Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 9 Issue 11, November - 2022

Analysis Of Lora-Based Iot Sensor Node Required Transmitter Power Variation With Communication Range And Bit Error Performance Configurations

Kufre M. Udofia
Department of Electrical/Electronic and Computer Engineering,
University of Uyo, Nigeria
kmudofia@uniuyo.edu.ng

Abstract— In this paper, analysis of LoRa-Based IoT sensor node required transmitter power variation with communication range and bit error performance configurations is presented. The operating signal to noise ratio, SNRopr and link margin were first determined for different BER after which Egli propagation loss model was used with different communication ranges to compute the required transmitter power for different spreading factor settings of the LoRa transceiver. The results show that for SF of 7, the operating signal to noise ratio, SNRopr = -3.52935 dBm whereas the required signal to noise ratio for the SF of 7 is -7.5 dBm , hence, the link margin is 3.97 dBm. The results also show that for the BER = 1E-15, the operating signal to noise ratio, SNRopr and link margin decrease with SF, with SF of 12 having the lowest value. The results show that SF of 7 has the highest required transmitter power for each communication range while SF=12 has the least required transmitter power. Also, LoRa transceiver datasheet indicates that the maximum transmitter power permitted is 20 dBm. Based on the datasheet specifications, the results show that with BER = 1E-15, the SF = 7 LoRa transceiver cannot exceed 6.1 km communication range. Also, f while the SF =12 LoRa transceiver cannot exceed 13.5 km communication range with the given propagation loss. In all, the results show that the maximum communication range for BER =1 E -15 increases exponentially with the spreading factor, from a value of 6.093 km at SF = 7 to a value of 13.461 km at SF = 12.

Keywords— LoRaWAN, Transceiver, Required Transmitter, Communication Range, Bit Error

1. Introduction

The wireless communication and sensor technologies are greatly revolutionising the world with their support for Internet of things (IoT), as well as smart city applications [1,2,3,4,5]. This has become more prominent as many applications seek for timely or even real-time delivery of solutions, as well as location aware capabilities. In such cases, sensors are deployed to any location of interest to monitor the environmental parameters and communicate same to network gateways and servers where they are used for requisite operations [6,7,8, 9,10, 11,12,13,14, 15,15,17,18]. Designing such wireless networks that will connect the distributed wireless sensor nodes deployed even to remotes areas require adequate knowledge of different parameters that pertains to the environment, the sensor nodes and the other network link components [19,20,21, 22,23,24, 25,26,27, 28,29, 30,31, 32].

As regards the wireless signal propagation environment, issues of propagation loss must be considered such as free space path loss, diffraction loss, multipath loss, atmospheric loss and other losses that degrade the signal strength [33,34,35,36, 37,38,39, 40,41,42,43,44]. In any case, in order to accommodate those losses, the sensor nodes must have adequate transmitter power. However, sensor nodes are constrained in terms of resource including power, memory capacity, antenna gain, and processing capabilities. As such, especially for battery-powered sensor nodes, the lifespan of the sensor is highly dependent on the provisions that are made during the design of the network [45,46,47,48,49,50,51]. Accordingly, in this paper, the procedure that can be used at design time to determine the appropriate transmitter power required by a sensor node for different communication ranges and required bit error rate performance is presented. The requisite mathematical expressions for computing the relevant parameters are presented along with numerical examples based on LoRa-based IoT sensor node. The LoRa technology adopts Chirp Spread Spectrum (CSS) modulation scheme and operates in different chirp spreading factors [52,53,54,55,56,57]. As such, the BER used in the analysis is based on the LoRa CSS modulation scheme and the analysis is conducted for the different chirp spreading factors for a LoRa-based sensor node operating in the 125 kHz bandwidth.

2 Methodology

The general link budget expressions for received signal power (P_{tx}) with respect to pathloss and in terms of link margin (LM) are given as follows;

$$P_{rx} = P_{tx} + (G_{tx} + G_{rx}) - L_{Path} \quad (1)$$

$$P_{rx} = LM + S_{LoRa} \quad (2)$$

Where P_{tx} is the transmitter power, G_{tx} is the gain of the transmitter antenna, G_{rx} is the gain of the receiver antenna and S_{LoRa} is the LoRa transceiver sensitivity. The S_{LoRa} is defined in terms of the bandwidth (BW), the required signal to noise ratio (SNR_{RQD}) and the noise figure (NF) as follows;

$$S_{LoRa} = -174 + 10\log_{10}(BW) + NF + SNR_{RQD} \quad (3)$$

Hence,

$$P_{tx} = P_{rx} - (G_{tx} + G_{rx}) + L_{Path} \quad (4)$$

$$P_{tx} = LM + S_{LoRa} - (G_{tx} + G_{rx}) + L_{Path} \quad (5)$$

In this paper, the Egli model is used to determine the pathloss, which is expressed as [58,59,60,61];

$$L_{Path} = P_{LEGL\_dBm} = G_{tx} + G_{rx} + 20Log\left(\frac{(h_t)(h_r)}{(d)^2}\right) + 20Log\left(\frac{40}{f}\right) \quad (6)$$

Where h_t and h_r the transmitter antenna height and receiver antenna height respectively, d represents the communication path length, and f is the frequency. For any given Bit Error Rate (BER) the operating signal to noise ratio, SNR_{OPR} can be determined as follows;

$$BER = \frac{1}{2}\left[1 - erf\left(\left(\frac{\log_{12}(SF)}{\sqrt{2}}\right)\left({E_b}/{N_O}\right)\right)\right] \quad (7)$$

$${E_b}/{N_O} = \frac{erfinv(1-2(BER))}{\left(\frac{\log_{12}(SF)}{\sqrt{2}}\right)} \quad (8)$$

$$SNR_{OPR} = 10\,log\left(\frac{E_b}{N_0}\right) + 10\log_{10}(SF) + 10\log_{10}\left(\frac{4}{4+n}\right) - 10\log_{10}(2^{SF}) \quad (9)$$

$$SNR_{OPR} = 10\log\left(\frac{erfinv(1-2(BER))}{\left(\frac{\log_{12}(SF)}{\sqrt{2}}\right)}\right) + 10\log_{10}(SF) + 10\log_{10}\left(\frac{4}{4+n}\right) - 10\log_{10}(2^{SF}) \quad (10)$$

The link margin, LM is given as;

$$LM = SNR_{OPR} - SNR_{RQD} \quad (11)$$

$$P_{tx} = SNR_{OPR} - SNR_{RQD} + S_{LoRa} - (G_{tx} + G_{rx}) + L_{Path} \quad (12)$$

3. Results and discussions

The operating signal to noise ratio, SNRopr and link margin were first determined for different BER. Next, the required transmitter power was computed for different communication ranges. The results for the operating signal to noise ratio, SNRopr and link margin for BER = 1E-15 and spreading factors which ranges from 7 to 12 are presented in Table 1 as well as in Figure 1. The results presented in Table 1 and Figure 1 show that for SF of 7, the operating signal to noise ratio, SNRopr = -3.52935 dBm whereas the required signal to noise ratio for the SF of 7 is -7.5 dBm , hence, the link margin is 3.97 dBm. This means that the operating signal to noise ratio is 3.97 dBm above the minimum required noise ratio for the SF of 7. The results also show that for the BER = 1E-15, the operating signal to noise ratio, SNRopr and link margin decrease with SF, with SF of 12 having the lowest value.

Table 2 The operating signal to noise ratio, SNRopr and link margin for BER =1E-15 and spreading factors which ranges from 7 to 12

SF	Operating SNRopr (dBm) for BER =1E-15	Link Margin (dBm) for BER =1E-15
7	-3.52935	3.97
8	-6.24797	3.75
9	-8.98602	3.51
10	-11.7422	3.26
11	-14.5147	2.99
12	-17.3019	2.70

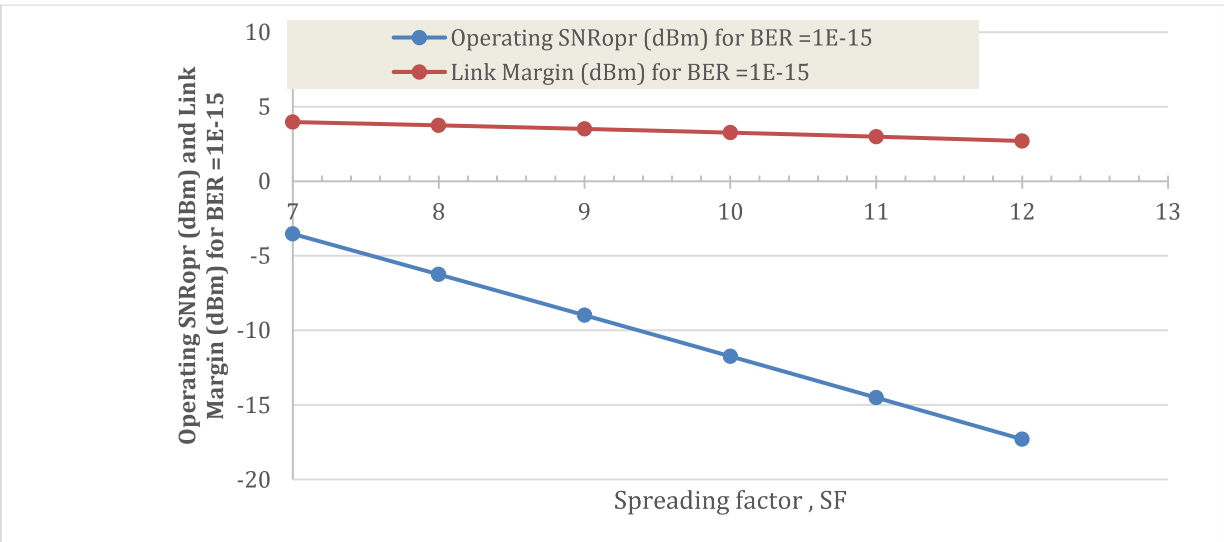

Figure 1 The operating signal to noise ratio, SNRopr and link margin for BER =1E-15 and spreading factors which ranges from 7 to 12

The Egli propagation loss model was used in computing the required transmitter power for BER = 1E-15 with communication range from 2 km to 12 km and the results are given in Table 2 and Figure 2. The results show that SF of 7 has the highest required transmitter power for each communication range while SF=12 has the least required transmitter power. According to the datasheet of the LoRa transceiver, the maximum transmitter power permitted is 20 dBm. Hence, for the SF =7 , the transmitter power for different communication range, d is shown in Figure 3. The results show that with BER = 1E-15 , the SF = 7 LoRa transceiver cannot exceed 6.1 km communication range. Also, for the SF =12, the transmitter power for different communication range, d is shown in Figure 4. The results show that with BER = 1E-15, the SF = 12 LoRa transceiver cannot exceed 13.5 km communication range with the given propagation loss.

Table 2 The results of the required transmitter power for BER = 1E-15 with communication range from 2 km to 12 km

SF	Required Transmitter Power (dBm) for d = 2 km and BER =1E-15	Required Transmitter Power (dBm) for d = 3 km km and BER =1E-15	Required Transmitter Power (dBm) for d = 6 km km and BER =1E-15	Required Transmitter Power (dBm) for d = 9 km km and BER =1E-15	Required Transmitter Power (dBm) for d = 12 km km and BER =1E-15
7	0.6	7.7	19.7	26.8	31.8
8	-2.1	5.0	17.0	24.1	29.1
9	-4.8	2.2	14.3	21.3	26.3
10	-7.6	-0.5	11.5	18.6	23.6
11	-10.3	-3.3	8.7	15.8	20.8
12	-13.1	-6.1	6.0	13.0	18.0

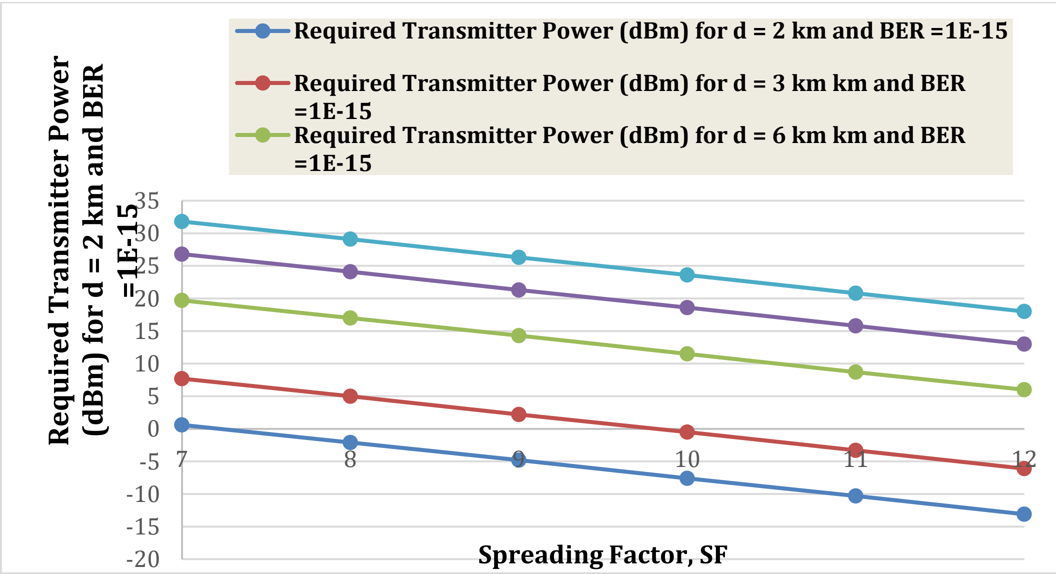

Figure 2 The required transmitter power for BER = 1E-15 with communication range from 2 km to 12 km

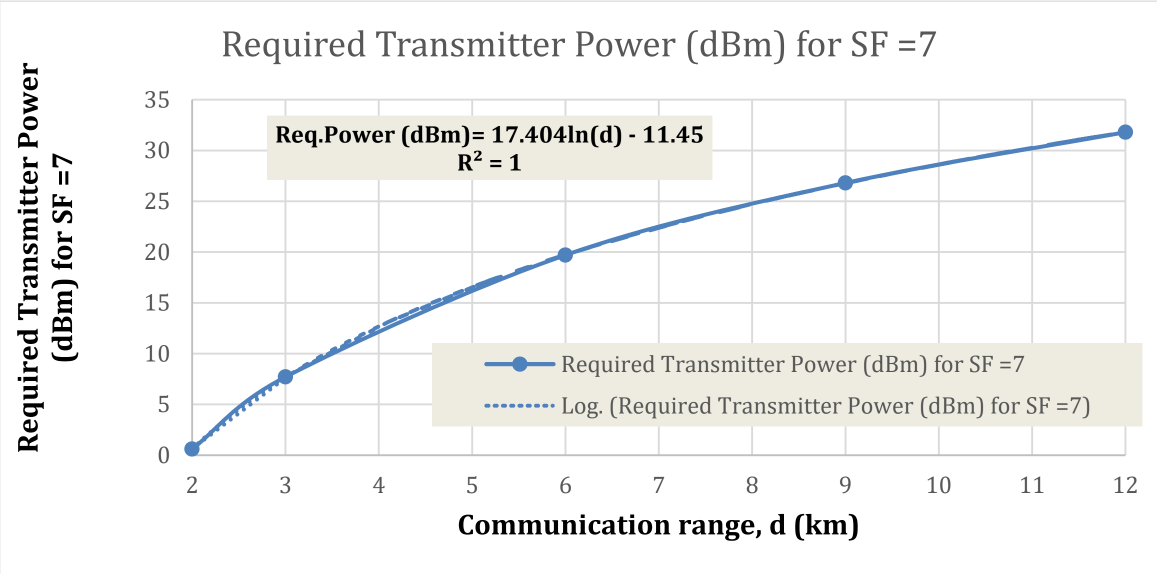

Figure 3 The transmitter power for different communication range, d for SF =7

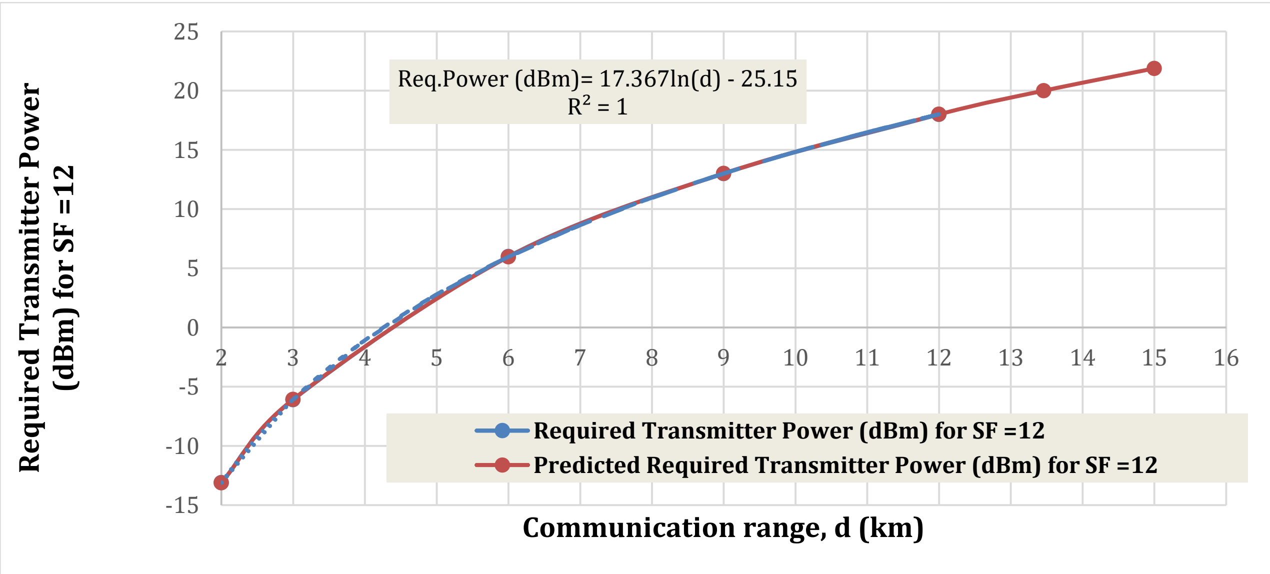

Figure 4 The transmitter power for different communication range, d for SF =12

Similarly, the results for the operating signal to noise ratio, SNRopr and link margin for BER = 1E-12 and spreading factors ranging from 7 to 12 are given in Table 3 while the required transmitter power for BER = 1E-152 with communication range from 2 km to 12 km are given in Table 4. The results show that for SF of 7, the operating signal to noise ratio, SNRopr = -4.05602 dBm whereas the required signal to noise ratio for the SF of 7 is -7.5 , hence, the link margin is 3.44 dBm. This means that the operating signal to noise ratio is 3.44 dBm above the minimum required noise ratio for the SF of 7. The results also show that for the BER = 1E-12, the operating signal to noise ratio, SNRopr and link margin decrease with SF, with SF of 12 having the lowest value.

Table 3 The results for the operating signal to noise ratio, SNRopr and link margin for BER = 1E-12 and spreading factors ranging from 7 to 12

SF	Operating SNRopr (dBm) for BER =1E-12	Link Margin (dBm) for BER =1E-12
7	-4.05602	3.44
8	-6.77464	3.23

9	-9.51269	2.99
10	-12.2688	2.73
11	-15.0413	2.46
12	-17.8286	2.17

Table 4 The results for the required transmitter power for BER = 1E-152 with communication range from 2 km to 12 km

SF	Required Transmitter Power (dBm) for d = 2 km and BER =1E-12	Required Transmitter Power (dBm) for d = 3 km km and BER =1E-12	Required Transmitter Power (dBm) for d = 6 km km and BER =1E-12	Required Transmitter Power (dBm) for d = 9 km km and BER =1E-12	Required Transmitter Power (dBm) for d = 12 km km and BER =1E-12
7	0.1	7.2	19.2	26.2	31.2
8	-2.6	4.4	16.5	23.5	28.5
9	-5.3	1.7	13.7	20.8	25.8
10	-8.1	-1.0	11.0	18.0	23.0
11	-10.9	-3.8	8.2	15.3	20.3
12	-13.7	-6.6	5.4	12.5	17.5

In addition, the graph for the operating signal to noise ratio, SNRopr for BER = 1E-6, 1E-12, and 1E-15 and spreading factors which ranges from 7 to 12 are presented in Figure 5. The results presented in Figure 5 show that the BER =1E-15 has the highest range of values for SNRopr while the BER =1E-6 has the lowest range of values for SNRopr. Again, the graph for the link margin for BER = 1E-6, 1E-12, and 1E-15 and spreading factors ranges from 7 to 12 are presented in Figure 6. The results presented in Figure 6 show that the BER =1E-15 has the highest range of values for link margin while the BER =1E-6 has the lowest range of values for link margin. Furthermore, the graph for the required transmitter power for BER = 1E-6, 1E-12, and 1E-15 and spreading factors ranging from 7 and 10 are given in Figure 7. The results show that the required transmitter power increases with decrease in BER and also the required transmitter power for SF =7 is higher than that for SF = 10.

Further analysis of the maximum communication range of the LoRa transceiver for BER =1 E -15 for SF of 7 to 12 gave the results shown in Table 5 as well as in Figure 8. The results presented in Figure 8 indicates that the maximum communication range, dmax (km) for BER =1 E -15 increases exponentially with the spreading factor, from a value of 6.093 km at SF = 7 to a value of 13.461 km at SF = 12. The model for estimating the maximum communication range, dmax (km) for BER =1 E -15 is obtained from Figure 8 as;

$$\mathbf{dmax = 2.0022e^{0.1587(SF}} \quad \mathbf{(13)}$$

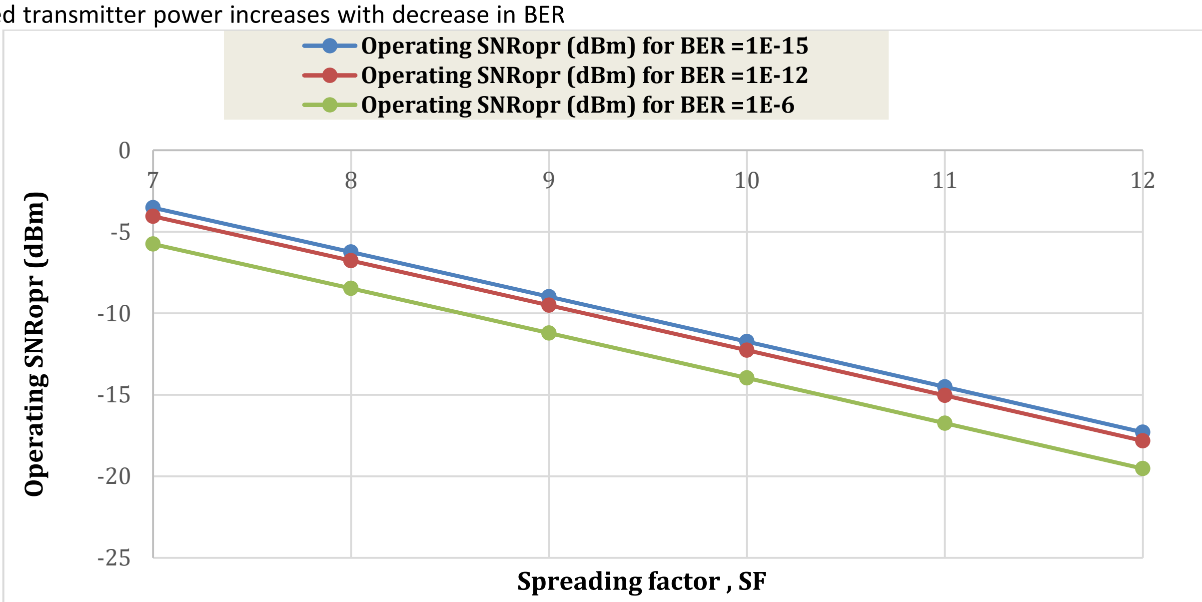

Figure 5 , The graph for the operating signal to noise ratio, SNRopr for BER = 1E-6, 1E-12, and 1E-15 and spreading factors ranging from 7 to 12

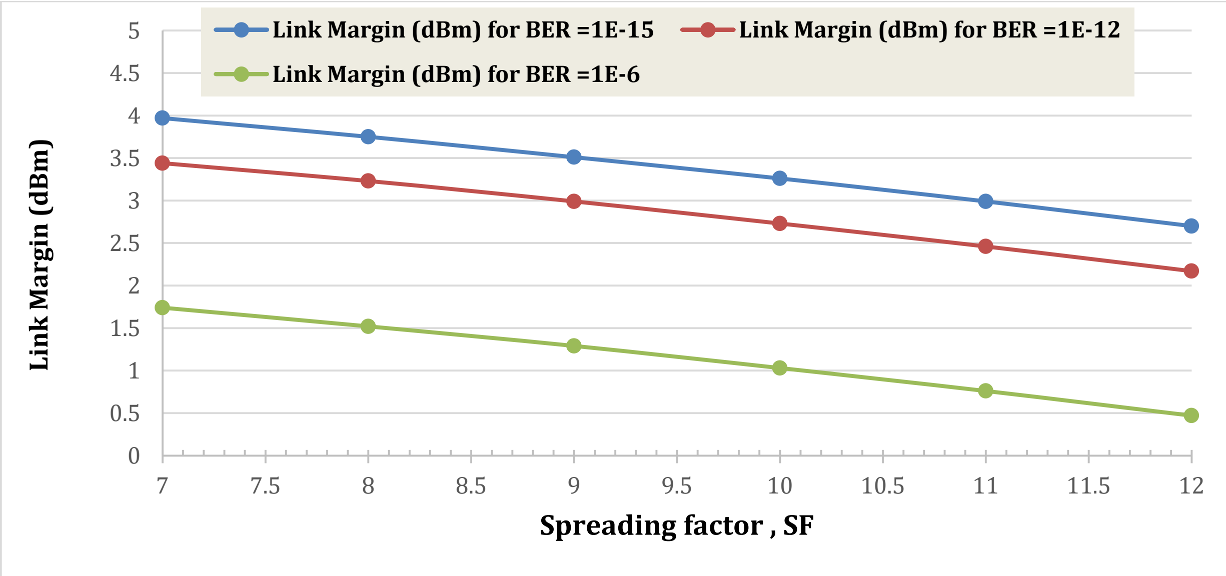

Figure 6 The graph for the link margin for BER = 1E-6, 1E-12, and 1E-15 and spreading factors ranging from 7 to 12

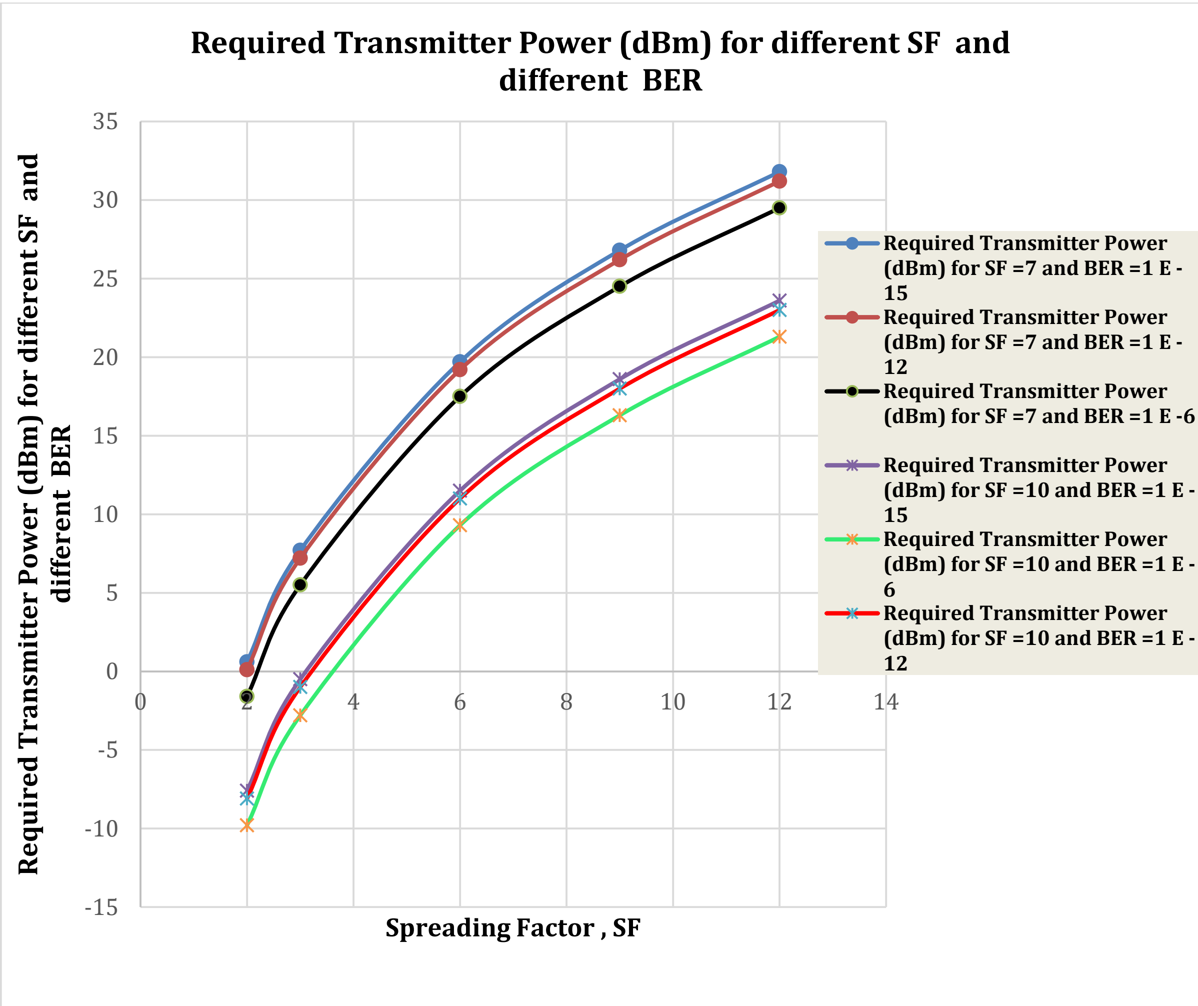

Figure 7 The graph for the required transmitter power for BER = 1E-6, 1E-12, and 1E-15 and spreading factors ranging from 7 and 10

Table 5 The maximum communication range , dmax (km) for BER =1 E -15 for SF of 7 to 12

SF	Maximum Communication Range , dmax (km) for BER =1 E -15
7	6.093
8	7.115
9	8.346
10	9.76
11	11.473
12	13.461

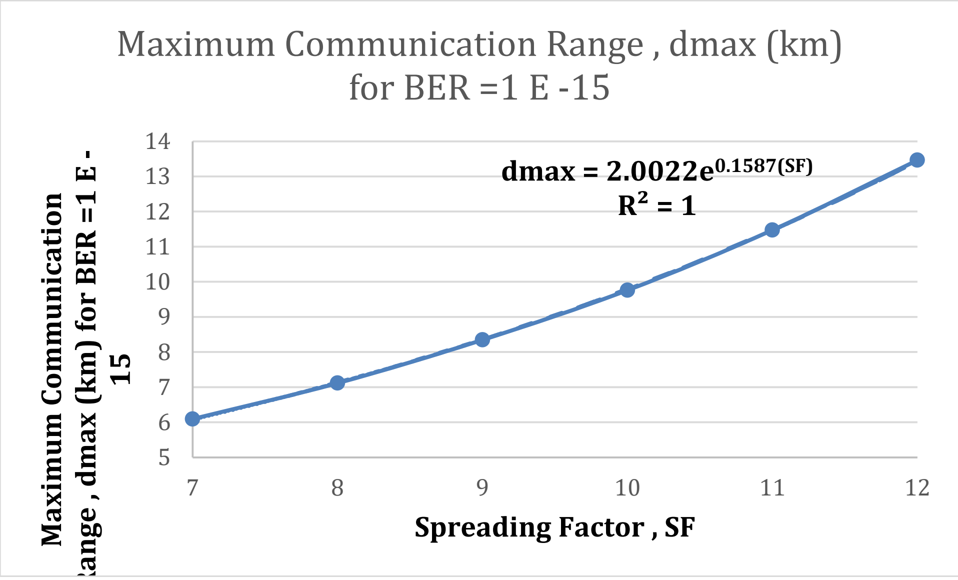

Figure 8 The maximum communication range, dmax (km) for BER =1 E -15 for SF of 7 to 12

4. Conclusion

An approach for assessing the required transmitter power for LoRa transceiver used in wireless sensor network is presented. The study determined the required transmitter power for the LoRa transceiver for different bit error rare (BER) and different communication ranges. The analysis was repeated for six different spreading factor settings of the LoRa transceiver. The Egli propagation loss model was used for the computation of the propagation loss for any given communication range. The BER value was first used to determine the operating signal to noise ratio and then the link margin. Thereafter, the Eglis model was employed to determine the the propagation loss for the different communication ranges considered in the study. Eventually, for each communication range the required transmitted power for the LoRa transceiver was determined. Also, the maximum communication range that can be realised with any given s factor setting of the LoRa transceiver was also determined. In all, the required transmitter power increases as BER decreases. Also, the required transmitter power increases as BER SF decreases.

References

1. Jin, J., Gubbi, J., Marusic, S., & Palaniswami, M. (2014). An information framework for creating a smart city through internet of things. *IEEE Internet of Things journal*, *1*(2), 112-121.
2. Shahanas, K. M., & Sivakumar, P. B. (2016). Framework for a smart water management system in the context of smart city initiatives in India. *Procedia Computer Science*, *92*, 142-147.
3. Akpakwu, G. A., Silva, B. J., Hancke, G. P., & Abu-Mahfouz, A. M. (2017). A survey on 5G networks for the Internet of Things: Communication technologies and challenges. *IEEE access*, *6*, 3619-3647.
4. Kalu, C., Ozuomba, Simeon. & Udofia, K. (2015). Web-based map mashup application for participatory wireless network signal strength mapping and customer support services. *European Journal of Engineering and Technology, 3 (8)*, 30-43.
5. Solanki, A., & Nayyar, A. (2019). Green internet of things (G-IoT): ICT technologies, principles, applications, projects, and challenges. In *Handbook of research on big data and the IoT* (pp. 379-405). IGI Global.
6. Ozuomba Simeon (2019) Evaluation Of Optimal Transmission Range Of Wireless Signal On Different Terrains Based On Ericsson Path Loss Model Vol. 3 Issue 12, December – 2019 Available at : http://www.scitechpub.org/wp-content/uploads/2021/03/SCITECHP420157.pdf
7. Othman, M. F., & Shazali, K. (2012). Wireless sensor network applications: A study in environment monitoring system. *Procedia Engineering*, *41*, 1204-1210.
8. Samuel, Wali, **Simeon Ozuomba,** and Philip M. Asuquo **(2019).** EVALUATION OF WIRELESS

SENSOR NETWORK CLUSTER HEAD SELECTION FOR DIFFERENT PROPAGATION ENVIRONMENTS BASED ON LEE PATH LOSS MODEL AND K-MEANS ALGORITHM. EVALUATION, 3(11). ***Science and Technology Publishing*** *(SCI & TECH) Vol. 3 Issue 11, November - 2019*

9. Awan, K. M., Shah, P. A., Iqbal, K., Gillani, S., Ahmad, W., & Nam, Y. (2019). Underwater wireless sensor networks: A review of recent issues and challenges. *Wireless Communications and Mobile Computing*, *2019*.

10. Njoku, Felix A., **Ozuomba Simeon**, and Fina Otosi Faithpraise **(2019).** Development Of Fuzzy Inference System (FIS) For Detection Of Outliers In Data Streams Of Wireless Sensor Networks. ***International Multilingual Journal of Science and Technology*** *(IMJST) Vol. 4 Issue 10, October - 2019*

11. Mois, G., Folea, S., & Sanislav, T. (2017). Analysis of three IoT-based wireless sensors for environmental monitoring. *IEEE Transactions on Instrumentation and Measurement*, *66*(8), 2056-2064.

12. Simeon**, Ozuomba. (2020).** "Analysis Of Effective Transmission Range Based On Hata Model For Wireless Sensor Networks In The C-Band And Ku-Band." ***Journal of Multidisciplinary Engineering Science and Technology*** *(JMEST) Vol. 7 Issue 12, December - 2020*

13. Aslan, Y. E., Korpeoglu, I., & Ulusoy, Ö. (2012). A framework for use of wireless sensor networks in forest fire detection and monitoring. *Computers, Environment and Urban Systems*, *36*(6), 614-625.

14. Samuel, W., **Ozuomba, Simeon,** & Constance, K**. (2019).** SELF-ORGANIZING MAP (SOM) CLUSTERING OF 868 MHZ WIRELESS SENSOR NETWORK NODES BASED ON EGLI PATHLOSS MODEL COMPUTED RECEIVED SIGNAL STRENGTH. ***Journal of Multidisciplinary Engineering Science and Technology*** *(JMEST) Vol. 6 Issue 12, December – 2019*

15. Bianchi, V., Ciampolini, P., & De Munari, I. (2018). RSSI-based indoor localization and identification for ZigBee wireless sensor networks in smart homes. *IEEE Transactions on Instrumentation and Measurement*, *68*(2), 566-575.

16. Simeon**, Ozuomba. (2020).** "APPLICATION OF KMEANS CLUSTERING ALGORITHM FOR SELECTION OF RELAY NODES IN WIRELESS SENSOR NETWORK." ***International Multilingual Journal of Science and Technology*** *(IMJST) Vol. 5 Issue 6, June – 2020*

17. Abdollahzadeh, S., & Navimipour, N. J. (2016). Deployment strategies in the wireless sensor network: A comprehensive review. *Computer Communications*, *91*, 1-16.

18. Johnson, Enyenihi Henry, **Simeon Ozuomba**, and Ifiok Okon Asuquo. **(2019).** Determination of Wireless Communication Links Optimal Transmission Range Using Improved Bisection Algorithm. ***Universal Journal of Communications and Network,*** *7(1), 9-20.*

19. Matin, M. A., & Islam, M. M. (2012). Overview of wireless sensor network. *Wireless sensor networks-technology and protocols, 1*(3)**.**

20. **Simeon, Ozuomba (2014)** "Fixed Point Iteration Computation Of Nominal Mean Motion And Semi Major Axis Of Artificial Satellite Orbiting An Oblate Earth." ***Journal of Multidisciplinary Engineering Science and Technology (JMEST)*** *Vol. 1 Issue 4, November – 2014*

21. Rault, T., Bouabdallah, A., & Challal, Y. (2014). Energy efficiency in wireless sensor networks: A top-down survey. *Computer networks*, *67*, 104-122.

22. **Simeon, Ozuomba. (2017).** "Determination Of The Clear Sky Composite Carrier To Noise Ratio For Ku-Band Digital Video Satellite Link" ***Science and Technology Publishing*** *(SCI & TECH) Vol. 1 Issue 7, July – 2017*

23. Bhushan, B., & Sahoo, G. (2018). Recent advances in attacks, technical challenges, vulnerabilities and their countermeasures in wireless sensor networks. *Wireless Personal Communications*, *98*(2), 2037-2077.

24. Gisbert, J. R., Palau, C., Uriarte, M., Prieto, G., Palazón, J. A., Esteve, M., ... & González, A. (2014). Integrated system for control and monitoring industrial wireless networks for labor risk prevention. *Journal of Network and Computer Applications*, *39*, 233-252.

25. Imoh-Etefia, Ubon Etefia, **Ozuomba Simeon**, and Stephen Bliss Utibe-Abasi. **(2020).** "Analysis Of Obstruction Shadowing In Bullington Double Knife Edge Diffraction Loss Computation." ***Journal of Multidisciplinary Engineering Science Studies*** *(JMESS) Vol. 6 Issue 1, January – 2020*

26. Ali, S., Qaisar, S. B., Saeed, H., Khan, M. F., Naeem, M., & Anpalagan, A. (2015). Network challenges for cyber physical systems with tiny wireless devices: A case study on reliable pipeline condition monitoring. *Sensors*, *15*(4), 7172-7205.

27. Gupta, H., Vahid Dastjerdi, A., Ghosh, S. K., & Buyya, R. (2017). iFogSim: A toolkit for modeling and simulation of resource management techniques in the Internet of Things, Edge and Fog computing environments. *Software: Practice and Experience*, *47*(9), 1275-1296.

28. **Simeon, Ozuomba,** Ezuruike Okafor SF, and Bankole Morakinyo Olumide **(2018).** Development of Mathematical Models and Algorithms for Exact Radius of Curvature Used in Rounded Edge Diffraction Loss Computation. Development, 5(12). *Journal of Multidisciplinary Engineering Science and*

Technology (JMEST) Vol. 5 Issue 12, December – 2018

29. Liu, Y., He, Y., Li, M., Wang, J., Liu, K., & Li, X. (2012). Does wireless sensor network scale? A measurement study on GreenOrbs. *IEEE Transactions on Parallel and Distributed Systems*, *24*(10), 1983-1993.
30. Dialoke, Ikenna Calistus, **Ozuomba Simeon**, and Henry Akpan Jacob. **(2020)** "ANALYSIS OF SINGLE KNIFE EDGE DIFFRACTION LOSS FOR A FIXED TERRESTRIAL LINE-OF-SIGHT MICROWAVE COMMUNICATION LINK." ***Journal of Multidisciplinary Engineering Science and Technology*** *(JMEST) Vol. 7 Issue 2, February - 2020*
31. Horneber, J., & Hergenröder, A. (2014). A survey on testbeds and experimentation environments for wireless sensor networks. *IEEE Communications Surveys & Tutorials*, *16*(4), 1820-1838.
32. **Simeon, Ozuomba. (2016)** "Comparative Analysis Of Rain Attenuation In Satellite Communication Link For Different Polarization Options." ***Journal of Multidisciplinary Engineering Science and Technology*** *(JMEST) Vol. 3 Issue 6, June – 2016*
33. Balkees, P. S., Sasidhar, K., & Rao, S. (2015, August). A survey based analysis of propagation models over the sea. In *2015 International Conference on Advances in Computing, Communications and Informatics (ICACCI)* (pp. 69-75). IEEE.
34. Akaninyene B. Obot , **Ozuomba Simeon** and Afolanya J. Jimoh **(2011); "***Comparative Analysis Of Pathloss Prediction Models For Urban Macrocellular"* ***Nigerian Journal of Technology (NIJOTECH)*** Vol. 30, No. 3 , October 2011 , PP 50 – 59
35. Phillips, C., Sicker, D., & Grunwald, D. (2012). A survey of wireless path loss prediction and coverage mapping methods. *IEEE Communications Surveys & Tutorials*, *15*(1), 255-270.
36. Kalu Constance, **Ozuomba Simeon**, Umana, Sylvester Isreal (2018). Evaluation of Walficsh-Bertoni Path Loss Model Tuning Methods for a Cellular Network in a Timber Market in Uyo. ***Journal of Multidisciplinary Engineering Science Studies*** *(JMESS) Vol. 4 Issue 12, December - 2018*
37. Han, C., Wu, Y., Chen, Z., & Wang, X. (2019). Terahertz communications (TeraCom): Challenges and impact on 6G wireless systems. *arXiv preprint arXiv:1912.06040*.
38. **Ozuomba, Simeon,** Johnson, E. H., & Udoiwod, E. N. **(2018).** Application of Weissberger Model for Characterizing the Propagation Loss in a Gliricidia sepium Arboretum. ***Universal Journal of Communications and Network, 6(2), 18-23.***
39. Akinyemi, P., Adeoye-Oladapo, O. O., & Kolebaje, O. T. Influence of Building Heights and Nature of Rooftop Views on Propagation Loss Prediction for Tropical Environment in Ondo State, Nigeria. *International Journal of Computer Applications*, *975*, 8887.
40. Njoku Chukwudi Aloziem, **Ozuomba Simeon**, Afolayan J. Jimoh **(2017)** Tuning and Cross Validation of Blomquist-Ladell Model for Pathloss Prediction in the GSM 900 Mhz Frequency Band , ***International Journal of Theoretical and Applied Mathematics***
41. Banday, Y., Rather, G. M., & Begh, G. R. (2019). Effect of atmospheric absorption on millimetre wave frequencies for 5G cellular networks. *IET Communications*, *13*(3), 265-270.
42. Constance, Kalu, **Ozuomba Simeon**, and Ezuruike Okafor SF**. (2018).** Evaluation of the Effect of Atmospheric Parameters on Radio Pathloss in Cellular Mobile Communication System. Evaluation, 5(11). ***Journal of Multidisciplinary Engineering Science and Technology*** *(JMEST) Vol. 5 Issue 11, November - 2018*
43. Jacob, M., Priebe, S., Dickhoff, R., Kleine-Ostmann, T., Schrader, T., & Kurner, T. (2012). Diffraction in mm and sub-mm wave indoor propagation channels. *IEEE Transactions on Microwave Theory and Techniques*, *60*(3), 833-844.
44. Akaninyene B. Obot , Ozuomba Simeon and Kingsley M. Udofia (2011); "Determination Of Mobile Radio Link Parameters Using The Path Loss Models*" NSE Technical Transactions , A Technical Journal of The Nigerian Society Of Engineers,* Vol. 46, No. 2 , April - June 2011 , PP 56 – 66.
45. Alam, S., & De, D. (2014). Analysis of security threats in wireless sensor network. *arXiv preprint arXiv:1406.0298*.
46. Rghioui, A., Sendra, S., Lloret, J., & Oumnad, A. (2016). Internet of things for measuring human activities in ambient assisted living and e-health. *Network Protocols and Algorithms*, *8*(3), 15-28.
47. Kim, S., & Eom, D. S. (2013). Link-state-estimation-based transmission power control in wireless body area networks. *IEEE journal of Biomedical and Health Informatics*, *18*(4), 1294-1302.
48. Jawad, H. M., Jawad, A. M., Nordin, R., Gharghan, S. K., Abdullah, N. F., Ismail, M., & Abu-AlShaeer, M. J. (2019). Accurate empirical path-loss model based on particle swarm optimization for wireless sensor networks in smart agriculture. *IEEE Sensors Journal*, *20*(1), 552-561.
49. Simbeye, D. S., & Yang, S. F. (2014). Water quality monitoring and control for aquaculture based on wireless sensor networks. *Journal of networks*, *9*(4), 840.
50. Ibarra, E., Antonopoulos, A., Kartsakli, E., Rodrigues, J. J., & Verikoukis, C. (2015). QoS-aware energy management in body sensor nodes powered by human energy

harvesting. *IEEE Sensors Journal*, *16*(2), 542-549.

51. Olasupo, T. O., Otero, C. E., Otero, L. D., Olasupo, K. O., & Kostanic, I. (2017). Path loss models for low-power, low-data rate sensor nodes for smart car parking systems. *IEEE transactions on intelligent transportation systems*, *19*(6), 1774-1783.
52. Nguyen, T. T., Nguyen, H. H., Barton, R., & Grossetete, P. (2019). Efficient design of chirp spread spectrum modulation for low-power wide-area networks. IEEE Internet of Things Journal, 6(6), 9503-9515.
53. Qian, Y., Ma, L., & Liang, X. (2018). Symmetry chirp spread spectrum modulation used in LEO satellite Internet of Things. *IEEE Communications Letters*, *22*(11), 2230-2233.
54. de Almeida, I. B. F., Chafii, M., Nimr, A., & Fettweis, G. (2021). Alternative chirp spread spectrum techniques for LPWANs. *IEEE Transactions on Green Communications and Networking*, *5*(4), 1846-1855.
55. Dunlop, B., Nguyen, H. H., Barton, R., & Henry, J. (2019, May). Interference analysis for LoRa chirp spread spectrum signals. In *2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE)* (pp. 1-5). IEEE.
56. Mroue, H., Nasser, A., Parrein, B., Hamrioui, S., Mona-Cruz, E., & Rouyer, G. (2018, June). Analytical and simulation study for LoRa modulation. In *2018 25th International Conference on Telecommunications (ICT)* (pp. 655-659). IEEE.
57. Pasolini, G. (2021). On the LoRa chirp spread spectrum modulation. Signal properties and their impact on transmitter and receiver architectures. *IEEE Transactions on Wireless Communications*.
58. Oluwole, F. J., & Olajide, O. Y. (2013). Radio frequency propagation mechanisms and empirical models for hilly areas. *International Journal of Electrical and Computer Engineering (IJECE)*, *3*(3), 372-376.
59. Ajose, S. O., & Imoize, A. L. (2013). Propagation measurements and modelling at 1800 MHz in Lagos Nigeria. *International Journal of Wireless and Mobile Computing*, *6*(2), 165-174.
60. Joseph, I., & Konyeha, C. C. (2013). Urban area path loss propagation prediction and optimisation using hata model at 800mhz. *IOSR Journal of Applied Physics (IOSR-JAP)*, *3*(4), 8-18.
61. Fanan, A. M., Riley, N., Mehdawi, M., & Ammar, M. (2016, November). Comparison of propagation models with real measurement around Hull, UK. In *2016 24th Telecommunications Forum (TELFOR)* (pp. 1-4). IEEE.