

A PROPAGATION STUDY OF XBEE P2P LINKS FOR SHORT-RANGE IOT APPLICATIONS IN OUTDOOR ENVIRONMENTS AT 868 MHZ

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Abstract

This study presents a preliminary propagation analysis for short-range point-to-point (P2P) wireless communication employing XBee modules operating at the 868 MHz in outdoor environments. In order to facilitate straightforward planning and deployment of XBee P2P links in the context of short-range Internet of Things (IoT) applications, empirical measurements were conducted under line-of-sight (LOS) conditions in urban, suburban, and rural environments. The performance of five well-known empirical path loss models, including Free Space Path Loss (FSPL), Two-Ray Ground Reflection, Log-distance, Hata-Okumura, and Cost231-Hata, was then evaluated based on Received Signal Strength Indicator (RSSI) data. The findings indicate that the FSPL model demonstrates the highest level of accuracy in rural areas, while the Log-distance model exhibits better performance in urban and suburban contexts. In contrast, the Two-Ray and Cost231-Hata models demonstrate a comparatively limited degree of agreement with the measured data across all environments. It is expected that these findings may offer valuable insights for the simple deployment of energy-efficient and cost-effective XBee-based P2P networks in outdoor IoT settings.

Keywords: XBee, Internet-of-Things, Path Loss, Propagation Models, Performance Assessment, Suburban, Rural, Urban

868 MHZ FREKANSINDA AÇIK ALAN ORTAMLARINDA KISA MENZILLI IOT UYGULAMALARI İÇİN XBEE P2P BAĞLANTILARININ YAYILIM ÇALIŞMASI

Özet

Bu çalışma, dış ortamlarda 868 MHz'de çalışan XBee modüllerini kullanan kısa menzilli noktadan noktaya (P2P) kablosuz iletişim için bir ön yayılma analizi sunmaktadır. Kısa menzilli Nesnelerin İnterneti (IoT) uygulamaları bağlamında XBee P2P bağlantılarının doğrudan planlanmasını ve dağıtımını kolaylaştırmak için kentsel, banliyö ve kırsal ortamlarda görüş hattı (LOS) koşulları altında ampirik ölçümler yapılmıştır. Serbest Uzak Yol Kaybı (FSPL), İki Işınlı Zemin Yansıması, Log-mesafe, Hata-Okumura ve Cost231-Hata dahil olmak üzere beş iyi bilinen ampirik yol kaybı modelinin performansı, Alınan Sinyal Gücü Göstergesi (RSSI) verilerine dayanarak değerlendirilmiştir. Bulgular, FSPL modelinin kırsal alanlarda en yüksek doğruluk seviyesini gösterirken, Log-distance modelinin kentsel ve banliyö bağlamlarında daha iyi performans sergilediğini göstermektedir. Buna karşılık, Two-Ray ve Cost231-Hata modelleri tüm ortamlarda ölçülen verilerle nispeten sınırlı derecede uyum göstermektedir. Bu bulguların, dış mekan IoT ortamlarında enerji tasarruflu ve uygun maliyetli XBee tabanlı P2P ağlarının basit bir şekilde konuşlandırılması için değerli bilgiler sunması beklenmektedir.

Anahtar Kelimeler: XBee, Nesnelerin İnterneti, Yol Kaybı, Yayılım Modelleri, Performans Değerlendirmesi, Yarı-Kırsal, Kırsal, Şehir

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1. Introduction

Short-range Internet of Things (IoT) applications in outdoor environments refer to the integration of IoT technologies that operate within a limited communication range, typically using protocols or technologies such as Bluetooth, Zigbee, Wi-Fi, or even IQRF [1], [2]. These systems can be implemented in environments where low power consumption and real-

time responsiveness are crucial. Examples may include localization [3], smart traffic [4], smart lighting [5], and smart agriculture solutions [6]. The core advantage of short-range IoT solutions lies in their ability to provide efficient and low-latency communication among devices [7]. Furthermore, due to their relatively low cost and ease of deployment, short-range IoT solutions are pivotal in advancing the scalability and accessibility of smart technologies [8].

On the other hand, the selection of an appropriate wireless communication technology remains a significant challenge in the context of outdoor IoT applications [9]. Zigbee could be one the promising technologies (protocols) based on the IEEE 802.15.4 standard, designed for low-power, low-data-rate, and short-range applications. Zigbee operates primarily in the 2.4 GHz ISM band globally, with additional support for 868 MHz in Europe and 915 MHz in North America [10]. Moreover, it supports multiple network topologies, including star, tree, and mesh. XBee modules are widely used hardware implementations that simplify wireless communication by offering plug-and-play solutions, and they are particularly effective in point-to-point (P2P) communication when configured with 802.15.4 firmware, while also supporting Zigbee protocol for mesh networking [11], [12]. Compared to other technologies such as Wi-Fi, Bluetooth, and IQRf, Zigbee may offer lower power consumption and cost, moderate communication range, and enhanced scalability. While Wi-Fi provides higher data throughput and broader coverage at the cost of increased power usage, BLE excels in ultra-low power scenarios but is limited in network complexity [13], [14]. IQRf, a less mainstream yet versatile technology, provides robust mesh networking with extended range and ultra-low power consumption [15], positioning it closer to Zigbee in terms of application suitability for IoT contexts.

For the effective deployment of short-range wireless communication systems in practical scenarios, it is essential to accurately predict coverage performance. In particular, XBee modules can be used for low-power, low-data-rate, and short-range IoT applications. To this end, it can be configured for P2P communication over the 868 MHz ISM band, offering a lightweight alternative to more complex networking protocols such as Zigbee mesh networking [16]. However, a reliable estimation of the coverage area requires a thorough understanding of propagation impairments affecting P2P wireless links. Among these impairments, path loss (PL) is recognized as the most significant factor influencing the quality and reliability of wireless links [17]. It is well known that PL is highly sensitive to environmental factors, and thus, selecting an accurate path loss model is crucial for efficient system deployment [18].

In the literature, extensive studies have examined the propagation characteristics of Zigbee-based networks at 2.4 GHz in short-range outdoor environments [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30]. The work in [19] analyzes Wireless Sensor Network (WSN) performance in forests and bean agriculture areas, focusing on Received Signal Strength Indicator (RSSI)-based power prediction models and identifying the most suitable one for such applications. In [20], the authors examine outdoor propagation modeling in WSNs, particularly the effect of distance, obstacles, and topology on RSSI and path loss in various conditions. The study in [21] evaluates wireless transmission between Arduino-based nodes using XBee modules, assessing RSSI levels,

packet loss, and indoor/outdoor attenuation models. Research in [22] investigates the impact of transmission range on ZigBee quality parameters in both indoor and open-area settings. The work in [23] presents a comprehensive performance analysis of XBee modules under various conditions, including static and moving obstacles, packet load variation, and measurements. In [24], an extensive comparison of encrypted and unencrypted ZigBee communication is conducted through real-world indoor and outdoor testbeds. The study in [25] evaluates the performance of the XBee module under various conditions in both indoor and outdoor environments to determine signal strength. In [26], three propagation models are assessed using RSSI-based field measurements with LoRa and ZigBee technologies in vegetated outdoor areas. Similarly, [27] compares the various vegetation propagation models against empirical path loss measurements in open fields. The study in [28] investigates ZigBee link efficiency on sloped agricultural terrain, where elevation blocks communication between nodes. Addressing communication reliability in precision agriculture, [29] highlights the challenges posed by ZigBee-based networks in such environments. Lastly, the research in [30] investigates the extended range capabilities of ZigBee technology and its suitability for Smart Meter networks in varying environmental conditions.

On the other hand, research addressing outdoor propagation analysis of XBee-based P2P links operating at 868 MHz remains very limited in the literature [31], [32]. The study presented in [31] presents a protocol for timed and reliable communication over off-the-shelf wireless technologies. The protocol is implemented and evaluated using both commercial cellular networks and self-deployed XBee modules operating at 868 MHz. It is demonstrated that XBee 868 MHz modules offer a cost-effective and flexible solution for long-range communication with deterministic performance. The results also validate the effectiveness of using XBee 868 MHz in ensuring timely and reliable data transmission. This then makes it highly suitable for industrial and mission-critical applications with strict latency and reliability demands. In [32], the deployment of a wireless sensor network using XBee 868 MHz modules is investigated. It highlights their potential as a robust alternative to 2.4 GHz solutions, which often experience interference and limited range. Through real-world experimentation across university buildings, the study shows that XBee 868 MHz modules can achieve reliable long-range communication (up to 300 meters) with low packet loss, even in challenging outdoor conditions. These findings underline the suitability of XBee 868 MHz for applications requiring stable and energy-efficient wireless links in environments where 2.4 GHz networks may be unreliable.

Therefore, despite the widespread use of short-range IoT technologies and numerous studies on Zigbee-based networks at 2.4 GHz, there remains a significant gap in the literature regarding the performance of XBee-based

systems operating at 868 MHz under real-world outdoor conditions. Understanding how environmental characteristics affect signal propagation at this frequency is essential to design efficient and scalable IoT deployments. Although IoT applications in areas such as smart cities, agriculture, and industrial monitoring are rapidly expanding, there is still a lack of practical and empirical guidance on modeling and predicting wireless coverage at 868 MHz in various outdoor environments using simple XBee-based P2P configurations. Addressing this gap constitutes the primary motivation of this study. This study is devoted to providing a preliminary propagation analysis to enable a simple and accurate deployment of XBee P2P links in outdoor environments at 868 MHz for short-range IoT applications. To this end, first, the propagation measurements were conducted using line-of-sight (LOS) links in urban, suburban, and rural areas. Then, the prediction accuracy of five well-known empirical path loss models, including Free-Space Path Loss (FSPL), Two-Ray Ground Reflection, Log-distance, Hata-Okumura and Cost231-Hata against the measurements based on the RSSI data was comparatively assessed. The results reveal that the FSPL model demonstrated the highest accuracy in rural environments, while the Log-distance model performed best in suburban and urban environments. In contrast, the Two-Ray Ground Reflection and Cost231-Hata models showed comparatively poor agreement with the measured data across all environments.

The remainder of this paper is organized as follows: Section 2 provides an overview of the well-known empirical PL models. In Section 3 the measurement campaigns conducted for this study are detailed. The experimental results are discussed in Section 4, followed by an analysis and interpretation of these findings in Section 5. Finally, Section 6 presents concluding remarks and outlines potential directions for future work.

2. Path Loss Models

This section provides a concise overview of well-known empirical PL models, specifically those applicable to outdoor environments at 868 MHz [33].

2.1. Free-Space Path Loss Model

The FSPL model can be used to characterize distance-related PL in open environments under ideal free-space conditions. In general, this model provides a lower bound of communication link losses. It can be logarithmically expressed as follows [2]:

$$PL_f[\text{dB}] = 32.44 + 20\log(d) + 20\log(f) \quad (1)$$

where d is the separation distance between the T_x and R_x in kilometers (km), and f is the frequency of the signal in MHz.

2.2. Two-Ray Ground Reflection Model

The Two-Ray Ground-Reflection Model is a simplified model that is commonly used to predict the PL between a T_x and R_x which are in LOS and close to the ground. In the model, both the direct path and the ground-reflected

path of the signal are considered. Unlike other models, this model is frequency-independent, which simplifies its application. The PL for this model can be expressed as [34]:

$$PL_{2ray}[\text{dB}] = 40 \log d - (10 \log G_{T_x} + 10 \log G_{R_x} + 20 \log h_{T_x} + 20 \log h_{R_x}) \quad (2)$$

where G_{T_x} and G_{R_x} are the antenna gains of T_x and R_x , respectively, h_{T_x} and h_{R_x} are the heights of T_x and R_x in meter, respectively, and d is the separation distance between the T_x and R_x in meters (m).

2.3. Log-Distance Model

The Log-Distance model, derived from the FSPL model, aims to enhance accuracy by including environmental data. The PL can be calculated by the following expression [17]:

$$PL_{LS}[\text{dB}] = PL_f(d_0) + 10n\log\left(\frac{d}{d_0}\right) \quad (3)$$

where n is the path loss exponent that varies depending on propagation environment, $PL_f(d_0)$ is the reference (free-space) path loss in dB at a reference distance (d_0) in meters, d is the separation distance between the T_x and R_x in meters (m).

2.4. Okumura-Hata Model

The Okumura-Hata (or simply Hata) model is another well-known empirical PL model that predicts transmission losses in various outdoor environments by considering the effects of reflections, scattering, and diffraction caused by surrounding objects. The PL can be calculated for urban areas as follows [35]:

$$PL_{H,urban}[\text{dB}] = 69.55 + 26.16 \log(f) - 13.82 \log(h_{T_x}) - \alpha_{h_{R_x}} + (44.9 - 6.55 \log(h_{T_x})) \log(d) \quad (4)$$

where f is the frequency of the signal in MHz, d is the separation distance between the T_x and R_x in kilometers (km), and $\alpha_{h_{R_x}}$ is the gain correction factor for h_{R_x} in dB. Depending on the environment, the parameter $\alpha_{h_{R_x}}$ can be calculated as:

$$\alpha_{h_{R_x}} = (1.1 \log(f) - 0.7)h_{R_x} - (1.56 \log(f) - 0.8) \quad (5)$$

Following this, for suburban areas, the PL can be determined by

$$PL_{H,suburban}[\text{dB}] = PL_{H,urban} - 2 \left[\log\left(\frac{f}{28}\right) \right]^2 - 5.4 \quad (6)$$

while it can be calculated for rural areas as

$$PL_{H,rural}[\text{dB}] = PL_{H,urban} - 4.78 \log(f)^2 + 18.33 \log(f) - 40.98 \quad (7)$$

2.5. COST231-Hata Model

The COST 231-Hata model is a widely used model to predict PL , particularly in urban environments. It is an extended version of the Hata model. The PL is then calculated as follows [36]:

$$PL_{C231}[\text{dB}] = 46.3 + 33.9 \log(f) - 13.82 \log(h_{T_x}) - \alpha_{h_{R_x}} + (44.9 - 6.55 \log(h_{T_x})) \log(d) + C \quad (8)$$

where the parameters f , d , and h_{T_x} are defined in (4), and C is the correction factor and defined as 0 dB for suburban and rural environments. For an urban environment, on the other hand, it is defined as 3 dB, and the expression to calculate the parameter $\alpha_{h_{R_x}}$ given in (5) is updated by

$$\alpha_{h_{R_x}} = 3.2 \left(\log(11.75 h_{R_x}) \right)^2 - 4.97 \quad (9)$$

3. Measurement Campaigns

The measurements were conducted to evaluate the prediction accuracy of the empirical path loss models overviewed in the previous section within a specific deployment of the XBee network in outdoor environments. This section first outlines the measurement setup, followed by a description of the measurement environments. Subsequently, the measurement scenarios and the parameters used in the measurements are detailed.

3.1. Measurement Setup

The measurement setup is illustrated in Fig. 1. As shown in the figure, a simple P2P configured system consisting of a T_x node and a R_x node was used to establish XBee links. The nodes were mounted on the top of the stands with equal heights above the ground (1.7 m). For data transmission, a portable power bank was used as a power source for the T_x node to ensure simplicity in the setup. For data reception, the R_x node was connected to a computer (laptop) to facilitate the measurement of RSSI data through a graphical interface known as the XBee Configuration and Test Utility (XCTU). Mainly, configuration and deployment are streamlined by the XCTU. In this way, it enables rapid implementation and customization.

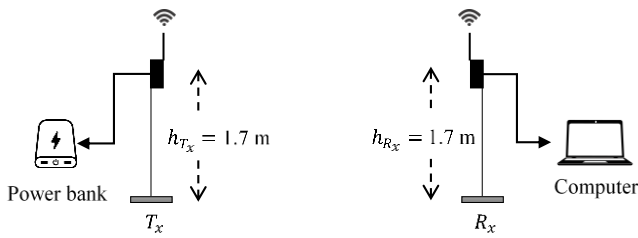


Figure 1. Measurement setup.

In the measurement setup, both T_x and R_x nodes were comprised of a dipole antenna with 2.1 dBi gain and a Digi XBee SX 868 MHz RF module stacked on Digi XBee 3 Micro Dev Board, as depicted in Fig. 2. The Digi XBee SX 868 is a high-performance, sub-GHz RF module designed for wireless communication within the 868 MHz ISM band, primarily targeting applications in the European region. It supports long-range data transmission of up to 14.5 km in line-of-sight (LOS) conditions with 2.1 dBi gain antennas, and operates at a maximum RF data rate

of 80 kbps. The module is suitable for P2P, point-to-multipoint (P2MP), mesh, and broadcast communication topologies, offering both transparent (AT) and API operating modes for flexible system integration. Its robust design, energy-efficient sleep modes, and compliance with ETSI regulations make it particularly well-suited for remote monitoring and telemetry systems. The technical specifications of the XBee module, on the other hand, are summarized in Table 1 [37].



Figure 2. The main components of T_x and R_x nodes.

Table 1. Technical specifications of Digi XBee SX 868 RF module.

Specification	Value/Description
Data Rate	10 Kbps or 80 Kbps
Transmitted Power	13 dBm
Sensitivity	113 dBm (at 10 Kbps) –106 dBm (at 80 Kbps)
LOS Range (Theoretical)	Up to 14.5 km (with 2.1 dBi antenna, in rural area)
Power Consumption	55 mA (max.)
Latency	69.99 ms (max.)
Modulation	Gaussian Frequency Shift Keying (GFSK)
Spreading	Frequency Hopping Spread Spectrum (FHSS)

3.2. Measurement Environments and Scenario

The measurements were carried out in urban, suburban, and rural environments in the vicinity of Atilim University, located in İncek, Ankara, Turkey. The environments were selected based on the intensity of vehicular and pedestrian traffic, vegetation density, and the height of trees and buildings. The satellite view of selected environments are shown in Fig. 3, where the LOS links are also illustrated. As can be observed in Fig. 3(a), the absence of short vegetation and potential sources of signal attenuation such as pedestrians, vehicles, and buildings around the link renders this area suitable for rural measurements. In contrast, the presence of stationary objects, low-rise buildings, and sparse yet distinguishable vegetation, as seen in Fig. 3(b), characterizes the environment as appropriate for suburban measurements. On the other hand, the area depicted in Fig. 3(c), which includes dense pedestrian and vehicular traffic, tall structures, and extensive vegetation due to surrounding gardens has been selected for urban measurement scenarios.



Figure 3. Measurement environments: (a) Rural, (b) Suburban, and (c) Urban.

Before the measurements, default firmware settings and radio parameters were used in XCTU to implement the XBee modules in a P2P configuration [38]. All measurements were conducted under LOS conditions. During the measurements, the position of the R_x was kept fixed, while the T_x was relocated to various predefined positions. The separation distance (d) between the T_x and R_x ranged from 10 m to 150 m. The spacing between two consecutive T_x positions, d_i , was set to 10 m, where $i = 1, 2, \dots, n$, and $n = 15$. An example of the measurement setup is illustrated in Fig. 4. At each measurement point (i), the T_x was configured to continuously transmit data packets for a duration of 3 min, resulting in the reception of 150 packets per T_x location. Based on the collected data for each environment, the average RSSI values were calculated. Here, it is important to note that measurements were taken only when there was a clear LOS link. If temporary obstructions such as vehicles or pedestrians blocked the LOS, resulting in a NLOS condition that typically requires a different and more complex channel model, the measurement was repeated. This procedure ensured that only LOS data were collected. Different environments were selected to analyze how surrounding objects and terrain affect propagation characteristics while maintaining LOS conditions. Therefore, no packet loss observed during the measurements.

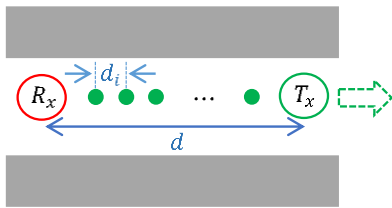


Figure 4. Illustration of measurement scenario.

4. Results and Analysis

The averaged RSSIs at each location of the T_x for LOS links constructed in urban, suburban, and rural environments are listed in Table 2. To calculate the PL for the averaged RSSIs, standard radio link budget was used as

$$PL(d)[dB] = P_{T_x} + G_{T_x} + G_{R_x} - P_{R_x} \quad (10)$$

where P_{T_x} is the transmitted power in dBm, P_{R_x} is the received power or RSSI in dBm, G_{T_x} and G_{R_x} are the antenna gains of T_x and R_x in dB, respectively.

Table 2. Average of RSSIs for the measurement environments (in dB).

d (m)	Urban	Suburban	Rural
10	-44.5	-42	-40
20	-48	-45	-41
30	-56	-47	-43
40	-55	-55	-45
50	-59	-52	-47.5
60	-60.5	-54.5	-50
70	-59.5	-55.5	-52
80	-73	-63.5	-52.5
90	-71.5	-68	-53.5
100	-70	-65.5	-55.5
110	-71	-66	-56
120	-84.5	-69	-56
130	-81	-71.5	-59.5
140	-72	-69	-56.5
150	-75.5	-72	-57

After determining the PL s for the averaged RSSIs, the PL values were obtained using the models presented in Section 2 for comparison. The PL s obtained from (10) and the models for urban, suburban, and rural environment are listed in Table 3, Table 4, and Table 5, respectively. Moreover, Fig. 5, Fig. 6, and Fig. 7 show comparison between the models and the measured the PL values in urban, suburban, and rural environment, respectively. Here, for the calculations using Log-distance model, the reference distance (d_0) was considered to be 1 meter. Additionally, the path loss exponent (n) was determined through linear regression analysis, employing the least squares method, to model the relationship between RSSI and the logarithm of distance. Accordingly, the path loss exponent exhibited an increasing trend from rural to urban environments, with the values of 1.79, 2.83, and 3.18, respectively.

Table 3. The path loss values for the urban environment (in dB).

d (m)	FSPL*	Two-ray*	Log-dist.	Hata	Cost 231	Measured
10	51.2	26.6	62.2	55.9	58.5	61.7
20	57.2	38.6	71.5	69.0	71.6	65.2
30	60.8	45.7	77.0	76.6	79.2	73.2
40	63.3	50.7	80.9	82.1	84.6	72.2
50	65.2	54.5	83.9	86.3	88.8	76.2
60	66.8	57.7	86.3	89.7	92.3	77.7
70	68.1	60.4	88.4	92.6	95.2	76.7
80	69.3	62.7	90.2	95.1	97.7	90.2
90	70.3	64.8	91.8	97.3	99.9	88.7
100	71.2	66.6	93.2	99.3	101.9	87.2
110	72.0	68.2	94.5	101.1	103.7	88.2
120	72.8	69.7	95.7	102.8	105.3	101.7
130	73.5	71.1	96.7	104.3	106.8	98.2
140	74.1	72.4	97.7	105.7	108.2	89.2
150	74.7	73.6	98.7	107.0	109.5	92.7

*Due to the identical predictions from the FSPL and Two-Ray Ground Reflection models in suburban and rural environments, these results are not included in Tables 4 and 5.

Table 4. The path loss values for the suburban environment (in dB).

d (m)	Log-dist.	Hata	Cost231	Measured
10	59.2	46.1	55.4	59.2
20	67.6	59.1	68.5	62.2
30	72.6	66.8	76.1	64.2
40	76.1	72.2	81.6	72.2
50	78.8	76.4	85.8	69.2
60	81.0	79.9	89.2	71.7
70	82.9	82.8	92.1	72.7
80	84.5	85.3	94.6	80.7
90	85.9	87.5	96.8	85.2
100	87.2	89.5	98.8	82.7
110	88.4	91.3	100.6	83.2
120	89.4	92.9	102.3	86.2
130	90.4	94.4	103.8	88.7
140	91.3	95.8	105.2	86.2
150	92.1	97.1	106.5	89.2

Table 5. The path loss values for the rural environment (in dB).

d (m)	Log-dist.	Hata	Cost231	Measured
10	49.2	27.5	55.4	57.2
20	54.6	40.6	68.5	58.2
30	57.8	48.2	76.1	60.2
40	60.0	53.7	81.6	62.2
50	61.8	57.9	85.8	64.7
60	63.2	61.3	89.2	67.2
70	64.4	64.2	92.1	69.2
80	65.5	66.7	94.6	69.7
90	66.4	68.9	96.8	70.7
100	67.2	70.9	98.8	72.7
110	68.0	72.7	100.6	73.2
120	68.6	74.4	102.3	73.2
130	69.3	75.9	103.8	76.7
140	69.8	77.3	105.2	73.7
150	70.4	78.6	106.5	74.2

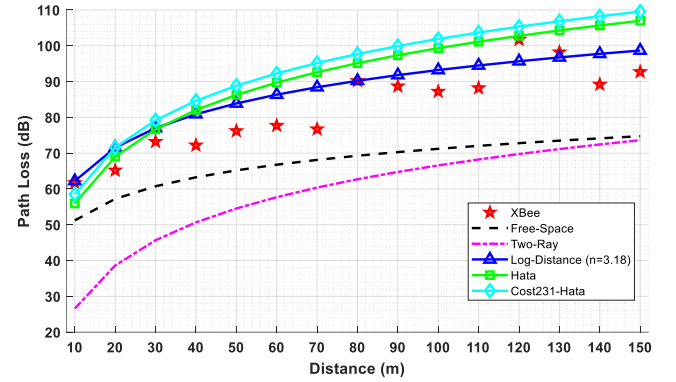


Figure 5. Comparison of measured (XBee) and simulated path loss in an urban environment.

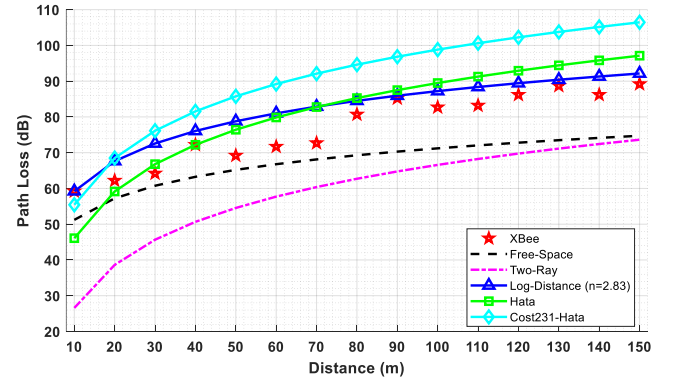


Figure 6. Comparison of measured (XBee) and simulated path loss in a suburban environment.

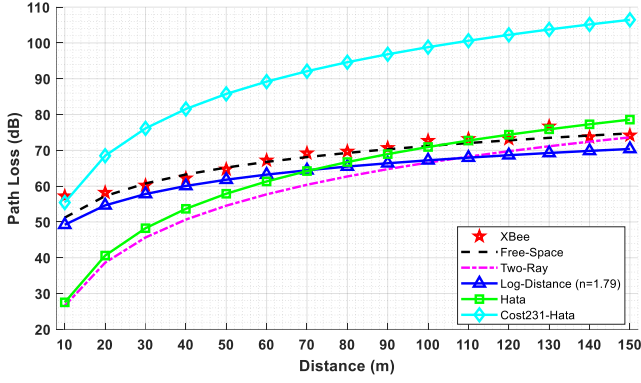


Figure 7. Comparison of measured (XBee) and simulated path loss in a rural environment.

The performance of each model was assessed using four statistical metrics: (a) coefficient of determination (R^2), (b) root mean squared error (RMSE), (c) mean absolute error (MAE), and (d) the standard deviation (σ) of the residuals [39]. These metrics collectively capture model accuracy, average error, and prediction consistency. The results are listed for rural, suburban, and urban environment are listed in Table 6, Table 7, and Table 8, respectively.

From the results listed in Table 6, in rural environment, it is clear that the FSPL model demonstrated the strongest agreement with the measured PL values, achieving a R^2 of 0.90, RMSE of 1.92 dB, a MAE of 1.25 dB, and a standard deviation of residuals of 1.49 dB. These results confirm its effectiveness in a LOS rural environment. The Hata model, since originally developed for urban propagation, showed a weaker performance with R^2 of -1.83, RMSE of 10.21 dB, MAE of 6.84 dB, and a standard deviation of 8.53 dB, suggesting moderate bias and noticeable error spread. The Two-Ray Ground Reflection and Cost231-Hata models performed even more poorly, with RMSE values of 11.91 dB and 23.86 dB, MAE values of 9.31 dB and 6.84 dB, and standard deviations of 7.42 dB and 8.53 dB, respectively. Their highly negative R^2 values indicate both systematic inaccuracy and lack of consistency, rendering them unsuitable for rural deployments with near-ground antenna configurations and moderate-range XBee links at 868 MHz.

According to the results listed in Table 7, the Log-distance model again provided the most reliable estimates, yielding an R^2 of 0.65, an RMSE of 5.82 dB, an MAE of 4.93 dB, and a standard deviation of 3.09 dB, in suburban environment. The Hata model also showed relatively good performance, with R^2 of 0.46, RMSE of 7.21 dB, MAE of 6.40 dB, and a standard deviation of 5.83 dB. In contrast, the FSPL model produced an R^2 of -0.13, RMSE of 10.39 dB, and a standard deviation of 4.12 dB. The Cost231 and Two-Ray models again performed poorly, with RMSE values of 14.79 dB and 18.67 dB, and standard deviations of 5.83 dB and 4.90 dB, respectively. For urban environment, the results listed in Table 8 show that the Log-distance model achieved the best

performance, with an R^2 of 0.67, RMSE of 6.49 dB, MAE of 5.65 dB, and a standard deviation of 4.53 dB. It provided both good predictive accuracy and relatively stable error behavior. The Hata model followed with moderate performance metrics with an R^2 of 0.18, RMSE of 10.27 dB, MAE of 9.16 dB, and a standard deviation of 5.93 dB. Yet, it indicated higher average error and greater variability. The Cost231 model resulted in even higher deviations, with an RMSE of 12.45 dB and a standard deviation of 5.92 dB, while the FSPL and Two-Ray models exhibited higher RMSE values above 16 dB and 24 dB, respectively, and standard deviations over 5 dB.

Table 6. The performance of the PL models based on statistical metrics (rural).

Model	R^2	σ	RMSE	MAE
FSPL	0.90	1.72	1.92	1.25
Two-Ray	-2.85	7.42	11.91	9.31
Log-dist.	0.39	1.56	4.72	4.45
Hata	-1.83	8.53	10.21	6.84
Cost231	-14.46	8.53	23.86	22.53

Table 7. The performance of the PL models based on statistical metrics (suburban).

Model	R^2	σ	RMSE	MAE
FSPL	-0.13	4.12	10.39	9.53
Two-Ray	-2.64	4.90	18.67	18.01
Log-dist.	0.65	3.09	5.82	4.93
Hata	0.46	5.83	7.21	6.40
Cost231	-1.28	5.83	14.79	14.09

Table 8. The path loss values for the rural environment (urban).

Model	R^2	σ	RMSE	MAE
FSPL	-1.07	5.95	16.35	15.23
Two-Ray	-3.57	5.27	24.29	23.71
Log-dist.	0.67	4.53	6.49	5.65
Hata	0.18	5.93	10.27	9.16
Cost231	-0.2	5.92	12.45	11.37

4. Discussion

The findings achieved from this study highlight the importance of selecting PL models based on environmental characteristics to construct XBee P2P networks at 868 MHz in short-range applications. Moreover, given the widespread use of the 868 MHz ISM band in various wireless communication applications, the insights gained from this study may also be beneficial for researchers working on other short-range radio

systems operating at this frequency, beyond its demonstrated application with XBee transceivers.

The comparative analysis reveals that while the FSPL model yields accurate predictions in rural LOS conditions, its performance degrades in environments with more complex propagation mechanisms. The Hata model is moderately effective across urban and suburban environments. However, it does not provide the same level of consistency as the Log-distance model, which emerges as the most robust and adaptable under varying propagation conditions. The poor performance of the Two-Ray and Cost231 models across all environments suggests limited practical applicability. The performance limitation of these models can be caused by several factors.

Although the Two-Ray Ground Reflection model is theoretically suitable for LOS conditions, it assumes a propagation scenario, where the antenna heights are significantly elevated and the direct and ground-reflected rays dominate the received signal. However, at relatively low antenna heights as considered in this study (1.7 meters), the path difference between the direct and reflected components is expected to be minimal, which often results in destructive interference at short ranges (< 1 km). Furthermore, ground reflections may not follow the ideal smooth-surface assumption, particularly in environments with grass, soil irregularities, or nearby objects, further distorting the expected interference pattern. This makes the model highly sensitive to small variations in geometry and environment, which can explain its large RMSE values and negative R^2 across all scenarios. Additionally, as the Two-Ray model is frequency-independent, its applicability across different frequency bands, especially at sub-GHz levels, may be inherently limited, further reducing its predictive reliability in the context of this study.

The poor performance of the Cost231 model can similarly be explained by a mismatch between its original design parameters and the experimental conditions of this study. The Cost231 model, which is an empirical extension of the Hata model designed for urban macrocell environments, was originally developed for base station deployments with transmitter heights typically ranging from 30 to 200 meters. Its assumptions are poorly aligned with P2P links where both antennas are positioned close to ground level, as in this study. Furthermore, the model is optimized for frequency bands between 1500 MHz and 2000 MHz, while the 868 MHz operating frequency used in the measurements lies well outside its intended range. Operating outside of the intended frequency range likely compromises its ability to account for propagation characteristics that are more prominent at lower frequencies, such as diffraction, ground-wave attenuation, and near-field effects, which are particularly relevant in low-height, short-range communication links. As a result, the Cost231 model fails to capture the actual signal behavior observed in the measurements, leading to its poor empirical performance.

5. Conclusion

In this study, a propagation study on the planning and deployment of a low-height P2P configured network for short-range XBee links at 868 MHz in rural, suburban and rural environments is presented. In this context, the propagation measurements were conducted using LOS links with both transmitter and receiver placed at a height of 1.7 meters. The accuracy of five well-known empirical path loss models, including FSPL, Log-distance, Hata, Cost231, and Two-Ray Ground Reflection against field measurements was then evaluated using statistical metrics. The results indicate that in rural environments, the FSPL model yielded the highest accuracy with an R^2 value of 0.90 and the lowest RMSE of 1.92 dB, MAE of 1.25 dB, and a standard deviation of 1.49 dB, outperforming all other models. In both suburban and urban environments, the Log-distance model demonstrated better performance, achieving R^2 values of 0.67 and 0.65 respectively, along with the lowest RMSE, MAE, and standard deviation values. Conversely, the Two-Ray Ground Reflection and Cost231-Hata models showed comparatively poor agreement with the measured data across all environments.

Although the obtained results may provide some useful insights on deployment of XBee P2P networks for short-range IoT applications in outdoor environments, further investigations with extended datasets are still required to enhance the generalizability of the findings. Therefore, as a future work, the authors aim to focus on conducting more comprehensive measurements across a wider range of transmitter-receiver separation distances and under controlled conditions, including separate tests for LOS and non-line-of-sight (NLOS) scenarios. More specifically, the objective is to progress beyond the use of average-based path loss models by incorporating more comprehensive channel characterization techniques. Particularly, the modeling framework may be extended to include amplitude distribution analysis, spatial correlation between measurement points, and scenario-dependent scattering models. Additionally, time-correlation models may be developed to capture signal variations in mobile receiver scenarios, along with detailed shadowing distributions for urban environments. Frequency selectivity and temporal dispersion may also be investigated through high-resolution signal measurements. These enhancements would enable a more rigorous, theoretically grounded, and statistically robust modeling approach.

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