Low-Power Wide-Area Network and Long-Range Communication Technologies

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Long-Range (LoRa) technology, renowned for its low-power, long-range capabilities in Internet of Things (IoT) applications, faces challenges in real-world scenarios, including fading channels, interference, and environmental obstacles.

IoT Wireless Sensor Networks LoRa NLoS

1. Introduction

The Internet of Things (IoT) is revolutionizing industry and society worldwide, with an estimated 500 billion connected devices expected by 2030 [1][2][3]. The Industrial Internet of Things (IIoT) is a key enabler of Industry 4.0, providing ubiquitous connectivity and innovative services and applications [4]. The industrial environment is always a difficult challenge for wireless communication and wireless sensing. They present a series of constraints and difficulties that make the environment unique and different from other situations, such as offices, buildings, and indoor environments. Usually, the presence of high temperatures, excessive dust and particles, different obstacles, and metallic devices make it difficult to send data over long/medium distances at the right data rate and bandwidth [5]. Large numbers of IoT devices have been integrated into numerous specialized solutions and applications, connected by wireless Low-Power Wide-Area Network (LPWAN) technologies [6][7].

There are several competing LPWAN technologies today, adopting various techniques to achieve long-range, low-power consumption, and high scalability [8]. LPWAN networks have been designed to overcome the challenges of handling IoT and IIoT applications, enabling them to sense their surroundings, respond as required, and activate at any time to upload data to the cloud in real time [9]. LoRaWAN, a protocol in LPWAN, is widely regarded as one of the most effective and successful technologies in the field [10]. Defined by the LoRa Alliance, LoRaWAN uses the Long-Range (LoRa) physical layer to provide long-range wireless communications at low data rates and minimal power consumption, operating in unlicensed bands [11].

By 2026, LoRa will be used for more than 50% of LPWAN connections because of its adaptability for both indoor and outdoor applications [12]. It makes low-speed data transfer possible over great distances with little infrastructure and low power usage. It is employed in energy management, asset tracking, environmental monitoring, and machine monitoring applications [13]. Indeed, several issues can make implementing wireless communications in industrial settings challenging. Transmissions are altered, on the one hand, by interference brought about by signal reflection, echoes, and multipath attenuation. Multipath propagation is the outcome of these interferences, which are brought on by reflecting surfaces or obstructions. Furthermore, the interference caused by other wireless devices operating within the same frequency band also affects the overall performance of communication. Wireless communications have interfered with high noise levels produced by electromagnetic emissions from numerous industrial sources, such as large equipment, strong generators, and lasers [14][15].

In this direction, effective implementation of LoRa in IIoT applications requires careful consideration of several critical factors, including network coverage, signal strength, sources of interference, and specific data transmission requirements. To ensure optimal performance and seamless integration, it is essential to evaluate these factors in detail. Key metrics such as Signal-to-Interference-plus-Noise ratio (SINR) and Bit Error Rate (BER) are typically used to evaluate LoRa systems. The SINR plays a crucial role in determining the quality of communications, with higher values indicating stronger signals relative to interference and noise, resulting in improved data transmission efficiency and reduced errors. On the other hand, BER quantifies the accuracy of data transmission, with lower values indicating higher data reliability and quality. In the dynamic IIoT landscape, where robust communication solutions are essential to overcome interference problems, LoRa is emerging as a promising approach [16]. However, uncertainties remain regarding its performance in challenging Non-Line-of-Sight (NLoS) conditions, which are prevalent in the complex tapestry of urban environments.

2. Various Works using Low-Power Wide-Area Network and Long-Range Communication Technologies

Several research works have been conducted in the area of LPWANs for IoT applications. Magrin et al. focus on the performance of LPWAN technology, particularly in urban scenarios [17]. Simulation results demonstrate the scalability of LPWAN networks, achieving high packet success rates even with a significant number of endpoints. Another study by Askhedkar et al. explores the use of alternative frequency bands for LPWAN transmissions, emphasizing range and data rate considerations [18]. They present a path-loss model for long-range LPWAN communications. James et al. propose an innovative public transport tracking system using wireless communication between bus stops and a central base station [19]. This system significantly reduces costs compared to conventional tracking methods and provides real-time monitoring with minimal power consumption. Sanchez-Iborra et al. explore the integration of LPWAN communications within the vehicle ecosystem [20]. Specifically, they apply LoRa technology to vehicular communications, demonstrating unprecedented ranges and opening avenues for novel services in the vehicular ecosystem.

Patel et al. delve into the experimental study of LPWAN for mobile IoT applications [21]. Their results show the impact of mobility on LPWAN performance and highlight the need for mobility-aware LPWAN protocols. Petajajarvi et al. study the coverage of LoRa LPWAN through real-world measurements [22]. Their experiments show impressive communication ranges of over 15 km over land and nearly 30 km over water and present a channel attenuation model derived from measurement data for the 868 MHz ISM band. Sobot et al. present a two-tier LPWAN system based on Unmanned Aerial Vehicle (UAV) base stations designed for dynamic deployment in remote rural environments [23]. This innovative UAV-based LPWAN network adds a layer of mobile base stations

(Tier 2) to the existing macrocellular LPWAN network (Tier 1), providing connectivity to LPWAN user devices in areas without direct Tier 1 network coverage.

Abdul Razak presents a lane-change decision aid and warning system utilizing LoRa-based Vehicle-to-Vehicle (V2V) communication technology [24]. The system aims to enhance driver decision-making during lane changes on highways, providing visual and audible warnings to both host and approaching vehicle drivers. Using LoRa for V2V communication, the system offers contextual information to support safe lane-changing decisions. Soy focuses on LPWAN-based agricultural vehicle tracking using LoRa and NB-IoT technologies [25]. The study investigates coverage limits in urban, suburban, and rural environments, providing analytical expressions for maximum transmission range based on the data path-loss model. This research contributes to the development of LPWAN-based tracking systems for smart farms.

The global adoption of LoRa networks for diverse IoT applications necessitates a closer look at dense environments and the robustness of LoRa transmissions. Pham et al. focus on this concept, exploring the integration of a Carrier Sense mechanism to reduce collisions in both short and long LoRa messages [26]. Their work proposes a journey toward a Carrier Sense Multiple Access (CSMA) protocol tailored for LoRa networks, offering experimental validation through a low-cost IoT LoRa framework. The focus extends beyond theory, with practical implementation involving innovative long-range image sensor nodes. In their exploration, Benkhelifa et al. delve into LoRa waveform theory, unveiling its intricacies and establishing a comprehensive understanding [27]. They quantify orthogonality, presenting expressions in continuous- and discrete-time domains. Cross-correlation functions reveal non-orthogonality across various LoRa spreading factors, emphasizing the impact of displacement and bandwidth variation. The key finding is that LoRa modulation is inherently non-orthogonal.

Sandoval et al. enhance LoRa-based networks by optimizing transmission configurations for improved performance [28]. They introduce a bounding technique, reducing energy and time by up to 73%, enabling the derivation of individual node propagation behavior crucial for deriving optimal network-level configurations. This approach, surpassing traditional alternatives like LoRaWAN ADR, allows swift adaptation to environmental changes, resulting in a remarkable 15% performance boost. In another work, Sandoval et al. optimize the LoRa-based networks by addressing challenges in disseminating global configuration due to regional limitations on ISM bands [29]. They employ tools from the machine learning realm, formulating the updating process as a Reinforcement Learning (RL) problem. This approach results in optimal disseminating policies, enhancing per-node throughput by an impressive 147% compared to established alternatives. Tapparel et al. proposed a standard-compatible LoRa PHY Software-Defined Radio (SDR) prototype based on GNU Radio [30]. Experiments have been carried out to evaluate LoRa’s error rate for coded and uncoded cases to demonstrate that the developed open-source implementation provides a sound basis for further research. They illustrated the end-to-end experimental performance results of a LoRa SDR receiver at low SNR.

Table 1 compares the main aspects of various LPWAN and LoRa studies, providing a quick reference to identify their contributions and implications in the field of low-power, wide-area networking.

Table 1. Exploring LPWAN landscapes: a comparative overview.

Study	Focus	Experimental Setup	Major Findings
[17]	LPWAN performance in urban scenarios	Simulation	Scalability of LPWAN networks with high success rates
[18]	Alternative frequency bands for LPWAN	Not specified	Path-loss model for extended-range LPWAN communication
[19]	Wireless tracking system for public transport	Wireless communication between bus stops and central base station	Cost-effective real-time monitoring with minimal power consumption
[20]	LPWAN communications in vehicular ecosystem	Application of LPWAN technology (LoRa) to vehicular communications	Unprecedented coverage ranges in vehicular ecosystem
[21]	Experimental Study of LPWAN for mobile IoT applications	Not specified	Impact of mobility on LPWAN performance, need for mobility-aware protocols
[22]	Coverage of LoRa LPWAN through real-life measurements	Real-life measurements	Impressive communication ranges of over 15 km on land, nearly 30 km on water
[23]	UAV-based LPWAN system in remote rural environments	Two-tier LPWAN system with UAV base stations	Connectivity augmentation in remote rural areas
[24]	LoRa-based lane-change decision aid	Vehicle-to-vehicle communication using LoRa	Enhanced driver decision-making during lane changes
[25]	LPWAN-Based agricultural vehicle tracking	LoRa and NB-IoT technologies for agricultural tracking	Analytical expressions for maximum transmission range based on data path-loss model
[26]	Carrier Sense mechanism in LoRa networks	Low-cost IoT LoRa framework	Reduction of collisions in both short and long LoRa messages
[27]	Exploration of LoRa waveform theory	Quantification of orthogonality in LoRa waveforms	Nonorthogonality across various LoRa spreading factors
[28]	Bounding technique for individual node propagation	Reduction of energy and time for individual node propagation	73% reduction in energy and time, leading to optimal network configurations
[29]	Machine Learning for disseminating global configuration	Reinforcement learning for disseminating policies	147% increase in per-node throughput compared to alternatives

Study	Focus	Experimental Setup	Major Findings
[30]	Open-source LoRa physical layer prototype on GNU Radio	Real testbed implementation to evaluate the error rate of LoRa for uncoded and coded cases	Testbed error rate performance is within 1 dB of MATLAB simulations
Researchers' Work	Reliability of LoRa in NLoS conditions	Real-world settings with mobility, LoRa PHY SDR using GNU Radio	Comprehensive assessment of BLER, SINR, and data rate, demonstrating approximately 90.23% reliability

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ions, and optimization techniques, researchers' research introduces a practical dimension. Real-world experimental measurements consider environmental elements such as plants, buildings, and obstacles, providing a detailed assessment of LoRa’s performance. The innovation lies in the introduction of mobility to replicate NLoS circumstances, achieved through an open-source prototype of a LoRa physical layer Software-Defined Radio (SDR), developed using GNU Radio. This approach allows researchers to capture the dynamic impact of signal diffraction in realistic scenarios. Researchers comprehensive assessment of reliability, considering BER, SINR, and data rate, contributes to a holistic understanding of LoRa’s communication performance under challenging conditions. Beyond theoretical advancements, researchers' work offers practical insights crucial for the real-world deployment of LoRa technology, marking a significant stride in the pursuit of robust LPWAN solutions for IoT applications.

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