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Research Article

Path Loss Modeling based on Optimal Path Profile in V2I Environment

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***Abstract*—This paper presents a predicted path loss model based on path profile in suburban Vehicle-to-Infrastructure propagation environments for 433MHz Sub-GHz band. Effecting of path profile parameters (Received Signal Strength, Transmitter - Receiver antenna heights, Transmitter - Receiver separating distance, Spreading Factor, Bandwidth, and coding rate) on link quality is considered as a crucial matter to maintain link availability at maximum path loss. The proposed model is based on the log-distance path loss model for line-of-sight propagation scenario. The path loss model is constructed based on the polynomial regression approach. Additionally this paper uses the principal of weighted product model to estimate the optimal path profile parameters which provide an optimum path loss. Through these advancements, this research aims to enhance the robustness of Vehicle to Infrastructure communication systems in suburban settings. This work is then compared with recent studies based on the criteria which consider the chosen environment, utilized wireless technology, operating frequency, transmission power, and path loss modeling analysis methods.**

***Index Terms*— Path loss modeling; long-range wireless technology; vehicle to infrastructure; suburban; optimization**

I. INTRODUCTION

The Internet of Things (IoT) characterizes a network that relates different applications and devices via the internet. This includes products such as cellphones, personal computers, household equipment, vehicles, and numerous of other devices. Each application or device has a singular identifier and can interact with other devices in the same network [1]. The Internet of Vehicles (IoV) is a special case of IoT, as depicted in Fig.1.

IoV involves integrating the internet into vehicles, enabling communication between vehicles and roadside infrastructure. This technology can enhance safety, leverage traffic flow, and provide drivers with assistance and information. IoV also helps the progress of autonomous vehicles and designing smart cities and transportation system. Some of IoV utilizations are collision avoidance, traffic congestion alert [2].

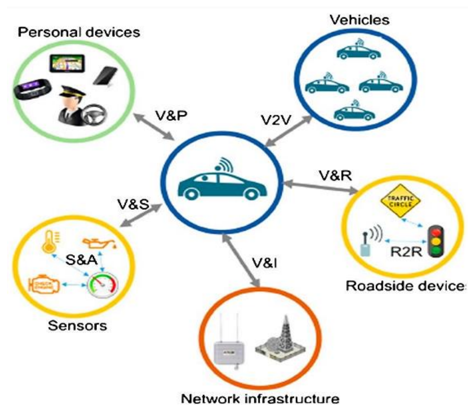


Fig. 1. IoV communications [3]

The Long Range Wide Area Network (LoRaWAN) is one of the structural templates for simplifying IoV communications, which uses Long Range (LoRa) modulation [4]. LoRa is the physical layer in LoRaWAN and was discovered by Semtech Corporation [5, 6]. Designing a wireless network covers the identification of the maximum distance between network nodes that guarantees a credible wireless connection [7]. Many technical coefficients (transmitter (Tx) power, operating frequency, and receiver (Rx) sensitivity) can affect the design of a wireless network [8].

With LoRa, the configuration coefficients (Spreading Factor (SF), Bandwidth (BW), and Coding Rate (CR)) can affect the communication quality of LoRaWAN and propagation connectivity.

Path Loss (PL) models are major in wireless communication, as these models predict the performance of the transmission connectivity between Tx and Rx in different channels. These models are worthy in planning and designing of a wireless network [9]. LoRaWAN design relies on PL measurements which are relied on predictive propagation models that assist radio engineers to enhance networks performance through influential design [10].

This paper discusses outdoor medium to define the optimal path profile coefficients, such as; Received Signal Strength Indicator (RSSI), which is a measurement of the power level that a radio receiver is experiencing from a signal being received, Tx-Rx antenna heights, Tx-Rx separation distance, SF, BW, and CR; for a Vehicle-to-Infrastructure (V2I) LoRaWAN system that operates at 433MHz. The aim is to assign the maximum PL at which the best possible connectivity is still maintained between a vehicle and infrastructure.

II. Related Works

Many studies have scouted about the relation between Tx and Rx performance in various mediums and conditions, using different wireless technologies to communicate via propagation modeling. Developing a precise propagation model to classify propagation losses is a critical issue that improves the accuracy of PL predictions at network designing [11]. LoRa is a wireless technology that is utilized for LoRaWAN design in IoT field. The setting coefficients of LoRa are defined based the used application. These coefficients affect PL prediction and affect the PL modeling that depends on experimental measurements that rely on the Path Loss Exponent (PLE). Thus, LoRa coefficients influence the quality and performance of the connection based on their selected groups. The next studies concentrate on PL modeling via different propagation models that impact LoRa technology through various frequencies and in several environments.

In the study accomplished by Karttunen et al. [12], the analyzation took place at urban area with operating frequency of 28GHz to deduce a weighted and distance-dependent PL model. The conducted study by Allen et al. [13] developed a set of outdoor-indoor PL models at different operating frequencies utilizing Singular Value Decomposition (SVD) with Least Mean Square (LMS) Error. In the implemented study by Unterhuber et al. [14], many PL propagation models were examined at 5.2GHz for Train-to-Train (T2T) environment PL modeling pursued for monitoring by simplifying information interchange to precisely define the location and speed of trains in country, suburban, and subway mediums. In the study by Bertoldo et al. [15], the assessment of indoor propagation revealed that Keenan's model is the most suitable choice for designing an office radio link based on LoRa operating at a frequency of 868 MHz. In Ingabire et al.'s study [16], outdoor propagation investigation was performed on four propagation models with an operating frequency 868MHz in an urban IoT environment with LoRaWAN technology. Two estimation results were obtained; COST-231 Hata and Okumura Hata models both underestimate the RSS while Extended Hata and ITU R 1225 models both over-estimate the RSS. In the research conducted by Zakaria et al. [17], two regions—urban and suburban—were analyzed for PL propagation modeling at an operating frequency of 3.5 GHz, resulting in the extraction of two PLEs for each area.

The subsequent studies focus on PL evaluation based on LoRa configurations at various operating frequencies, each set within different parameter environments, and analyze different methods.

In the studies conducted by Wu et al., Callebaut et al., and Lin et al. [18-20], PL evaluation of a LoRa link was examined in an outdoor environment at operating frequencies of 433 MHz and 868 MHz, with transmitting powers of 0 dBm, 13 dBm, and 20 dBm, respectively. This analysis aimed to determine the maximum PL constrained by the LoRa Rx sensitivity based on the derived PL model. In the study by Callebaut et al. [19], PL evaluation was conducted on point-to-point LoRa connections employing low-height terminals. This resulted in increased PL and a higher number of lost packets due to lower received signal strength (RSS), in contrast to a typical star topology network featuring a base station positioned at a greater elevation. In the conducted survey by Kongsavat et al. [9], a smart meter evolved with LoRaWAN to work at 920 and 925MHz frequencies with a transmitting power of 12dBm. Authors represented a PL model for urban regions, utilizing Root Mean Square Error (RMSE) to estimate and contrast their model with typical propagation models. The outcomes marked that the error of the estimated model was less than that in the Okumura-Hata model. In the study by Lin et al. [21], an underground LoRa based on wireless channel is modeled; researchers was found that maximizing BW led to minimized sensitivity, which passively affected the quality of the received signal, as the Data Rate (DR) increased with the maximized BW. On the contrary, maximizing SF led to minimize the DR while improving link quality, enhancing communication accuracy, and expanding propagation distance. In the study by Akram et al. [22], the Time on Air (ToA) was discussed based on divergences in SF and BW coefficients. Researchers found that ToA maximized as SF is raised; however ToA minimized with an increase in BW. In the study by Anzum et al. [23], LoRa propagation was examined meanwhile experimental measurements took manner at a frequency of 433MHz in a palm oil plantation. Line-of-Sight (LoS) measurements were used to calculate the PLE; with different SFs demonstrating unique propagation characteristics that significantly influenced the PLE. Researchers were found that the PLE varies based on both BW and SF. Additionally; an increase in BW resulted in a reduction in both communication range and sensitivity. Juang, R.T [24], proposes a machine learning-based PL model for 5G networks in urban environments. The model utilizes building profile data along the propagation path. Key steps include feature selection, PCA-based feature extraction, and polynomial regression for PL prediction. Simulation and real-world results demonstrate the proposed model outperforms conventional approaches, reducing prediction error by over 20%. Aramice, G.A. et al. [25], present a vehicle black box system that enhances safety and accurately records traffic fines using a vehicular sensor network within the IoV framework and 433MHz Long Range technology. The system features gas and flame sensors for security and a GPS module for location verification with timestamps to dispute fines. The system employs Vehicle-to-Vehicle (V2V) and V2I communication, evaluating signal strength via RSSI values. By utilizing LoRa technology instead of GSM or Bluetooth, the authors tackle cost and coverage issues from earlier studies.

III. LONG RANGE TECHNOLOGY

LoRa wireless technology enables data transmission over distances of 5 to 15 km using Chirp Spread Spectrum modulation with a (SF) of 7 to 12 and data rates from 30 bps to 50 kbps. LoRa features high robustness, multipath resistance, immunity to the Doppler Effect, and low power consumption. LoRa transceivers operate in ISM frequency bands of 868 MHz and 433 MHz. The effectiveness of LoRa is affected by physical factors: SF, BW, and CR. These parameters impact bit rate and LoRa noise resistance. But in general, five configuration parameters were selected in LoRa radio to determine communication link performance when designing LoRaWAN at suburban sites; these tunable parameters are Transmission Power (TP), Frequency (f), SF, BW, and CR [26-28].

The SF is the ratio of the symbol rate to the chip rate. Each SF represents an orthogonal channel for separate transmission in a LoRaWAN network. The value 2^{SF} indicates the number of chips per symbol and increases with SF [29]. While higher SF improves packet duration, SNR, distance, and RX sensitivity, data rate is reduced, resulting in slower information transfer. SF is adjustable: higher SFs are used for weak signals, while lower SFs are preferred for strong signals, affecting transmission speed. Increasing SF expands the range [1, 19, 30, and 31].

IV. PATH LOSS MODELS

The characteristics of a radio communication channel encompass the operating frequency, the types of antennas employed, and the characteristics of the propagation environment. To effectively analyze a communication channel, considering radio signal propagation is essential [32]. The usage of PL models is to estimate a reduction in RSS, and these models vary based on the medium (free space, suburban, and urban) specifications. Moreover, features like the characteristics of the medium, the Tx-Rx separating distance, and the antenna heights of Tx-Rx also affect PL [20].

The free space model represented in Eq. (1) is utilized to describe the decreasing in RSS along the direct path [33]:

$$P_L(d) = 20\log_{10} d + 20\log_{10} f + 20\log_{10}(\tfrac{4\pi}{c}) \qquad (1)$$

Where (d) acts the Tx-Rx separating distance, (f) acts the operating frequency and (c) acts speed of light.

The log-distance PL model is the most repeatedly used model for both (suburban and urban) regions. This model is distance (d) and PLE (n) dependent model, and is given in Eq. (2) [34]:

$$P_L(d) = P_L(d_0) + 10n\log_{10}\left({}^{d}/_{d_0}\right) \qquad (2)$$

Where (d_0) represents the reference distance from the Tx and (d >d_0), $P_L(d_0)$ represents the reference distance PL, the PLE (n) value describes the PL variation rate as (d) increased.

The presence of buildings and trees as obstacles along the path between the Tx and the Rx leads to log-normal fading or shadowing. These obstacles absorb a portion of the transmitted power, which affects the RSS [35]. The log-normal shadowing PL model expressed as [20]:

$$P_L(d) = P_L(d_0) + 10n\log_{10}\left({}^{d}/_{d_0}\right) + X_\sigma \qquad (3)$$

Where ($X\sigma$) is a Gaussian random variable with a mean of zero and a standard deviation of σ in dB, as σ increases, the model is regarded as less reliable [20]. The received power $P_r(d)$ at a distance (d) and transmitted power (P_t) is equal to:

$$P_r(d) = P_t - P_L(d) \qquad (4)$$

However, since the log-distance PL model shows that the received power decreases logarithmically with increasing distance (d), the average received power at distance (d), denoted as $P_r(d)$, can be expressed as follows [35]:

$$P_r(d) = P_r(d_0) - 10n\log_{10}\left({}^{d}/_{d_0}\right) \qquad (5)$$

$P_r(d_0)$, represents the received power at reference distance (d_0), and considered as the RSSI at certain distance (d_0) [20], and then Eq. (6) is obtained:

$$RSSI(d) = RSSI(d_0) - 10n\log_{10}\left({}^{d}/_{d_0}\right) + X_\sigma \qquad (6)$$

Where (X_σ) equals zero at no fading.

V. PATH LOSS MODEL EXTRACTION

In a wireless communication system, the PLE is a parameter that reflects how quickly the signal strength diminishes with increasing distance. Accurate determination of the PLE (n) is critical, serving as a key factor in designing radio signal propagation for wireless communication systems and can help predict the accuracy of radio propagation behavior [11].

The PLE is usually specified via empirical measurements of RSSI at different distances, followed by adequate a model the gathered data. With LoRaWAN, many parameters affect PLE, such as, operating frequency, surrounding medium, and used antenna type. One of the parameters affecting PLE is signal BW. LoRaWAN utilizes spread spectrum modulation, which spreads data over a large frequency range. The obtainable BWs in LoRaWAN ranges between 125 kHz to 500 kHz, and the specific value of PLE may differ depending on the used BW. In general, PL increases as BW minimizes, as a narrower BW focuses signal power to a smaller frequency band, making BW more susceptible to interference and absorption by objects like buildings and trees.

Crucially, PLE is extremely dependent on the operating environment. For illustration, in urban regions, PLE is higher than in rural regions due to the large number of objects that absorb or scatter the signal strength. Moreover, LoRa is designed to implement dynamically in mediums with a large PLE and considerable PL, providing long-range connectivity.

In addition, since PLE is determined empirically, variation may occur across different scenarios, locations and mediums.

PLE differs based on the specific medium and is affected by parameters such as signal frequency, antenna type, and the presence of objects. Table 1 presents PLE values for different mediums.

TABLE 1
PLE RANGES FOR VARIOUS MEDIUMS [35]

Medium	PLE Limits
Free space	2.0
Urban	3.0 to 4.0
Suburban	2.5 to 3.5
Indoor	1.6 to 2.7
Rural	2.0 to 3.0

PLE (n) for single reading sample presented as [36]:

$$n = \frac{RSSI(d_0) - RSSI(d)}{10\,log_{10}\left(d/_{d_0}\right)} \tag{7}$$

For (N) locations, the PLE can be calculated using the Least Mean Square (LMS) error method to reduce the discrepancy between the *measured RSSI(d)* at distance (*d*) and the *calculated RSSI(d)* using the following formula [17]:

$$\mathrm{F(n)} = \sum_{i=1}^{N}\left(\mathrm{RSSI_i(d_i)} - \mathrm{RSSI(d_0)} - 10\mathrm{n}\log_{10}\left(\mathrm{d_i}/_{\mathrm{d_0}}\right)\right)^2 \tag{8}$$

Where $\mathrm{RSSI_i}$ represents the measured RSSI in i-th sample at $\mathrm{d_i}$ distance. The standard deviation (σ) serves as an effective indicator of the shadow fading parameter and is expressed as [14]:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(\text{measured RSSI} - \text{calculated RSSI})^2}{N}} \tag{9}$$

The calculated (n) used to extract the PL model used to describe the environment under study.

After obtaining (n) and (σ), Eq. 6 used to get PL model of the form:

$$P_L(d) = (\alpha + \sigma) - \beta\log_{10}(d) \tag{10}$$

Where:

$$\alpha = \mathrm{RSSI(d_0)} + \log_{10}(\mathrm{d_0}) \tag{11}$$

$$\beta = 10\mathrm{n} \tag{12}$$

$$\sigma = \begin{cases} 0 & \text{at no shadowing effect} \\ > 0 & \text{at shadowing effect} \end{cases} \tag{13}$$

Once the PL mathematically calculated, the optimization can be characterized.

VI. RSSI MEASURING SCENARIO

Measurements were taken from a drive test at a selected road site in Baghdad City, which has a width of approximately 9 meters, with surrounding buildings about 10 meters tall and medium-height trees on both sides ranging from 4 to 6 meters, Fig.2 shows the site under study.

Fig. 2. Site under Study (Google Earth Image)

In Fig.2, a base station (marked with a red map marker) represents the Rx, while 11 locations (marked with blue map markers) indicate the distances measured from the base station using Google Earth Maps, identified as the positions of the Tx (vehicle) during the drive test. Fig. 3 illustrates a schematic of the measurements taken at two base station heights of 2.5 m and 4 m, with the height of the end node (LoRa vehicle) being approximately 1 meter.

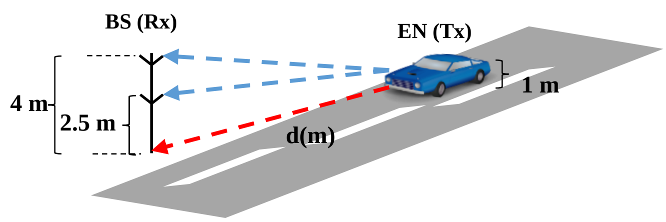


Fig. 3. Measurements Schematic Scenario based Antenna Heights

The calculations and analyses in this study are conducted within the following defined scopes, boundaries, limitations, and constraints:

1. Selecting the LoRa module (SX1278) from Semtech Corporation.
2. Configuring the LoRa module parameters with the following values: SF of 7, 9, 10, and 12; BW options of 125, 250, and 500 kHz; and CR of 4/5 and 4/7.
3. Setting the transmission output power for the Tx to 17 dBm.
4. Installing the Rx antenna at heights of 2.5 and 4 meters.
5. Using a LoRa frequency modulation of 433MHz.
6. Selecting a suburban site in Baghdad City.

VII. EVALUATION METRICS

A. Distance Correlation

The RSSI values, measured through a drive test using the Semtech SX1278 LoRa module, are regarded as actual measurements and can be employed to estimate the distance between the Tx and Rx as follows:

From Eq. (6), the Tx-Rx distance estimation formula is obtained as:

$$d = d_0 10^{-\left[\frac{RSSI(d) - RSSI(d_0) + X_\sigma}{10n}\right]} \tag{14}$$

The error between the measured distance and the actual distance between the Tx and Rx is determined using:

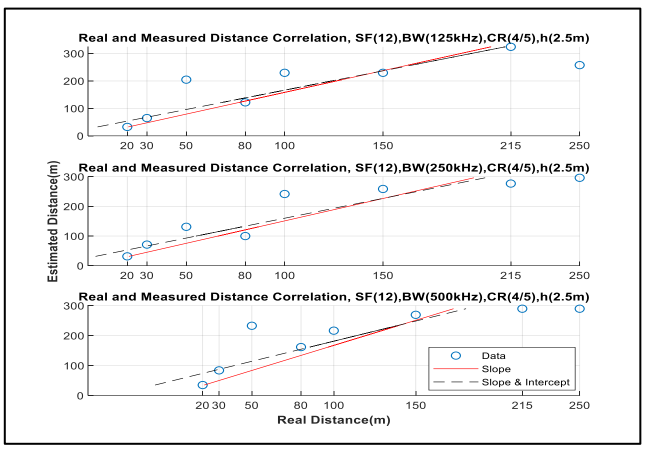
$$e_i = d_r - d_m \tag{15}$$

Where, (e_i) represents the distance measurement error, (d_r) is the real distance between Tx-Rx nodes, and (d_m) is the measured distance (d) in Eq. (14).

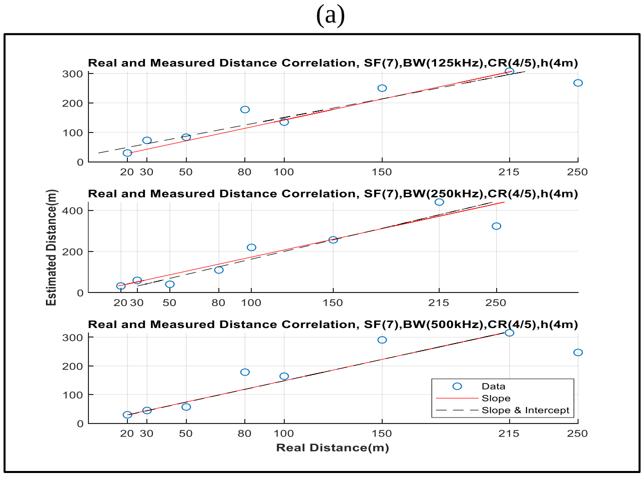
A correlation is required between Tx-Rx (measured and estimated) distances [37]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(d_{r_i} - \widehat{d_{m_i}}\right)^2}{\sum_{i=1}^{n}\left(d_{r_i} - \overline{d_{r_i}}\right)^2} \tag{16}$$

The best correlation coefficients are (R^2=0.8232) and (R^2=0.8760) at {SF(12), BW(250kHz), Rx antenna height of (h=2.5m)} and {SF(7), BW(125kHz), Rx antenna height of (h=4m)} respectively, as shown in Fig.4(a) and Fig.4(b):



(a)



(b)

Fig. 4. Distance Correlation at:
(a) {SF(12), BW(250kHz), Rx antenna height of (h=2.5m)}
(b) {SF(7), BW(125kHz), Rx antenna height of (h=4m)}

B. Path Loss optimization

The Weighted Product Model (WPM) is a Multi-Criteria Decision-Making (MCDM) method used for optimization, and is widely recognized as a standard numerical analysis technique for decision-making [38]. The goal is to identify the policy (AP_L) that maximizes the accumulated PL. This policy is characterized by the set {SF, BW, CR}, representing the configuration combinations used for the LoRa module during transmission.

Eq. (17) formally defines this maximization of (AP_L) [39]:

$$max\ (AP_L\{SF, BW, CR\}) = \prod_{i=1}^{8} P_L(d_i)^{\omega_i} \tag{17}$$

Table 2 briefs the symbols in Eq. (17):

TABLE 2
MAXIMIZATION POLICY SYMBOLS

Symbol	Representation
AP_L	Accumulative PL value at i distance in meters, $i = 20, 30, 50, 80, 100, 150, 215\ and\ 250$
ω	weighting vector, $\omega = 0.35, 0.2, 0.2, 0.1, 0.05, 0.05, 0.03, 0.02$
SF	the selected spreading factor values, $SF = [7, 9, 10, 12]$
BW	the selected bandwidth values in kHz, $BW = [125, 250, 500]$
CR	the selected code rate values, $CR = [4/5, 4/7]$

The set configuration {SF, BW, and CR} has 24 possible combinations. Each of these combinations results in different values of RSSI measured during drive tests. The different RSSI values then lead to the calculation of different PL values for each combination set at each distance being considered.

The goal is to determine the maximum PL value at which a reliable link can still be maintained, according to the established policy. Fig. 5 illustrates the optimal PL values for specific {SF, BW, CR} set at various distances and two heights of Rx antenna.

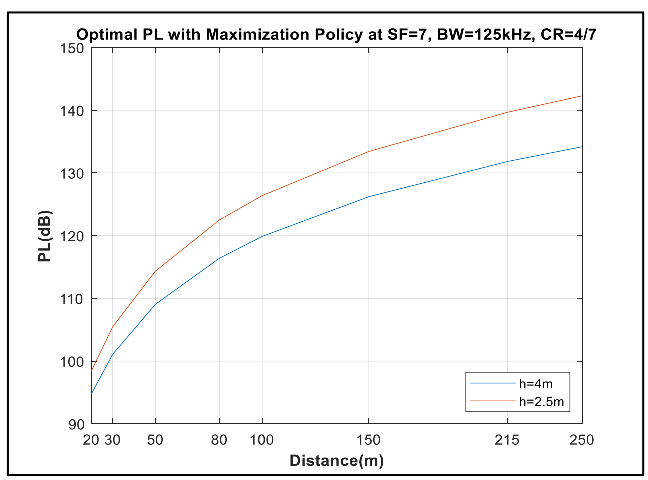


Fig. 5. Optimum Path Loss

VIII. Comparison

This work is compared to recent works according to the criteria shown in Table 3. The criteria in the table consider chosen environment, utilized wireless technology, operating frequency, transmission power, and PL modeling analysis methods).

TABLE 3
CRITERIA COMPARISON WITH OTHER RELATED WORKS

[Ref.] year	Environment/Wireless Technology	Operating Frequency (MHz) / P_t (dBm)	P_L Modeling Analysis Methods
[18] 2017	Outdoor/Radio Frequency	433 and 868 / (0, 13, 20)	RMSE
[9] 2020	Urban/LoRa	920 and 925 / 12	RMSE
[16] 2020	Outdoor/LoRa	868 / not mentioned	Mean Absolute Error
[23] 2022	Outdoor/LoRa	433 / not mentioned	RMSE
This work	Outdoor (suburban)/LoRa	433	WPM

IX. Discussion

Based on the results and discussions presented earlier, the following observations can be made:

1. Improper placement of the Rx can lead to a significant increase in path loss.
2. Rx antenna height may effect in PL minimization.
3. Propagation models form the foundation of channel modeling, to describe how a radio signal changes during its propagation from the Tx to the Rx.
4. As the separation distance between the Tx and Rx increases, the path loss also rises.
5. Path loss tends to increase more rapidly at greater distances in civilian/urban areas compared to other environments.
6. The measurement data presented can be valuable for researchers in the context of site planning and link budget analysis for telecommunication system deployments.

X. Conclusion

This paper presents a generalized PL model tailored for suburban environments, based on empirical propagation modeling and actual drive test RSSI measurements. The design of a LoRaWAN-based Internet of Vehicles (IoV) system was assessed in terms of PL measurements. The influence of LoRa parameters—specifically SF, BW, and CR—on link performance was evaluated by estimating coverage range and PL using PLE calculations. An optimal policy was proposed to maximize PL, showing that the optimal PL was achieved with LoRaWAN parameters of SF = 7, BW = 125 kHz, and CR = 4/7, based on the measured RSSIs and predicted PL model at two Rx antenna heights (2.5m and 4m). The best distance estimation for a Rx antenna height of 2.5 meters is obtained using a SF of 12 and a BW of 250 kHz, with a R^2 of (0.8232), for an Rx antenna height of 4 meters, the best distance estimation is obtained using an SF of 7 and a BW of 125 kHz, with a R^2 of (0.8760).

Future work may explore different antenna heights and their impact on link performance within this PL modeling framework, comparing results with other propagation models such as the Okumura-Hata model. Additionally, other locations, including urban sites, could be incorporated into this study, and the influence of vehicle speed may also be analyzed in future research.

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Author Contributions Statement

Authors: Gregor A. Aramice and Abbas H. Miry proposed the research problem.

Authors: Gregor A. Aramice and Jaafar Q. Kadhim developed the theory and carried out the calculations.

Authors: Gregor A. Aramice and Abbas H. Miry verified the analytical methods and investigated the results of this article.

All authors analyzed the findings and participated in the final article.

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