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Hybrid Propagation Model for Sigfox Unlicensed Low Power Wide Area Networks in Urban Environments

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ABSTRACT

Low Power Wide Area Network (LPWAN) technology has gained widespread application in various fields, including in urban environments. Sigfox is one of the LPWAN technologies that have been widely adopted and support connectivity for thousands of end devices. However, understanding the performance of the Sigfox network especially in urban environments is crucial due to the impact of path loss. Path loss models, such as the Okumura-Hata and the Third Generation Partnership Project (3GPP) propagation models are commonly used to estimate path attenuation based on parameters such as propagation models take into account factors, including carrier frequency, distance, antenna height, and terrain profile. In this study, the path loss performance of Sigfox using the Okumura-Hata, 3GPP, and a newly proposed Hybrid propagation model was investigated. The proposed Hybrid model combines the strengths of the Okumura-Hata and 3GPP models. The key strength of the proposed Hybrid model is that provides a more comprehensive and accurate path loss estimation for Sigfox in urban environments. The analysis presented in this paper serves as a valuable for understanding the potential of the proposed Hybrid model for the field of Sigfox technology. Our results demonstrate the potential of the proposed Hybrid model for improving path loss accuracy in urban environments.

Keywords:

Sigfox; Propagation; Path loss; Okumura-Hata; 3GPP; Hybrid

1. Introduction

Low Power Wide Area Network (LPWAN) is a wireless telecommunications category that offers long-range communication that covers distances of up to a hundred kilometres. Smart cities, agriculture management, smart farming sensor networks, monitoring systems, and pollution monitoring are examples of LPWAN applications [1-3].

Sigfox is one of the LPWAN technologies that gains popularity and supports connectivity for thousands of end devices. The performance of the Sigfox network especially in urban environments is crucial due to the impact of path loss**.** Path loss describes the decrease in an electromagnetic wave's power density as it travels from the transmitter to the receiver [4,5]. This attenuation can

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occur due to various factors, including propagation characteristics and obstacles present in the path between the base station and mobile station [6]. Path loss models are valuable planning tools for achieving optimal levels in wireless communication networks [7]. The Okumura-Hata and the Third Generation Partnership Project (3GPP) propagation models are examples of path loss models. These models are commonly used to estimate path attenuation based on parameters such as propagation models take into account factors, including carrier frequency, distance, antenna height, and terrain profile.

To combine these models in order to produce more precise and thorough path loss forecasts, there is a research gap in the literature. In order to close this gap, the suggested HybridPath model makes use of the advantages of both approaches. This paper's main contribution is to study how the suggested Hybridpath model for path loss estimates behaves in urban settings. For various base station antenna heights, the Okumura-Hata and 3GPP models will be contrasted with the suggested HybridPath model. The proposed Hybridpath model's ability to increase path loss estimation precision in urban settings will also be investigated in this study.

2. Propagation Models

In particular environmental circumstances, the propagation model is crucial for obtaining the best accuracy [8]. Figure 1 shows the hierarchy of the propagation models. Okumura-Hata and 3GPP models are types of empirical path loss models [4]. Empirical radio propagation models using field measurement data and statistical analysis to predict received signal strength [9].

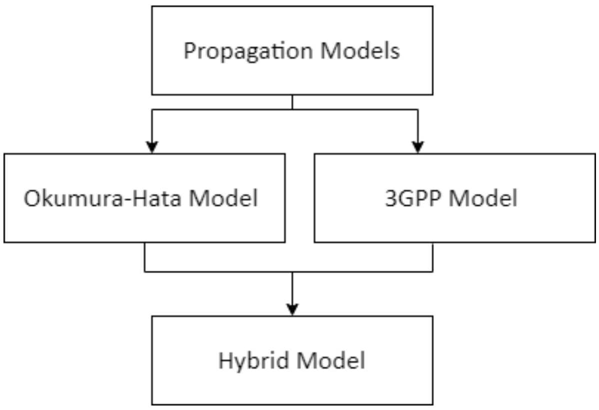

Fig. 1. Propagation Models

In this study, the main focus is on the Okumura-Hata, and 3GPP propagation models, which are known for their good balance between accuracy and performance. Meanwhile, a newly proposed HybridPath model combines the strengths of the Okumura-Hata and 3GPP models. Table 1 the fundamental parameter of selected propagation models [8].

Table 1
The fundamental parameters of selected propagation models [8]

Model	Okumra-Hata	3GPP
Frequency, *f*	150 –1900 MHz	<2600 MHz
Base Station Height, b_h	30-200 m	0-50 m
Mobile Device Height, m_h	1-10 m	-
Base Station – Mobile Device Distance, *d*	1-20 km	<8 km

2.1 Okumura-Hata Model

The propagation model provides the median value of the propagation loss and is based on the extensive measurements made in Tokyo [8]. The Hata-Okumura model, in particular, is widely used in the wireless communication industry for estimating path loss in RF planning [7]. Okumura-Hata propagation models have been analysed in various environments, including urban and rural environments, to assess their accuracy and suitability [8].

The Okumura-Hata radio propagation model is commonly used as a path loss modelling tool in the wireless communication industry [10]. The Okumura Hata propagation model was used for coverage planning and budget linking [10]. According to research conducted by [8-10], the Okumura-Hata model is utilised to simulate path loss in the urban environment. Path loss (in decibels, dB) is written as

$$P_L = A + B \log(d) + C \tag{1}$$

where A, B, and C are parameters that depend on frequency, f and mobile device, m_h [13]. Factor A increases with carrier frequency, f_c and decreases with increasing height of the base station, b_h and mobile device, m_h. Additionally, the path loss exponent (proportional to B) decreases with increasing height of the b_h. The model is intended for large cells, with the b_h being placed higher than the surrounding rooftops [13].

The basic path loss (P_{Loss}) is expressed in decibels (dB) as

$$P_{Loss(oh)} = k1 + k2log_{10}(f) - 13.82log_{10}(b_h) - a(m_h) + (44.9 - 6.55log_{10}(b_h))log_{10}d \tag{2}$$

The basic path loss (P_{Loss}) for urban is expressed as

$$P_{Loss(oh)} = 69.55 + 26.16\ log_{10}(f) - 13.82log_{10}(b_h) - a(m_h) + (44.9 - 6.55log_{10}(b_h))log_{10}d \tag{3}$$

where f represents in MHz, the base station height, b_h and mobile device height, m_h denotes in meters, and distance, d indicates in kilometres from transmitting to the receiving. These values serve as a constant offset (in dBm) and a multiplier for the logarithm of the distance between the b_h and m_h. The terrain parameter, a(m_h) is a function of the mobile device of height, and is specifically defined for urban environments with f> 200 MHz as

$$\mathrm{a(m_h)} = 3.20(log_{10}(11.75m_h))^2 - 4.79 \tag{4}$$

where m_h represents the height of the mobile device. The parameter a(m_h) serves as the correction factor for the mobile station antenna. The terrain parameter is an important consideration in network design [7]. Table 2 summarizes the conditions of the parameters for urban environments.

Table 2
Conditions parameters for urban environments

Parameters	Urban
Frequency, f	150MHz<f>1499MHz
k_1	69.55
k_2	26.16
terrain parameter $\mathrm{a(m_h)}$ or correction factor, *cf*	$3.20(log_{10}(11.75m_h))^2 - 4.79$

2.2 Third Generation Partnership Project (3GPP) Model

The 3GPP model is commonly used in the telecommunications industry for network planning and propagation modelling. This propagation model applies to macro cells in the urban environment. The path loss is defined as

$$P_{L(3GPP)} = 40(1 - 4.10^{-3}b_h)log_{10}(d) - 18og_{10}(b_h) + 21og_{10}(f) + 80 \quad (5)$$

where distance, *d* represents the distance between the transmitter and receiver, *f* is denoted in MHz, and b_h denotes in meters. The 3GPP path loss model is valid for b_h values between 0 and 50 m with transmitter-receiver separation from a few hundred meters to kilometres. However, this model is not for not particularly accurate for shorter distances.

2.3 HybridPath Model

HybridPath is a new potential propagation model that combines the strength of the Okumura-Hata and 3GPP models to improve the accuracy of path loss predictions in urban environments for Sigfox. The 3GPP model is commonly used in cellular communication systems to estimate the loss of signal strength between a base station and end device, while the Okumura-Hata model is an empirical path loss model that is based on the well-known Hata model. The resulting path loss is defined in Eq. (6) by taking the summation of the path loss that occurred in Okumura-Hata as shown in Eq. (3) and 3GPP models in Eq. (5).

$$P_{L(Hybridpath)} = P_{L(oh)} + P_{L(3GPP)} \quad (6)$$

The proposed HybridPath model can be implemented by selecting the appropriate model based on the environment and scenario. For urban environments, the Okumura-Hara model can be used, while for suburban environments, the 3GPP model can be used. The proposed HybridPath model switches between these models based on the scenario classification, providing a more accurate path loss estimation for Sigfox in different environments.

3. Sigfox Technology

This section provides an overview of the Sigfox technology considered in our study is explained. Sigfox represents the unlicensed operation in the industrial, scientific and medical (ISM) band. Sigfox is a type of LPWAN technology for IoT applications that getting more attention in the realm of IoT applications. Sigfox supports both unidirectional and bi-directional communication, For uplink (UL), it uses Binary Phase Shift Keying (BPSK) modulation, while for downlink (DL), it uses Gaussian Frequency Shift Keying (GFSK) [12-14].

Sigfox is subject to duty cycle restrictions in Europe, limiting the number of the transmitted packets per day to 140 messages in the uplink and 4 messages in the downlink. This means that Sigfox allows a maximum number of messages per day is 144 packets with only one packet every 10 minutes [2,17,18]. Sigfox's MAC layer is more efficient for uplink communication due to the limitations of downlink [19]. However, the effect of this strictest regulation helps conserve energy and prolong the battery lifetime [2]. As a result, Sigfox is ideal for sensor data collecting but not for devices that require regular transmission because of traffic limitations [20].

The duration of message transmission in a network, from beginning to the end, is known as the transmission time. Uplink payloads can be a maximum of 12 bytes long and downlink payloads can be a maximum of 8 bytes long per day using Sigfox [14,16,18,21,22]. In general, messages should arrive at the base station within 2 seconds [2]. Small data sizes can be sent with Sigfox due to its short payload length [22]. It has a high communication latency and low transmission bit rates, which makes it vulnerable to interference from other technologies [22].

M. S. Farooq and K. Mekki *et al.,* claimed that Sigfox is the ideal choice for applications involving continuous monitoring, asset tracking, and control [21,22]. Due to its long-range communication, ultra-low power consumption, prolonged battery life, low data rate, and cost-effectiveness, it is especially well-suited for some use cases, including smart farming, environment control, smart agriculture, and asset tracking [10,21,25]. The Sigfox technical characteristics are listed in Table 3.

Table 3
Summarizes the specifications of Sigfox technical

Technical	Sigfox
Spectrum	Unlicensed
Modulation scheme	BPSK (UL) and GFSK (DL)
Maximum messages per day	140 (UL) and 4 (DL)
Maximum payload length	12 bytes (UL) and 8 bytes (DL)
Battery lifetime	10 years
Application	Smart farming, smart agriculture, environment control and asset tracking

4. Simulation Setup

In this section, the network performance in different propagation models for Sigfox are explained namely the Okumura-Hata, 3GPP and proposed HybridPath models. The parameters of study for these models are the operating frequency (f_c), distance between the transmitter and receiver (d), base station antenna height (b_h), mobile device antenna height (m_h), and terrain profile (e.g. urban and rural) using 433 MHz as the frequency band designated for Sigfox in Asia region. Table 4 summarizes the simulation parameters for Sigfox technology from transmitter to receivers based on the scenarios described.

Table 4
Simulation Parameters for Sigfox

Technology	Sigfox
Propagation model	Okumura-Hata, 3GPP and proposed HybridPath
Operating frequency, f	433 MHz
Distance between transmitter and receiver, d	10 km (urban)
Base station antenna height, b_h	30 m and 50 m
Mobile device antenna height, m_h	1 m

First, the specific Sigfox radio parameters were studied, especially data related to the propagation environment, such as terrain information, base station and mobile device antenna heights, and others. Next, the simulation scenario was conducted based on the specific Sigfox radio parameter using the Okumura-Hata, 3GPP and HybridPath models separately. The propagation of electromagnetic waves based on the models' algorithms was simulated and analysed. If the results meet the requirements, proceed to the next process by applying the propagation models again. Finally, the differences in path loss, signal strength, or other relevant metrics between the three models were analysed by comparing the results obtained from the Okumura-Hata, the 3GPP and the proposed HybridPath models. The simulation process flowchart for the investigation and evaluation of the performance of Sigfox in an urban environment using different propagation models is shown in Figure 2.

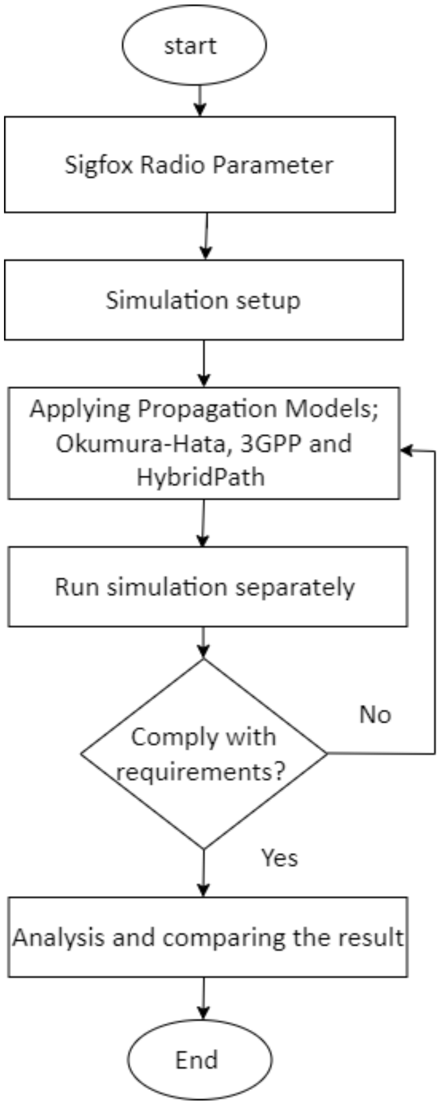

Fig. 2. The evaluation of different propagation models flowchart

5. Results & Discussion

In this part, three propagation models have been simulated specific environments and the frequency band used by Sigfox to provide accurate predictions of path loss. However, it is crucial to note that the performance of these models may vary depending on the specific urban environment and other factors.

Table 5 shows the Sigfox in an urban environment using Okumura-Hata, 3GPP, and proposed HybridPath models. The comparison of Sigfox in the urban environment using propagation models with differences b_h.

Table 5
Sigfox in an urban environment using Okumura-Hata, 3GPP and proposed HybridPath models

Specifications	Value
Model	Okumura-Hata, 3GPP, and proposed HybridPath
d_{urban}	1 km
b_h	30 m and 50 m

For a maximum distance of 1 km between the base station and the mobile device, the path loss performance of the models mentioned in this section is displayed in all of the figures. The main pattern of the graphs is consistent with other research in that it exhibits a logarithmic rise in route loss with increasing distance. The same behaviour is examined in Figure 3 and Figure 4, but a different propagation model was used.

The simulation results are presented. Based on Figure 3 shows that the Okumura-Hata model performed better when the base station antenna height *(b_h)* was 50 m, with an average path loss of 104.2 dB. In comparison, when b_h was 30 m, the average path loss was 106.6 dB. According to a study conducted by Avs *et al.,* [11], the Okumura-Hata model was used because Sigfox works well in urban environments using this propagation model. The maximum path loss increases as the distance of *d* increases whereas the maximum path loss decreases as the distance of b_h increases. But, no changing maximum path loss during changing m_h.

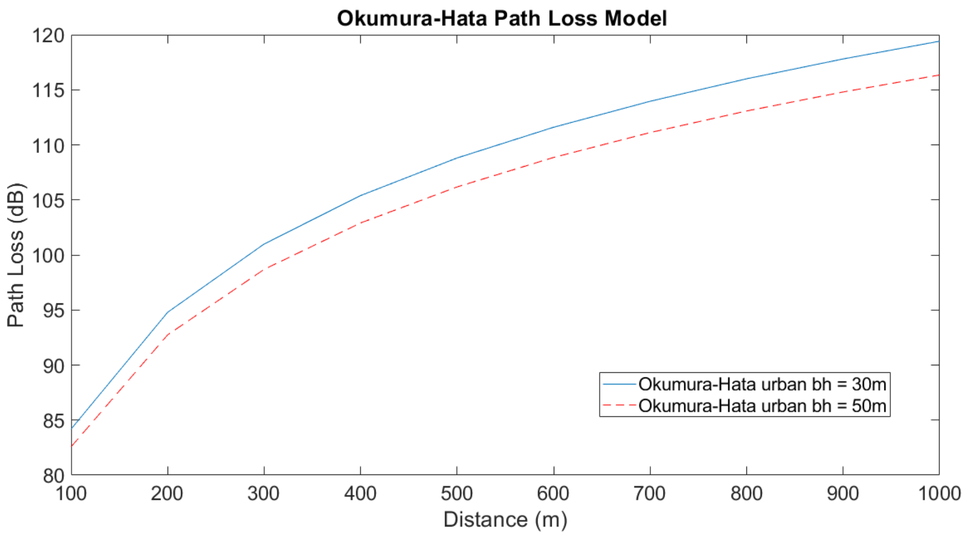

Fig. 3. Path loss performance with different b_h in urban environment using Okumura-Hata model

Based on Figure 4 shows that the 3GPP model performed better when the base station antenna height (b_h) was 30 m, with an average path loss of 76.7 dB. In comparison, when b_h was 50 m, the average path loss was 87.3 dB. Figure 4 is proportional with the results showed in Figure 3 for an urban environment. These results are consistent with the 3GPP model's validity for b_h ranging from 0 to 50 m. The maximum path loss increases with the distance of *d* increases whereas the maximum path loss increases with the distance of b_h increases.

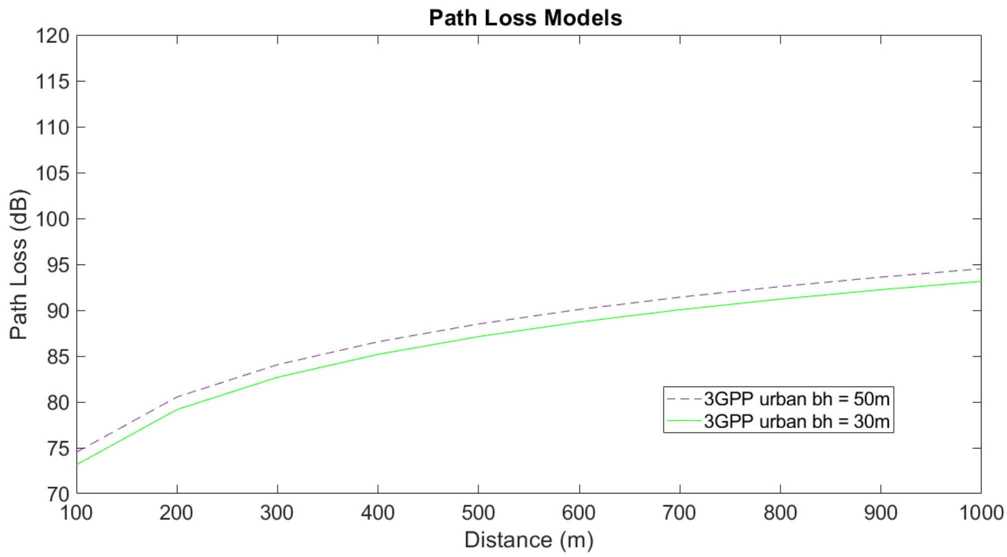

Fig. 4. Path loss performance with different b_h in using the 3GPP model

The comparison between the Okumura-Hata and 3GPP models is shown in Figure 5. In these graphs, the Okumura-Hata model produced the pessimistic results in urban settings, whereas the 3GPP model is the most hopeful at wider distances. The smallest difference between the two models at low distance values is nearly 10 dB, but it rapidly rises to 25 dB at 1 km. This is so that it can be used in a variety of circumstances. The 3GPP model is appropriate for many cellular types.

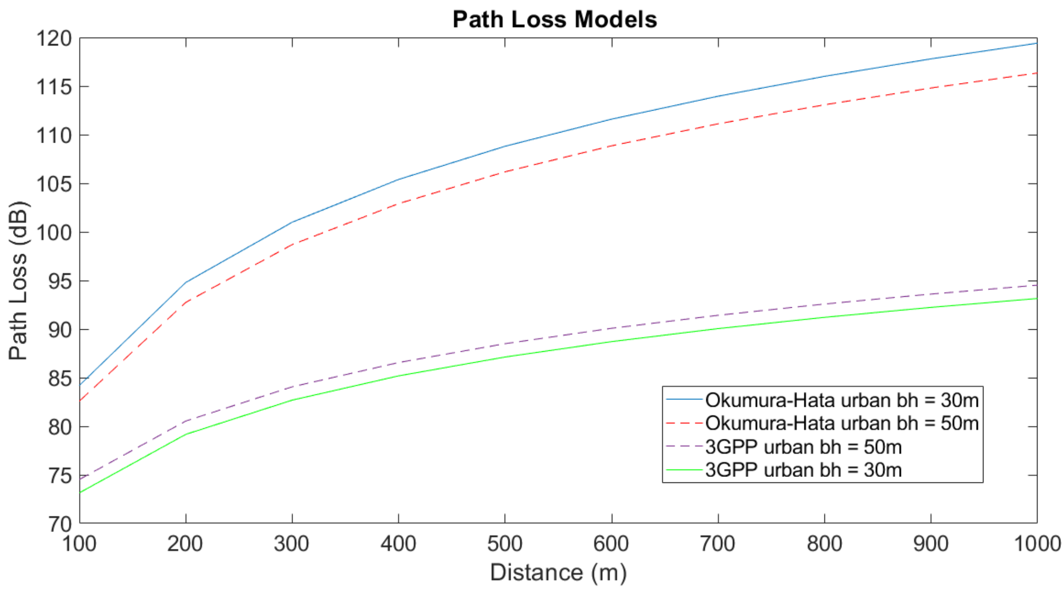

Fig. 5. Path loss performance with different b_h in using Okumura-Hata and 3GPP models

Figure 6 shows that the proposed HybridPath model, which combines the Okumura-Hata and 3GPP formulas, performed better when the base station antenna height (b_h) was 50 m, with an average path loss of 97 dB. In comparison, when b_h was 30 m, the average path loss was 98.5 dB. These results are similar to Okumura-Hata, where the maximum path loss decreases as the distance of b_h increases.

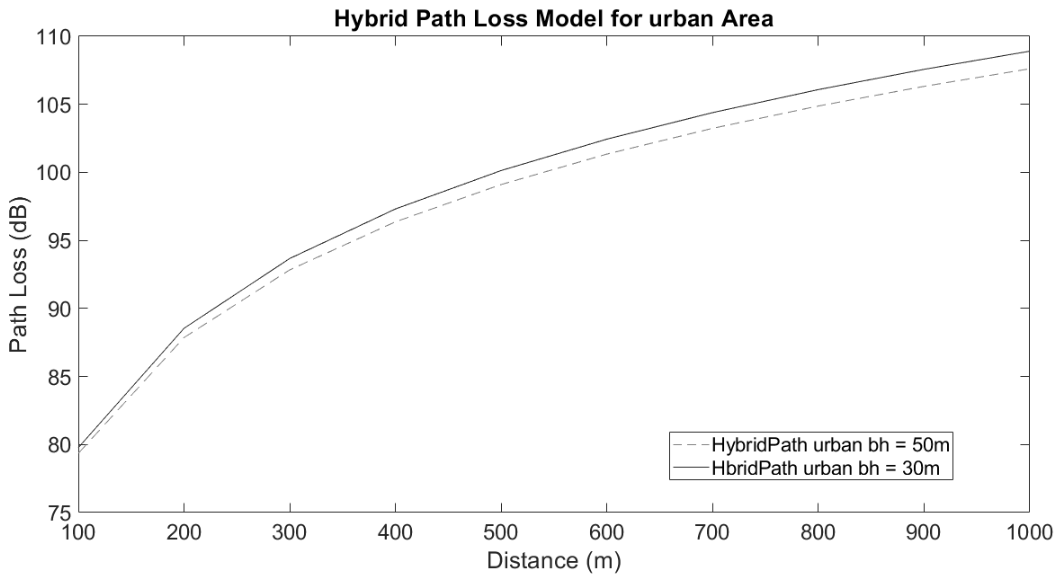

Fig. 6. Path loss performance with different b_h using HybridPath model

Table 6 summarises the average path loss in an urban environment using Okumura-Hata, 3GPP, and proposed HybridPath models. According to the results, it is concluded that in an urban environment, the proposed HybridPath model performed better which is 97 dB and accurately estimated path loss than the Okumura-Hata model which is 104.2 dB at a frequency of 433 MHz with b_h is 50 m. The proposed HybridPath model is considered one of the models proving improvement over the Okumura-Hata propagation model. Thus, this model can provide valuable insights into the accuracy and suitability model for Sigfox in urban environments.

Table 6
The average path loss in urban scenarios using Okumura-Hata, 3GPP, and proposed HybridPath models

Specifications	Okumura-Hata	3GPP	HybridPath
b_h = 30 m	106.6 dB	76.7 dB	98.5 dB
b_h = 50 m	104.2 dB	87.3 dB	97 dB

Figure 7 compares the path loss performance of the proposed HybridPath, Okumura-Hata, and 3GPP propagation models in the urban setting with varying base station antenna heights (b_h). The outcomes show that the 3GPP model performs better than the other models for greater separations between the transmitter and receiver in an urban setting. It always shows the least average path loss. It is crucial to keep in mind that the proposed HybridPath model still has room for development.

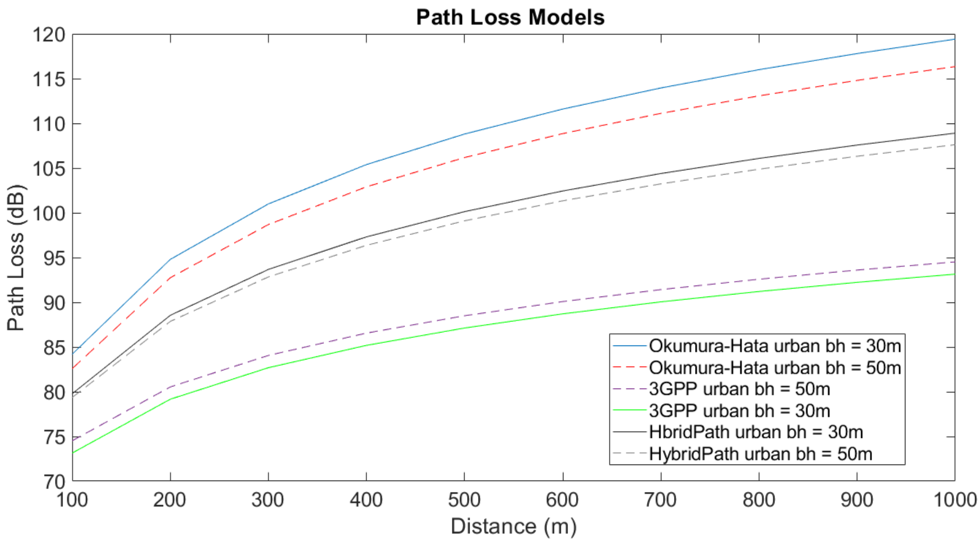

Fig. 7. Path loss performance with different b_h using Okumura-Hata, 3GPP and HybridPath models

The Okumura-Hata and 3GPP models' best features are combined in the proposed HybridPath model. While the 3GPP model fine-tunes the forecasts in accordance with particular circumstances and environments, the Okumura-Hata model integrates accurate topography maps to increase the accuracy of predictions. Due to this combination, the proposed HybridPath model can offer insightful information about the precision and applicability of path loss estimation for Sigfox in urban settings.

6. Conclusions

We explored the performance of the HybridPath propagation path models in Sigfox and proposed them in this study. The outcomes were contrasted with those of other urban propagation models, namely the Okumura Hata and 3GPP. In order to identify the best solutions, the study first compared the path attenuation of the two main LPWAN propagation models (Okumura-Hata and 3GPP models). The HybridPath concept was then suggested as a fresh propagation mechanism for Sigfox technology to use in urban settings.

Based on the findings, it can be concluded that the suggested HybridPath model, by offering a more thorough and precise path loss estimation for Sigfox, performs better than the Okumura-Hata model in urban contexts. The 3GPP model, however, performed better in terms of path loss performance than the other propagation models. Despite this, the suggested HybridPath model still has room for improvement based on the propagation parameters since it was built using the Okumura-Hata and 3GPP models. With additional research, the proposed HybridPath model can be enhanced and expanded to include new varieties of terrains, operation frequencies, and implementation circumstances. Further research and evaluation may be necessary to explore the proposed HybridPath model's performance for Sigfox in urban environments as well as in rural environments.

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