Comparative Performance Analysis of Empirical Propagation Models for LoRaWAN 868MHz in an Urban Scenario

Eugen Harinda, Salaheddin Hosseinzadeh, Hadi Larijani and Ryan M. Gibson,
School of Engineering and Built Environment
Glasgow Caledonian University, Glasgow G4 0BA, UK
E-mail: (Eugen.Harinda, Salaheddin.Hosseinzadeh, H.Larijani, Ryan.Gibson)@gcu.ac.uk

***Abstract*—Empirical propagation models are vital tools for planning and deployment of any wireless communication network as they depend less on terrain data and are faster to execute. In this paper, NS3 is used to simulate radio propagation for Long range wide area network (LoRaWAN) at 868 MHz in an urban environment using the Okumura-Hata model, the COST-231 Hata, and the COST 231 Walfish-Ikegami (COST-WI). LoRaWAN use radio frequency 868 MHz for communication in Europe. The predicted received signal strength values are compared with the real-world measurements taken in the city of Glasgow to analyze the validity and accuracy of the empirical models when used for planning and coverage prediction in LoRaWAN networks. The comparison between models and measurements shows that Okumura-Hata under-estimated the received signal strength in Glasgow city scenario while COST-WI over-estimated the same power. Similarly, the Okumura-Hata model showed higher accurate predictions whereas COST-WI accuracy was the least. The magnitude of mean absolute error indicates how big or small models prediction error can be expected. This study can be used to give an insight into the effectiveness and accuracy of empirical propagation models for evaluation of Internet of Things (IoT) connectivity with LoRaWAN networks in a non-line of sight (NLOS) urban environment.**

Keywords*—*LoRaWAN, Empirical Propagation Models, Received Signal Strength, NS3, Urban Environment

I. Introduction

Empirical propagation models have been a tool for radio performance analysis in research and industry due to the ability to fast-track radio coverage information for network planning. Unlike deterministic models, empirical models do not use terrain data, which requires more time and resources to process. However, the simulation of radio wave propagation using empirical models requires validation of the simulation results using field measurements data. The propagation of radio waves may take place within complex or simple environmental variables which can affect the reception of radio signals. It makes computer simulation and propagation models pretty vital tools for network planning to reduce the uncertainties surrounding the received signal strength falling below the minimum acceptable receiver threshold. Some studies [1]- [2] have used empirical propagation models to evaluate the propagation performance for various wireless communication technologies at certain frequencies. But, little has been done to analyze the same for low-power wide-area networks (LPWANs). In LoRaWAN networks, for instance, most of the efforts have been invested in field measurements [3]–[5].

LPWAN [6] is a low-power wide-area wireless telecommunication network for the provision of long-range and low bit rate communications. This technology can be used for connectivity of *Things* operating sensors on a battery. It is useful to note the difference between LPWAN and the usual wireless WAN (Wide Area Network). While the latter requires an increased power and data rate to connect people and businesses, the former uses low power and data rate ranging from 0.3 Kbps to 50 Kbps for each channel [7]. Like other radio communications, the transmitted signal power undergoes attenuation in the path between the end-devices and gateways, and the magnitude of the signal power reduction largely depends on the transmission environment.

In this paper, the empirical radio propagation models are used in NS3 to simulate radio signals transmission and reception in LoRaWAN at 868 MHz in the city environment. The predicted signal strength received using the three models will be compared and evaluated for validity and accuracy against the measured data. Lora, one of LPWAN technologies operates on LoRaWAN network in the license-free ISM frequency band [8] and has found a wide acceptance in the industry for the Internet of Things connectivity in cities, suburban and rural areas, and is set to become a key enabler of the smart transport solutions.

The main contributions of this paper are:

- Developing COST-WI propagation model into LoRaWAN simulator for NS3.
- Analysis of the real-world data measured in Glasgow city using Lora transceivers and gateways for LoRaWAN propagation performance.
- Critical analysis of three empirical models and the measurements to evaluate the accuracy of models in the city of Glasgow.

This paper is arranged in the following order: Section I introduces Lora, LoRaWAN and empirical models investigated

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in this study. Section II is a summary of the related work and purpose of analyzing models performance. Section III gives details about the field measurements. Section IV explains NS3 simulation set up. Section V presents a comparative performance analysis. Finally, part VI contains the conclusion and prospects for future work.

A. LoRa AND LoRaWAN

Long Range (Lora) [9], a physical layer technology developed by Semtech, is a digital wireless modulation technique used to create long-range radio communications for the IoT connectivity. In order to achieve a considerable communication range and retain the characteristics of having low power like the frequency shift keying (FSK) based modulation systems, Lora employes chirp spread spectrum modulation, a technology that was not yet commercial at the time, but used for decades to obtain long distance communication and withstand interference in the militaries and space communications [9]. Lora modulation uses the spreading factor (SF) parameter, which may be between 7 and 12 to implement varying types of physical layer packets, with different time lengths. The SF allow increased receiver sensitivity due to the flexibility to trade between data rate and coverage, and higher SF produces packets that last longer for increased reliable signal reception compared to low SFs [10]. For detailed information regarding Lora gateway sensitivity for various SF, the frequency band, the power and data rates assignments, readers may refer to [11] and [12]. While Lora definition is at the lowest layer of the system, LoRaWAN definition is at the upper layers.

LoRaWAN [13] describes the communication protocols and the network system architecture. The two features dictate end-devices power usage, the QoS, the system security and the heterogeneous applications within the network [9]. LoRaWAN V1.0 specification [13] published in January 2015 describes LoRaWAN network protocol and the network architecture. It is mainly for low battery-powered applications, in most cases the sensor networks, which may be mobile or at the fixed locations. Three network components, namely; the end-devices, the gateways (or base stations) and the network server are defined in the specification and form a LoRaWAN network. Drawing from the relationship between Lora PHY layer and LoRaWAN protocol, the latter describes the system communication protocol and the network architecture while the former enables long-range communication, making LoRaWAN the network upon which Lora operates for IoT connectivity. Figure 1. shows a typical deployment of LoRaWAN networks in a star-of-stars topology, with different kinds of devices presented. The mode of communication between network equipment is wireless radio when end-devices send messages to one or more Lora gateways, which relay the received signals to the Lora network server through a reliable and high-throughput cable link, and vice-versa.

B. Empirical Radio Propagation Models

Empirical radio propagation models [14] build the ability to predict the received signal strength on the field measurement data and statistical analysis. They enable researchers and network operators of any wireless communication systems to estimate and analyze networks coverage to understand the effects of radio wave propagation parameters and plan for network roll-out before implementation. The propagation effects are heavily site-specific and dependent on the terrain, the operating frequency, the transmitter and receiver antenna height. While there is not a standard way to predict the radio coverage of an area, accurate characterization of the wireless radio channels using fundamental parameters and statistical models is vital for the coverage prediction of radio signals. This study will consider the Okumura-Hata model, the COST-231 Model, and COST-231 Walfish-Ikegami model to predict the minimum received signal strength as a function of distance, the frequency, the height of LoRaWAN gateway and other vital parameters.

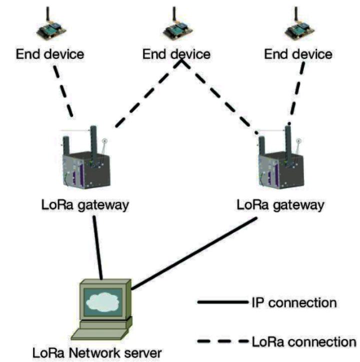

Fig. 1. LoRaWAN Network Architecture

C. Okumura-Hata Model

Unlike the Okumura model [15], which plots the empirical results characterizing the effects of propagation over some parameters in Tokyo, Hata model [16] established mathematical equations that correspond to the results of the Okumura's plots for various parameters. These models made it easy to analyze the propagation effects with computer simulations, where the path loss is calculated based on the factors that are dependent on the frequency range 150-1500 MHz, distance range 1- 20 km and the height of an antenna. The model presents path loss factors and a correction factor that accounts for the effects of propagation loss in the Urban, Sub-Urban and open areas. However, the model's path loss can be considered basic tool when used in an urban area due to assumptions that omit obstructions loss in the city environment. The path loss, P_{Loss} equation for the Hata model in dB for urban areas is given below [15].

$$P_{Loss} = 69.55 + 26.16log_{10}(f) - 13.82log_{10}(h_t) - a(h_r) + (44.9 - 6.55log_{10}(h_t)log_{10}(d) \quad (1)$$

where the correction factor a(h_r) [17] is represented as follows:

$$a(hr) = (1.1log_{10}(f) - 0.7)h_r - (1.56log_{10}(f) - 0.8)dB \quad (2)$$

D. COST-231 Hata Propagation Model

COST 231-Hata-Model [17] is an extension of Hata model to cover a wider range of frequency band. The model's path loss prediction is based on the basic system parameters ranging between 1500-2000 MHz for frequency, 1-20 km for distance, and 1-10 m and 30-200 m for end-device and gateway antenna height respectively. The mathematical formulae for various application of this model are given below [18]:

$$P_{Loss} = 46.3 + 33.9log_{10}(f) - 13.82log_{10}(h_b) - ah_m + (44.9 - 6.55log_{10}(h_b)log_{10}(d) + c_m \quad (3)$$

where, f is operating frequency in MHz, d is distance between the end-device and gateway in km. h_r and h_m are antenna height above the ground in meters for the gateway and end-device respectively. The variable c_m equals 0 dB for both sub-urban and open environments or 3 dB in urban areas. The variable ah_m for urban areas is defined [19]as:

$$ah_m = 3.20(log_{10}(11.75h_r))^2 - 4.97, forf > 400MHz \quad (4)$$

and as below for sub-urban or rural areas:

$$ah_m = (1.1log_{10}f - 0.7)h_r - (1.56log_{10}f - 0.8) \quad (5)$$

E. COST-231 Walfish-Ikegami

Abbreviated as COST-WI [20], the model is a compound of Walfish and Ikegami models, and improves the path loss prediction through the consideration of more data to characterise large and medium-sized urban environments [21], that is, the buildings heights h_{Roof}, the widths of roads w, the separation between buildings b, and the angle θ with respect to the direct radio path. The range of fundamental parameters considered are between 800-2000 MHz for frequency, 0.02-5 km for distance, 1-3 m and 4-50 m for end-device and gateway antenna height respectively. The model makes a difference between the line-of-sight (LOS) and non-line-of-sight (NLOS) [22] and the mathematical formulae for both cases are defined in (6) and (7) below. If there exists a LOS in the street, the path loss is defined as:

$$P_{Loss} = 42.64 + 26log_{10}(d) + 20log_{10}(f) \quad (6)$$

In the case of NLOS, the path loss is the defined as a combination of path loss due to free space L_o, the rooftop to street diffraction and the scatter L_{rts}, and the multiple screen diffraction loss L_{msd}. This path loss totality is mathematically described as follows [21]:

$$P_{Loss} = Lo + Lrts + Lmsd \quad (7)$$

where: L_o, the attenuation due to free space is given as:

$$P_{Loss} = 32.45 + 20log_{10}(d) + 20log_{10}(f) \quad (8)$$

Lrts, the diffraction loss from the rooftop to street is determined as in the following formula:

$$L_{rts} = -16.9 - 10log_{10}(w) + 10log_{10}(f) + 20log_{10}(h_b - h_r) + Lori. \quad (9)$$

Here, w is width of the roads, h_b and h_m are the height of building and end-device mobile station respectively. The street orientation correction factor, Lori [23] is given as:

$$L_{ori} = \begin{cases} -10 + 0.35\alpha & \text{for } 0° < \alpha < 35° \\ 2.5 + 0.0755(\alpha - 35) & \text{for } 35° < \alpha < 55° \\ 4 - 0.0114(\alpha - 55) & \text{for } 55° < \alpha < 90° \end{cases} \quad (10)$$

where α, is the street orientation angle. L_{msd}, the multi-screen loss, represent diffraction loss from multiple obstacles and it is determined by the following mathematical representation:

$$L_{msd} = L_{bsh} + K_a + K_d log_{10}(d) + k_f log(f) - 9log_{10}(s_b) \quad (11)$$

where: the correction factors, L_{bsh} and k_a represent path loss when the gateway is above and below the rooftops respectively. The terms k_d and k_f quantify the diffraction loss as a factor of the distance and frequency, and are defined in [24] as follows:

$$L_{bsh} = \begin{cases} -181log(1 + h_t - h_b) & h_t > h_b \\ 0 & h_t \leq h_b \end{cases} \quad (12)$$

$$k_a = \begin{cases} 54 & h_t > h_b \\ 54 - 0.8(h_t - h_b) & h_t < h_b \text{ and } d_{km} \geq 0.5km \\ 54 - 1.6(h_t - h_b)\text{d} & d_{km} < 0.5km \end{cases} \quad (13)$$

$$k_d = \begin{cases} 18 & h_t > h_b \\ 18 - 15(h_t - h_b)/h_b & h_t \leq h_b \end{cases} \quad (14)$$

$$k_f = -4 + \begin{cases} 0.7(f_{MHz}/925 - 1) & \text{for medium-size city and suburban} \\ 1.5(f_{MHz/925-1}) & \text{for metropolitan centers} \end{cases} \quad (15)$$

II. Related Work

Although LoRaWAN is a recent wireless technology, there is quite a good number of published work that has extensively used the propagation models to show the feasibility of radio coverage, a practice that facilitates network planning, particularly the initial network deployment. A comparative analysis of path loss due to Okumura-Hata and COST-231 models was done in [2] for LTE propagation. This study used frequencies 1000 MHz, 1500 MHz, and 2000 MHz, and changed the gateway antenna height in the different environment. A study [1] about radio propagation models used in LTE cellular network, found that path loss significantly decreased when used COST-231 for path loss prediction in Urban, SubUrban and rural areas. This study changed the end-device antenna height from 30 m to 80 m. Another study [3] for LoRaWAN theoretical coverage that used the topographic data and Okumura-Hata model over different environmental showed that the received signal power was above -130 dBm for the lowest data rate (when SF = 12) and covered 7 km in

Urban and Sub-Urban, and 19 km in rural scenarios. Aloys *et al* [4] found a difference between LoRaWAN specified and the observed RSSI in an urban environment for each SF. A study at Cambridge [25] indeed indicates that overall, COST-231 Hata model over-estimated the path loss in all propagation environments. In [12], there was a constant difference of about 27 dB received signal power between Okumura-Hata and the LoRaWAN measurements. Yuvraj.S [15] compared the Okumura-Hata and COST-231 Hata for prediction of received signal strength at different distances and antenna heights. However, the operating frequency, the environment, and the tools used ware not indicated. In [26], there is a comparative analysis of Okumura-Hata and COST-231 Hata for path loss using frequencies 1500 MHz, 1800 MHz, and 2000 MHz. The study used different transmitter and receiver antenna heights while considering different propagation environments in MATLAB. Randeep S.C *et al* [27] compared the received power and the impact of increasing the transmitter antenna height for Okumura-Hata and COST-231 Hata in Sub-Urban areas, but the study does not establish the tools used, the wireless technology involved and the operating frequency. In [28] real-world indoor measurements for LoRaWAN were taken using Lora module SX1272 transceivers. Another study [29] evaluated LoRaWAN performance using a combination of neural network propagation model and measured data.

A. Purpose of Performance Analysis

Considering the fact that LoRaWAN is a new technology, a number of studies have evaluated the performance of LoRaWAN propagation in Urban areas, based mainly on the field measurements [3], [4], [12], [30], [31]. Planning for any wireless network based on the field measurement data can be a complicated exercise (especially in cities) as it involves more time and resources. There is little work regarding the use of standard propagation models to assess the propagation performance of LoRaWAN networks. This work compares the simulated LoRaWAN network performance at 868 MHz in an urban environment using the Okumura-Hata model, the COST-231 model, and COST-WI. Also, the study uses real-world data measured in the city of Glasgow to comprehend the validity and accuracy of empirical propagation models when used for the planning and prediction of radio-coverage of LoRaWAN networks. This study can be used to give an insight into the effectiveness of empirical propagation models for evaluation of IoT connectivity with LoRaWAN networks at 868 MHz in NLOS urban environment.

III. Field Measurements

Measurements were taken from the city of Glasgow, the United Kingdom and used to validate model's simulation results. These real-world data were collected using a LoRaWAN end-device with a Multitech mDot module, that is regulated by a Raspberry Pi single board computer and a Kerlink gateway equipped with Lora SX1301 [32]. Three LORaWAN gateways were used to receive the packets sent from a mobile LoRaWAN end-device at walking speed from different locations and increasing distance within the city away from the gateways. The transmitting end-device was set to operate at 868 MHz and 14 dBm. While the end-device randomly sent the packets, LoRaWAN gateways at 30 m on top of George More building, Glasgow Caledonian University, 27 m on top of Skypark and 27 m on top of James Weir building at Strathclyde University received and dropped the packets based on the Lora sensitivity. Figure 2. displays the city topology of the locations from where measurements were carried out.

Fig. 2. A Google map showing LoRa Gateways and a LoRa end-device in Glasgow measurement locations

IV. Simulations

The simulation was performed using the NS3, with codes written in C++. The simulator has five major classes: the Node (end-device) class and the Application class to provide methods for handling the representation of communicating devices and system or user application programs to be simulated respectively. The Channel class provides methods for managing communication between the subnet objects and connecting end-devices to subnets while the NetDevice class contains ways which handle connections between end-devices and the channel objects. As the simulated network grows, the Topology helper class automatically establishes some connections between the end-devices, the NetDevices, and the channels.

The simulator consists of Lora PHY layer which represents Lora chips functionality and the way Lora transmissions behave, and the LoRaWAN MAC layer which must act according to official LoRaWAN specifications. Two classes represent two main modules: the LoRaPhy class and LoRaMac class. The extension of these two classes gives other classes that model features of LoRaWAN end-devices and Lora gateway.

To Determine the performance of Lora transmissions, the link model between the end-devices and Lora gateway uses many classes. These are LoraChannel which calls the user preferred

TABLE I. Simulation Parameters

Parameters	Values
Operating frequency	868 MHz
Bandwidth	125 kHz
End-device transmit power	14 dBm
Gateway antenna height	50 m
End-device antenna height	1 m
Distance between tx and rx	2275 m
Building to building distance	74 m
Average buildings height	16 m
Street width	22 m
Buildings separation	8 m
Street orientation angle	45^0
Shadowing correction factor	10 dB

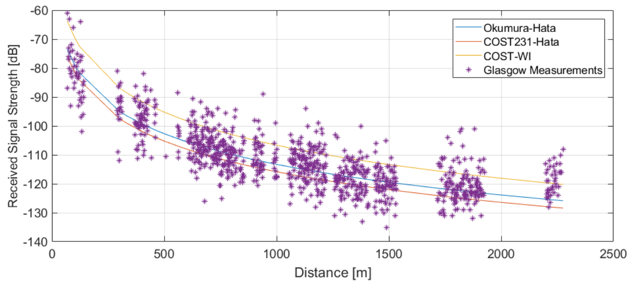

Fig. 3. comparison between the models and LoRa 868MHz measured data

propagation loss models for the calculation of received signal power and GatewayLoraPhy which implements the uplink sensitivity based on an SX1301 data sheet. The class LoraInterferenceHelper executes an application case where multiple transmissions exist. It also uses collision matrix for rejection when received packets have a similar spreading factor at the same reception time. This access resolution mechanism is typical of Aloha systems performance where the collision of two packets means the loss of both. The class PropagationLossModel also implemented at the link level predicts the received signal power based on the propagation models and other parameters including those listed in Table I. As Lora operates in the Unlicensed band, the class LogicalloraChannelHelpert monitors the transmission time and duty cycle at the MAC layer. The simulation trace sources track the lifetime of a packet, the received signal power, distance between the transmitter and receiver, packet size, sending time, whether the packet is correctly received or lost, the operating frequency, spreading factor, if the packet loss is due to interference or absence of receive channels, the data rate, etc. Table I. shows some of the parameters used to configure the end-device and propagation loss model.

V. Comparative Performance Analysis

The prediction accuracy of the propagation models under this study is evaluated using statistical analysis. It is based on the equations for performance comparison between the model's simulation data and received signal power measurements. It is the results of performance comparison between the estimated and measured data that will determine the validity of LoRaWAN 868 MHz simulations using the mentioned empirical propagation models in the city environment. Figure 3. compares the models predicted and measured data for the LoRaWAN 868 MHz in NLOS conditions as a function of the distance, in meters and received signal strength, in dB. The clustered data observed is an indicator that there were packets not received from some measurement locations. This loss of packets can be attributed to signal power attenuation due to high density and a considerable number of tall buildings in the area. The error statistics regarding the mean prediction error, μ_e mean absolute error, $|\Delta y|$ and the standard deviation of the prediction error, σ_e are calculated and used to evaluate the propagation models performance against the real-world data. In this paper, Δ_{yi} denotes the difference between estimated and measured data whereas N indicate the total number of data considered samples. These terms as used for the analysis are calculated in the formulae below:

$$\Delta_{yi} = Power_{estimated} - Power_{measured} \qquad (16)$$

$$\mu_e = \frac{1}{N}\sum_{i=1}^{N}\Delta_{yi} \qquad (17)$$

$$|\Delta y| = \frac{1}{N}\sum_{i=1}^{N}|\Delta_{yi}| \qquad (18)$$

$$\sigma_e = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\Delta_{yi} - \mid \Delta_y \mid)^2} \qquad (19)$$

The radio propagation environment considered for measurements and simulations is NLOS since there is no direct visibility between the LoRaWAN end-device and LoRaWAN gateways in the measured locations. Table 2. indicates the statistical error performance metrics calculated in equations (17-19) for the measured and models predicted values in the NLOS locations. As the mean prediction errors are determined based on the difference between predictions and measurements, a significant mean positive or negative value means models over-estimate or under-estimates the received signal power. Mean absolute error is used to measure the accuracy of models prediction. It's size; the big or small value indicates the expected average magnitude of the prediction error from the model predictions. The mean prediction error shows that while both the Okumura-Hata and COST-231 Hata propagation models under-estimated the received signal power, COST-WI model over-estimated the same power for LoRaWAN networks in Glasgow city. It can be noted from Fig 2. that Okumura-Hata model has the highest accuracy ($|\Delta y|$ = 5.564 and σ_e = 9.158) while COST-WI is the lowest accurate ($|\Delta y|$ = 7.413 and σ_e = 7.454). One aspect of COST-WI prediction error may be due to a considerable portion of the river Clyde which is open and water conductivity which affected the reception distance [33]. It is an experimental study done on three large rivers, that is, Illinois, Mississippi, and Skeena river.

VI. Conclusion and Future Work

LoRaWAN operating at 868 MHz was simulated in NS3 to predict the received signal strength using Okumura-Hata, COST-231 Hata and COST-WI empirical propagation models in the city of Glasgow, the UK. Measurements obtained in this city were compared against models predictions to account for the accuracy of propagation models when used for network planning of LoRaWAN networks in an urban environment. The comparison results show that Okumura-Hata and COST-231 Hata under-estimated the received signal strength in the

TABLE II. Statistical Error Performance Metrics

Error parameters	Okumura-Hata	COST-231	COST-W.I
μ_e	-0.366	-2.915	6.484
$\|\Delta y\|$	5.564	6.131	7.413
σ_e	9.158	11.425	7.454

city of Glasgow while COST-WI over-estimated the signal power received at LoRaWAN gateways. The Okumura-Hata model shows higher prediction accuracy whereas COST-WI is the least accurate in this city environment. The number of simulated predictions and the collected measurements is relatively not sufficient in terms of volume to establish a firm conclusion. Further investigation of COST-WI prediction accuracy for increased simulation and measurement coverage is required. It can help to ascertain if the model's over-prediction possess an advantage over the other two used models given that the model's design and official use is for an urban environment. Expanding models used in this paper to accurately model the actual measurements taken and using advanced machine learning methods is the subject of future research work.

References

[1] N. Shabbir, M. T. Sadiq, H. Kashif, and R. Ullah, "Comparison of radio propagation models for long term evolution (lte) network," *arXiv preprint arXiv:1110.1519*, 2011.

[2] N. Nkordeh, A. Atayero, F. Idachaba, and O. Oni, "Lte network planning using the hata-okumura and the cost-231 hata pathloss models," 2014.

[3] R. Sanchez-Iborra, J. Sanchez-Gomez, J. Ballesta-Viñas, M.-D. Cano, and A. F. Skarmeta, "Performance evaluation of lora considering scenario conditions," *Sensors*, vol. 18, no. 3, p. 772, 2018.

[4] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A study of lora: Long range & low power networks for the internet of things," *Sensors*, vol. 16, no. 9, p. 1466, 2016.

[5] S. Hosseinzadeh, H. Larijani, K. Curtis, A. Wixted, and A. Amini, "Empirical propagation performance evaluation of lora for indoor environment," in *Industrial Informatics (INDIN), 2017 IEEE 15th International Conference on*. IEEE, 2017, pp. 26–31.

[6] D. Ismail, M. Rahman, and A. Saifullah, "Low-power wide-area networks: opportunities, challenges, and directions," in *Proceedings of the Workshop Program of the 19th International Conference on Distributed Computing and Networking*. ACM, 2018, p. 8.

[7] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of lpwan technologies for large-scale iot deployment," *ICT Express*, 2018.

[8] M. Luvisotto, F. Tramarin, L. Vangelista, and S. Vitturi, "On the use of lorawan for indoor industrial iot applications," *Wireless Communications and Mobile Computing*, vol. 2018, 2018.

[9] LoRa®Alliance, "A technical overview of LoRa® and LoRaWAN™," https://lora-alliance.org/sites/default/files/2018-04/what-is-lorawan.pdf/, 2015, [Online; accessed 25-September-2018].

[10] F. Van den Abeele, J. Haxhibeqiri, I. Moerman, and J. Hoebeke, "Scalability analysis of large-scale lorawan networks in ns-3," *IEEE Internet of Things Journal*, vol. 4, no. 6, pp. 2186–2198, 2017.

[11] D. Magrin, M. Centenaro, and L. Vangelista, "Performance evaluation of lora networks in a smart city scenario," in *Communications (ICC), 2017 IEEE International Conference On*. IEEE, 2017, pp. 1–7.

[12] L. Feltrin, C. Buratti, E. Vinciarelli, R. De Bonis, and R. Verdone, "Lorawan: Evaluation of link-and system-level performance," *IEEE Internet of Things Journal*, 2018.

[13] T. E. T. K. I. O. N. Sornin (Semtech), M. Luis (Semtech), "Lorawan™ specification," *LoRaWAN™ Specification v1.1 — LoRa Alliance™*, vol. 2015, 2015.

[14] S. Faruque, *Radio frequency propagation made easy*. Springer, 2014.

[15] Y. Singh, "Comparison of okumura, hata and cost-231 models on the basis of path loss and signal strength," *International journal of computer applications*, vol. 59, no. 11, 2012.

[16] I. Joseph and C. Konyeha, "Urban area path loss propagation prediction and optimisation using hata model at 800mhz," *IOSR Journal of Applied Physics (IOSR-JAP)*, vol. 3, no. 4, pp. 8–18, 2013.

[17] J. Milanovic, S. Rimac-Drlje, and K. Bejuk, "Comparison of propagation models accuracy for wimax on 3.5 ghz," in *Electronics, Circuits and Systems, 2007. ICECS 2007. 14th IEEE International Conference on*. IEEE, 2007, pp. 111–114.

[18] F. J. Oluwole and O. Y. Olajide, "Radio frequency propagation mechanisms and empirical models for hilly areas," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 3, no. 3, pp. 372–376, 2013.

[19] J. Milanović, S. Rimac-Drlje, and I. Majerski, "Radio wave propagation mechanisms and empirical models for fixed wireless access systems," *Tehnički vjesnik*, vol. 17, no. 1, pp. 43–53, 2010.

[20] K. Hari, D. Baum, A. Rustako, R. Roman, and D. Trinkwon, "Channel models for fixed wireless applications," *IEEE 802.16 Broadband wireless access working group*, 2003.

[21] J. Milanović, G. Šimac, and K. Mazor, "Performance analysis of empirical propagation model for long term evaluation (lte) network," in *Smart Systems and Technologies (SST), International Conference on*. IEEE, 2016, pp. 69–74.

[22] R. Jain, "Channel models: A tutorial," in *WiMAX forum AATG*, 2007, pp. 1–6.

[23] S. Ranvier, "Path loss models," *Helsinki University of Technology*, 2004.

[24] L. M. Correia, "A view of the cost 231-bertoni-ikegami model," in *Antennas and Propagation, 2009. EuCAP 2009. 3rd European Conference on*. IEEE, 2009, pp. 1681–1685.

[25] V. Abhayawardhana, I. Wassell, D. Crosby, M. Sellars, and M. Brown, "Comparison of empirical propagation path loss models for fixed wireless access systems," in *Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st*, vol. 1. IEEE, 2005, pp. 73–77.

[26] E. Khatun and S. B. M. Era, "Comparative analysis of okumura-hata and cost 231 path loss models for wireless mobile communications," Ph.D. dissertation, East West University, 2017.

[27] R. S. Chib, Y. Singh, S. Singh, R. Gupta, and S. Chib, "Performance & evaluation of propagation models for sub-urban areas," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 4, no. 2, 2015.

[28] S. Hosseinzadeh, H. Larijani, and K. Curtis, "An enhanced modified multi wall propagation model," in *Global Internet of Things Summit (GIoTS), 2017*. IEEE, 2017, pp. 1–4.

[29] S. Hosseinzadeh, M. Almoathen, H. Larijani, and K. Curtis, "A neural network propagation model for lorawan and critical analysis with real-world measurements," *Big Data and Cognitive Computing*, vol. 1, no. 1, p. 7, 2017.

[30] A. J. Wixted, P. Kinnaird, H. Larijani, A. Tait, A. Ahmadinia, and N. Strachan, "Evaluation of lora and lorawan for wireless sensor networks," in *SENSORS, 2016 IEEE*. IEEE, 2016, pp. 1–3.

[31] J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hanninen, and M. Pettissalo, "On the coverage of lpwans: range evaluation and channel attenuation model for lora technology," in *ITS Telecommunications (ITST), 2015 14th International Conference on*. IEEE, 2015, pp. 55–59.

[32] LoRa®Alliance, "WIRELESS and SENSING PRODUCTS Datasheet," https://www.semtech.com/uploads/documents/sx1301.pdf, 2017, [Online; accessed 25-September-2018].

[33] L. M. Peters, U. G. Reinhardt, and M. A. Pegg, "Factors influencing radio wave transmission and reception: use of radiotelemetry in large river systems," *North American Journal of Fisheries Management*, vol. 28, no. 1, pp. 301–307, 2008.