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A Standard Ray Tracing Technique for Predicting Signal Strength of Wireless Sensor Network in Smart Building

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Abstract—In this paper, a standard ray tracing model based on Geometrical Optics (GO) is proposed for predicting the signal strength of Wireless Sensor Network (WSN), ZigBee nodes, in an indoor environment. The signal strength is calculated analytically. The results are compared with numerical analysis implemented in FEKO computational electromagnetic software, and agreement is demonstrated. Also, the model is verified by a simple measurement campaign in a straight corridor section of commercial building, and results agreement is obtained. The results show that the proposed technique is capable of predicting the signal strength of WSN sensors in a corridor section of indoor environment with good accuracy, fast calculation time, and low computational resources and complexity. The proposed analytical model and measurement dataset can help WSN designers select the best locations of ZigBee nodes in a straight corridor section with good signal quality.

1. INTRODUCTION

Wireless Sensor Network (WSN) has been used for a lot of applications, such as agriculture, military, industry, communications infrastructure, hospitality units, and residential buildings due to its cost-effective and low power features [1, 2]. As building's energy consumption is growing worldwide, so many smart buildings are installing WSN sensors to manage the building energy consuming services more efficiently [3]. Also, WSN is widely used in smart home automation [2], security and surveillance systems [4–6], building diagnostic systems [3], and environmental applications, especially in physical parameters monitoring such as temperature and humidity [3]. WSN is a multi-hope network that consists of distributed sensors nodes and can be deployed in a wide area as a mesh network topology in which data is passed through many intermediate devices which are allowed to send and receive the data at the same time.

The WSN sensors have many communication standards that are used for data transfer, such as Wi-Fi, ZigBee, and Bluetooth. ZigBee technology [7, 8] is used in this research due to its low power and low cost standard, and it is widely used for building control applications such as alarm sensors, lighting control, air-conditioning and heating, and appliances monitor [9]. ZigBee is considered an enhancement of the original IEEE 802.15.4 standard which uses the Open Systems Interconnection (OSI) layer 3 and layer 4 to configure additional communication features such as authentication, encryption, data routing, and forwarding capabilities in a better way.

In order to guarantee a reliable communication link for data transmission between the sensors inside buildings, a lot of research has been done to predict the signal strength of WSN ZigBee nodes, so it can help the designers in determining the best nodes locations with good signal quality and low interference. The previously proposed models are based on using path loss models [10] while designing and implementing a reliable wireless communication link is difficult when an inaccurate path-loss model is used [11]. The estimation of a path-loss model based on traditional methods has been proven to be inaccurate [11], and it is more site specific. So in order to have an accurate signal strength estimation

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in indoor environment, a full wave numerical analysis can be used, such as the Finite Element Method (FEM), while this approach requires very complex mathematical operations and high computing power. Therefore, an approximate numerical technique is required.

Ray tracing is a widely used technique for calculating radio signal strength in an indoor environment [12]. The concept of the ray tracing method is based on the fact that at high frequencies the electromagnetic wave propagation can be approximated like rays that travel in straight lines provided that the permittivity of the medium is homogeneous. Geometrical Optics (GO) approximates the field strength at any point as the sum of the field of the direct ray from the transmitter to the receiver, plus the field of rays reflected from different surfaces. While reflection points move off the edges of reflecting surfaces, discontinuities can occur. In order to smooth such discontinuities, the Geometrical Theory of Diffraction (GTD) is used to include rays diffracted from edges [13]. There is a practical limitation in applying GTD to indoor propagation because each diffraction point on an edge behaves as a secondary source giving rise to a new family of rays, so including all of such secondary sources becomes very time consuming and in many cases impractical.

The main objective of the present work is to propose a simple and fast numerical analysis based on the standard ray-tracing technique to predict the signal strength of WSN ZigBee nodes with a line of sight communication link in an indoor environment. In Section 2, the model is proposed and verified by numerical analysis using FEKO software package. Finally, measurements are conducted in order to verify the analytical analysis, and results agreement is obtained. The list of abbreviations and acronyms used in the paper are listed in Table 1.

Table 1. List of abbreviations and acronyms used in the paper.

Abbreviations	Full Description
GO	Geometrical Optics
WSN	Wireless Sensor Network
OSI	Open Systems Interconnection
FEM	Finite Element Method
GTD	Geometrical Theory of Diffraction
RL-GO	Ray Launching Geometrical Optics
SBR	Shooting and Bouncing Rays
RSSI	Received Signal Strength Indicator

2. STANDARD RAY TRACING MODEL

As highlighted, the proposed model is based on the standard GO ray-tracing technique which approximates the propagation of electromagnetic waves by simple reflection and refraction. The propagation model used in the present research is an enhancement of the Two-Ray model [14], shown in Fig. 1, as multi-reflections from the structure boundaries are considered in the analysis for predicting the field strength of WSN nodes with a line of sight communication.

The transmitting antenna of height h_1 and the receiving antenna of height h_2 are placed at distance d from each other. The received signal P_r can be expressed by summing the contribution from direct and reflected rays as [14]

$$P_r = P_t \left(\frac{\lambda}{4\pi}\right) \left[\frac{1}{r_1} e^{(-jkr_1)} + \Gamma(\alpha) \frac{1}{r_2} e^{(-jkr_2)}\right]^2 \tag{1}$$

where P_t is the transmitted power, r_1 the direct distance from the transmitter to the receiver, r_2 the distance through reflection on the ground, and $\Gamma(\alpha)$ the reflection coefficient depending on the angle of

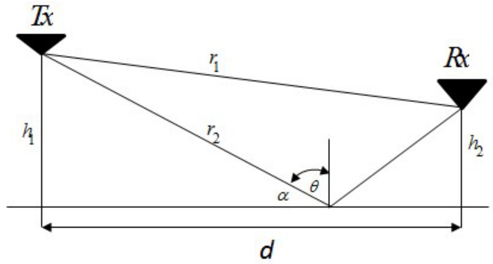


Figure 1. Two-Ray wave scattering model [14].

incidence α and the polarization. The reflection coefficient is given by [14]

$$\Gamma(\theta) = \frac{\cos(\theta) - a\sqrt{\varepsilon_r - \sin^2(\theta)}}{\cos(\theta) + a\sqrt{\varepsilon_r - \sin^2(\theta)}} \tag{2}$$

where $\theta = 90 - \alpha$ and $a = 1/\varepsilon$ or 1 for vertical or horizontal polarization, respectively. ε_r is the relative permittivity of the reflected surface. Due to the low power consumption of ZigBee nodes, most of the signal transmission ranges only 10–100 meters with a line of sight, so the proposed model can be used for signal strength prediction for most of the practical implementation of ZigBee sensors in an indoor environment like indoor positioning and tracking systems with a line of sight link.

A code, developed in MATLAB [15] environment, that implements the proposed ray tracing model is presented. It accounts for the direct ray and for rays reflected from the structure boundaries. Walls are modeled as layered structures, accounting for the angle and polarization dependences of the reflection and the transmission coefficients. Rays are kept calculated till their field strengths reach a minimum threshold set by the user. The computational cost is determined by the number of reflections taken into account and the complexity of the floor plan. The proposed model is used to calculate the signal strength of two ZigBee nodes across a straight corridor section in an indoor environment, and the results are verified by a numerical analysis which is done by using computational electromagnetic software FEKO [16]. FEKO simulation is based on Ray Launching Geometrical Optics (RL-GO) method. FEKO's RL-GO [11] method, also called Shooting and Bouncing Rays (SBR), is a ray-based technique like ray tracing that models the wave scattering based on ray propagation, reflection, and refraction theory. Huygens sources are used for each ray to model the ray interactions with metallic and dielectric structures. The ray-launching process is mainly controlled by the total number of multiple interactions which are allowed [16].

Figure 2 shows the calculated signal strength using the proposed model and FEKO RL-GO for two ZigBee nodes in a corridor section with gypsum walls. The operating frequency is assumed to be 2.4 GHz. The length, width, and height of the corridor are assumed to be 36 m, 2.34 m, and 2.4 m, respectively. The permittivity of the walls is 2.7, and conductivity is $\sigma = 0.01$ s/m. The section is

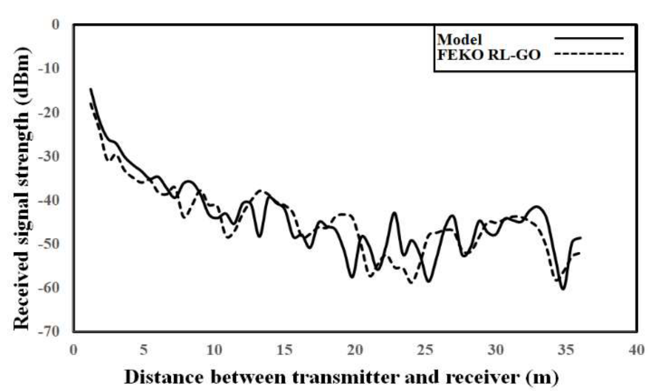


Figure 2. Received signal strength (dBm) for two nodes in corridor segment with a length of 36 m.

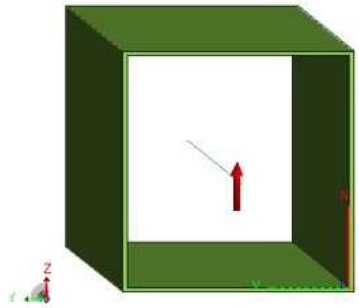


Figure 3. FEKO simulation model with a unit dipole excitation.

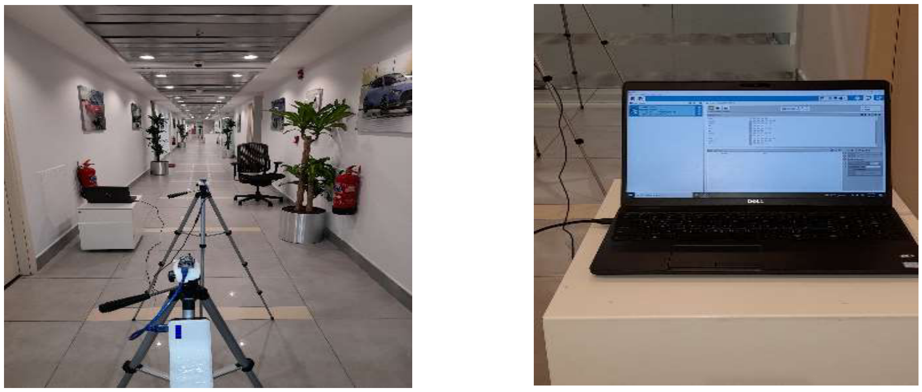
excited by a unit dipole which is located at the point (1.1 m, 1.1 m, 0.6 m) as shown in Fig. 3.

The error is calculated by comparing the percentage difference between the simulation and model results, and it is found that the relative error is 10.4% for the proposed results. The good accuracy of the model compared with the FEKO simulation results can be noted. The computational time for the model is about 0.21 seconds with a threshold up to the fifth level of reflection per sample for a total number of 60 samples across the corridor while regarding FEKO, the computational time is about 42 minutes. The simulations for FEKO and MATLAB are done using a laptop, DELL 5550 series, with core I7 processor and 32GB RAM. It can be noted that the proposed model is so fast compared to the computational electromagnetic software package noting that the used FEKO RL-GO simulation analysis is designed for electrically large structures at high frequencies, so it is expected that the simulation time and computational resources will be much higher if we use one of the full wave techniques for more accurate results. It is worth noting that the maximum computing power used by Matlab during the peak of analytical analysis is about 10.2% of the total processing power while for numerical analysis using FEKO, it reaches 40% of the total computing resources which can warrant more efficiency and less complexity for the analytical analysis compared to numerical one.

3. MEASUREMENTS

In this section, sample results are presented to verify the accuracy of the proposed model by comparing the obtained results with experimental results. A simple scenario of a straight corridor section in a commercial building with gypsum walls is verified experimentally at Wi-Fi frequency 2.4 GHz. The energy-efficient wireless ZigBee XBee S2C module [17, 18] was selected as the WSN in the experiment. The ZigBee S2C offers an acceptable communication range with high scalability, low power consumption, and low cost. In this experiment, two ZigBee XBee S2C nodes were used to evaluate the model accuracy by measuring the received signal strength in the corridor. The first XBee node was the router node, and the other XBee node was the coordinator. Both nodes are fixed on a stand at a height of 1.1 m above the ground. The locations of the nodes are kept at the center of the corridor with an initial distance of 0.6 m between the two nodes. The width and height of the corridor are 2.34 m and 2.4 m, respectively. The coordinator is kept fixed while the router is moving, and measurements were recorded every 0.6 m from the coordinator node until 36 m of the corridor was reached, as shown in Fig. 4. The router node was connected to a laptop via a USB port to collect the Received Signal Strength Indicator (RSSI) in the site using X-CTU software [18]. RSSI readings were recorded for each of the 60 test points. The transmitting and receiving antennas are kept vertically polarized.

Figure 5 shows a comparison between the measured signal in dBm and the analytical results for the same problem. Good agreement between the measured and calculated signal strengths is obtained. The slight differences between measured and model results can be explained due to differences of the boundary conditions of the actual corridor like holes or doors across the corridor section. The calculated error between the model and measured results is about 11.6%. Although the proposed model is simple with limited accuracy in a complex environment, it can still be used as a fast tool with low computational power for the prediction of the signal strength of WSN nodes in an indoor environment with a line of sight communication. The model can help designers in determining the best location of the sensors with a line of sight communication like sensors that are located in corridors or open areas.



(a) (b)

Figure 4. Measurement setup. (a) Transmitter and receiver nodes. (b) X-CTU software.

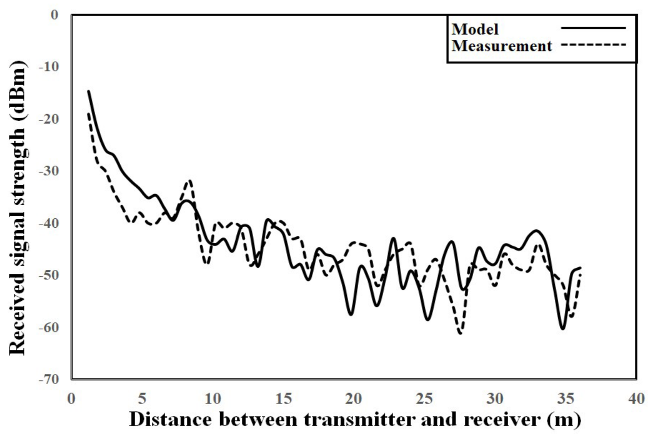


Figure 5. Received signal strength (dBm).

4. CONCLUSION

In this paper, a standard ray-tracing model based on geometrical optics is presented. The model is used as a fast tool for predicting the signal strength of WSN nodes with a line of sight link. The model has been verified by computational electromagnetic software analysis and measurements. A good agreement was found. The results show that the proposed simple model provides a satisfactory prediction of signal strength with fast calculation time and low computational power. The proposed analysis can be extended in future work to include complex environment effects such as furniture effects, human and holes effects, and the interference of existing WI-FI sources with same operating frequency. The proposed measurements dataset can also be used by other researchers in any future work which is related to the signal attenuation rate of ZigBee sensors in straight corridor section.

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