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ABSTRACT
The Internet of Things (IoT) is expanding rapidly, with many applications requiring low-power, and long-range connectivity. One of the popular technologies for the IoT is Low-Power Wide-Area Networks (LPWAN), specifically LoRa, which promises to provide connectivity to remote and rural areas. However, the performance of LoRa in such areas remains poorly understood. In this study, the connectivity and range evaluation of LoRa networks were performed in a rural setting. The objective was to understand the coverage, reliability, and connectivity of LoRa in real-world conditions and compare the results with the advertised performance of this technology. The findings of this study provided valuable insights into the suitability of LoRa for IoT applications in rural areas and guide to design decisions for IoT networks. The experimental setup involved battery-powered mobile stations (nodes) mounted on top of 2.5m tall stands and transmitting data to a base station (gateway) installed on top of a 25m high building. The wireless channel characteristics utilized were the Signal-to-noise Ratio (SNR) and Received Signal Strength Indicator (RSSI) metrics, across eight test locations. To estimate connectivity and range of operation within the 868 MHz ISM band, the collected findings were utilized to establish a relationship model in an area comparable to the selected research station.

Keywords
IoT, LPWANs, WSNs, LoRa, LoRa-WAN, connectivity, range, RSSI, SNR

1. INTRODUCTION
There has been a growing interest in low-power wide area networks (LPWANs). Numerous companies in the sector, such as Sigfox and LoRa (technology and service providers for LPWANs in Kenya), have expanded their products/services market scope internationally. The Long-range (LoRa) alliance was formally released at the Mobile World Congress 2015 and later by the Weightless special interest group. The organization is increasingly getting its operations standardized, optimizing implementation cost, battery life, and coverage [1]. However, data rates are compromised due to a smaller bandwidth, longer paging times, and lower transmission power limit. Nevertheless, Wireless Sensor Networks (WSNs) benefit from extensive global standards with numerous suppliers, operators and solid with dependable operational features. Some of the most promising areas of use for LPWANs are in the automotive sector (fleet management, smart traffic control, real-time traffic data, incident alerting systems and reporting), smart metering (electricity, water, and gas amenities), and the monitoring of smart homes (thermostat control and security systems) [2] [3] [4]. Figure 1 gives a typical illustration of the applications of the LoRaWANs.

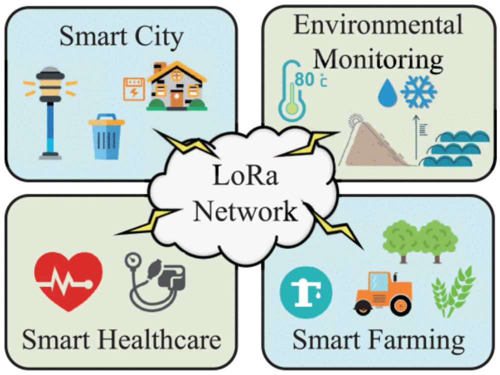

Figure 1. Exemplification of common use cases for the LoRaWANs [5]

Although conventional WSNs and LPWANs have many similarities regarding network needs and devices, their respective techniques vary significantly. For instance, base stations (concentrators and gateways) must reach their end devices for contemporary LPWAN technologies [6]. In contrast, WSN frameworks establish contact via a star-shaped network centered on the base stations [7]. Hence, optimizing the position of the base station improves the effectiveness of network setups, thus, simplifying and reducing the nodes' cost to a level that makes mass manufacture feasible. On the other hand, restricting the number of messages transmitted each day by each node enables the framework to achieve an average lifespan of about four years when operating on a duty cycle of 60 minutes [8]. Additionally, an access point's range coverage depends on the adopted technology alternative.

For Sigfox, LoRa, and Weightless LPWAN protocols, long-range communication is accomplished via sub-GHz radio bands and low data rates to increase receiver sensitivity [9]. Sigfox and Weightless LPWAN typically utilize ultra-narrow band radio transmissions, allowing the development of radio receivers with exceptional sensitivity [10]. In contrast, LoRa is a long-range wireless communication technology for long-lasting battery-powered applications [11]. LoRa modulation is an exclusive spread spectrum technique based on chirp wideband modulation using sequential frequency-modulated pulses [12]. In addition, the LoRa framework predominantly features two independent layers: a physical layer employing the Chirp Spread Spectrum (CSS) radio modulation and the Medium Access Control (MAC) and application layers defined by LoRaWAN [13]. The CSS modulation is a spread-spectrum approach that encodes data utilizing high-bandwidth chirp pulses modulated with linear frequency. Due to its capacity to endure interference, CSS has been adopted by the military and space organizations for long-distance communications. On the other hand, MAC protocols mandate the approach of connecting numerous devices to a single media network. Consequently, LoRaWAN can adopt as its MAC layer either as the pure ALOHA alternative with duty-cycle constraints or a considerate spectrum access mechanism, such as the Listen Before Talk (LBT) alternative. Although the MAC layer is accountable for establishing a stable and effective link between WSN nodes, it is also responsible for energy waste. [14]. Several LoRa-related papers have appeared in the published literature. Petajajarvi et al. [9] The LoRa coverage was analyzed, and a channel attenuation model was suggested for usage at the University of Oulu in Finland. This article compares several long-range technologies, notably LoRa, [1] [13]. In [11], the authors analyzed LoRa's performance and suggested LoRaBlink facilitate multi-hop communications. This article presents experimental research examining and empirically assessing the proprietary elements of LoRa's claimed observable performance in practice.

1.1 Long Range Wide Area Network (LoRaWAN)

LoRaWAN describes the architecture and communication protocol system. Standard LoRaWAN networks are designed around the star network topology, whereby a gateway acts as a relay for data between endpoints and a centralized server [15]. On the other hand, LoRa's physical layer defines the length of the essential mechanism over long distances [16]. Hence, a network server forwards data from all connected devices to an application server. The benefits of utilizing a star topology include saving battery life and decreasing network complexity since nodes do not need to function as relays to distribute or convey data from other nodes because each node only gets its data [17]. Therefore, the protocol and network design significantly impact a node's battery life, the capability of network customer satisfaction, the number of services provided, and network monitoring.

LoRa Network Architecture

The star topology in the LoRa infrastructure consists of three distinct device variants. To increase the reach of communications and the size of the network's cells, the information of other nodes is relayed directly to the end nodes in a mesh [18]. Consequently, nodes receiving and transferring irrelevant data increase network complexity, decrease network capacity, and shorten battery life [19]. However, when a long-range connection is realized, the framework's long-range star design becomes more battery-efficient [4]. For the LoRa network architecture, the end devices connect with gateways through LoRaWAN. Gateways send LoRaWAN signals from endpoints to the network server through a backhaul connection with maximum bandwidth, often Ethernet or 3G. Network servers are responsible for receiving data from connected devices, decoding the data, and finally sending the appropriate data back to the devices making the gateways essentially bidirectional relays or protocol converters as shown in Figure 2.

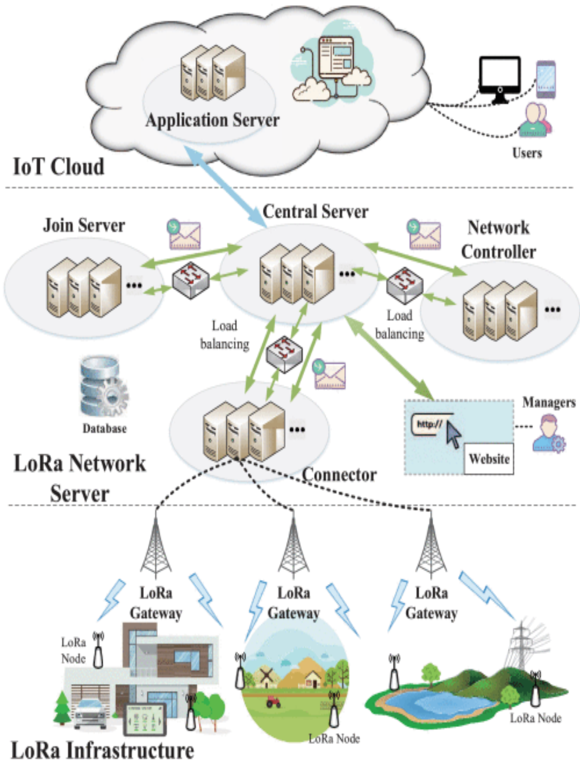

Figure 2. LoRa network architecture [5]

1.1.1 Parameters of the Physical Layer and Network Capacity

Bandwidth (BW), Spreading Factor (SF), and Code Rate are accessible LoRa modulation modification parameters (CR). The chirp rate is proportional to the BW, while the symbol and bit rates are proportional to the frequency BW for a given spreading factor [20]. Hence, doubling the frequency bandwidth would effectively be twice the transmission rate. Widening the channel's BW reduces the receiver's responsiveness, while increasing the SF boosts it as depicted in Table 1.

Table 1: Semtech LoRa receiver sensitivity in dBm at different BW and SFs, taken from [21].

BW	SF 7.00	SF 8.00	SF 9.00	SF 10.00	SF 11.00	SF 12.00
125kHz	-123.00	-126.00	-129.00	-132.00	-133.00	-136.00
250 kHz	-120.00	-123.00	-125.00	-128.00	-130.00	-133.00
500 kHz	-116.00	-119.00	-122.00	-125.00	-128.00	-130.00

The total of concurrent channels, the velocity of data transmission, the length of the carrier, and the frequency of node transmissions significantly impact network capacity. For instance, due to the spread spectrum nature of LoRa's modulation, communications with different spreading factors tend to be orthogonal [22]. Consequently, the optimal battery life for a particular node is only achieved by adjusting the spreading factor, which affects both the integrated bandwidth efficiency and the adaptive data range.

1.2 Channel Characteristics

1.2.1 Signal-to-Noise Ratio

The signal-to-noise ratio (SNR) measures the relative strength of a desired signal compared to background noise in a system. The higher the SNR, the clearer and more distinguishable the signal is [23]. The SNR can be expressed in decibels (dB) and is calculated by dividing the signal power by the noise power. In various fields, such as communication systems, imaging, and audio processing, the SNR plays a crucial role in determining the quality and reliability of the signal. A high SNR is desirable to ensure accurate signal transmission, clear image and sound, and minimal errors in data [24]. On the other hand, a low SNR can result in signal degradation, data loss, and poor-quality images or audio.

1.2.2 Received Signal Strength Indicator

Received Signal Strength Indicator (RSSI) is a measurement of the power present in a received radio signal, expressed in decibels (dBm) [25]. The RSSI value estimates the strength of a wireless signal at a specific location. It is also an important parameter for various applications in wireless communication, such as determining the proximity of a device to an access point, identifying the source of interference, or optimizing the placement of wireless devices. RSSI is typically used in combination with other metrics, such as signal-to-noise ratio (SNR) or bit error rate (BER), to get a more comprehensive picture of the wireless signal quality [26]. However, it is important to remember that RSSI is an indirect signal quality measurement and can be influenced by signal reflection, absorption, and multi-path fading factors.

2. METHOD

The purpose of this study is twofold: To conduct field performance experiments for the determination of LoRa connectivity and range for wireless sensor systems; presentation and discussion of connection and range assessment findings; The balance of this work is structured as follows: Section 2 gives an insight and

LoRaWAN experimental techniques; Section 3 explains and analyses in depth experimental performance investigations; Section 4 presents the results, discussion, and assessment for LoRaWAN. The conclusion is given in Section 5, and the acknowledgments settle the article.

2.1 Measurement Setup

The measurements were conducted at the Dedan Kimathi University of Technology in Central Kenya over three days and at various times of the day. The institution is in a rural location, and the tallest residential structures are six stories tall. There are noticeable variances in height throughout the region's varied topography. Throughout the measurements, the base station remained stationary. End devices were distributed at 300m, 400m, 400m … 1000m in line-of-sight (LOS) locations from a 2.5m tall stand as shown in Figure 3. They were configured to periodically transmit payloads (radio packets) to the base station. In each broadcasted payload, a measurement of the RSSI and the SNR was obtained and stored in a database, the InfluxDB.

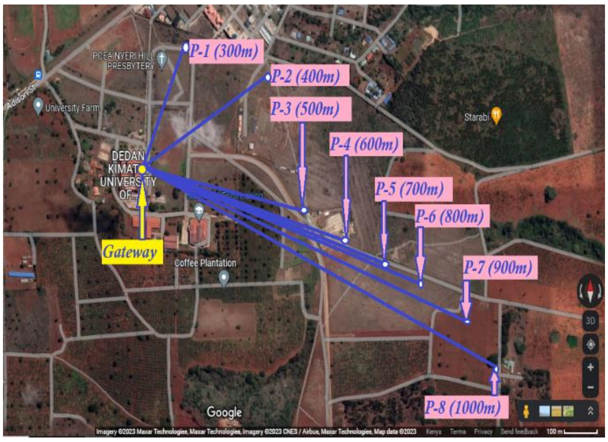

Figure 3: Test points geographical locations. [extracted from google maps]

2.1.1 Base Station

At the Dedan Kimathi University of Technology, the LoRaWAN Industry terminal (based on the MultiTech Conduit) was set up and installed on the roof of a strategically placed building at around 25 m above the ground as portrayed in Figure 4. This received the radio packets from the nodes and uploaded them to The Things Network (TTN) server. TTN ensures data transfer security by providing credentials for the authentication mechanism. As a programmable gateway for the Internet of Things, it can be set up quickly and grow without effort (IoT). In terms of reconfigurability, manageability, and scalability, it is unparalleled as a communication gateway for IoT applications. In addition, it is appropriate for public and private LoRaWAN projects. The characteristics and functions of the gateway are summarized in Tables 2 and 3.

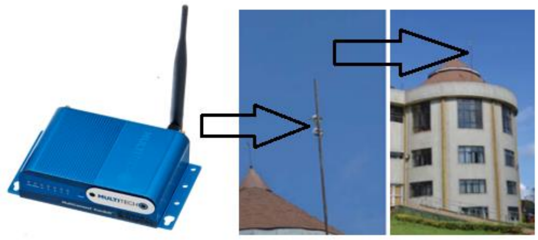

Figure 4: The LoRaWAN Gateway for Industry (based on the MultiTech Conduit).

Table 2: The LoRaWAN industry gateway specifications (subject to environmental factors and placement of nodes/sensors and gateways).

Antenna	LoRa Female SMA, Cell 2dBi	27 dBm max output
Connectivity	Ethernet (RJ45)	Optimal 3FF Micro SIM
Enclosure	Size (161 mm by 107mm by 42mm)	Weight 1.45kg

Table 3: The LoRaWAN Industry gateway functionality (sensitive to environmental variables and the deployment of nodes/sensors).

Temperature	Minimum: - 30.0 °C	Maximum: +70.0 °C
Range	20 km for LOS antenna setting	Up to 3 km for an urban setting
Framework	Wall/ Desktop	Power rating 9V UK/EU

2.1.2 End Device

The final device was a LoRaWAN Transceiver Shield-equipped STM32 Nucleo board revealed in Figure 5. 9V batteries powered the nodes throughout the measurements. The signal's transmitting strength was +14 dBm at a frequency range of 868MHz. The node was affixed to a stand about 2.5m above the ground. The nodes would send out a payload that included the RSSI and the SNR of the signal they had received to the base station every 60s for an hour with no delivery control or automated retransmission procedures.

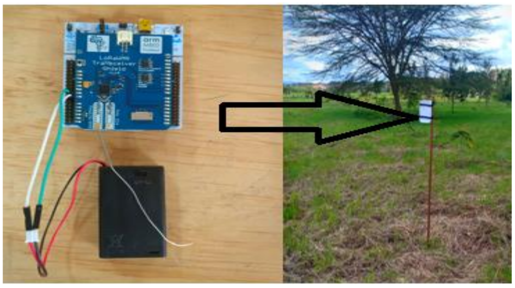

Figure 5: STM32 Nucleo board, equipped with a LoRaWAN transceiver shield

3. RESULTS AND DISCUSSION

The channel characteristics relied on the Signal-to-Noise Ratio (SNR) and the Received Signal Strength Indicator (RSSI). The cleaned and sorted data arrays for every fixed test location are given in Tables 4 and 5. They contain the head (first four elements of a data frame) and the tail (last four elements of a data frame). The maximum number of packets successfully recorded for a data location was sixty-one at 900m and 1000m from the gateway. In the two tables, NaN means that a value was not received; therefore, it can be regarded as a null value (not a number).

Table 4: Observed SNR (dB) values for every test location

S. No	300m	400m	500m	600m	700m	800m	900m	1000m
0	7.8	4.8	-1.5	0.8	-6.5	-5.8	1.8	2.8
1	5.8	5.8	0.8	2.0	-4.5	-5.0	2.0	2.0
2	7.8	7.2	-0.2	2.5	-4.5	-6.0	0.5	1.5
...	...	...	...	...	...	...	...	...
57	NaN	6.2	NaN	NaN	NaN	NaN	-3.0	-3.0

Table 5: Observed RSSI (dBm) values for every test location

S. No	300m	400m	500m	600m	700m	800m	900m	1000m
0	-97.0	-99.0	-112.0	-106.0	-111.0	-114.0	-113.0	-115.0
1	-94.0	-96.0	-112.0	-106.0	-112.0	-113.0	-110.0	-112.0
2	-96.0	-100.0	-107.0	-109.0	-113.0	-113.0	-113.0	-116.0
...	...	...	...	...	...	...	...	...
59	NaN	-101.0	NaN	NaN	NaN	NaN	-111.0	-112.0
60	NaN	NaN	NaN	NaN	NaN	NaN	-110.0	-114.0
61	NaN	NaN	NaN	NaN	NaN	NaN	-113.0	-116.0

Table 6: The Mean SNR (in dB) and Mean RSSI (in dBm) for the Eight Test Locations

Location distance (m)	300.00	400.00	500.00	600.00	700.00	800.00	900.00	1000.00
Mean SNR (dB)	6.988	5.917	-0.563	0.664	-4.552	-7.004	-0.083	-0.083
Mean RSSI (dBm)	-96.3	-100.5	-109.6	-108.20	-111.90	-112.20	-112.20	-113.10

The relationship between these two parameters for every successfully received packet is illustrated in Figure 6. A significant deviation is noticeable between both parameters. The SNR and the RSSI have a linear dependency. The SNR was only above 0dB in ideal radio conditions. For weaker signals (below -100 dBm), the SNR is inconsistent. The results indicate that the SNR is a more limiting factor than RSSI, as a sample with low RSSI can still have a relatively good SNR.

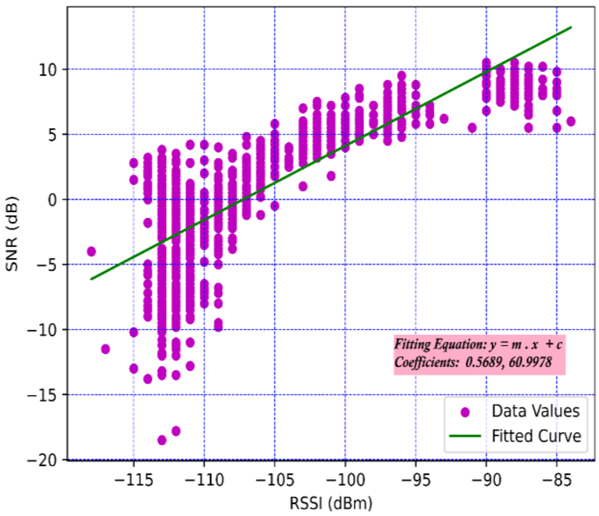

Figure 6: Experiential relationship between SNR and RSSI for successfully transmitted packets

The box plots in Figure 7 and Figure 8 allowed a fast graphical evaluation of the SNR and the RSSI for each of the eight test locations. At 300m, 900m, and 1000m, the recorded RSSI values exhibited the greatest scattering and skewness, while the test location at 800m displays the direct opposite of these results. For the SNR, the

greatest dispersion was witnessed at the nearest distance between the node and the gateway, 300m. The median SNR and RSSI values shift about non-linearly depending on several factors; including how much attenuation, shadowing, reflection, refraction, transmission, and diffraction present in free space.

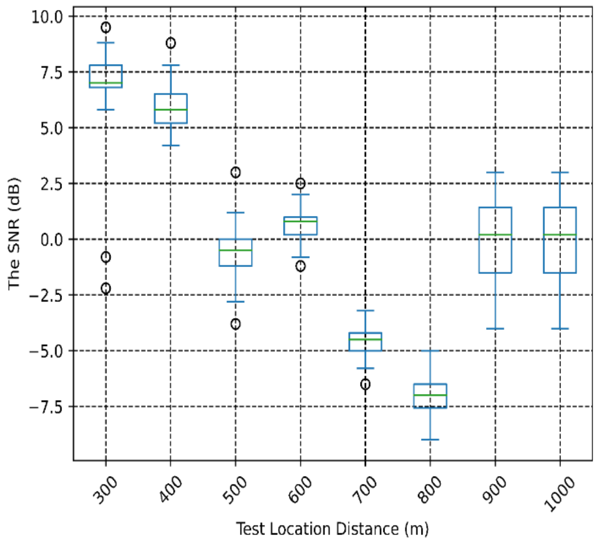

Figure 7: Observed box plots for SNR of successfully transmitted packets

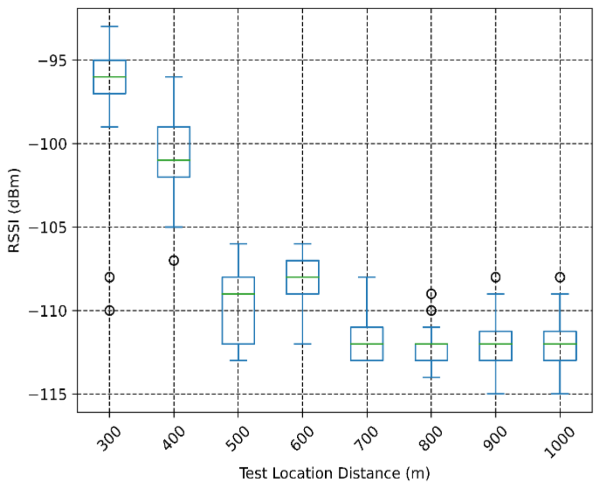

Figure 8: Observed box plots for RSSI of successfully transmitted packets

Since RSSI is typically a negative number from -120 dBm to -30dBm, a stronger signal manifests as a reading approaching 0. At 300m from the gateway, the average signal strength was -96.30dBm, while at 1000m, the average transmission power was -113.10dBm. The dynamic range is therefore calculated to be approximately 17dB. Each test location's estimated mean RSSI attributes are listed in Table 6. The strongest signal certainly manifests at the test location nearest to the gateway, and this value decreases progressively as the test locations get further from the gateway. Although SF12 is typically used at -136dBm, no data transmissions below -113dBm were recorded during the campaign. The SNR values are between – 7dB and 7dB. The captured SNR levels align with theoretical expectations as they do not fall below -20dB. The experiential relationships of the RSSI and the SNR were used to fit a propagation model in the 1000m range in Figure 9 and Figure 10. Even though this was insufficient, preliminary findings suggest that more experiments would yield a perfect fit.

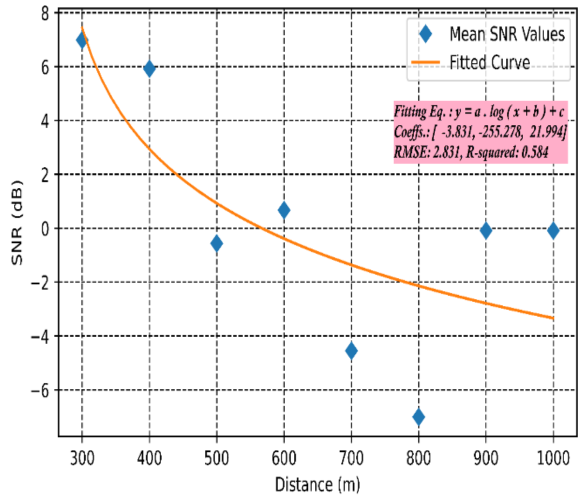

Figure 9: Experiential relationship between SNR and distance for successfully transmitted packets

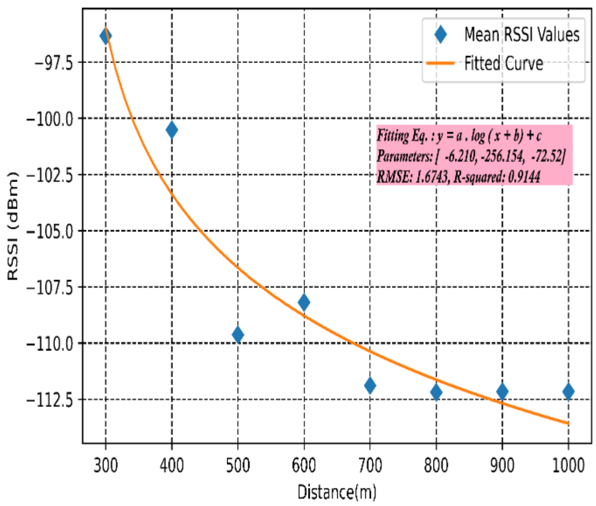

Figure 10: Experiential relationship between RSSI and distance for successfully transmitted packets

4. CONCLUSION

This paper presents a dataset analysis for LoRaWAN technology measurements in a rural area scenario of Dedan Kimathi University of Technology, Nyeri, Kenya. The dataset contains information from eight outdoor test locations with predetermined distances from the gateway. The dataset helps analyze the deployment and improvement of LoRaWAN operation for IoT use cases. The paper also explores the short-term characteristics of the real-world LoRaWAN network based on a brief measurement campaign. The short-term measurements revealed that RSSI fluctuated significantly within almost a 17dB range over two days, and SNR fluctuated within a 15dBm range. The rural setting measurement campaign discovered that LoRaWAN technology is a reliable communication technology for wireless applications. The results also showed that the geographically closest node provided the best RSSI or SNR, even though this was not guaranteed. These results suggest that conventional empirical propagation models may be developed and accurately predict path loss values, highlighting the need for further experiments beyond the range of 1km. This dataset can be a useful starting point for developing such a model. However, further research is recommended in the field by comparing the impact of distance and both LOS and Non-Line-of-Sight (NLoS) variables to optimize the formulation of a comprehensive channel attenuation model.

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6. REFERENCES

[1] W. San-Um, P. Lekbunyasin, M. Kodyoo, W. Wongsuwan, J. Makfak and J. Kerdsri, “A long-range low-power wireless sensor network based on U-LoRa technology for tactical troops tracking systems,” in 2017 Third Asian Conference on Defence Technology (ACDT), Phuket, Thailand, 2017.

[2] P. Sommer, Y. Maret and D. Dzung, “Low-Power Wide-Area Networks for Industrial Sensing Applications,” in 2018 IEEE International Conference on Industrial Internet (ICII), Seattle, WA, USA, 2018.

[3] Shahjalal, K. Hasan, M. Islam, M. Alam, F. Ahmed and Y. M. Jang, “An Overview of AI-Enabled Remote Smart-Home Monitoring System Using LoRa,” in 2020 International Conference on Artificial Intelligence in Information and Communication (ICAIIC), Fukuoka, Japan, 2020.

[4] M. Centenaro, L. Vangelista, A. Zanella and M. Zorzi, “Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios,” IEEE Wireless Communications, vol. 23, no. 5, pp. 60-67, 2016.

[5] Z. Qihao, Z. Kan, H. Lu, X. Jinyu and X. Rongtao, “Design and Implementation of Open LoRa for IoT,” IEEE Access, vol. 7, pp. 100649-100657, 2019.

[6] R. Kir, “Long-Range Data Transmission on Flying Ubiquitous Sensor Networks (FUSN) by Using LPWAN Protocols,” in International Conference on Distributed Computer and Communication Networks, 2017.

[7] Y. Chung, J. Y. Ahn and J. D. Huh, “Experiments of A LPWAN Tracking(TR) Platform Based on Sigfox Test Network,” in 2018 International Conference on Information and Communication Technology Convergence (ICTC), Jeju; South Korea, 2018.

[8] D. M. Hernandez, G. Peralta, L. Manero, R. Gomez, J. Bilbao and C. Zubia, “Energy and coverage study of LPWAN schemes for Industry 4.0,” in 2017 IEEE International Workshop of Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM), Donostia, Spain, 2017.

[9] P. Ryckebusch, S. Giannoulis, I. Moerman, J. Hoebeke and E. D. Poorter, “Modelling the energy consumption for over-the-air software updates in LPWAN networks: SigFox, LoRa and IEEE 802.15.4g,” Internet of Things , pp. 104-119, October 2018.

[10] K. Nolan, W. Guibene and M. Kelly, “An evaluation of low power wide area network technologies for the Internet of Things,” in 2016 International Wireless Communications and Mobile Computing Conference (IWCMC), Paphos, Cyprus, 2016.

[11] D. H. Kim, J. Y. Lim and J. D. Kim, “Low-Power, Long-Range, High-Data Transmission Using Wi-Fi and LoRa,” in 2016 6th International Conference on IT Convergence and Security (ICITCS), Prague, Czech Republic , 2016.

[12] A. J. Wixted, P. Kinnaird, H. Larijani, A. Tait, A. Ahmadinia and N. Strachan, “Evaluation of LoRa and LoRaWAN for wireless sensor networks,” in 2016 IEEE SENSORS, Orlando, FL, USA, 2016.

[13] L. Leonardi, F. Battaglia, G. Patti and L. L. Bello, “Industrial LoRa: A Novel Medium Access Strategy for LoRa in Industry 4.0 Applications,” in IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, USA, 2018.

[14] L. Leonardi, L. L. Bello, F. Battaglia and G. Patti, “Comparative Assessment of the LoRaWAN Medium Access Control Protocols for IoT: Does Listen before Talk Perform Better than ALOHA?,” Electronics, vol. 9, no. 4, 4 March 2020.

[15] J. d. C. Silva, J. J. P. C. Rodrigues, A. M. Alberti, P. Solic and A. L. L. Aquino, “LoRaWAN — A low power WAN protocol for Internet of Things: A review and opportunities,” in 2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech), Split, Croatia, 2017.

[16] Q. Yu, H. Wang and Z. Lu, “Group-Based CSS Modulation: A Novel Enhancement to LoRa Physical Layer,” IEEE Wireless Communications Letters , vol. 11, no. 3, pp. 660-664, 2022.

[17] R. P. Centelles, F. Freitag, R. Meseguer and L. Navarro, “Beyond the Star of Stars: An Introduction to Multi-hop and Mesh for LoRa and LoRaWAN,” IEEE Pervasive Computing, vol. 20, no. 2, pp. 63-72, 2021.

[18] D. Eridani, E. D. Widianto, R. D. O. Augustinus and A. A. Faizal, “Monitoring System in Lora Network Architecture using Smart Gateway in Simple LoRa Protocol,” in 2019 International Seminar on Research of Information Technology and Intelligent Systems (ISRITI, Yogyakarta, Indonesia, 2019.

[19] H. Huh and J. Y. Kim, “LoRa-based Mesh Network for IoT Applications,” in 2019 IEEE 5th World Forum on Internet of Things (WF-IoT), Limerick, Ireland , 2019.

[20] L. M. Figueiredo and E. F. Silva, “Cognitive-LoRa: adaptation-aware of the physical layer in LoRa-based networks,” in 2020 IEEE Symposium on Computers and Communications (ISCC), Rennes, France, 2020.

[21] 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.

[22] T. T. Nguyen, H. H. Nguyen, R. Barton and P. Grossetete, “Efficient Design of Chirp Spread Spectrum Modulation

for Low-Power Wide-Area Networks," IEEE Internet of Things Journal , vol. 6, no. 6, pp. 9503-9515, 2019.

[23] K. Robert, R. Pall and M. Timothy J, "Definition of signal-to-noise ratio and its critical role in split-beam measurements," ICES Journal of Marine Science,, vol. 62, no. 1, p. 123–130, 2005.

[24] H. S. Muhammad and A. Yousef, "Signal-to-Noise Ratio Comparison of Several Filters against Phantom Image," Journal of Healthcare Engineering, vol. 2022, 2022.

[25] S. Farahani, "ZigBee Wireless Networks and Transceivers," in Location Estimation Methods, Newnes, 2008, pp. 225-246.

[26] K. Gagandeep, H. G. Sindhu and K. Harleen, "Optimizing the LoRa network performance for industrial scenario using a machine learning approach," Computers and Electrical Engineering, vol. 100, 2022.

[27] "Sigfox.com," Sigfox - The Global Communications Service Provider for the Internet of Things (IoT), [Online]. Available: http://www.sigfox.com/en/. [Accessed 01 November 2019].

[28] "Lora-alliance.org," Home page | LoRa Alliance™, [Online]. Available: https://www.lora-alliance.org/. [Accessed 02 November 2019].

[29] "Weightless.org," Weightless - Setting the Standard for IoT, [Online]. Available: http://www.weightless.org/. [Accessed 02 November 2019].

[30] "GSA," Nokia - LTE M2M: Optimizing LTE for the Internet of Things - GSA, [Online]. Available: https://gsacom.com/paper/nokia-lte-m2m-optimizing-lte-for-the-internet-of-things/. [Accessed 03 November 2019].

[31] S. Andreevy, O. Galinina, A. Pyattaev, M. Gerasimenko, T. Tirronen, J. Torsner, J. Sachs, M. Dohler and Y. Koucheryavy, "Understanding the IoT connectivity landscape: a contemporary M2M radio technology roadmap," IEEE Communications Magazine, vol. 53, no. 9, pp. 32-40, 2015.

[32] A. Berni and W. Gregg, "On the Utility of Chirp Modulation for Digital Signaling," IEEE Transactions on Communications, vol. 21, no. 6, pp. 748-751, 1973.

[33] A. Springer, W. Gugler, M. Huemer, L. Reindl, C. C. W. Ruppel and R. Weigel, "A wireless spread-spectrum communication system using SAW chirped delay lines," IEEE Transactions on Microwave Theory and Techniques, vol. 49, no. 4, pp. 754-760, 2001.

[34] J. Petäjäjärvi, K. Mikhaylov, A. Roivainen, T. Hänninen and M. Pettissalo, "On the coverage of LPWANs: Range evaluation and channel attenuation model for LoRa technology," in 2015 14th International Conference on ITS Telecommunications (ITST), 2016.

[35] "Lora-alliance.org," What is LoRaWAN® | LoRa Alliance™, [Online]. Available: https://lora-alliance.org/resource-hub/what-lorawanr. [Accessed 05 November 2019].

[36] "Revspace.nl," DecodingLora - RevSpace, [Online]. Available: https://revspace.nl/DecodingLora. [Accessed 03 November 2019].

[37] N. Rathod, P. Jain, R. Subramanian, S. Yawalkar and M. Sunkenapally, "Performance Analysis of Wireless Devices for a Campus-wide IoT Network," in The 2015 International Workshop on Wireless Network Measurements and Experimentation, 2015.

[38] "The Things Network," MultiTech Conduit, [Online]. Available: https://www.thethingsnetwork.org/docs/gateways/multitech/. [Accessed 13 September 2019].

[39] "STMicroelectronics," STM32 Nucleo Boards - STMicroelectronics, [Online]. Available: https://www.st.com/en/evaluation-tools/stm32-nucleo-boards.html. [Accessed 22 August 2019].