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Long Range Communication Radio Channel Propagation: A Review

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Abstract
LoRa, or Long Range, is an increasingly popular wireless communication technology for Internet of Things (IoT) applications, offering long-distance connectivity with low power consumption. Radio channel propagation plays a critical role in determining the performance of a LoRa system. This paper provides a comprehensive review of radio channel propagation in the context of LoRa communications. It introduces various factors influencing LoRa signal propagation and examines recent research efforts aimed at understanding the propagation characteristics of LoRa radio channels and addressing the associated challenges. In conclusion, selecting an appropriate propagation model for LoRa, the propagation model requires consideration of environmental variations ranging from urban to rural settings. The Free Space Path Loss model is suitable for open areas and short distances, while the Log-Distance Path Loss provides flexibility across various conditions. The Okumura-Hata model is well-suited for urban and suburban environments, the ITU-R P.1546 model offers broad coverage across a wide range of environmental types, and the SUI model presents a comprehensive solution to a wide range of conditions. The appropriate model selection depends on the deployment of location, frequency of operation, and specific environmental conditions in which LoRa is implemented.

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I. INTRODUCTION

In the rapidly advancing era of the Internet of Things (IoT), wireless communication has become the backbone for connecting millions of sensor and actuator devices worldwide [1]-[4]. In this context, Long-Range (LoRa) technology has emerged as one of the leading solutions to provide reliable and efficient connectivity, especially in large and distributed environments [5]-[8]. LoRa offers a wide range of communication capabilities and low power consumption, making it ideal for various IoT applications, ranging from environmental monitoring to asset management. However, the performance of a LoRa system is greatly influenced by signal propagation in the radio channel.

A deep understanding of LoRa radio channel propagation is critical in designing reliable and efficient systems [9], [10]. By understanding signal propagation characteristics and identifying associated challenges, system design can be optimized, service quality can be improved, and device battery life can be extended [11]. This paper aims to provide a comprehensive review of radio channel propagation in the context of LoRa communications.

This research explores the factors influencing LoRa signal propagation, investigates the challenges faced, and evaluates current research efforts aimed at addressing radio channel propagation issues in LoRa communications. The in-depth understanding of LoRa radio channel propagation in this paper is intended to serve as a foundation for researchers, engineers, and practitioners in developing reliable and efficient wireless communication solutions for IoT applications in the future.

II. LONG-RANGE COMMUNICATION

A. LoRa Radio Channel Propagation

In Indonesia, the LoRa operating frequency is 923-925 MHz, which complies with the AS923 regional standard [2], [12], [13]. This means that LoRa devices used in Indonesia must support this frequency range to operate legally. This frequency falls within the ISM (Industrial, Scientific, and Medical) band, which is available for unlicensed use. In Indonesia, this frequency is commonly used for IoT and Machine-to-Machine (M2M) applications, enabling long-distance data transmission with low power consumption [2]. Table 1 summarizes the LoRa operating frequency ranges used worldwide.

Each frequency band exhibits different signal propagation characteristics, including range, resistance to interference, and indoor penetration capabilities [14]. In addition, transmitter power limit and other configuration parameters may vary based on r
egional regulations [15].

Topography and environment conditions significantly impact LoRa signal propagation, influencing the range, reliability, and overall performance of a LoRa communications system. The Earth's surface features such as hills, valleys, or plains can affect signal propagation differently [6], [16]. In hilly and rugged terrains, physical obstructions may reduce the effective range [9], [17]. Meanwhile, the height of the transmitter and receiver antennas also plays a critical role in determining the performance of the LoRa system. Higher antenna placement allows for better line-of-sight (LoS), minimizing obstructions and enhancing signal reach [18], [19].

Table 1
LoRa working frequency range in the world

LoRa Band	Frequency	Location	Description
EU868	863-870 MHz	European Union and most other countries outside North America	ISM
US915	902-928 MHz	United States, Canada, and several other countries in North America	ISM
AU915	915-928 MHz	Australia	ISM
AS923	923-925 MHz	Asia Pacific and several other countries in the Asian region	ISM
KR920	920-923 MHz	South Korea	
IN865	865-867 MHz	India	

Urban environments, characterized by tall buildings, dense infrastructure, busy streets, and many vehicles can produce complex reflections and signal shadowing that impact LoRa signal propagation [20], [21]. While rural areas offer more open propagation paths, factors such as vegetation and soil conditions still influence signal behavior [10], [22]. Building walls and certain building materials can absorb or reflect signals, affecting communication reliability [23]. In general, higher antenna placement increases the likelihood of an unobstructed line-of-sight, reducing signal attenuation and extending range [22]-[25]. Electromagnetic interference and physical obstacles, such as building walls further contribute to LoRa signal propagation [26], [27]. Obstacles and interference in LoRa communications can come from various sources and significantly affect system performance. Table 2 outlines the types of obstacles and interference in LoRa communication systems.

Table 2
Obstacles and Disruptions in LoRa Communication

Obstacle	Type	Description
Physical Barriers	Buildings	Buildings can pose a significant physical obstacle to LoRa signal propagation, especially in urban environments. Walls, roofs, and other building structures can absorb or reflect signals, reducing the reliability and range of communications.
	Soil and Vegetation	Contoured ground or dense vegetation, such as trees, can block or dampen LoRa signals. These effects can be significantly exacerbated in rural or forest environments.
	Distance	Long distances between the transmitter and receiver can also be an obstacle, especially if the signal experiences significant attenuation as the distance increases.
Electromagnetic Interference	Radio Interference	Interference from other devices using the same radio spectrum can disrupt LoRa communications performance. Sources of interference may include other wireless communications devices, mobile transmitting systems, or other electromagnetic interference.
	Noise	Noise or unwanted signal interference from sources such as electrical equipment or other electronic devices can reduce the quality of the LoRa signal.
Fading	Multipath Fading	Multipath fading occurs when signals reach the receiver via different paths and experience constructive or destructive interference. This can cause signal strength fluctuations and reduce communication reliability.
Obstacle	Fading Due to Environmental Changes	Fading can also be caused by environmental changes, such as changes in weather or device mobility. Changes in signal propagation properties, such as refraction or diffraction, can cause fluctuations in the strength of the received signal.

Mitigating obstacles and interference is essential for designing a reliable and efficient LoRa system. By understanding the sources of these obstacles and interference, steps can be taken to reduce their impact, including strategic placement of LoRa devices, selection of appropriate frequencies, and use of more sophisticated coding and modulation techniques.

B. Challenges in LoRa Radio Channel Propagation

Multipath fading is a phenomenon in which radio signals reach the receiver via different paths, experiencing constructive or destructive interference [16], [28]. In the context of LoRa, multipath fading presents a significant challenge, as signals arriving through multiple paths may differ in phase and amplitude, resulting in fluctuations in received signal strengths. This can result in a decrease in signal quality and impact the reliability of LoRa communications [7], [17].

Fading can also be caused by environmental changes, such as changes in weather or device movement. These changes in signal propagation properties, such as refraction or diffraction, can cause fluctuations in the signal strength received by the LoRa receiver. Interference from other devices in the radio spectrum can disrupt the performance of LoRa communications. Interference is one of the main challenges in LoRa communications, as it can disrupt system performance and reduce the reliability of data transmission. Other devices using the same radio spectrum or adjacent frequencies, including Wi-Fi, Bluetooth, and other wireless devices, can cause interference. Handling interference is crucial in ensuring the LoRa network's good performance.

Efficient power management is also essential in LoRa applications, particularly in wireless sensor networks powered by batteries. Improving power usage efficiency can help extend device battery life, reduce battery replacement frequency, and lower maintenance costs.

Several strategies can be adopted to achieve efficient power management in LoRa applications, including using an efficient sleep mode to reduce power consumption during inactivity. In addition, optimizing data transmission and reception settings minimizes power consumption. Selecting the optimal delivery interval for sensor data based on application requirements is also one of the efficient power managements. Other strategies are implementing data compression techniques to reduce the amount of data sent and using efficient modulation techniques such as LoRa to minimize power consumption at the transmitter. By implementing efficient power management strategies, LoRa applications can achieve optimal performance while extending device battery life and reducing operational costs [19].

III. RESULTS AND DISCUSSION

A. Radio Channel Propagation Model

Developing appropriate radio channel propagation models is essential in understanding and predicting LoRa system performance [29], [30], [31], [32], [33], [34]. These models help to describe how radio signals propagate and are influenced by the surrounding environment ultimately, affecting the quality of LoRa communications [35], [35], [36].

Accurate modeling of radio channel propagation is crucial for optimizing LoRa system performance. By understanding how LoRa signals behave in various environmental conditions, more efficient networks can be designed, service quality can be enhanced and the successful implementation of IoT applications using LoRa technology can be ensured.

B. Antenna Optimization

Optimized antenna designs play a critical role in improving the range and reliability of LoRa communications [37], [38], [39], [40], [41], [42]. Given the complexity and variability of the environments in which LoRa technology is implemented, various propagation models have been developed to reflect different signal behavior characteristics. Table 3 presents the commonly used LoRa radio channel propagation models.

Table 3
LoRa Radio Propagation Model Channels

Model Propagation	**Descriptions**
Free Space Path Loss (FSPL) [10], [11], [17], [43]	$FSPL = 92{,}45 + 20\log_{10}(D) + 20\log_{10}(f)$
Two-Ray Ground Reflection [22]	$PL(dB) = 40\log D - (10\log G_t + 10\log G_r + 20\log H_t + 20\log H_r)$
Rayleigh Fading [44], [45]	$h(t) = \sum_{n=1}^{N} a_n e^{j(2\pi f_n t + \varphi_n)}$
Rician Fading [45]	$pdf(r) = \frac{r}{\sigma^2} e^{\frac{r^2+A^2}{2\sigma^2}} I0(\frac{rA}{\sigma^2}), r \geq 0$
Nakagami-m Fading [10], [46]	$f_R(r) = \frac{2m^m r^{2m-1}}{\Gamma(m)\Omega^m} e^{-(m/\Omega)r^2}$
Saleh-Valenzuela [47]-[50]	$h(\tau) = \sum_{l=1}^{l} \sum_{k=1}^{K_l} \beta_k, le^{j\theta k,l} \delta(\tau - T_l - T_{k,l})$
Urban Macrocell Path Loss [25], [51]-[53]	$PL_{UMa} = 161.04 - 7.01\log_{10}(W) + 7.5\log_{10}(h) - (24.37 - 3.7(h/h_{BS})^2\log_{10}(h_{BS}) +$ $(43.42 - 3.1\log_{10}(h_{BS}))(\log_{10}(d) - 3) + 20\log_{10}(fc) - (3.2(\log_{10}(11.75h_{UT}))^2 - 4.97)$
Log-Distance Path Loss [25], [47], [51], [54], [55], [56]	$L = L_0 + 10\gamma lo_{10}\frac{d}{d_0} + X_g$
Cost 231 Hata [23], [57]-[62]	$PL = 46.3 + 33.9\log_{10}(f) - 13.82\log_{10}(h_t) - a(h_r) + [44.9 - 6.55\log_{10}(h_t)]\log_{10}(d) + C_m$ Urban $a(h_r) = 1.1\log_{10}(f) - 0.7)h_r - (1.56\log_{10}(f) - 0.8)$ $PL_{suburban} = PL_{urban} - 2[\log 10(\frac{f}{28})]^2 - 5.4$
Okumura-Hata [12], [14], [24], [57], [62]-[64]	$PL = 69.55 + 26.16\log_{10}(f) - 13.82\log_{10}(h_t) - a(h_r) + [44.9 - 6.55\log_{10}(h_t)]\log_{10}(d)$ Urban $a(h_r) = 1.1\log_{10}(f) - 0.7)h_r - (1.56\log_{10}(f) - 0.8)$
ITU-R P.1546-4 [12], [14], [57], [62]-[66]	$PL = E_f - E_m + \Delta E + 20\log_{10}(d) - 20\log_{10}(h_r) - G_t$
Extended Hata [14], [63]	$PL_{rural} = PL_{urban} - 4.78\log 10(\frac{f}{28})]^2 + 18.33\log_{10}(f) - 40.94$
Walfisch-Bertoni [60], [66]-[68]	$L_{rts} = -16.9 - 10\log_{10}(W) + 10\log_{10}(f) + 10\log_{10}(h_r - h_{roof}) + 20\log_{10}(d)$

	$Lmsd = 18\log_{10}(1+\frac{d}{db}) + 15\log_{10}(h_{roof} - h_t)$
One-Slope [10], [17], [43]	$PL(d) = PL(d_0) + 10n\log_{10}(\frac{d}{d_0})$ Urban: n ≈ 2.7 - 3.53, Suburban: n ≈ 2 - 2.7, Rural: n ≈1.6n - 2
Standford University Model [10], [14]	$PL = A + 10\gamma\log_{10}(\frac{d}{d_0}) + X_f + X_h + s$

The selection of an appropriate radio channel propagation model is essential to accurately predict LoRa system performance under various environmental and operational conditions. Table 4 shows the factors that influence the selection of LoRa propagation channels with a specific focus on antenna design.

Table 4
Factors Influencing the Selection of LoRa Propagation Channels

Technology	Description
Increased Gain	A well-designed antenna can have a higher gain, increasing the strength of the transmitted and received signal. With higher gain, the range of LoRa communications can be extended, especially when the signal must cover long distances or pass through obstacles such as buildings or trees.
Amplified Radiation Pattern	An optimized antenna design can produce a more focused and consistent radiation pattern. This can lead to a more even power distribution across the coverage area, minimizing shadow zones or areas of low power. The boosted radiation pattern can also help reduce interference with signals from other devices.
Distraction and Noise Reduction	Optimized antennas can also help reduce sensitivity to unwanted interference and noise. By designing antennas with a more focused radiation pattern and reducing sensitivity to unwanted directions, interference and noise can be minimized, increasing the reliability of LoRa communications.
Adjustment to the Environment	The optimized antenna design can also consider the environment in which the LoRa system will be operated. Antennas specifically designed for urban, rural, or industrial environments can provide better performance according to specific application requirements.
Adjustment to Operating Frequency	The optimized antenna design can also be adapted to the LoRa operating frequency. This includes considering the optimal wavelength and signal propagation characteristics at a specified frequency to improve overall system performance.

Table 4 outlines the role of antenna characteristics in selecting appropriate LoRa propagation channels, focusing on antenna design. Increased Gain refers to the ability of a high-gain antenna to strengthen signal transmission and reception, thus extending the communication range and improving performance in obstructed environments. Amplified Radiation Pattern describes how an optimized radiation pattern ensures more uniform power distribution and reduces coverage gaps or shadow zones. Distraction and Noise Reduction highlights the role of directional antennas in minimizing sensitivity to interference and noise from unwanted directions, thereby enhancing communication reliability. Adjustment to the Environment emphasizes that antenna design should align with the deployment setting—urban, rural, or industrial—to ensure optimal performance under specific environmental conditions. Finally, Adjustment to Operating Frequency underscores the importance of tailoring the antenna to LoRa's frequency band, which involves optimizing for wavelength and propagation characteristics, thereby improving overall system efficiency and signal integrity.

The application of Artificial Intelligence (AI) in LoRa communication systems presents significant opportunities to enhance network efficiency, adaptability, and reliability. AI can dynamically predict radio channel propagation characteristics using real-world environmental data such as topography, building density, and weather conditions. By leveraging machine learning algorithms, LoRa systems can automatically adjust parameters like spreading factor, bandwidth, and transmission power in response to changing propagation conditions. AI also supports the design and adaptation of smart antennas. Through methods such as evolutionary algorithms or reinforcement learning, antenna gain, and radiation patterns can be optimized for specific operational environments. AI also plays a crucial role in energy consumption optimization and maintaining Quality of Service (QoS), enabling devices to manage active periods and transmission settings efficiently without compromising performance. AI-based interference detection system can autonomously identify and mitigate noise or signal disruptions, preserving communication stability. Furthermore, AI accelerates the simulation and validation of antenna and propagation models by creating digital environments that replicate real-world scenarios. In this way, AI integration is not merely a supporting tool but a fundamental pillar in developing intelligent, robust, and scalable LoRa-based IoT communication infrastructure for the future.

IV. CONCLUSION

Radio channel propagation is a critical factor in determining the performance of a LoRa communication system. By understanding the characteristics of signal propagation and addressing associated challenges, more effective solutions can be developed to support long-range wireless connectivity with low power consumption in IoT applications. Continued research and innovation in this area will play a vital role in improving the efficiency and reliability of future LoRa systems. In selecting propagation models for LoRa, it is essential to consider environmental variations ranging from urban to rural settings. The Free Space Path Loss model is suitable for open areas and short-range communications, while the Log-Distance Path Loss model provides flexibility across different conditions. The Okumura-Hata model is particularly well-suited for urban and suburban environments, whereas the ITU-R P.1546 model provides broad coverage across a diverse range of environmental types. The SUI model offers a comprehensive approach for a wide range of conditions. Ultimately, the choice of propagation model should be based on the deployment of location, frequency of operation, and specific environmental conditions in which LoRa system is implemented. Furthermore, the integration of AI enables dynamic prediction of radio channel characteristics by analyzing real-time data such as topography, building density, and weather conditions. This enhances the adaptability and performance of LoRa-based communication systems, paving the way for more intelligent and resilient IoT infrastructures

CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the paper's publication.

AUTHOR CONTRIBUTION

The authors confirm contribution to the paper as follows: study conception and design: Ruliyanta; data collection: Ruliyanta; analysis and interpretation of findings: Ruliyanta, Idris Kusuma; draft manuscript preparation: Ruliyanta. All authors had reviewed the findings and approved the final manuscript.

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