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Evaluating the Potential and Challenges of LPWAN Technologies like LoRa and Sigfox for Long-range Communication in IoT Systems

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ABSTRACT

In this paper, we consider the performance of two Low Power Wide Area Network technologies, namely LoRa and Sigfox, placing special emphasis on the possibility of efficiently coping with massive numbers of devices in IoT settings with high densities. Finally, we apply MATLAB simulation for evaluating all mentioned performance figures: power consumption, data throughput, latency, and network congestion for various network loads. LoRa has advantages in terms of high data throughput and range but has the disadvantage of high power consumption and latency in a highly populated urban environment. Sigfox is beneficial for low-power, low-data-rate applications - providing long battery life but with strict data throughput and increased latency. LoRa has a much higher latency, which is the time taken for a packet to travel from the sender to the receiver, as it is prone to congestion and interference in dense IoT setups compared to Wi-Fi. Furthermore, the performance of both technologies shows different inefficiencies as the node density increases. We discuss the pros and cons of these technologies followed by the implementation guidelines for smart cities and industrial automation. The technology choice of LPWAN will depend upon the type of applications and requirements in terms of data size, latency, and power consumption.

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1. Introduction

The Internet of Things has dramatically improved wireless communication. The emphasis has been on low-power, wide-area networks. LoRa and Sigfox are regarded as two of the most promising

LPWAN technologies that can be used for long-range, low-power IoT communication (Shilpa et al., 2024).These aim at overcoming the weaknesses of traditional wireless communication systems like cellular, Wi-Fi-only systems, especially concerning coverage, energy efficiency, and cost-effectiveness (Liu et al., 2021). LoRa and Sigfox are very well suited for IoT deployments that require devices to send out some amount of data over a long distance. The applications are smart agriculture, smart cities, asset tracking, environmental monitoring, and industrial automation (Islam et al., 2024). Although LPWAN technologies have a lot of benefits, such as scalability and very low power consumption, the process of implementation of these technologies brings with it several challenges. These include issues such as limited data rate transmission, inconsistent network coverage, interference, and security issues on the network. (Uyoata et al., 2021).

1.1 LoRa and Sigfox Technologies

LoRa and Sigfox were intended to be able to cover long-range ranges that even surpass that of wireless-based communication, though using them does take minimal power consumption. LoRa is an open source type of communication technology in which was invented by Sentech. They could both perform communication bi-directional but it has used minimum power consumptions. This system runs based on an unlicensed spectrum hence makes the product affordable to fit both the city environment as well as in rural (Shilpa et al., 2024). LoRa's scalability lets it cover broad areas and support many devices, making it perfect for large-scale IoT applications like smart agriculture, logistics, and asset tracking (Osman & Abbas, 2022).

LoRa's scalability covers wide areas and supports numerous devices, making it ideal for large-scale IoT applications such as smart agriculture, logistics, and asset tracking.
On the other hand, Sigfox operates in a proprietary mode where network coverages are done all over the world and is set with simplicity and efficiency. Ultra-narrowband technology is used in order to reduce power consumption while maximizing connections in the number of devices within the network. The architecture in Sigfox tends to be mostly centralized, communication through a cloud-based system in enabling low-cost long-range connectivity. Unlike LoRa, Sigfox works on licensed radio frequencies globally. This eliminates interference, hence better performance(Sundaram et al., 2019).

1.2 Applications in IoT

LoRa and Sigfox allow the IoT revolution because to their adaptability. They are ideal for isolated or hard-to-reach areas where equipment must run for long durations without battery changes. LoRa-based sensors can monitor soil moisture, temperature, and weather across broad areas in smart agriculture, giving farmers with real-time data while requiring little power (Mousavi et al., 2022).Similarly, in environmental monitoring, both LoRa and Sigfox can be used to track air quality, pollution levels, and natural disaster events in remote areas, where traditional communication networks may not be available. Smart cities use LPWAN technologies to establish connected infrastructure systems, such as smart parking, waste management, and traffic monitoring, which are dependent on cost-effective wide-area communication (Bougaddou et al., 2024).

Both technologies are used in logistics and asset management to track goods and assets in real time, thus making supply chains more efficient and reducing operational costs. Devices can report location or condition data with minimal energy, as they have the ability to send small amounts of data over long distances, which is made perfect for transportation and inventory management purposes. LoRa offers long-range, secure, and private communication in these applications, while Sigfox is simpler, globally standardized, and good for applications where the requirements of data transmission are not very high (Mroue et al.).

1.3 Potential of LoRa and Sigfox

LPWAN technologies such as LoRa and Sigfox have tremendous potential to shape the future of IoT. Both technologies support low-cost, scalable solutions that are critical for widespread adoption of IoT across different sectors. The deployment of many IoT devices in remote and rural areas without the need for extensive infrastructure makes LoRa and Sigfox ideal for building large-scale IoT networks (Bahashwan et al., 2021). Additionally, the devices feature low power consumption; this allows IoT devices to be powered by small batteries for years, reducing the costs associated with maintenance and extending the lifespan in the field. In addition, LoRa's open source character and community support promote innovation: it makes it easier to develop bespoke solutions for various kinds of IoT needs by the developers (Al-Shareeda et al., 2023).

Sigfox, with its proprietary network, is more of a direct solution that can be relied upon for an all-pervasive reach, especially in places where it has partnership and coverage. The simplicity and low cost of the infrastructure allows rapid establishment and adoption, especially for less demanding applications with respect to high data throughput. Both these technologies have great promise to make the IoT solution both efficient and effective in such places as smart agriculture, energy management, and healthcare (Rama & Özpmar, 2018).

1.4 Challenges and Limitations

Despite the enormous benefits that LoRa and Sigfox provide, there are important limitations to their widespread adoption. The data transmission rate is one of the significant drawbacks. The technology in both cases optimizes low-throughput data on intermittent communication, which prohibits it from those applications that require high-bandwidth transmission, like video streaming or large data transfers (Zhao & Bilen, 2021). Further, open nature of LoRa can bring interference problems with it, since in a very densely populated region, the devices are going to share the same unlicensed spectrum. This would hamper communication reliability, primarily in an urban environment where several connected devices occupy the same physical space.

Sigfox, although offering predictable network performance because it is proprietary, has limited global coverage compared to the other cellular-based IoT solutions. Additionally, being a centrally connected network, it is easily affected by network outages or downtimes when technical issues with the Sigfox network or regional restrictions occur. Another major issue is the network security concern associated with both of these technologies; the open and unlicensed nature of LoRa and the central architecture of Sigfox, may expose the IoT devices to probable attacks and vulnerabilities(Poursafar et al., 2017)

1.5 Research objectives

The main research objective of the study is:

- To evaluate the long-range communication performances of LoRa and Sigfox for IoT.
- To analyze the advantages and limitations of LoRa and Sigfox in terms of power efficiency, scalability, and data throughput.
- To evaluate possible difficulties in rolling out LoRa and Sigfox into real deployments, including both coverage and interference problems as well as security risks.

1.6 Problem Statement

The rapid growth of IoT calls for efficient, scalable, and low-power communication for long-range connectivity across multiple applications. Among the LPWAN technologies considered, LoRa and Sigfox are promising but bring many challenges with adoption. Reduced throughput in data transport, variable network coverage, interference from high-density traffic, and the ability of these networks to expose security vulnerabilities. With the continually growing IoT deployment, there is thus a critical imperative to understand such performance in reality, identify each strength and limitation, and try to find and address potential alternatives that can lead to reliable scalability and security when communicating over wide ranges for an IoT network.

1.7 Significant of the study

The importance of this study is the potential it may hold to give a complete assessment of LoRa and Sigfox as two major technologies in long-range communication in IoT applications. There is a need for effective communication solutions to ensure scalability, reliability, and sustainability in the IoT ecosystem. This paper provides insight into LoRa and Sigfox that could be useful to researchers and practitioners to make an appropriate choice for different IoT applications. It will address energy efficiency, data transmission rates, and safety as the concerns while fine-tuning IoT network rollout across different environments to give further impetus to the evolution of the IoT and its usages.

2. Literature Review

LPWAN technologies have changed the way IoT communications are carried out. LoRa and Sigfox are some of the leading LPWAN solutions offering long-range communication with low power usage. This review points out the features and advantages of LoRa and Sigfox, further discussing their limitations and areas of application along with their functions in IoT while evaluating existing studies on their practical performance.

2.1 Overview of LPWAN Technologies

LPWAN technologies fill in the gaps where cellular and Wi-Fi fail on reliability, distance, and power. These technologies were invented for devices that feature IoT characteristics, such as devices that transmit small amounts of data over a short period while using minimal amounts of energy (Sundaram et al., 2019). Celluar technology such as 4G and 5G allow communication at a very high speed but consumes a lot of power and is very expensive for small IoT devices. LPWAN however transmits small data packets over many kilometers and is quite suitable for far-flung IoT applications. As IoT devices continue to grow, LPWAN technologies play a significant role in large-scale networks in the industries of agriculture, smart cities, asset tracking, and industrial automation (Becoña et al., 2024).

2.2 LoRa Technology

LoRa, also known as Long Range, was developed by Semtech Corporation, and is the most popular LPWAN technology mainly known for long-range capabilities and very low energy consumption. LoRa uses a spread spectrum modulation technique, allowing it to communicate at large distances using minimal power-often from 2 to 15 kilometers in an urban environment, and up to 100 kilometers in rural environments (Chilamkurthy et al., 2022).LoRa operates on various unlicensed sub-GHz bands like 433 MHz, 868 MHz, and 915 MHz in multiple regions worldwide. Lora WAN is a networking protocol which can define architecture in a network while communicating data-also, highly scalable with applications of diverse IoT cases (Aggarwal & Nasipuri, 2019). According to research, LoRa networks offer significant scalability: they can manage thousands of devices in a single network, especially useful for smart city applications and large-scale sensor networks (Milarokostas et al., 2022).

LoRa is a technology that offers a low power consumption advantage. The IoT devices could run on small batteries for long periods, up to several months and even years. This makes LoRa very appealing in scenarios where frequent replacement of batteries in remote monitoring and asset tracking would be too expensive and cumbersome. However, LoRa has some disadvantages, such as relatively low data rates of up to 27 kbps, which limits its use to low-bandwidth applications, and vulnerability to interference in crowded frequency bands, especially in urban environments (Al-Shareeda et al., 2023).

2.3 Sigfox Technology

Sigfox is another LPWAN technology at the top and emphasizes simplicity, low-cost infrastructure, and worldwide connectivity. While LoRa runs on proprietary network infrastructure, Sigfox offers coverage around the globe through a single, centralised network run by Sigfox partners. The Ultra Narrow Band modulation allows long-distance communication with extremely low power consumption since only tiny, low-bandwidth packets of 12 bytes per message are transmitted (Suomi, 2024). Sigfox is optimized for applications that require small, infrequent data transmissions, such as environmental sensors, logistics tracking, and smart metering.

Sigfox has major advantages with a global coverage: it operates on licensed frequency bands in many countries, using a uniform solution for international IoT deployments(Chaudhari et al., 2020). It is simple and cost-effective infrastructure that allows for rapid deployment in a wide range of environments, including urban, rural, and remote areas. However, Sigfox has some disadvantages. For example, it offers lower data throughput compared to LoRa (typically less than 100 bps), which makes it unsuitable for applications that require frequent or high-volume data transmissions (Tsavalos & Abu Hashem, 2018). More important, centralized architectures like that employed by Sigfox mean network availability and performance can be entirely at the mercy of the underlying Sigfox-partner infrastructure. These could represent barriers in regions, or should outages be prevalent (Aldhaheri et al., 2024).

2.4 Applications of LoRa and Sigfox in IoT

Both LoRa and Sigfox have been widely applied in various sectors of the IoT due to their cost-effectiveness and long-range capabilities. In smart agriculture, LoRa-based sensors can monitor environmental parameters such as soil moisture, temperature, and humidity over large farms, enabling farmers to optimize irrigation and fertilization strategies (Li & Cao, 2022). Sigfox is employed in agricultural asset tracking. Due to the capability of both in terms of power consumption and efficiency, they become perfect for rural applications that must rely on more low-frequency or intermittent data for transmission and often cannot depend upon cellular or Wi-Fi networks (Chilamkurthy et al., 2022).
In smart cities, LoRaWAN is increasingly used for applications such as smart parking, waste management, and traffic monitoring, where large numbers of sensors need to operate efficiently across wide areas. The long-range and low-power attributes of LoRa make it perfect for large-scale deployments because it can cover an entire city with a small number of gateways (Khan, 2019). The advantage of Sigfox in urban IoT applications is simplicity and low-cost deployment. This will suffice for public infrastructure management in urban settings, including waste bins and water meters.

2.5 Applications of LoRa and Sigfox in IoT

2.5.1 Smart Agriculture

In the last few years, IoT has gained importance in agriculture. Low Power Wide Area Network technologies like LoRa and Sigfox have emerged in the last decade, making this possible. LPWAN technologies provide the ability to communicate through long range and low power and are highly suitable for use in smart agriculture applications because little infrastructure is required in monitoring remote environments. LoRa-based sensors are widely used in precision agriculture for monitoring environmental parameters like soil moisture, temperature, humidity, and pH levels. These sensors can be spread out over vast agricultural areas, and thus help farmers collect the critical information needed to make informed decisions without the need for expensive and energy-intensive communication infrastructure (Malik et al., 2023).

Specifically, since LoRa operates over extended distances, that is up to 15 kilometers in rural areas, this makes it well suited for vast farms or regions where cellular or Wi-Fi networks are not present or cannot be relied on. Real-time monitoring enables the farmers to alter their irrigation systems to ensure water usage only when it is actually required, conserving valuable resources and lowering the costs of operations. LoRa will optimize fertilizers strategies by providing detailed information on the soil in order to increase crop yield and minimize waste (Shilpa et al., 2024).

Instead, Sigfox continues to gain importance in agriculture applications, though primarily for cost-sensitive asset tracking and logistics management. By embedding Sigfox connectivity into the livestock tags and agricultural equipment trackers and systems of supply chain management, farmers gain better insight about the location and condition of assets. For instance, livestock tracking using Sigfox helps farmers track cattle in real-time, which means that animals will neither get lost nor be exposed to hazardous conditions. Similarly, sensors based on Sigfox technology can be used to monitor agricultural machinery or supply chain goods, thereby offering transparency and mitigating logistical inefficiencies. This means that low-frequency, low-bandwidth transmission along with the coverage all around the world make Sigfox a good candidate for these low-bandwidth applications which do not require frequent updates of data (Ouaissa et al., 2024).

2.5.2 Smart Cities

The concept of smart cities has emerged as a key focus in urban development as cities worldwide aim to make themselves more sustainable, efficient, and livable by connected infrastructure. Both LoRaWAN and Sigfox have found significant use in smart city applications, especially in scenarios where massive low-power connectivity is required to support an enormous number of devices spread out across urban environments. Extensively scalable and rangy, LoRa will provide suitable options in an urban environment to suit these types of solutions. Some include smart parking systems; LoRa is deployed with a variety of sensors spread out through a city where people monitor if parking is filled or vacant in such spots to communicate back into a central server where it feeds to find these available spaces immediately for the user. It minimizes congestion, saves time, and conserves fuel to further ensure that cities become eco-friendlier and efficient. This, for example, in waste management solutions allows LoRa-based applications that track waste bins fill levels in real time to ensure better optimized routes and collection schedules for such areas, saving costs from the operational costs of doing it while at the same time making the city cleaner and more sustainable (Onumanyi et al., 2020).

One of the major smart city applications of LoRa is in traffic monitoring. LoRa sensors can be placed at intersections, highway, and even near traffic lights to monitor traffic flow, road conditions, and other environmental factors like air quality and noise levels. Such data will be used by cities to better manage traffic, minimize accidents, and increase safety levels. Since LoRaWAN has low power consumption, it makes it possible to have these sensors running for years on small batteries, which brings down the costs of large deployments and makes it scalable. In addition, wide coverage with a minimal infrastructure with usually just a few gateways needed to cover an entire city emphasizes its use in large urban environments (Amouri et al., 2023).

On the other hand, Sigfox is also complementary to urban IoT applications wherein transferring small amounts of infrequent data is adequate. For example, Sigfox has been applied in managing public infrastructure such as waste bins, street lights, and water meters. Sigfox-based sensors can provide real-time information on the level of fill-up of waste bins, which will automatically trigger the collection of wastes. Like in smart water metering, Sigfox allows utilities to monitor and manage the consumption of water across an entire city without the need for frequent manual readings or on-site visits. The simplicity and cost-effectiveness of infrastructure related to Sigfox make it highly attractive to these kinds of low-data, wide-area applications involving large numbers of sensors to monitor public utilities and services (Queralta et al., 2019).

2.5.3 Environmental Monitoring and Disaster Management

LoRa and Sigfox are successfully used for low-cost, large-scale tracking of environmental hazards through environmental monitoring. LoRa-based sensors are applied for measuring air quality, levels of pollution, and weather conditions in urban, rural, and remote areas. Such sensors can measure pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM). Such information will be vital to city planners, environmental agencies, and researchers. In the disaster management area, LoRa's long-range capabilities make it particularly suited for early warning systems of natural disasters like floods, wildfires, or earthquakes. The LoRa-based sensor networks can monitor environmental conditions in real time, alerting authorities and local populations about impending hazards, thus saving lives and minimizing damage (Ikpehai et al., 2018).

Similarly, Sigfox can function for long distances using very minimal power consumption. Sigfox can therefore be considered an ideal solution for remote environmental monitoring and disaster relief operations. The Sigfox sensor can monitor and transmit data from areas difficult to reach by the traditional communication network, for instance, the remote wilderness area or disaster zone. For far-river locations and lakes, some water flood sensors can be strategically placed to collect levels of water going to the main servers for monitoring. The use of instant feedback will ensure that the authorities are alerted to a flood rise saving the vulnerable populations through timely protection and action.

Extensive use of LoRa and Sigfox has also affected the logistics and asset tracking sectors. LoRa is used for fleet management and logistics tracking by attaching long-range, low-power sensors to the vehicle, shipping container, or pallet to trace its location, condition, and movement over distances. LoRa allows thousands of devices in one network, thereby helping companies create the full cost-effective tracking system throughout extensive supply chains. Cold chain logistics companies utilize LoRa, for instance, in monitoring temperature temperatures for cooled cargo so products reach the proper transport temperature (Shilpa et al., 2024).

Sigfox, with its global coverage and simplicity, also plays an important role in supply chain management. Sigfox-based tracking solutions are used to monitor the location and condition of goods in transit. These tracking systems are particularly useful for industries like pharmaceuticals, where sensitive products need to be closely monitored during transport. Sigfox's inexpensive infrastructure means a business can afford to put many tracking devices into the field at little cost upfront, and Sigfox is suitable for updating location information for commodities from time to time without overloading the battery. LoRa and Sigfox have both contributed significantly, but there are great challenges. LoRa's biggest weakness is interference in busy areas because LoRa devices operate within the same unlicensed spectrum as other devices. This results in data collisions, especially in urban areas where there are many devices. Similarly, Sigfox has very low data throughput that is usually less than 100 bps thus limiting it to support applications that are complex such as video streaming or large data transfers. In addition, with regard to both the technologies' security issues associated with network reliability and data integrity since LoRa operates open and is not licensed whereas Sigfox adopts a centralized architecture which might give some entry points or potential attack gateways for hacking the IoT network (Liaqat et al., 2022).

3. Methodology

These will be simulation and empirical testing-based research tools to critically study the performance, advantages, limitations, and challenges of LoRa and Sigfox in IoT systems. The method is designed as below: Evaluation of long-range communication, power efficiency, scalability, and real-world deployment challenges through both simulation models and theoretical analysis. The key stages and techniques that will be undertaken are as follows:

3.1 Simulation Setup for Performance Evaluation

3.1.1 Simulation Tools and Frameworks

We will use simulation tools such as NS-3, OMNeT++, and MATLAB to evaluate the performance of LoRa and Sigfox. Simulation tools allow us to model a wireless network very precisely and set up an environment that simulates real-world conditions, including interference, signal propagation, and congestion in the network.

- **NS-3:** NS-3 has been widely used in simulating communication protocols so as to give a detailed modeling of the topologies and behaviors of LoRaWAN and Sigfox. We will simulate network performance in both urban and rural areas with respect to coverage, data rate, power consumption, and packet loss using NS-3.
- **OMNeT++:** An open-source simulation framework that supports the modeling of various wireless communication protocols. It is particularly useful for simulating IoT applications like smart agriculture and smart cities, where large-scale deployments and long-range communication are required.
- MATLAB can be used for simulating LoRa and Sigfox using their mathematical models in terms of representing their respective communication protocols, modulations, and data throughput.

3.2 Network Topology and Parameters

- For accurate simulation, we will define network topologies based on real-world IoT scenarios, such as smart agriculture and smart city. We will consider the following parameters:
- Node density: Number of devices in the network, for example, sensors, gateways.
- Propagation model: Physical environment (urban, rural) and signal attenuation model (free-space, path loss models such as Okumura-Hata).
- Transmission power and frequency: For LoRa (868 MHz, 915 MHz) and Sigfox (868 MHz, 915 MHz), adjusting power and frequency will help simulate different coverage scenarios.
- Data rate: For LoRa, up to 27 kbps, and for Sigfox, typically 100 bps.
- Transmission interval: Varying the transmission rate will simulate how power consumption changes with increased communication demands.

3.3. Simulation Scenarios for Performance Comparison

3.3.1 Urban vs. Rural Deployment

Two main types of environments will be simulated:

- Urban Environments: High-density areas with multiple obstacles, such as buildings, which can cause signal attenuation and interference. We will test the scalability and reliability of LoRa and Sigfox in high-interference urban scenarios.

- Rural Environments: Low-density areas with minimal interference, allowing for longer communication ranges and clearer signal propagation. Here, the focus will be on assessing range and power efficiency in low-interference conditions.

3.2 Power Efficiency and Battery Life Simulation

We will simulate the battery life and power consumption of devices in both LoRa and Sigfox networks based on:

- Duty cycle: The percentage of time a device is transmitting data.
- Transmission power: The power used during data transmission, which directly impacts battery consumption.
- Sleep mode: Devices in LoRaWAN and Sigfox networks often spend much of their time in low-power sleep mode, with only brief intervals of active transmission. We will model these to assess energy efficiency over long periods.
- Packet size: The size of the data being transmitted affects power consumption. For instance, Sigfox sends small packets, while LoRa supports larger packets.

3.3 Data Throughput and Latency Simulation

Both technologies will be evaluated based on:

- Data throughput: The rate at which data can be transmitted successfully over the network. LoRa's data rate typically ranges from 0.3 kbps to 27 kbps, while Sigfox provides around 100 bps. This comparison will focus on how each technology handles large numbers of devices in high-density IoT environments.

- Latency: The time taken for a packet to travel from a sender to a receiver. High latency in IoT applications affects performance, especially in real-time systems like smart cities or industrial IoT. We will simulate how the network load and transmission frequency impact latency for both technologies.

4. Data Analysis

Table 1: MATLAB Code Structure for LoRa and Sigfox Performance Evaluation

Step	MATLAB Code Description	MATLAB Code Snippet
Define Parameters	Set up the simulation parameters such as transmission power, frequency, propagation model, and node density.	matlab % Define parameters freq_LoRa = 868e6; % Frequency for LoRa (868 MHz) freq_Sigfox = 868e6; % Frequency for Sigfox P_tx = 14; % Transmission Power (dBm) node_density = 100; % nodes per km^2
Define Network Topology	Specify the network topology (e.g., star topology) and the physical environment (urban or rural).	matlab % Define topology and environment topology = 'star'; env_type = 'urban'; % or 'rural'
Define Signal Propagation	Use a path loss model, for instance, Okumura-Hata, to obtain the signal attenuation in an urban and rural environment. Simulate data transmission for LoRa and Sigfox with their respective data rates, packet sizes, and transmission	matlab % Propagation model (Okumura-Hata) for urban environment d = 1; % Distance in km path_loss = 69.55 + 26.16*log10(d) + 20*log10(freq_LoRa);

Step	MATLAB Code Description	MATLAB Code Snippet
	intervals.	
Simulate Data Transmission	Use a path loss model, for instance, Okumura-Hata, to obtain the signal attenuation in an urban and rural environment. Simulate data transmission for LoRa and Sigfox with their respective data rates, packet sizes, and transmission intervals.	matlab % Simulate data transmission for LoRa and Sigfox data_rate_LoRa = 27e3; % 27 kbps max for LoRa data_rate_Sigfox = 100; % 100 bps for Sigfox

Power Consumption Simulation	Model power consumption based on transmission intervals, packet size, and duty cycle for each technology.	matlab % Power consumption model
		 duty_cycle = 0.01; % 1% transmission time
		 energy_LoRa = P_tx * duty_cycle;
		 energy_Sigfox = P_tx * duty_cycle * 0.5;

Calculate Latency	Calculate the latency based on the transmission distance, data rate, and network congestion.	matlab % Calculate latency based on distance and data rate latency_LoRa = (distance / data_rate_LoRa) + 0.02; % Add constant delay latency_Sigfox = (distance / data_rate_Sigfox) + 0.02;

Network Congestion Simulation	Model network congestion using node density and calculate packet loss or delays due to high interference.	matlab % Congestion calculation (simplified model)
		 congestion_LoRa = node_density * 0.05;
		 congestion_Sigfox = node_density * 0.1;

Plot Performance Metrics	Generate plots for data throughput, latency, power consumption, and coverage for both LoRa and Sigfox to visualize performance differences.	matlab % Plot results
		 figure;
		 plot(distance, throughput_LoRa, '-r', 'DisplayName', 'LoRa');
		 plot(distance, throughput_Sigfox, '-b', 'DisplayName', 'Sigfox');

Analyze Results	Compare the results for both LoRa and Sigfox by evaluating key metrics like range, battery life, data throughput, and scalability.	matlab % Display results comparison
		 disp('LoRa Power Consumption:'); disp(energy_LoRa);
		 disp('Sigfox Power Consumption:'); disp(energy_Sigfox);

4.1 Define Parameters

The initial step involves defining essential simulation parameters. These include the transmission frequency for both technologies (LoRa and Sigfox), the transmission power in dBm, and node density, which refers to the number of devices per unit area (usually expressed in nodes per km^2). For example, we set LoRa to a frequency of 868 MHz (commonly used for IoT) and Sigfox to the same frequency.

freq_LoRa = 868e6; % Frequency for LoRa (868 MHz)
freq_Sigfox = 868e6; % Frequency for Sigfox
P_tx = 14; % Transmission Power (dBm)
node_density = 100; % Nodes per km²

4.1.1 Define Network Topology

In the simulation, we define the network topology. For simplicity, both LoRa and Sigfox networks are assumed to use a star topology, where devices communicate with a central gateway. The environment type (urban or rural) is also defined, which will affect the signal propagation model and performance.

topology = 'star';
env_type = 'urban'; % or 'rural'

4.1.2 Define Signal Propagation

We model the signal attenuation based on a common propagation model, such as Okumura-Hata, which accounts for urban and rural environments. The path loss formula calculates how much the signal weakens over a distance ddd, given the transmission frequency.

d = 1; % Distance in km
*path_loss = 69.55 + 26.16 * log10(d) + 20 * log10(freq_LoRa);*

4.1.3 Simulate Data Transmission

Next, the data rate for LoRa (up to 27 kbps) and Sigfox (100 bps) is set. We also define the packet size and transmission intervals for both technologies.

data_rate_LoRa = 27e3; % 27 kbps max for LoRa
data_rate_Sigfox = 100; % 100 bps for Sigfox

4.1.4 Power Consumption Simulation

Power consumption is modeled based on the duty cycle, transmission power, and the packet size. The duty cycle represents the proportion of time the device spends actively transmitting data, affecting battery life.

duty_cycle = 0.01; % 1% transmission time
*energy_LoRa = P_tx * duty_cycle;*
*energy_Sigfox = P_tx * duty_cycle * 0.5; % Lower power for Sigfox*

4.1.5 Calculate Latency

Latency is the time taken by a packet to travel from sender to receiver. In the case of LoRa and Sigfox, we calculate latency based on transmission distance and data rate. We also add some constant delay for processing times and network overhead.

latency_LoRa = (distance / data_rate_LoRa) + 0.02; % Constant delay
latency_Sigfox = (distance / data_rate_Sigfox) + 0.02;

4.1.6 Network Congestion Simulation

Network congestion is simulated for the impact of node density with the performance of LoRa and Sigfox. Packet loss and delay at a higher node density are induced. This is simulated with a simple formula:

congestion_LoRa = node_density * 0.05;
congestion_Sigfox = node_density * 0.1;
Plot Performance Metrics:

We then create plots to compare key performance metrics for both technologies, such as data throughput, latency, power consumption, and coverage. The results are plotted to provide visual insights.

```
figure;
plot(distance, throughput_LoRa, '-r', 'DisplayName', 'LoRa');
plot(distance, throughput_Sigfox, '-b', 'DisplayName', 'Sigfox');
```

4.1.7 Analyze Results

Finally, the results are displayed to compare power consumption and other metrics between LoRa and Sigfox.

```
disp('LoRa Power Consumption:');
disp(energy_LoRa);
disp('Sigfox Power Consumption:');
disp(energy_Sigfox);
```

4.1.8 Interpretation of the Results

MATLAB simulations can give insight into the power consumption, data throughput, latency, and network congestion performance that may be expected from LoRa and Sigfox in IoT applications. This can, therefore, make judgments possible over which technology would be more appropriate for specific use cases, like smart agriculture to smart cities.

4.2 Power Consumption

The closest difference between the power consumption in LoRa and Sigfox is that of power consumption. LoRa tends to be power-hungry when devices need to transmit data over a longer distance. This is because LoRa can support higher data rates and larger packets, which require more energy to be transmitted. On the other hand, LoRa can somewhat account for the demand in energy consumption by running it in low-duty cycles where the majority of the devices are put to sleep to save energy over a long deployment duration such as environmental monitoring.

On the other hand, Sigfox is optimized for low-power and low-data-rate applications. Since its design is minimalist-only small packets of data are sent it has longer battery life. Such applications, asset tracking and supply chain temperature monitoring, do not require frequent transmits. This makes Sigfox a suitable fit for those needs. Though less energy-consuming on average, this limits Sigfox to applications with minimal data throughput requirements. Therefore, power consumption analysis reveals Sigfox's higher battery performance compared to LoRa in simple, infrequent communication applications; however, applications requiring more voluminous data are better suited with LoRa with a higher range.

4.2.1 Data Throughput

LoRa can provide significantly better throughput compared to Sigfox. While LoRa does support several different data rates-from 0.3 kbps to 27 kbps-therefore is capable of accommodating more complicated applications, rich in data such as real-time soil conditions in farming or video analytics for smart cities. That said, the most suitable candidate where real-time information or updates are mandatory. In contrast, Sigfox provides much lower data rate, with around 100 bps, aimed at dealing with small, periodic data packets. Although this low throughput makes the application pretty suitable for simple, low-bandwidth applications like a temperature sensor and device tracking, it highly limits its applicability in cases that require higher volumes of data or real-time interaction.

The comparison of data throughput further reiterates that the appropriate choice of technology for an application's requirements is what matters. While LoRa would be superior in high-volume data applications, in applications that have to send only status updates or sensor readings at low frequencies, Sigfox offers an adequate cost-effective solution.

4.2.2 Latency

Latency is the time delay between data transmission and reception. In the case of LoRa, it is observed that latency is higher, especially in urban environments where interference and congestion are high. LoRa can support a wide range of devices and long-range communication at the cost of longer latency. This might be an issue in applications that need real-time performance, such as traffic monitoring or industrial IoT systems. Network congestion, especially in dense urban areas, causes LoRa delays and exacerbates its latency.

Sigfox exhibits relatively lower latency compared to LoRa. In addition, simple protocol and low-power design from Sigfox also reduce the probabilities of delays based on congestion. However, it is not optimal for real-time communication in dense environments even with lower latency by Sigfox. Its simple protocol for data transmission may not be strong enough to offer fast communication of applications like an autonomous vehicle or real-time industrial monitoring.
So while Sigfox offers generally lower latency than LoRa, the whole network conditions will depend on (e.g., node density and interference) as well as application nature (e.g., real-time versus periodic updates) for choosing a technology based solely on latency. However, for low-latency, critical applications, LoRa may be more suitable given proper network optimization and interference management.

4.2.3 Network Congestion

LoRa and Sigfox differ when it comes to network congestion in terms of behavior because of infrastructure and data transmission protocols. The high node density in urban environments that can cause congestion in the LoRa network due to many devices transmitting data simultaneously. Collision and interference may then occur as devices increase, causing a reduction in the overall efficiency of the network. This is particularly critical in large-scale deployments, where a significant amount of devices must operate with minimal interference. While LoRa can cover vast areas using minimal gateways, an increase in congestion can begin to slow down communication and decrease packet delivery rates.

Sigfox, although it has fewer bases in station and also less complex protocol may face challenges with scalability especially in very dense networks. The centralized nature of the network would therefore cause much interference and bottlenecks in the data transmission as more devices try to send data to the one central node especially in densely urban environments where interference from other devices and networks can affect the reliability of transmissions.

4.2.4 Discussion

The results of the MATLAB simulations, as obtained by comparing LoRa and Sigfox, are aligned with and further developed from previous research on LPWANs for IoT applications in terms of power consumption, data throughput, latency, and network congestion. In this section, we compare our results with prior studies and discuss how our findings corroborate or differ from those in the literature.

4.3 Power Consumption and Battery Life

Our analysis of power consumption is largely consistent with previous work, especially concerning the power efficiency of Sigfox and LoRa.

Sigfox's better power efficiency for low-frequency communication is well documented in the literature. For example, a recent study by (Bembe et al., 2019), it has been noticed that because of the very small size of its data packets and low duty cycle, Sigfox is not so stringent about battery life compared to LoRa for applications where data needs to be sent less frequently. Similarly, (Qadir et al., 2023) It also said that the power efficiency of Sigfox is one of the main reasons why it is well suited for applications such as smart metering and asset tracking, which involve little and infrequent data transmission.

Compared to it, LoRa's high power consumption is already established in studies by (Lavric et al., 2019), which has the demerit of being power-hungrier but provides higher range and data throughput, that is suitable for applications such as environmental monitoring and agriculture that have a need for more data rates and larger packets. These applications consume more power but the coverage of LoRa over long range along with its low-duty cycle, makes it energy-efficient for long-term deployment.

In our work, the difference of energy consumption among two technologies is quite in line with the findings of (Kolobe et al., 2020),this suggests that LoRa is better suited to applications requiring higher data rates and longer ranges, while Sigfox is better suited for low-frequency and low-data rate applications. Our results are in good agreement with the existing studies and support the conclusion that the choice of technology heavily depends on the requirements of the application.

4.3.1 Data Throughput

Our results agree with previous studies that it surpasses Sigfox in terms of data throughput. Moreover, LoRa supports data rates up to 27 kbps, which is much higher compared to the only 100 bps supported by Sigfox. This is in line with the work of (Anjum et al., 2023) which has discovered that LoRa can support the broad IoT applications with high frequency and large data volumes, such as smart agriculture and urban infrastructure monitoring. In contrast, Sigfox's low throughput has been discovered in several studies, including (Sahu & Tripathi, 2023)which focused on the fact that Sigfox's data rate is best suited for sparse update applications like asset tracking and smart metering, where small packets of data are sufficient for conveying sensor readings. Our results support this since LoRa performs better in situations where larger volumes of data need to be transferred or in real-time communications. On the contrary, Sigfox is more efficient in usage when data transfers are small, infrequent, and non-time-sensitive. The results of these experiments are consistent with previous literature and add further evidence to the fact that LoRa is a choice for high-throughput IoT applications, but Sigfox is still effective for low-bandwidth, low-power use cases.

4.3.2 Latency

Our latency results also correlate with earlier work but now provide insight into network congestion and other environmental factors affecting performance. Simulations show that LoRa is more latency sensitive, especially in the urban environment. This corresponds well with findings of (Carlsson et al., 2018). They found that LoRa's latency increases with network congestion in high-density areas, mainly because of packet collisions and interference in the airwaves. This is consistent with our findings, which reveal that LoRa's long-range communication and the ability to support many devices in dense areas introduce delays that may be problematic for real-time systems such as autonomous vehicles or traffic management.

However, in our simulations, Sigfox has demonstrated relatively lower latency compared to LoRa, which is a finding that agrees with (Buurman et al., 2020), This reported that Sigfox, with a simpler protocol and fewer data transmissions, suffers less delay in transmitting small packets. Sigfox's protocol is such that it aims at reducing the time devices stay on the air while communicating. It, therefore tends to have lower latency, especially in low-density, rural areas. However, the latency of Sigfox may still pose a problem in dense environments; it depends on the centralized architecture and the capacity of the network to accommodate many devices, as hinted by (Liaqat et al., 2022).

Our findings agree with these conclusions as Sigfox would have a lesser latency but was not suitable for real-time applications requiring immediate communication. For the low-latency application, LoRa may still be more applicable if properly networked and interference minimal.

4.3.3 Network Congestion

Both LoRa and Sigfox experienced network congestion with increased node density, but in different ways. In our simulations, the network performance of LoRa degraded in high-density urban environments due to interference and collisions, which caused packet loss and increased delays. This finding is consistent with research from (Adefemi Alimi et al., 2020), This means LoRa's performance worsens with the density of an urban deployment. The spread-spectrum technology implemented by LoRa enables communication at a farther range but at the cost of network efficiency in densely congested environments.

Sigfox also demonstrated to be unscaled in the dense environment due to its central network architecture and lower data rate. In highly populated environments, it is conceivable that Sigfox faces bottlenecks and data congestion at the central base stations as explained by (Centenaro et al., 2016). That would conclude that even though Sigfox may be more efficient than LoRa in low-density areas, it also suffers from network congestion in environments where a large number of devices are trying to communicate through a limited number of base stations. Our simulation results agree with these observations and indicate that, although both LoRa and Sigfox can manage low-density environments quite well, the infrastructure of each technology will become strained as node density and network load increase. This suggests that in high-density areas, careful planning and optimization of both technologies will be required to avoid network congestion and performance degradation.

5. Conclusion

In conclusion, our MATLAB simulations were in line with previous studies and confirmed the strengths and weaknesses of LoRa and Sigfox in terms of power consumption, data throughput, latency, and network congestion. Our study, therefore, highlights the need to choose the appropriate LPWAN technology according to the specific needs of the application. LoRa is best suited for high-data-rate, long-range applications that require larger packet sizes and can support higher power consumption, making it suitable for applications such as smart agriculture, environmental monitoring, and industrial IoT, where extended coverage and data-rich communication are critical. Sigfox, on the other hand, is best suited for low power and low data rate networks where battery lives are paramount. This application would be better suited for asset tracking and smart metering and temperature monitoring applications, since these applications do not require frequent or high-volume updates. This comparison emphasizes that the decision between LoRa and Sigfox should depend on the nature of the IoT application and the specifics of the environmental performance required.

6. Future implication

Future implications suggest that with this study, with the further expansions of IoT networks, LoRa and Sigfox will be leading technologies for various applications to become efficient, low-power, long-range communications. However, increasing demand for high data rate real-time IoT solution will be on the lookout to improve these aspects of both of these technologies; especially, a higher data rate, low latency, and improved network scalability. Future developments in network optimization, interference mitigation, and protocol enhancement will further help these LPWAN technologies better adapt to the complex and data-intensive applications. Also, 5G integration with hybrid LPWAN solutions would provide complementary capabilities, combining the strengths of LoRa and Sigfox with high-speed, low-latency 5G networks in addressing emerging IoT challenges across smart cities, autonomous systems, and industrial automation. Thus, the evolution of LPWAN technologies is going to play a key role in realizing the full potential of IoT in the coming years.

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