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Original Scientific Paper

COMPARISON OF LORAWAN AND MOBILE IOT NETWORKS AND SERVICES

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Abstract: The Internet of Things (IoT) is transforming the telecom world by introducing billions of low power devices each day since the start decade of this century. Massive IoT deployments are provided by using mobile IoT technologies in 4G, 5G and beyond. On the other side, there are widespread non-cellular or non-mobile IoT solutions such as LoRaWAN that provide long-range, low-power solution in areas with limited mobile coverage. As more low power and low demanding IoT devices connect to the global Internet, choosing the right network technology for their connectivity is becoming increasingly important. Thus, this paper compares LoRaWAN, used for wide-area networks connecting low power devices, and mobile IoT technologies like Narrowband IoT (NB-IoT) and LTE-M. We compare how these technologies handle data, their battery life, how fast they send data, how many devices they can support, how much data they can handle, and how far their network can reach. This paper contributes to being able to decide which technology is best for different IoT scenarios.

Keywords: 5G networks, Internet of Things, IoT, latency, long range, LoRa, LoRaWAN, LTE-M, NB-IoT, network coverage, QoS, scalability.

СПОРЕДБА НА LORAWAN И МОБИЛНИ IOT МРЕЖИ И УСЛУГИ

Апстракт: Интернетот на нештата (IoT) го трансформира светот на телекомуникациите со воведување милијарди уреди со мала моќност секој ден од почетокот на деценијата на овој век. Масовните распоредувања на IoT се обезбедени со користење на мобилни технологии на IoT во 4G, 5G и пошироко. Од друга страна, постојат и не-целуларни решенија за IoT кои се широко распространети, како што е LoRaWAN, што обезбедува долгорочно решение со мала моќност во области со ограничена мобилна покриеност. Со оглед на тоа што сè повеќе IoT уреди со мала моќност и ниски барања се поврзуваат на глобалниот Интернет, изборот на вистинската мрежна технологија за нивно поврзување станува сè поважен. Оттука, овој труд го споредува LoRaWAN, кој се користи за мрежно поврзување на IoT уреди со мала моќност на поголеми растојанија, и мобилните IoT технологии како теснопојасниот IoT (NB-IoT) и LTE-M. Гледаме како овие технологии се справуваат со податоците, нивната батерија, колку брзо испраќаат податоци, колку уреди можат да поддржат, колку податоци можат да ракуваат и до каде може да достигне нивната мрежа. Зборуваме и за тоа колку лесно се поставуваат и колку чинат. Овој труд допринесува да може да се одлучи која технологија е најдобра за различни сценарија за IoT.

Клучни зборови: 5G мрежи, Интернет на нештата, IoT, латентност, долг дострел, LoRa, LoRaWAN, LTE-M, NB-IoT, мрежна покриеност, QoS, приспособливост

I. INTRODUCTION TO IOT

THE Internet of Things (IoT) is a technology that enables intelligent sensing and actuation for various objects by exchanging information with a core network. This allows people to remotely manage or monitor the behavior of devices from systems located hundreds of kilometers away using various types of IoT technology. In both academia and industry, IoT-based systems have proliferated over the last few years, providing multiple new applications, such as smart homes, intelligent transportation, smart hospitals, and smart cities [1].

Massive IoT refers to applications that are less latency-sensitive and have relatively low throughput requirements but require a huge volume of low-cost, low-energy consumption devices on a network with excellent coverage [2]. The growing popularity of IoT use cases in domains that rely on connectivity spanning large areas, and the ability to handle a vast number of connections, is driving the demand for massive IoT technologies.

One of the core components of IoT networks is connectivity, provided by various types of wired and wireless (terrestrial and non-terrestrial) communication technologies [2]. Among these, Low-Power Wide-Area

Network (LPWAN) has emerged as the preferred connection option for IoT networks due to its long communication range, low energy consumption, and low cost. LPWAN protocols can provide connectivity for numerous low-power battery-operated devices used in delay-tolerant applications with limited throughput per device.

LPWAN technologies like LoRaWAN, Sigfox, NB-IoT, and LTE-M have their own technical features, business models, and deployment strategies. For instance, NB-IoT and LTE-M, standardized by the 3rd Generation Partnership Project (3GPP), operate on the licensed spectrum, offering high data rates and bandwidth with quality-of-service guarantees, albeit at the cost of higher energy consumption and complexity. In contrast, Sigfox and LoRaWAN operate on the unlicensed spectrum, providing long-range communication with low power consumption, suitable for applications where cost and energy efficiency are critical [1], [3].

In summary, the IoT ecosystem's growth, and diversification of its applications, underscore the importance of robust, scalable, and efficient connectivity solutions. LPWAN technologies play an important role in addressing these needs, enabling the deployment of massive IoT networks that support a wide range of applications and services.

II. LoRaWAN Fundamentals

Standardized by the LoRa Alliance in 2015, LoRaWAN is a transformative IoT technology leveraging LoRa's chirp spread spectrum (CSS) modulation in sub-GHz ISM bands, such as 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia [4]. CSS spreads a narrow-band signal over a broader bandwidth, enhancing interference resilience, reducing noise, and securing signals. LoRaWAN enables bidirectional communication with adaptable data rates across six spreading factors (SF7 to SF12), balancing communication range and data rates [4]. This adaptability enhances network robustness but can increase deployment costs due to the need for multiple base stations.

This section explores LoRaWAN's architecture and key technologies, including physical and MAC layers, communication protocols, and data handling mechanisms. It highlights how LoRaWAN ensures efficient power use, robust security, and reliable device connections, making it highly effective for diverse IoT applications.

A. LoRa Physical Layer

Developed by *Semtech* in 2014, the LoRa physical layer employs chirp spread spectrum (CSS) modulation across sub-GHz ISM bands [5]. This technique produces chirp signals that maintain a consistent duration but vary in frequency from f_0 to f_1 over time T. In LoRa, there are two primary types of chirps: the base chirp and modulated chirps. The base chirp begins at a minimum frequency $f_{min} = -\frac{BW}{2}$ and rises to a maximum of $f_{max} = +\frac{BW}{2}$, with BW representing the spreading bandwidth of the signal [5]. Modulated chirps are derivatives of the base chirp, cyclically time-shifted to create distinct patterns essential for encoding different digital inputs.

Chirp signals enable robust communication by encoding symbols identified at the receiver through Fast Fourier Transform (FFT) analysis [5]. This process ensures reliable data transmission, even in challenging environments.

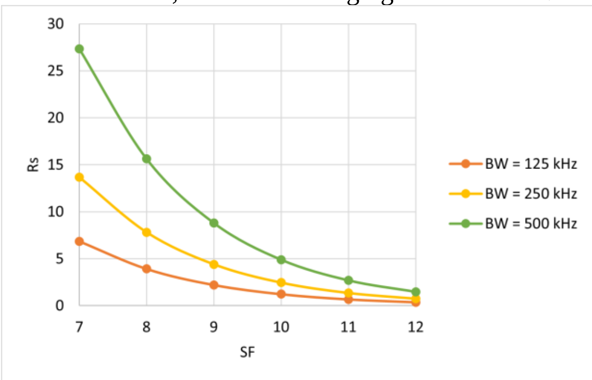

Fig. 1. Variation of the symbol rate Rs as a function of spreading factor for different bandwidths

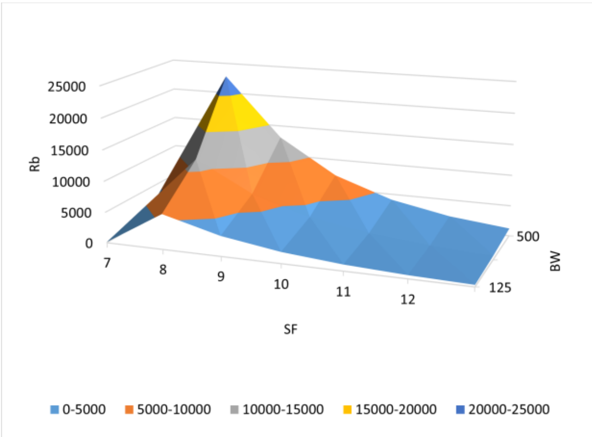

Fig. 2. Data rate Rb as a function of spreading factor and bandwidth for a code rate of 4/5

To describe this process quantitatively, we use two key equations. Equation (1) expresses the symbol rate R_s, where SF is the spreading factor affecting the number of possible cyclic shifts of the base chirp, and BW is the bandwidth in Hz that the signals occupy:

$$R_s = \frac{SF \times BW}{2^{SF}} \tag{1}$$

Equation (2) defines the data rate R_b, incorporating the code rate CR, which adjusts the robustness and error correction capacity:

$$R_b = SF \times \frac{\frac{4}{4+CR}}{\frac{2^{SF}}{BW}} \times 1000 \tag{2}$$

These equations highlight how adjustments in the spreading factor and bandwidth influence the efficiency and capacity of data transmission, essential for maintaining reliable communication across diverse and challenging environments [5].

Following this discussion, Figures 1 and 2 visually demonstrate the relationships outlined in equations (1) and (2), respectively. Figure 1 shows the variation in symbol rate R_s for different bandwidth settings, emphasizing the decrease in R_s with higher SF values. Figure 2 illustrates the impact of similar factors on the data rate R_b for a code rate of 4/5, suggesting similar trends for other code rates (4/6, 4/7 and 4/8).

The LoRa packet structure includes a preamble critical for synchronizing receivers with transmitters. The preamble can extend up to 65,536 symbols, with a fixed sequence followed by a programmable segment to aid in frame detection and synchronization [5]. This design enhances detection accuracy and network reliability, even in diverse operating conditions.

B. LoRaWAN MAC Layer

The MAC layer in LoRaWAN is essential for how devices communicate within the network, sitting above the PHY layer to translate raw data into structured communication between end devices and network infrastructure. It orchestrates complex operations to ensure reliable, efficient, and secure data transmission [6].

A critical function of the MAC layer is managing data rate and network bandwidth through the Adaptive Data Rate (ADR) protocol. ADR dynamically adjusts data transmission settings based on network conditions and device needs, optimizing signal quality and extending battery life [1].

1) Device Classes and Communication Protocols

LoRaWAN devices are categorized into three classes based on network requirements and power availability:

- **Class A**: The most energy-efficient, operates on a schedule allowing two short downlink receive windows after each uplink, suited for minimal downlink communication [1], [7].
- **Class B**: Adds scheduled downlink windows synchronized with gateway beacons to Class A's capabilities, facilitating more predictable communication [1], [7].
- **Class C**: Offers nearly continuous downlink receive windows, ideal for applications requiring low latency communication [1], [7].

2) Network Operations

The LoRaWAN MAC layer employs several protocols and strategies to enhance communication efficiency and ensure network stability:

- **Adaptive Data Rate (ADR)**: ADR optimizes communication settings by adjusting data rate (DR), spreading factor (SF), and transmission power (TP) based on network conditions. In ideal scenarios, it increases DR and reduces SF to conserve battery life by shortening transmission time. Under challenging conditions, ADR increases SF to ensure message delivery, albeit at slower rates. Additionally, ADR modulates transmission power to minimize energy use and network interference for nearby devices, while boosting power for distant ones to maintain stable connections.
- **Joining Procedure and Security**: Secure network access is ensured through two methods: Over-The-Air Activation (OTAA) and Activation by Personalization (ABP). OTAA provides robust security by authenticating devices with the network server during the join process, generating dynamic encryption keys. ABP offers quicker setup by pre-storing static keys, though it is less secure as keys remain unchanged unless updated manually. OTAA is preferred in environments requiring high security, while ABP suits applications where rapid deployment is prioritized.
- **Error Handling and Data Integrity**: Error correction codes and acknowledgment processes are used to detect and rectify data transmission errors, ensuring that messages are accurately received.
- **Channel Management**: The MAC Layer manages channel utilization to avoid collisions and ensure fair bandwidth distribution among all devices. This includes dealing with channel interference and implementing duty cycle restrictions as per regulatory requirements.
- **Downlink Scheduling**: Especially for Class B and Class C devices, the MAC layer schedules downlink transmissions to optimize gateway resources and ensure timely delivery of data without causing network congestion.

This comprehensive approach to network management underscores LoRaWAN's capability to maintain efficient and reliable communication across diverse IoT environments.

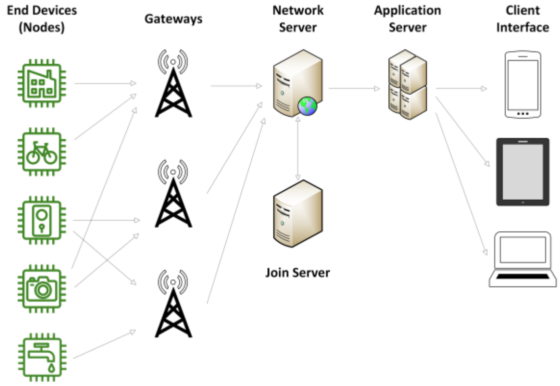

Fig. 3. LoRaWAN topology

C. LoRaWAN Network Topology

The topology of LoRaWAN is a fundamental aspect that enables its widespread application in IoT. It consists of several key components, each playing an essential role in the network's functionality. Understanding the interplay between these elements is very important to appreciate the efficiency and scalability of LoRaWAN. A LoRaWAN network has a star-of-stars topology, as illustrated in Figure 3, and we will explore each component in detail [8].

1) End Devices (Nodes)

End-devices, or nodes, are the 'things' in IoT. They typically comprise a microcontroller, a radio unit, and peripherals like sensors. These nodes use single-hop LoRa communication to transmit data to gateways, boasting low power consumption and extensive range capabilities [8].

2) Gateways

Gateways act as the communication hubs, equipped with LoRa transceivers and baseband processors for decoding multiple channels. They forward messages from nodes to the network server via IP connections like WiFi, Ethernet, or cellular networks, primarily using protocols such as *Semtech*'s UDP and MQTT [8].

3) Server Components

- **Network server:** At the core of the network's architecture, it manages access, routes messages, and handles node authentication and authorization, ensuring efficient message delivery to appropriate LoRaWAN applications [8].

- **Application servers:** Process data from nodes to create downlink payloads for applications, providing essential interfaces for data analysis and management [8].
- **Join server:** Manages over-the-air activation, distributing session keys to ensure secure connectivity within the network [8].

4) Client Interfaces

Client interfaces are the devices through which end-users interact with the system, ranging from mobile phones to desktop computers. They display data and provide interactive controls for managing the IoT environment.

III. LoRaWAN Technologies

While the fundamentals of LoRaWAN provide a solid understanding of its architecture and basic operational mechanisms, the "LoRaWAN Technologies" section delves into the advanced technical enhancements and integrations that expand its applicability and performance in the IoT ecosystem. This section will explore how recent innovations and forward-thinking applications are setting LoRaWAN apart in the competitive landscape of wireless communication technologies.

A. Advanced CSS Modulation Techniques

The LoRa physical layer, introduced in 2014, uses Chirp Spread Spectrum (CSS) modulation to enable long-distance communication while mitigating interference, fading, and Doppler effects. CSS modulates signals into chirp pulses that vary in frequency over time, spreading the signal across a broader bandwidth and reducing noise [1]. Unlike pseudo-random codes used in other spread spectrum techniques, CSS uses base and down-chirps, improving clarity and reach.

The Spreading Factor (SF) determines the number of bits encoded per symbol, ranging from 7 to 12. Higher SF values extend communication range but increase energy usage, while lower values support faster transmission at reduced range. Adjusting transmission parameters, such as bandwidth, coding rate and carrier frequency, further tailor performance based on application requirements. These features, combined with flexible gateway and server configurations, make LoRaWAN suitable for diverse IoT applications [1].

B. Energy Efficiency in LoRaWAN

Energy efficiency is critical for IoT devices in remote or hard-to-reach locations. LoRaWAN excels in this area by using Adaptive Data Rate (ADR) to optimize power usage based on signal quality. For example, ADR adjusts data rates to conserve energy in favorable conditions, extending battery life [8]. Additionally, devices operate in low-power sleep modes, waking only for necessary transmissions, further reducing energy consumption.

Operating on unlicensed frequency bands eliminates spectrum costs, enhancing affordability for businesses and municipalities. These factors, combined with LoRaWAN's long-range capabilities and duty cycling, make it a sustainable choice for IoT systems requiring minimal maintenance and long operational lifespans.

C. Duty Cycling in LoRaWAN

Duty cycling minimizes energy consumption by keeping devices in sleep mode and activating them only when needed. Techniques such as dual SYNC words and distinct uplink/downlink preambles reduce unnecessary energy use by quickly determining message relevance [5]. In dense networks, optimized receive windows and regulatory compliance with duty cycle limits (e.g., 0.1% to 10%) ensure efficient operation while adhering to local guidelines [7].

By balancing energy-saving features with regulatory requirements, duty cycling allows LoRaWAN devices to sustain long-term deployments, even in dense or regulated environments. These mechanisms solidify LoRaWAN as an energy-efficient and cost-effective solution for IoT applications.

IV. Mobile IoT for Telecom Operators (NB-IoT and LTE-M)

As IoT expands, the rollout of 5G networks is transforming connectivity standards, supporting a growing number of devices. Coexisting with 4G, 5G drives innovation in mobile IoT technologies like Narrowband IoT (NB-IoT) and LTE for Machines (LTE-M), which play critical roles in addressing diverse IoT needs, from simple sensor networks to complex industrial systems.

A. Technical Specifications and Advantages of NB-IoT and LTE-M

NB-IoT focuses on low-power, cost-effective communication for distributed devices, offering strong indoor and underground signal penetration. Standardized in 3GPP Release 13, it operates in LTE carriers, guard bands, or standalone mode, using a narrow 180 kHz bandwidth for high spectrum efficiency. Its simplicity keeps costs low, making it suitable for applications like utility metering and agricultural monitoring [9].

LTE-M, also standardized in 3GPP Release 13, supports higher data rates and mobility, with peak speeds up to four times faster than NB-IoT. It is ideal for applications requiring voice support and real-time data, such as health monitoring and vehicle tracking. LTE-M's energy-saving features allow for up to 10 years of battery life, while its compatibility with legacy networks and flexible duplex configurations enhances versatility [9], [10].

Both NB-IoT and LTE-M strengthen cellular networks to meet diverse IoT demands, reflecting strategic advancements in mobile technology.

B. Strategic Role of NB-IoT and LTE-M in Enhancing 5G IoT Connectivity

As 5G networks expand, NB-IoT and LTE-M have become integral to addressing the limitations of earlier network generations. These technologies enable large-scale, energy-efficient connectivity, supporting high device densities and enhancing indoor coverage.

NB-IoT excels in low-data, long-distance applications such as utility metering and agricultural monitoring, while LTE-M supports higher data needs and mobility for use cases like health monitoring and vehicle tracking [10]. Together, they fulfill 5G's goal of connecting diverse IoT environments, from urban centers to remote regions, with reliable and scalable solutions.

As 5G grows, NB-IoT and LTE-M will underpin advanced IoT systems ranging from simple sensors to complex smart grids and industrial processes, driven by significant investments from mobile operators upgrading infrastructure to meet increasing IoT demands [9], [10].

V. Comparison of LoRaWAN Non-Mobile and IoT Mobile Technologies NB-IoT and LTE-M

As the Internet of Things (IoT) grows, it is important to pick the right technology for different IoT applications. In this section, we will compare three major IoT technologies: LoRaWAN, NB-IoT, and LTE-M. Each one has its own benefits and fits different kinds of IoT setups. We will look at several important factors that you should consider when choosing an IoT technology. These factors include quality of service (QoS), battery life, latency, how many devices it can support, how much data it can send, how far and wide it can cover, how it is set up, and how much it costs. Understanding these points will help decide which technology is best for certain IoT needs, whether they are mobile or fixed. This comparison will clearly show how each technology works in different situations and explain why one might be better than another in certain cases.

A. Quality of Service (QoS)

QoS measures the reliability, data rate, and overall performance of a network, making it crucial for applications requiring consistent and dependable data transfer.

- **LoRaWAN**: LoRaWAN uses chirp spread spectrum (CSS) technology, providing a reliable connection in interference-prone environments. It dynamically adjusts data rates through bandwidth and spreading factor changes based on signal strength and distance. While this adaptability enables stable connections over long ranges, it can limit data rates when operating at extended distances [4].
- **NB-IoT**: By operating on a licensed LTE spectrum and employing synchronous protocols, NB-IoT ensures a stable connection with higher throughput than LoRaWAN. The licensed spectrum minimizes interference, making NB-IoT ideal for critical applications requiring predictable connectivity, such as smart metering and urban IoT deployments [11].
- **LTE-M**: LTE-M shares the licensed spectrum advantage with NB-IoT but supports higher data rates and lower latency, making it suitable for data-intensive and real-time applications like wearable health devices and emergency systems. Its robust QoS is tailored for scenarios where both reliability and responsiveness are vital [12].

In terms of QoS, both LTE-M and NB-IoT outperform LoRaWAN in QoS due to their licensed spectrum and advanced protocols. While LoRaWAN excels in long-range, low-cost deployments with minimal infrastructure, its QoS is less suited for high-data-rate or latency-sensitive applications.

B. Battery Life

Battery life is a critical factor in IoT deployments, especially for devices in remote locations where frequent maintenance is impractical. Each technology employs different strategies to optimize energy efficiency.

- **LoRaWAN**: Renowned for its low power consumption, LoRaWAN uses asynchronous communication, where devices transmit data only when necessary. Following the ALOHA protocol, this minimizes energy use and allows devices like environmental sensors or agricultural monitors to operate for extended periods on a single battery charge [11].
- **NB-IoT**: NB-IoT incorporates power-saving features such as extended Discontinuous Reception (eDRX) and Power Saving Mode (PSM), enabling devices to remain in low-power states for long durations, waking only for scheduled transmissions. While NB-IoT requires more power during active communication due to its synchronous protocol, these features make it ideal for use cases like utility metering and asset tracking, where data is reported intermittently [13], [14].
- **LTE-M**: LTE-M also leverages eDRX and PSM for energy efficiency, allowing devices to balance extended battery life with higher data rates and frequent communication needs. Unlike NB-IoT, LTE-M supports advanced features such as voice over LTE while maintaining efficient power usage, making it suitable for applications requiring both performance and longevity [14].

Each technology offers unique advantages: LoRaWAN excels in ultra-low-power, infrequent transmissions, NB-IoT balances efficiency with reliability for periodic updates, and LTE-M combines battery life with robust performance for versatile applications. Choosing the right technology depends on the device’s operational needs and the desired battery longevity.

C. Latency

Latency, the time taken for data to travel from source to destination, is critical for applications requiring real-time or near-real-time data processing.

- **LoRaWAN**: LoRaWAN typically exhibits higher latency due to its asynchronous communication protocol, where devices transmit data only when needed. While this approach conserves battery life, it results in delays that make it unsuitable for real-time applications. Class C devices can reduce latency by continuously listening for data, though at the cost of higher power consumption [4]. LoRaWAN is best suited for use cases like environmental monitoring, where occasional delays are acceptable [15].
- **NB-IoT**: NB-IoT achieves lower latency compared to LoRaWAN by using structured communication protocols over licensed LTE bands. This makes it suitable for applications like emergency alerts and real-time health monitoring, where timely data delivery is crucial. However, the reduced latency comes with higher power consumption, which may impact battery life in devices [4], [15].
- **LTE-M**: LTE-M provides the lowest latency of the three, with response times as low as 50-100 ms. It supports high data rates and real-time communication, making it ideal for demanding applications such as voice services, mobile monitoring systems, and advanced tracking. LTE-M combines low latency with robust performance, catering to both static and mobile IoT environments [15].

In conclusion, LoRaWAN is suitable for non-critical applications prioritizing battery life and wide-area coverage. NB-IoT balances moderate latency with reliable data delivery, fitting well in urban and industrial settings. LTE-M excels in real-time, latency-sensitive scenarios, making it the top choice for high-demand IoT applications like emergency services or mobile tracking.

D. Scalability

Scalability refers to an IoT network's ability to handle increasing device numbers and data volumes without performance degradation.

- **LoRaWAN**: Designed for wide-area, low-data-rate applications, LoRaWAN uses a simple ALOHA protocol that allows devices to transmit data independently, minimizing network coordination overhead [4]. While this approach supports moderate device densities, it may lead to packet collisions in highly dense networks, potentially limiting scalability.
- **NB-IoT**: NB-IoT significantly improves scalability, supporting up to 100,000 devices per cell by leveraging licensed spectrum and LTE-based signaling protocols [13]. Its structured network management ensures reliable performance in dense urban environments, making it ideal for large-scale IoT deployments requiring high connection density and stability.
- **LTE-M**: Similar to NB-IoT, LTE-M offers robust scalability but adds support for higher data throughput and lower latency. This makes LTE-M suitable for data-intensive applications like video surveillance and vehicle telematics, where both large-scale device connectivity and substantial data handling are needed [13].

In summary, LoRaWAN is better suited for moderate-density, low-data-rate applications with wide-area coverage. NB-IoT and LTE-M, with their LTE-based infrastructure, excel in managing high device densities and ensuring performance in urban and industrial IoT scenarios.

E. Payload Length

Payload length determines the type and volume of data that can be transmitted in a single message, making it a critical factor for applications like firmware updates, multimedia, or detailed sensor readings.

- **LoRaWAN**: LoRaWAN supports a maximum payload size of up to 243 bytes per transmission [4], [15]. This is sufficient for most IoT applications that send small data packets, such as temperature readings or GPS coordinates. The smaller payload size helps maintain LoRaWAN's low power usage and long-range capabilities, though it limits suitability for data-heavy use cases.
- **NB-IoT**: NB-IoT offers a significantly larger payload capacity of up to 1600 bytes [4], [15]. This makes it ideal for applications requiring substantial data transmission, such as utility metering or remote configuration of devices. The higher payload size provides flexibility for data-intensive applications.
- **LTE-M**: LTE-M supports a maximum payload size of 1000 bytes [15], striking a balance between NB-IoT and LoRaWAN. This capacity enables LTE-M to handle moderate data-intensive applications, such as voice over LTE (VoLTE) or aggregated sensor data, while maintaining energy efficiency.

LoRaWAN shines in scenarios requiring minimal data transmission over wide areas with low power consumption. NB-IoT is well-suited for data-intensive applications where power efficiency is less critical. LTE-M strikes a balance between the two, offering efficient performance for moderate data needs and versatile applications.

F. Network Coverage and Range

Coverage and range are key factors in IoT technology selection, determining network accessibility across various environments and the density of required base stations.

- **LoRaWAN**: LoRaWAN provides extensive coverage, with a single gateway covering up to 5 km in urban areas and up to 20 km in rural settings, depending on the environment and placement [15]. This makes it ideal for applications like remote monitoring and agriculture, where devices are spread across wide areas with minimal infrastructure.
- **NB-IoT**: Operating within the LTE framework, NB-IoT offers a shorter range compared to LoRaWAN, typically up to 10 km in rural areas and around 1 km in urban environments [15]. Its reliance on cellular infrastructure enables strong in-building penetration, making it suitable for urban applications like smart meters and indoor tracking. However, its range limitations may pose challenges in rural or remote areas without LTE infrastructure.
- **LTE-M**: LTE-M provides similar coverage to NB-IoT, with ranges exceeding 5 km depending on deployment specifics. Its ability to maintain signal integrity at high speeds and handle higher data rates makes it well-suited for mobile applications like vehicle tracking and emergency services [15].

LoRaWAN's extensive range and low base station density make it ideal for wide-area deployments like agriculture and remote monitoring. NB-IoT, with its strong in-building penetration and reliance on LTE infrastructure, is a reliable choice for urban and indoor applications. LTE-M bridges the gap by combining mobility support with robust coverage, offering flexibility for diverse IoT use cases such as vehicle tracking and emergency services.

G. Deployment Models

IoT technologies vary in their deployment models, influenced by flexibility, infrastructure requirements, and geographical suitability [13].

- **LoRaWAN**: LoRaWAN offers flexible deployment options, functioning as a private local network or a public network. Its hybrid model allows simultaneous coverage of localized operations, like factory floors, and broader regional areas with minimal infrastructure. This adaptability makes it ideal for varied applications requiring extensive geographic coverage and cost efficiency [4], [13].
- **NB-IoT**: Integrated into existing cellular networks, NB-IoT relies on licensed spectrum bands, enabling rapid deployment in urban areas with robust LTE infrastructure [13]. However, its reliance on cellular networks limits deployment flexibility in rural or underdeveloped regions. NB-IoT excels in providing

reliable, deep indoor coverage in dense urban environments.

- **LTE-M**: LTE-M builds on the cellular infrastructure of NB-IoT but adds support for mobility and higher data rates [13]. This makes it suitable for applications like asset tracking and emergency services, where reliable coverage and mobility are critical. LTE-M benefits from established cellular networks, ensuring robust performance for a wide range of mobile and stationary IoT deployments.

Each technology caters to specific needs: **LoRaWAN** is best for flexible, cost-efficient deployments across wide areas, while **NB-IoT** and **LTE-M** leverage cellular infrastructure to provide reliable coverage in urban and industrial settings. LTE-M's mobility support further broadens its application scope, making it the preferred choice for use cases requiring both coverage and mobility.

H. Cost Considerations

Cost is a key factor when selecting IoT technologies, with deployment costs varying based on infrastructure needs and spectrum usage.

- **LoRaWAN**: LoRaWAN is the most cost-effective option for wide-area, low-density applications. Its use of unlicensed spectrum eliminates spectrum fees, and its ability to cover large areas with fewer base stations reduces infrastructure costs. This makes it ideal for agricultural monitoring or remote asset tracking [13].
- **NB-IoT**: NB-IoT involves higher costs due to its reliance on licensed spectrum and existing cellular infrastructure [13]. Deployment can be expensive in areas lacking LTE coverage but is cost-effective in urban settings with dense device deployments, where its reliable connectivity and deep penetration justify the expenditure.
- **LTE-M**: LTE-M also operates on licensed spectrum, resulting in higher deployment costs like NB-IoT [13]. However, its support for real-time communication, voice services, and mobility justifies the investment in complex applications like emergency services and vehicle tracking. LTE-M’s broad functionality often translates to a higher return on investment in scenarios requiring both data intensity and mobility.

I. Overall Evaluation and Conclusion

In assessing the performance and suitability of LoRaWAN, NB-IoT, and LTE-M across various parameters, it is clear that each technology offers distinct advantages based on specific application needs. Figure 4 provides a visual representation of the summary based on previous discussion.

Each IoT technology has its optimal use cases based on its unique strengths. LoRaWAN is best suited for applications requiring broad coverage with minimal data transmission, making it ideal for agricultural or environmental monitoring in remote areas. NB-IoT excels in urban environments where high reliability is needed, such as for smart city applications and indoor monitoring. LTE-M, with its higher data rates and lower latency, is perfect for mobile applications and services that demand real-time communication, such as emergency services or vehicle tracking. The choice of technology should align with the specific requirements of coverage, data needs, and operational environment.

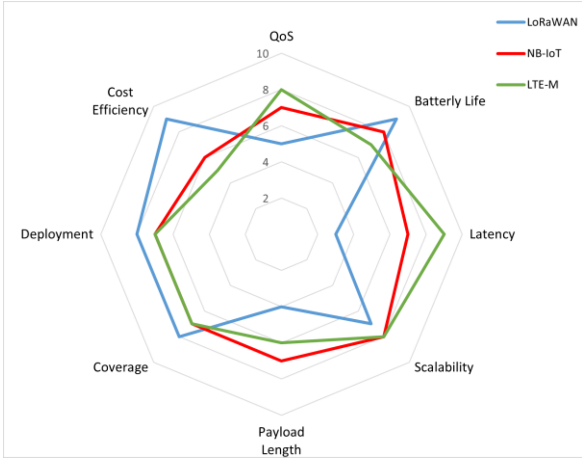

Fig. 4. LoRaWAN, NB-IoT and LTE-M main characteristics

VI. TELECOMMUNICATION BUSINESS AND REGULATORY ASPECTS FOR IOT INCLUDING LORAWAN

The 5G technology is a big change in the Internet of Things (IoT) landscape, affecting how businesses in telecommunications operate and how they are regulated. 5G is more than just a step up from previous technologies; it is a complete system designed to improve and bring together different IoT technologies. This system includes things like radio access technologies, network setups, cloud services, and devices that customers use, all managed by mobile network operators and service providers.

5G supports a massive number of connected devices, creating new opportunities across industries like healthcare, manufacturing, and smart cities. However, it also presents challenges related to regulatory compliance, network security, and data privacy. Organizations must navigate complex rules while ensuring robust security frameworks to support IoT deployments. Additionally, 5G complements technologies like LoRaWAN, which operates in unlicensed bands, by enabling hybrid connectivity models. This integration demonstrates 5G's potential to unify various IoT networks, fostering a more connected world.

A. Strategic IoT Approaches for Telecom Operators in the 5G Era

In the 5G era, telecom operators are well-positioned to lead the IoT revolution, thanks to their extensive network infrastructure and long-standing presence in the market Their established trust with customers helps smooth the adoption of IoT services, as people are more likely to accept new technologies from familiar providers [16], [17].

Over the years, operators have developed robust ecosystems, including physical infrastructure, customer support, and device management, allowing them to manage IoT services cost-effectively. Their expertise in network security and handling large-scale connectivity also ensures secure and efficient IoT deployments [16].

As 5G evolves, telecom operators are enhancing their networks to meet growing IoT demands, supporting applications like smart cities, health monitoring, and industrial automation. These advancements pave the way for new business models and opportunities in the IoT space.

B. Regulatory Considerations and Business Models in IoT Deployment

IoT technologies operate under varying rules and business models, influencing their deployment and accessibility. For instance, NB-IoT operates on licensed frequency bands, meaning only mobile network operators with a 4G license can offer NB-IoT services. This model allows operators to leverage existing infrastructure, minimizing legal hurdles and enabling quick deployment in many regions. However, because these services are tied to operators, they come with subscription costs for users. LTE-M, similar to NB-IoT, operates on licensed bands and offers higher data rates and voice support, making it suitable for a wider range of applications. Nevertheless, LTE-M shares similar regulatory constraints and cost implications, as it remains tied to operator-controlled deployment and pricing [3].

On the other hand, LoRaWAN uses unlicensed spectrum, allowing anyone to set up a network without requiring spectrum licensing. This flexibility reduces regulatory barriers, making LoRaWAN an attractive option for community-driven networks, such as The Things Network. In Europe, guidelines like CEPT Recommendation 70-03 govern LoRaWAN's use, but interpretations vary between countries. While this can make LoRaWAN easier and cheaper to deploy, it can also lead to inconsistencies in service and coverage due to the lack of unified standard [3].

While NB-IoT and LTE-M offer reliability and structured deployment through licensed networks, LoRaWAN provides flexibility and cost-efficiency by operating in unlicensed bands. The choice of technology depends on balancing regulatory ease, deployment costs, and specific application needs.

VII. CONCLUSIONS

In recent years, the Internet of Things (IoT) has seen remarkable growth, revolutionizing how we connect and manage devices across various sectors. This rise has been significantly supported by evolving technologies like LoRaWAN, NB-IoT, and LTE-M, each bringing unique strengths to the table, tailored to different application needs. When choosing the right technology for an IoT project, it is essential to consider the specific requirements of the task at hand, as there no a one-size-fits-all solution.

LoRaWAN stands out for its wide coverage and low power requirement, making it ideal for monitoring vast, remote areas such as farms or natural environments. On the other hand, NB-IoT is a better fit for urban settings where reliable connections and the ability to penetrate buildings are important, which is why it is often used in smart city initiatives and indoor applications. Meanwhile, LTE-M caters to scenarios that require mobility and real-time data transmission, such as tracking vehicles or emergency services.

Telecom operators are also playing a key role in advancing IoT through deployed 5G networks, increasing the capabilities and reach of technologies like NB-IoT and LTE-M. These developments are opening up new possibilities for IoT applications, offering better service options and supporting a broader range of business models.

In conclusion, as IoT continues to expand and develop, choosing the appropriate technology is very important and should be based on the unique requirements of each application. There is no inherently superior technology, each has its place based on its strengths. With the ongoing support of telecom operators and continuous improvement of network technologies, the future of IoT looks promising, offering more customized and efficient solutions for a connected world.

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