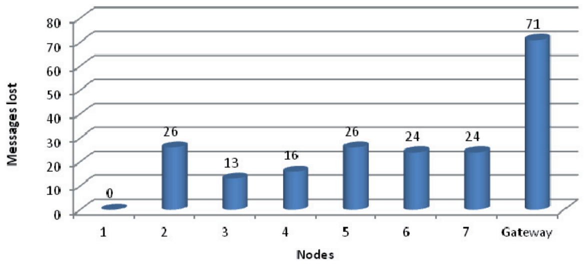


Fig. 11. Number of messages lost by node.

Fig. 11 shows the distribution of messages lost by node for a total amount of 20.000 messages transmitted. One can note that the gateway node, which is placed at a different altitude, is the one with the highest number of losses. This node doubles the number of messages lost, but the number of losses is still very low (0.355%). As the topology followed in this WSN is a chain a lost in node *i* implies that the other nodes of the chain ($k > i$) will not receive the message. Tab. 4 summarizes the accumulative distribution of messages lost by node. The packet error rate (PER) by node depicted in Tab. 5 is relatively homogeneous for all the nodes of the chain, ranging between 0.065 and 0.130% for regular nodes (#2 - #7), while the initiator node introduces no loss, and the gateway node almost triples the maximum value obtained for regular nodes. The PER obtained is very low, even if the sensor is at a lower height and therefore is not aligned with the rest of nodes. This shows that it is not required a great alignment of the infrastructure in order to grant a high effectiveness in message transmission.

Larger scenarios could be considered, in which a segmentation approach in the 3D ray launching simulation could be employed. By estimating average losses within the complete cuboid distribution, the regions in which power levels below the receiver sensitivity level or, if required, the noise floor level can be identified. This will lead to different smaller scenarios which can then be simulated in parallel, with accurate path loss estimation in each of these sub-scenarios, to finally combine the final coverage/capacity plots of the system under analysis (in the present case ZigBee). This could be useful for example in the design of a wireless sensor network in larger urban areas, with a higher amount of luminaries present.

		Node						
		#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
RSSI (dB)	**Average**	0.0000	-58.0382	-61.5182	-60.0677	-59.8993	-62.3874	-62.3792
	Std. dev.	0.0000	0.4750	0.6043	0.4655	0.5829	0.5270	0.5189
	Mode	0.0000	-58.0000	-61.5000	-60.0000	-59.5000	-62.5000	-62.5000
	Median	0.0000	-58.0000	-61.5000	-60.0000	-59.5000	-62.5000	-62.5000

Tab. 3. Received Signal Strength Indication (RSSI) by node.

		Node						
		#1	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**
Messages lost	**Average**	0.0000	0.0013	0.0020	0.0028	0.0041	0.0053	0.0065
	Std. Dev.	0.0000	0.0376	0.0466	0.0563	0.0669	0.0786	0.0859
	Mode	0	0	0	0	0	0	0
	Median	0	0	0	0	0	0	0

Tab. 4. Accumulative distribution of messages lost by node.

PER by node							
1	2	3	4	5	6	7	Gateway
0.000%	0.130%	0.065%	0.080%	0.130%	0.120%	0.120%	0.355%

Tab. 5. Packet Error Rate (PER) by node.

4. Conclusions

In this article, the demands for modeling the radio channel in outdoor spaces like they are found in a streetlight road are presented. The topological and morphological influence in the operation of a Wireless Sensor Network has been analyzed. The use of deterministic 3D ray launching algorithm implemented in-house allows the optimization in the placement of transceivers to improve system efficiency and obtain overall enhanced performance. Simulation as well as measurements results have been presented, showing good agreement between them. The results show that by considering radio planning in this type of environment, the overall system performance can be strongly optimized, reducing power consumption as well as non-desired interference levels. The proposed methodology can be extended in the near future in order to account for more complex situations, such as deployment of smart metering devices, light control wireless links on non-uniform lighting distributions (i.e., including devices located in indoor and NLOS conditions) or interactive communication of gateways with mobile devices.

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