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Survey of IoT for Developing Countries: Performance Analysis of LoRaWAN and Cellular NB-IoT Networks

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Abstract: Recently, Internet of Things (IoT) deployments have shown their potential for aiding the realisation of the Sustainable Development Goals (SDGs). Concerns regarding how the IoT can specifically drive SDGs 6, 11 and 9 in developing countries have been raised with respect to the challenges of deploying licensed and unlicensed low-power wide area network (LPWAN) IoT technologies and their opportunities for IoT consumers and service providers. With IoT infrastructure and protocols being ubiquitous and each being proposed for different SDGs, we review and compare the various performance characteristics of LoRaWAN and NB-IoT networks. From the performance analysis of our networks, NB-IoT, one of the standardised promising cellular IoT solutions for developing countries, is more expensive and less energy-efficient than LoRaWAN. Utilising the same user equipment (UE), NB-IoT consumed an excess of 2 mAh of power for joining the network and 1.7 mAh more for a 44-byte uplink message compared to LoRaWAN. However, NB-IoT has the advantage of reliably and securely delivering higher network connection capacity in IoT use cases, leveraging existing cellular infrastructure. With a maximum throughput of 264 bps at 837 ms measured latency, NB-IoT outperformed LoRaWAN and proved robust for machine-type communications. These findings will help IoT consumers and service providers understand the performance differences and deployment challenges of NB-IoT and LoRaWAN and establish new research directions to tackle IoT issues in developing countries. With Nigeria as a case study, for consumers and organisations at a crossroads in their long-term deployment decisions, the proposed LPWAN integrated architecture is an example of the deployment opportunities for consumer and industrial IoT applications in developing countries.

Keywords: cellular networks; developing countries; Internet of Things; licensed; Narrowband Internet of Things; rural areas; test network; unlicensed

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1. Introduction

The Internet of Things (IoT) plays a crucial role in achieving connected living through increased business activities, remote operations, and social interactions. IoT technologies are more pronounced in urban areas through applications such as smart city, smart manufacturing, wearables, smart homes, self-driving cars, etc. These applications are driven by factors such as established business use cases, the availability of communication network resources and coverage, power and regulatory frameworks. These factors affect the rate of IoT penetration in rural localities, especially in developing countries where power and communication network coverage issues limit deployment opportunities and the realisation of the United Nations' Sustainable Development Goals (SDGs) [1]. We believe that regions with limited terrestrial infrastructure will be best serviced by low Earth-orbiting (LEO) satellites and LPWAN-based IoT applications for services such as asset tracking and environmental monitoring, as these have the lowest demand for infrastructure. These approaches, however, may have drawbacks if two-way communication is not supported for communications between LEO satellites and ground-based IoT infrastructure.

As the Internet of Everything (IoE) continues to evolve, so too do the protocols and challenges associated with its applications and deployment. Traditional wired and short-range wireless technologies cannot meet the scale of demand for the remote data visualisation of wireless sensor networks. Adopting LPWANs allows such scalability and ease of deployment, but with new challenges arising including security, power consumption, and latency. These were identified as some of the issues taken into account in the LPWAN deployment and applicability index towards best practice in LPWANs [2]. An adaptive battery-aware algorithm has been proposed to effectively manage power consumption and charging processes in medical IoT devices that remotely collect patients' data continuously [3]. The latency of data transmission in IoT networks are multi-faced at different parts of the network. The data payload size for typical IoT networks is typically of the order of a few bytes, partly because LoRaWAN has a payload size of 51 bytes [4]. To transmit a higher data payload without implementation packet fragmentation support, technologies such as NB-IoT can reduce the number of transmissions, latency and energy consumption that would arise from multiple transmissions in LoRaWAN. An analytical framework has been proposed to examine the effects of scheduling data, control information, and coverage classes on latency and battery lifetime in distributed IoT networks [5]. The proposed models minimised the communication delay with high-performance trade-offs in channel scheduling. LPWANs can be vulnerable to security attacks, but LoRaWAN and NB-IoT offer sufficient security for certain applications if implemented with strong security policies and enforcement [6]; moreover, in [7], we identified the current security challenges of different low-power wide area network (LPWAN) IoT networks and platforms as they apply to different IoT use cases. The integrity, confidentiality, authenticity, privacy, and trust of IoT systems are still open research issues. Similarly, in [8], we presented an early insight into the Narrowband Internet of Things (NB-IoT) testbed design and implementation procedure. In this paper, we evaluated the performance of licensed and unlicensed low-power wide area (LPWA) IoT network options to demonstrate the use of cellular LPWANs to meet the SDGs. NB-IoT and LoRaWAN are sustainable potential solutions for affordably connecting billions of IoT devices, and the technologies (GSM and LTE) upon which NB-IoT depends are available in developing countries. Both technologies are among the most popular ones in the research community for industrial and consumer applications. These capabilities will help towards the provision of services such as safe drinking water through pollution-monitoring systems (SDG 6); extending business opportunities to rural areas through sustainable city creation (SDG 11); and extending affordable Internet connectivity to hard-to-reach locations to fast-track business opportunities by bridging the digital divide gap (SDG 9). A few of the most significant challenges of IoT adoption include the selection of the most efficient, secure, and cost-effective technology that will stand the test of time in this fast-changing technology regime. Focusing on the practicality of implementation, long-term cost efficiency, feasibility, and information security as performance indices [2], the performance of each IoT technology can be ranked based on the network QoS. However, the multiplicity of different IoT options makes the development of IoT networks a very difficult task, with issues including a shared hardware infrastructure at the gateway level, and the frequent lack of global harmonisation of spectrum bands suitable for IoT applications. As proposed in this paper, a unified proof of concept IoT platform solution will reduce the number of different types of physical infrastructure required across the IoT ecosystem as the technology evolves.

Despite the promises of IoT, research involving testbeds' performance of cellular IoT networks is limited. Research into cellular IoT network performance, such as that of NB-IoT, often relies on simulations and theoretical approaches. Based on network performance analysis carried out on real hardware, we evaluated NB-IoT and LoRaWAN testbeds for applications of IoT in developing countries, hard-to-reach locations, and rural localities. Using the same IoT devices (UE) as sensor nodes in the NB-IoT network and as sensor nodes and gateways in the LoRaWAN allows establishing the networks performance baseline for building a multi-tenant IoT infrastructure. Specifically, the main contributions of this work are as follows:

- A critical review of the requirements, opportunities, and challenges of the IoT for developing countries;
- A critical review of unlicensed and cellular LPWAN technologies, focusing on security, energy utilisation, standardisation, interoperability, policy & regulation, and QoS requirements;
- Evaluation of the performance of the NB-IoT testbed and proposal of a hybrid NB-IoT and LoRaWAN proof of concept to scale IoT deployment in developing countries;
- Investigation and evaluation of the performance of LPWANs. We compared the performance of both LoRaWAN and NB-IoT in terms of transmission latency, throughput, and battery utilisation, and analysed the benefits of NB-IoT for IoT applications against unlicensed LPWAN for developing countries;
- Through the evidence of the findings, we offer recommendations on the potential benefits and drawbacks of integrating LPWANs to scale IoT deployments.

The remaining parts of this paper are organised into the following sections. Section 2 presents the review of the current literature on LPWANs. Section 3 presents the main research goals. Section 4 discusses both licensed and unlicensed LPWAN IoT deployment opportunities in developing countries. Using Nigeria as a case study, a more comprehensive analysis of the technical challenges, policy regulations, spectrum, and security issues of unlicensed and cellular IoT technologies are also presented. Section 5 explains the underlying principles of low-power cellular technologies for IoT, including those of NB-IoT, EC-GSM-IoT, LTE-M, and 5G. The design framework and implementation of NB-IoT and LoRaWAN testbeds are given in Section 6 to evaluate the real-world performance of IoT networks. Through comparative analysis, results on power utilisation, security, latency, and throughput are presented in Section 7. The limitations and future research directions are presented in Section 8 before Section 9 concludes the paper with key points on how LPWANs can help in the realisation of the SDGs in developing countries, and with the potential benefits and drawbacks of the study.

2. Related Literature and Contribution

There are various opportunities and challenges of adopting IoT technology in both developed and developing countries. Many global climate change events in 2020 and early 2021 have revolved around how human activities and waste impact climate and water bodies and has created an increasing research interest in the field of IoT. Internet of Things [9] solutions have been used to monitor, collect and analyse different environmental measurements such as water quality data from small remote locations. In the Fiji Islands [10], IoT and remote sensing (RS) techniques were used to monitor the potential hydrogen, oxidation and reduction potential, temperature and conductivity levels of four different water sources. A wireless sensor network (WSN), as reviewed in [11], considered the use of LoRa and Sigfox technologies over Internet/3G/LTE to deliver an energy-efficient wireless sensor system for water quality monitoring. Other LoRaWAN studies for water quality monitoring were carried out due to its long-range data transmission in difficult terrains and low power consumption rate, as proposed by Jorge et al. [12]. For instance, Lake Dardanelle in the United States [13], the Facilities of South Africa Council for Scientific and Industrial Research (CSIR) [14], and Dong Lake in National Dong Hwa University China [15] have all been used as test beds for LoRaWAN technology with regard to various characteristics of water quality monitoring.

A GSM-based IoT solution has also previously been used to monitor the pH and turbidity level of water tanks in India [16]. The water quality of fish ponds and aquarium systems have also been monitored using IoT solutions. FishTalk enabled the remote feeding of fish and intelligent water quality control [17]. The study augmented the network with more IoT services, such as smart agriculture, where farm owners will remotely receive feedback on the health status of their farms. An early mathematical study on energyabundant vehicle-based relays for using NB-IoT to support crowded IoT deployment was proved to increase the link reliability and energy utilisation of IoT devices [18]. All these studies are based on mobile network operator (MNO) networks, which are not readily available in rural areas. GSM and cellular network standards that are older than LTE are mostly deployed in more rural areas, where these remote monitoring activities will be required. These are aspects of IoT applications in developing countries that would require both licensed and unlicensed LPWANs. Our contribution in this article will leverage a mix of LPWANs to bridge the IoT network connectivity gap surrounding IoT application opportunities in developing countries, as shown in Figure 1. An integrated IoT solution is needed that would offer improved quality of service (QoS) of NB-IoT and LoRaWAN, be cheaper to deploy with redundancy, and specifically promote the reuse of IoT radio access infrastructure. The power consumption, latency, throughput, and latency performance of NB-IoT and LoRaWAN are compared with measurements of environmental temperature and humidity that could be replaced with other applications of IoT in developing countries. These aspects of QoS requirements consider both the uplink (path between the IoT device and the server) and downlink (server-to-device) transmissions.

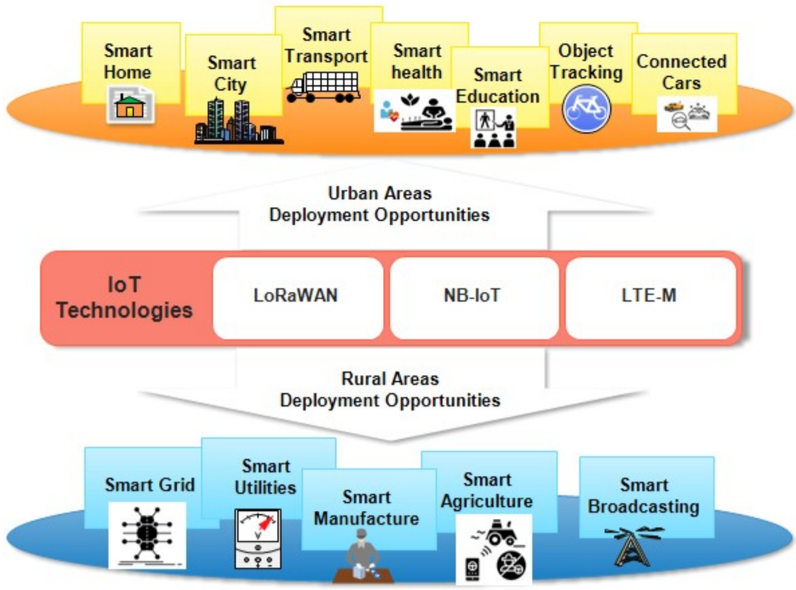

Figure 1. IoT deployment opportunities in developing countries.

3. Research Goals

The purpose of this research was to survey existing licensed and unlicensed LPWANs literature, and based on the findings, present IoT technologies deployment opportunities and challenges for expanding IoT connectivity in developing countries. As most existing studies, especially those of cellular networks such as NB-IoT, are simulation- and survey-based [5,19–21], this paper presents the results on the latency, data throughput, power consumption, and security of our LPWANs. To fill the literature gap for unlicensed and licensed test network performance for developing countries, we analysed and compared the results with our LoRaWAN and NB-IoT testbeds using the same UE. A few experiments that investigated NB-IoT and LoRaWAN performance exist but these are limited to power consumption and costs [22] and power consumption [23–25] using different UEs.

4. IoT Deployment Opportunities in Developing Countries

There are potential business-to-consumer (B2C) and business-to-business (B2B) opportunities of using LPWAN IoT technologies in developing countries, as shown in Figure 1. For example, the digital transformation of the farming sector in developing countries will ensure food security for the increasing population, and may increase the gross domestic product (GDP) and return on investment (ROI) [26,27] as well as support aspects of investment decision making through intelligent computing and big data analytics [28]. Other opportunities include improved security monitoring, increased productivity, quality control, transportation and supply chain optimisation. A well-established GSM and LTE cellular infrastructure could enable IoT to be more widely deployed in developing countries. In LTE and 5G, a 3GPP-standardised machine-to-machine (M2M) IoT solution can be relied on to deliver more bandwidth and device connection density per cell at lower latency. LoRa is also standardised, although perhaps to a lesser extent, towards co-existing with 4G and 5G ecosystems for IoT applications [29]. The requirements of massive, broadband and critical IoT applications can be met by different aspects of LPWAN technologies. Generally, massive IoT applications are delay-tolerant infrequent IoT devices of small data volumes used in challenging network connectivity and energy supply environments. Examples include smart metering and asset management where network roaming, extended coverage, and long battery life capabilities are required to reach all assets seamlessly. EC-GSM-IoT, NB-IoT, and LTE-M are the 3GPP-standardised protocols that meet the requirements of low-complexity IoT devices through GSM and LTE enhancements. This is the IoT application segment where the unlicensed LPWANs are also applicable.

Broadband IoT technology supports high-throughput IoT devices that deliver large data volumes at low latency based on mobile broadband MTC. The broadband IoT segment relies on pure LTE device capabilities to offer better performance than massive IoT. LTE-based IoT devices often support multiple antennae, carrier aggregation, scheduling mechanisms, spectral efficiency, and as a result can operate in extended coverage and power-saving mode. Examples include drones and wearables that require real-time operation and control. 5G NR broadband IoT will offer additional capabilities that can improve bandwidth and throughput mechanisms such as ultra-short duration transmission and retransmission, seamless base station handover, transmission diversity, and improved link budget and adaptation [30]. Frequencies greater than 6 GHz have extremely low latency, limited coverage and are suitable for local area services with high capacity and ultra-high reliability demand. The disadvantage of high frequency is the cost due to additional radio resources needed to increase signal coverage; with higher frequencies being used, a denser distribution of cells is required in order to provide coverage, compared with lower frequencies. The mid bands ranging from 1 to 6 GHz are suitable for wide-area IoT services with extremely low latency and ultra-high reliability. Frequency bands as low as sub-1 GHz are also suitable for wide-area IoT applications but these devices must have limited capacity requirements, due to the reduced availability of spectrum in these bands.

Critical IoT, on the other hand, is suitable for addressing the extreme IoT connectivity requirements of many applications of ultra-low latency, ultra-reliable, and very highly available IoT services. Examples of these use-cases include traffic control systems, smart grid automation, and automobile control which requires low latency (5–20 ms) [31] and high reliability (99.9999%) [32]. The automation segment covers industrial digital transformation supplemented by cellular networks. Industrial and consumer IoT or rural and urban IoT networks are a mix of the various IoT segments depending on the service and use-case requirements.

4.1. Leveraging Cellular Networks for IoT Deployments in Nigeria

The mobile network operators (MNOs) in Nigeria, as presented in Table 1, fall within the ITU Region 1 deployment bands [33]. All the deployment bands can support either NB-IoT or LTE-M-based IoT networks, except time division duplex (TDD) bands, such as band 42. Following the national approach of allocating spectrum to the MNOs, NB-IoT and LTE-M is set to thrive if roaming agreements and infrastructure sharing exist between MNOs. This presents a massive deployment opportunity for LTE-based IoT technologies in the in-band and guard-band modes in Nigeria (see Figure 2), as also identified for India's NB-IoT deployment towards smart city applications in the rural villages, suburban hubs, and urban capitals [34]. The spectrum will be repurposed to support new and more efficient services.

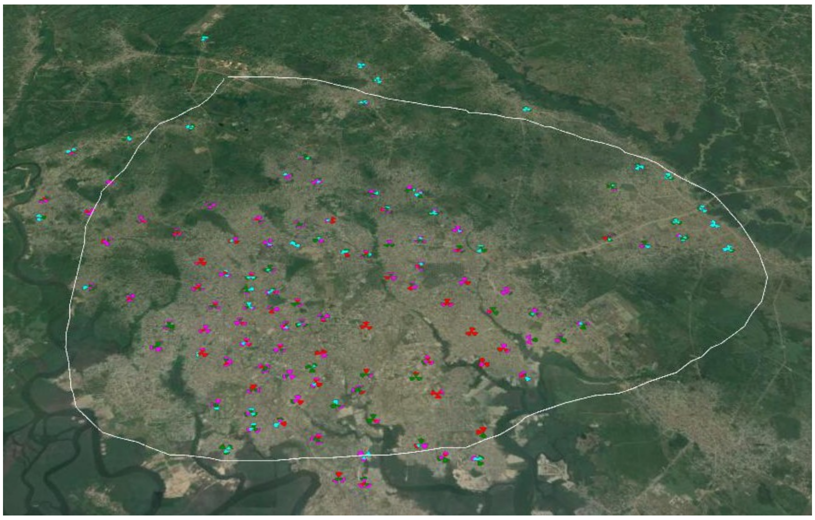

Figure 2. Typical LTE network distribution in urban areas in Nigeria. NB-IoT deployment leverages LTE infrastructure, which is mainly clustered within urban areas. The dots represent different sectors of two co-located 1800 MHz and 900 MHz sites. Red—the current number of users exceeds the expected number of users per cell; purple—the maximum number of users is reached; green—the number of users is within the range; blue—the number of users on the cell is low.

Table 1. Overview of MNOs in Nigeria with NB-IoT and LTE-M bands deployment opportunities.

Operators	Bands	Channel Bandwidth
9 Mobile	B1 (2100 MHz)	
	B3 (1800 MHz)	10
Airtel	B1 (2100 MHz)	
	B3 (1800 MHz)	5
MNT	B1 (2100 MHz)	
	(1800 MHz)	15
	B20 (800 MHz)	10
	B42 (3500 MHz)	10, 20
VDT	B40 (2300 MHz)	10, 20
ntel	B3 (1800 MHz)	15
	B8 (900 MHz)	5
Glo	B1 (2100 MHz)	
	28 (700 MHz)	10

In the Nigerian Communications Commission’s (NCC) frequency assignment tables, bands 3 and 8 are predominantly used for GSM while band 1 is used for GSM, 3G, and LTE [35]. Band 3 is the largest spectrum used for LTE deployment globally due to its large coverage and the ability of its services to be refarmed into band 1 with a robust option of carrier aggregation configuration for different bandwidths. On the other hand, 900 MHz is generally used for 2G, GSM, and data communications supporting broadband deployment and could have huge potential for IoT deployment. Depending on the deployment mode to be adopted by MNOs to support NB-IoT and LTE-M technologies, the possible impact on their networks would be the upgrade of baseband units, antenna systems, and eNB software and their introduction of new RF modules. The main technical challenge of NB-IoT penetration in developing countries such as Nigeria, as presented by Oluwaseun et al., is the sole reliance on broadband connectivity which stood at 50% in 2019 [26]. However, we envisaged that power supply, MNO business scenarios, security, policy standardisation, privacy, interoperability, and the cost of acquiring IoT devices are potential challenges that could be turned into opportunities. Other network infrastructures to be mentioned as among the common factors globally affecting IoT development include the provision of base stations for the extension of coverage to rural areas without an exponential rise in capital expenditure (CapEx) and operational expenditure (OpEx). Where practicable, the use of band 20 and band 8 for LTE-M and NB-IoT is recommended if indoor and outdoor penetration is desirable at the same time, but at a trade-off compared with band 3 in that each operator has less spectrum range. With band 20 and band 3 making 30 MHz and 75 MHz available, respectively, carrier aggregation will be needed to support non-NB-IoT users. IoT services will have lower performance/throughput on B20, but better range, meaning more users are served but with poorer connections.

4.1.1. Policy and Regulatory IoT Issues

To accelerate IoT development and investment in developing countries, a good policy and regulatory framework are needed in areas of security and privacy, standards, and government regulation [1]. These can be seen, for example, in the code of practice for consumer IoT security in the UK [36], the Unmanned Aircraft Systems (UAS) regulations and guidelines of the United States Federal Aviation Administration [37], and the security requirements for consumer IoT devices by ETSI [38]. Other policy and regulatory themes to be addressed include fair access to a sufficient spectrum range, managing communication taxes, ensuring end-to-end security, numbering, and addressing [39]. Radio spectrum is critical to IoT deployment and the regulation of radio frequency (RF) which, according to the International Telecommunication Union (ITU), can be performed independently at the national, regional, and global levels. In Africa, the African Telecommunication Union (ATU) comprises mobile and fixed telecom companies that formulate policies and strategies that promote technology integration across the continent. The regional approach sees regulatory bodies such as the West Africa Telecommunications Regulatory Assembly (WATRA), the East Africa Communication Organization, and the Communication Regulators' Association of Southern African (CRASA) managing regulations. Nigeria is a member of ITU Region 1 (ITU-R1) with the Spectrum Administration Department of National Communications Commission (NCC) responsible for managing, planning, and licensing the RF spectrum, as specified in the NCC Spectrum Administration Charter (SAC) [40]. The Federal Ministry of Communications (FMC) is the regulatory body governing the communication policy. Poor management of the RF spectrum is the result of a lack of adequate regulatory frameworks for an expensive and scarce natural resource described as a technological service of economic interest to all [33]. RF harmonisation facilitates use of the same spectrum for different services without issues in different countries in the same ITU region, since RF crosses national boundaries. However, different countries usually have different operators with varying individual allocations of spectrum based on their auction's strategy.

4.1.2. Spectrum and IoT Issues

The advent of IoT technologies has pushed for more wireless devices to operate in a different spectrum. Whereas NB-IoT and LTE-M operate in the licensed spectrum with minimal interferences, it uses hybrid automatic repeat request (HARQ) to guarantee data delivery, and narrowband fidelity (NB-FI), SIGFOX and LoRaWAN operate in the unlicensed ISM spectrum with duty cycle limitations. For these reasons, NB-IoT and LTE-M are most suitable for applications with a higher QoS of non-time-critical requirements. Transmissions within the ISM bands are not reliable and require the acknowledgement of uplink and downlink packets, due to their inherent potential for interference and collisions with other users of the spectrum. The higher QoS in NB-IoT and LTE-M networks are at the expense of a higher cost of acquiring a licensed spectrum. The sub-GHz spectrum auction was over USD 500 million/MHz in 2017 [19] and in 2021, an increase was seen in Ofcom's auctioning prices of 700 MHz and 3.6 GHz–3.8 GHz for 5G in the UK [41]. Six lots of 2 $\times$ 5 MHz (700 MHz band), four lots of 10 MHz (700 MHz band), and twenty-four lots of 5 MHz (3.6 GHz band) amounted to reserved prices of GBP 100 million/slot, GBP 1 million/slot, and GBP 20 million/slot, respectively.

Spectrum sharing is an essential part of IoT development. Spectrum bands between 1 GHz and 6 GHz that are suitable for IoT development in a cost-effective manner have been allocated for other uses. Finding an unused block of frequencies within a specific area is one easy way of solving spectrum issues or building a contiguous spectrum to meet a particular service requirement if applicable (suitable for the national auction approach). Due to the unavailability of a free spectrum, grey space sharing, as described in [42], is most applicable in situations where there is not a dynamic technology, and a particular frequency is used over a wide geographical area. A secondary user is only possible through established policy regulation and governance frameworks. The white space spectrum (WSS) is generally regarded as the region of unused spectrum within or around existing bands, and presents potential opportunities for IoT deployment in rural areas and developing economies [43].

4.1.3. Security and IoT Issues

Based on the security requirements of other wireless technologies for IoT, security and privacy issues are challenging and are considered in this paper for three IoT reference architectures: the perception; network; and application layers.

Application Layer—The application layer comprises the service management and business services demanded by IoT users through known protocols. Constrained application protocol (CoAP), transmission control protocol (TCP), user datagram protocol (UDP), and message queue telemetry transport (MQTT) are good examples of efficient IoT protocols for relaying services to users. In our test networks, we used the TCP protocol due to its high reliability in terms of data transmission. The security issues of the application layer include privacy protection, and other problems of intellectual property protection. The end users of IoT applications in some use cases may require anonymity to protect user identity. In this scenario, advanced encryption techniques and digital signatures will intelligently provide the necessary security.

Network Layer—As an intermediary function, the network layer allows data collected by the perception layer to be reliably transmitted to the application layer for processing and visualisation based on application requirements. Different Internet-based access network technologies applicable to IoT have been presented in Table 2 for device-to-device communication. However, it is also a channel through which security risks are introduced to the network. Malicious network signal interference could result in network nodes being compromised through denial of service (DoS), distributed denial of service (DDoS), or other network-related attacks such as IP and bandwidth spoofing. Transport layer security (TLS) and Internet protocol security (IPSec) have been demonstrated as an end-to-end security enablers for IoT deployment in constrained environments. In addition, the integrity and confidentiality of data in the NB-IoT network can be secured by cryptographic-based intrusion detection and prevention algorithms.

Table 2. Comparison of unlicensed and cellular IoT technologies [44–47].

Network Items	SigFox [48]	LoRaWAN [45]	NB-Fi [49]	NB-IoT [26]	LTE-M [50]
Bandwidth	100 Hz	250 kHz & 125 kHz	50 Hz–25.6 kHz	200 kHz	200 kHz
Modulation	BPSK	CSS	DBPSK	QPSK	QPSK
Standardisation	SigFox/ETSI	LoRA Alliance	WAVIoT	3GPP	3GPP
Max. Data Rate	100 bps	50 kbps	25 kbps	200 kbps	200 kbps
Bidirectional	HD	HD	FD & HD	HD	HD
Architecture	SoS	SoS	SoS	SoS	SoS
Frequency	ISM-bands	ISM-bands	ISM-bands	LTE-bands	LTE-bands
Payload	UL-12 B & DL-7 B	243 B	240 B	1600 B	256 B
Security	AES-128	AES-128	AES-256	LTE Enc	LTE Enc
Interference	High	High	High	Low	low
Urban Range	10 km	5 km	10 km	1 km	1 km
Rural Range	40 km	20 km	40 km	4 km	4 km

Note: B—bytes; SoS—star-of-stars; UL—uplink; DL—downlink; Enc—encryption.

Perception Layer—This is the IoT data generation layer which is aided by measurements by sensors and actuators located at the bottom of IoT architecture. The IoT devices can support edge processing and mostly wireless sensing enabled for remote access and tracking capabilities through gateways. The security of the data-generating edge devices is a sensitive part of IoT networks as they are prone to jamming, scrambling, spoofing, and other physical layer attacks [51]. The quality of data generated by the IoT depends on edge computing. IoT devices deployed in attack-prone areas need to be tamper-proof, with each device to be authenticated, verified, and the transmitted data encrypted.

4.2. Leveraging Unlicensed LPWANs for IoT Deployments

The recent advancement in wireless technology for Internet of Things applications has enabled the development of a wide range of sensor networks for environmental data collection. Low-range (LoRa) wide area network (WAN), generally referred to as LoRaWAN, is one of the low-power (LP) WANs encompassing classification requirements that is based on unlicensed spectrum, low cost, reduced power, and wide range of data transmission [52]. LoRaWAN connects multiple IoT devices through an open and standardised communication protocol for the Internet of Things and can be integrated with licensed bands such as the 4G/5G cellular networks [12]. Based on the chirp spread spectrum (CSS) modulation technique at the physical layer, LoRaWAN offers low channel interference and high coverage against a reduced data rate, as shown in Equation (1), where SF, R_b, and BW represents the spread factor, symbol rate, and bandwidth, respectively:

$$R_b = SFx \frac{1}{\frac{2^{SF}}{BW}} \text{bits/s} \tag{1}$$

For a fixed BW of 125 kHz, the symbol rates possible for the maximum (12) and minimum (7) values of SF are 366 bits/s and 6835 bits/s, respectively, before encoding.

4.2.1. LoRaWAN Architecture

The standard LoRaWAN architecture is a star-of-stars topology with its front-end, gateways, and back-end as three distinct layers. The front-end of the network is the proprietary LoRa radio frequency (RF) connection between the end devices and the LoRa gateways, as can be seen in Figure 3. The Fipy LoRa gateway incorporates the Semtech SX1272 chip which supports up to 22 km range with 100 nodes capacity. It collects the temperature and humidity data from the Pysense node and forwards these through the TTN to the application server where it is stored and processed. Our model was configured to operate in the 868 MHz frequency band on the TTN V2 cluster due for deprecation and shutting down in December 2021. For uplink communication, UE data is broadcast via LoRa gateways within range. The gateways act as repeaters by relaying the end device messages to a single network server where they are aggregated and de-duplicated. This eliminates any handover requirements between gateways when they are within the network coverage. The back-end is an IP-based connection between the network/application servers and the gateways. The network server is the received data aggregation point and the MAC layer encryption must be decrypted before an uplink data transfer to the application server. Application servers can be run by the network operator, or by the end-user of the application. The application key of each application server is then finally used to decrypt the real data payload. The reverse process occurs for a downlink data transfer. It is important to note that in most classes of operation, as discussed below, downlink messages can only be sent in response to an uplink message, since most LoRa devices will not listen at all times for downlink messages. The TTN network allows different application and database integration. In JSON format, node data is accessed through a REST API. An access key is needed for an HTTP request to the database. The application server is an HTTP web server for accessing the database.

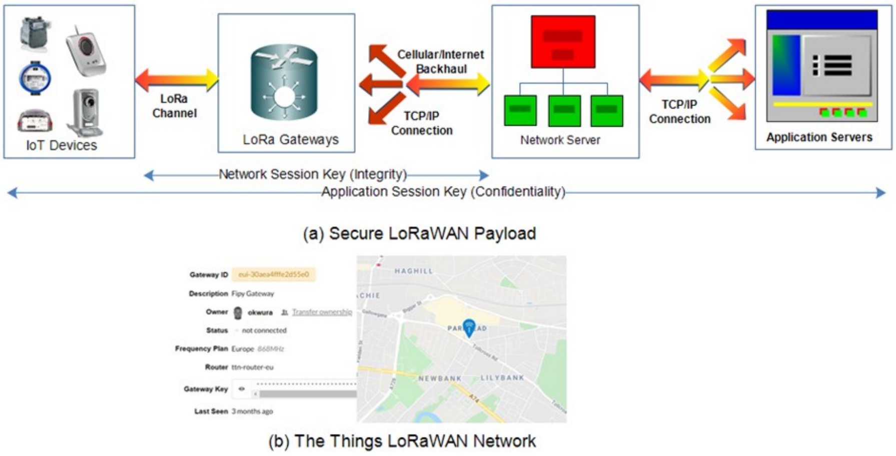

Figure 3. Secure LoRaWAN Architecture: (**a**) typical LoRaWAN architecture; and (**b**) LoRaWAN implemented on The Things Network.

4.2.2. Modulation Scheme

The LoRa modulation scheme is based on the chirp spread spectrum (CSS) whereby the chirp signal varies linearly with the frequency [52]. By applying different spread factors (SFs), a compromise may be achieved between the power consumption or transmission distance for a data rate according to Equation (1). The advantages of this type of modulation scheme include constant envelope, scalable bandwidth, resistance to Doppler effect, interference and multipath fading, and improved range, network and geolocation capabilities [12]. It also reduces the complexity of the receiver design since the time and frequency offset are identical. An adaptive data rate (ADR) is another mechanism employed to reduce the consumed RF power and the data rates of LoRa UEs.

4.2.3. Device Classes

There are three medium access control (MAC) operating classes of LoRaWAN IoT device layers specified in the LoRaWAN standard to satisfy certain applications with trade-offs between latency and energy utilisation. Each device class is distinguished by design in the energy consumption profile which relates to the time (duty cycle) it takes their radio receivers to receive a LoRaWAN message. LoRaWAN devices are limited by regulation to transmit under 1% of the time, to manage the spectrum and reduce collisions. The three classes are based on the same physical layer characteristics [53]:

Class A is a generic mode in LoRaWAN IoT modules that are battery powered, energy efficient, and are based on the ALOHA operational principle of uplink transmission predetermining downlink transmissions. Without a transmission in the uplink channel, downlink transmissions will be queued and delayed (latency introduced) because the uplink transmissions initiate the two possible downlink transmission windows. In this case, the devices only receive downlink packets in two short-lived windows, RX1 and RX2, immediately after the uplink transmission, TX1. The duration of the downlink receive windows is configurable. The receive delay parameter by default according to the LoRa Alliance parameter is a 1 s interval for maximum efficiency depending on the SF applied. The received delay is region-specific and reconfigurable through MAC layer commands. An acknowledged uplink transmission prevents packets retransmission, thereby saving energy. If there is no acknowledgement received, a re-transmission takes place with an increased spread function.

Class B devices are higher power consumption LoRa devices, designed to increase the receive windows of downlink transmissions that are scheduled without requiring an uplink transmission [54]. The synchronisation message from the gateways that increased the UEs energy demand allows downlink re-transmissions to be rescheduled. In this case, a gateway can multicast a message to the IoT devices within the network.

Class C devices are application dependent (for use-cases where a fixed power source is available). Typically, non-battery powered IoT modules can efficiently receive and transmit at any time. Class C LoRa devices continuously listen for downlink messages, and therefore are not suitable for power-constrained use-cases. A suitable application of this class is the traffic and packing systems where a power supply is fundamentally required for the system to function.

5. Low-Power Cellular Technologies for IoT

Wireless technologies play different important roles in the development of IoT. The comparison of key technologies enabling IoT deployments was presented in Table 2. The goal is to develop IoT technologies that maximise ROI in communication infrastructure and still maintain reliable connection and secure data transmission. While wired technology is a unique component of IoT networks in special use cases—mostly for on-premises applications and for backhaul connection to 5G or 4G infrastructure—wireless technologies are increasingly being used for cost reduction, mobility, deployment flexibility, and power consumption reasons. For deployment flexibility, a smart manufacturing environment for instance can be re-configured within a day without having to re-do the infrastructure, while on the other hand, the re-laying of fibre might take days or weeks to complete the same task.

For the seamless convergence of wired and wireless networks, it is necessary to advance the throughput, latency, and capacity of wireless technologies to meet the requirements of critical IoT applications in the 5G/IoT era [55]. The communication requirements, QoS, and use cases for WiFi (802.11) standards and wireless IoT technologies are different [56]. Factors such as hardware design, area of application, and the technology of implementation impact the technology of choice. In the use cases of IoT that require the transmission of a small amount of latency-insensitive data over a long distance at lower costs, such as water quality and environmental monitoring, licensed technologies should be considered if QoS is needed. Unlicensed technologies should be considered (in addition to licensed options) if QoS/reliability is not needed. Other wireless technologies such as ZigBee, Wifi, and Z-wave are alternatively used to support short-range applications but are categorised as power-hungry technologies [57].

3GPP initially standardised licensed technologies such as NB-IoT and LTE-M in release 13, and some improvements were introduced in subsequent 3GPP releases to provide a more efficient, secure and trusted IoT environment [30]. Currently, NB-IoT can achieve coverage enhancement of between 18 km and 25 km in urban and rural locations [9], operates through GSM and LTE infrastructure in a 200 kHz [58] and 180 KHz [59] wide carriers respectively, and supports low-power consumption. LoRaWAN and Sigfox are examples of unlicensed LPWAN technologies with LoRaWAN as a popular option in this category operating in the sub-GHz ISM band. However, deploying LoRa and NB-IoT together is a potential opportunity to scale the coverage and capacity of IoT networks [9], however, the backhaul of each network should be provisioned separately since their QoS/reliability requirements are different.

5.1. EC-GSM-IoT

The Extended Coverage Global System for Mobile Communication (EC-GSM-IoT) was one of the early solutions proposed for cellular machine-to-machine IoT applications from the GSM and General Packet Radio Service (GPRS) which was standardised by 3GPP. The software enhancement of the design features of GSM aimed to support mobile IoT development because of its wide global coverage and business needs between the early 1990s and 2015. The number of frequency bands pairs for global GSM deployment—900 MHz with 1800 MHz, and 850 MHz with 1900 MHz—make the manufacture of the global GSM device easier since an IoT device's worst-case complexity is to have dual band capabilities and a low module price (multiple bands support), which are among the characteristics that make GSM suitable for IoT. GSM standards were defined for voice and data based on voice and packet-switched technologies, respectively, [30]. General Packet Radio Service (GPRS), Enhanced Data Rates for GSM Evolution (EDGE), and Enhanced General Packet Radio Service Phase 2B (EGPRS2B) are variants of GSM enhancement to support higher data rates of up to 2 Mbit/s. An EC-GSM-IoT-based IoT was designed to co-exist with higher versions of cellular networks and benefits from their high capacity, extended coverage, roaming support, deep indoor penetration, low energy consumption depending on the number of RF bands supported, and security as well as privacy features [60]. This is a good option for IoT deployment in developing countries, where cellular networks are predominantly used for voice, such as in Nigeria, where the GSM mobile share of technology stood at 99.8% in 2021 [61], and in places where GSM coverage exceeds 4G.

It is important to state that the management of the spectrum has been a major challenge with some being refarmed and others shared between mobile network operators in order to provision global IoT services. With the advent of 5G, spectrum allocated for GSM may be further refarmed to support new technologies.

5.2. NB-IoT

Narrowband Internet of Things (NB-IoT) is an LTE-based radio access LPWAN technology for IoT applications which was standardised in 3GPP releases 13 through 16, as well as release 17 due in 2021 [62]. NB-IoT is increasingly used to support machine-type LTE, and 5G communication, such as by creating networks of sensors and other ultra-low IoT devices based on the benefits of enhanced coverage, deployment flexibility, deep penetration, and reduced energy consumption. The flexibility in deployment options comes from the wide range of frequency bands that LTE networks can support. For instance, the minimum bandwidth of 180 kHz requirements for both uplink and downlink make it possible to use one physical resource block (PRB) within an existing LTE network for NB-IoT deployment [63]. Refs. [20,48] compared the network performance of licensed and unlicensed LPWAN technologies. The findings show that NB-IoT has good penetrating power in all deployment modes with a maximum coupling loss performance of 164 dB. Other important features of NB-IoT are presented in Table 3. A comprehensive review of frequency bands, price, and other features of IoT devices that can be utilised for NB-IoT deployment were contained in our previous work [8].

Table 3. NB-IoT features.

Benefits of NB-IoT
Improved indoor coverage
New radio technology from 3GPP release 13 and above
Supports massive low data devices
Low latency sensitivity
Ultra-low device cost
Low device power utilisation
High assurance of quality of service
Inherited LTE security

In the southern part of Nigeria, where untapped natural gas and crude oil deposits stand at a record high, water and air pollution resulting from oil and gas exploration activities in and around these localities has been endemic as a result of illegal exploration activities such as pipeline vandalism and oil theft [26]. Crude oil spills and other chemical wastes have induced major water pollution threatening the health of those who live and work in these regions. With NB-IoT and other LTE-based sensor networks, it is possible to remotely monitor such parameters. An integrated wireless LPWAN presents the varieties of interoperable protocols for water and environmental data gathering before sending it over to a central data centre for analytics. Through the survey of wireless technologies available in the region, the authors were not aware of any LoRa and NB-IoT-based environmental monitoring system in and around the oil-polluted regions in Nigeria for either private or public use. The availability of wide LTE and GSM network coverage is what this study is leveraging to demonstrate the advantages of using an unlicensed spectrum to complement licensed technologies for scaling IoT deployment in developing countries.

5.2.1. NB-IoT Standardisations

The initial standardisation of NB-IoT was established in the 3GPP standard release 13 to utilise 180 kHz bandwidth LTE resource blocks for the uplink and downlink channel transmissions. The 3GPP release 13 standard outlines the LTE and GSM support capabilities for machine-type communications and the design targets of achieving a long battery life, massive connectivity, greater coverage, deeper penetration, and positioning enhancement. It was originally designed with the LTE modulation schemes, channel coding techniques, and numerology features in the communication type with a low data rate, restricted mobility, and latency requirements. To reduce the IoT module cost and complexity, the LTE-connected mode mobility was removed in NB-IoT [64].

To provide an enhanced user experience in NB-IoT applications and extend the applications to other use cases, 3GPP LTE release 14 was introduced. This allowed service offerings such as coverage enhancement, positioning accuracy, improved data rates, multicast capability, lower power class features, non-anchor carrier support, and the opportunity to support more IoT devices in one eNB [65]. Release 15 optimises early data transmission (EDT) support during the radio access (RA) connection procedure. It is used to enable transmission in the uplink channel within the RA connection procedure thereby reducing the connection setup time and signalling overhead, as shown in Figure 4. The process in EDT is that the IoT module initially indicates the intention to transmit data during the RA procedure by making use of the special (N) narrowband physical random-access channel (PRACH) preamble dedicated to EDT by the evolved base station in the system information blocks (SIBs). Data transmission in releases 13 and 14 is only possible after the RA procedure is completed. This standard has the advantage of reducing latency and improving the battery life of IoT devices deployed in limited network reception areas. The eNB transmits the maximum transport block size (TBS) for the data in EDT mode. Release 16 covers the enhancement in the 3GPP standardisation release 15 5G new radio (5G-NR) [30]. The NB-IoT enhancement in the standard includes the self-organising ability, able to co-exist with NR, mobility enhancement, improved multi-carrier operation, scheduling enhancement, improved transmission efficiency, and improved user equipment power consumption. The support for non-terrestrial access in 5G NR enhancement will enable the support for NB-IoT and eMTC deployment using satellites and high-altitude platforms (HAPs). The deployments standard is based on MNOs and UE capabilities but 3GPP release 14 and higher is recommended. With new IoT network roaming agreements in place, IoT devices will work out of the box in developing countries when they become available.

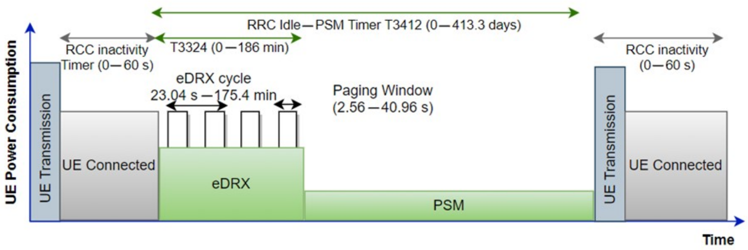

Figure 4. Overview of UE's duty cycle and power utilisation due to the 3GPP standardisation effort.

5.2.2. NB-IoT Deployment Modes

NB-IoT has three modes of deployment options, as presented in Figure 5. The standalone deployment, which is considered the most expensive, requires the installation of a new radio—such as in the case of GSM—and skills to develop and deploy. On the other hand, NB-IoT can be deployed in either the in-band or guard-band mode. The guard-band and in-band deployment options can use a single 180 kHz PRB of the LTE network. The standalone mode is independently deployed as a dedicated carrier using a spectrum greater than the required 180 kHz frequency bandwidth (400 kHz minimum). The GSM wireless access networks and satellite communication systems may be used to deploy NB-IoT in standalone mode. This is achieved by refarming a small slice of spectrum to include a 200 kHz and 100 kHz guard-band for different operators and the same operator, respectively, deploying both GSM and LTE [27]. Guard-band mode is deployed within the existing guard-band of LTE networks since 5% of the LTE channel bandwidth is not fully occupied. NB-IoT design technology, according to 3GPP release 15, will be migrated to 5G radio access to provision LPWAN services since both have been designed to support the same frequency bands and can coexist orthogonally [66]—but there is a limitation in terms of unwanted NR emission which degrades the NB-IoT carrier power level. The in-band deployment mode exists in the PRB of an LTE carrier. This is the operational mode on which the NB-IoT study was conducted. The initial features and specification of the NB-IoT is outlined in Table 4, leading to MNOs running trials and testbeds in different countries, as shown in Figure 6.

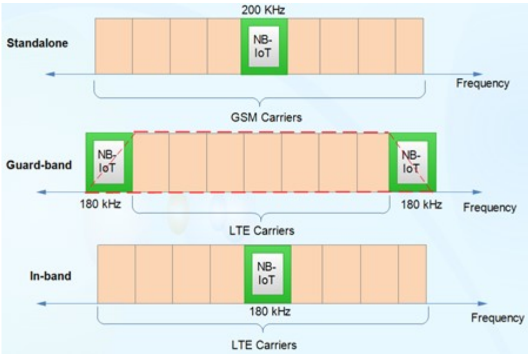

Figure 5. NB-IoT deployment modes.

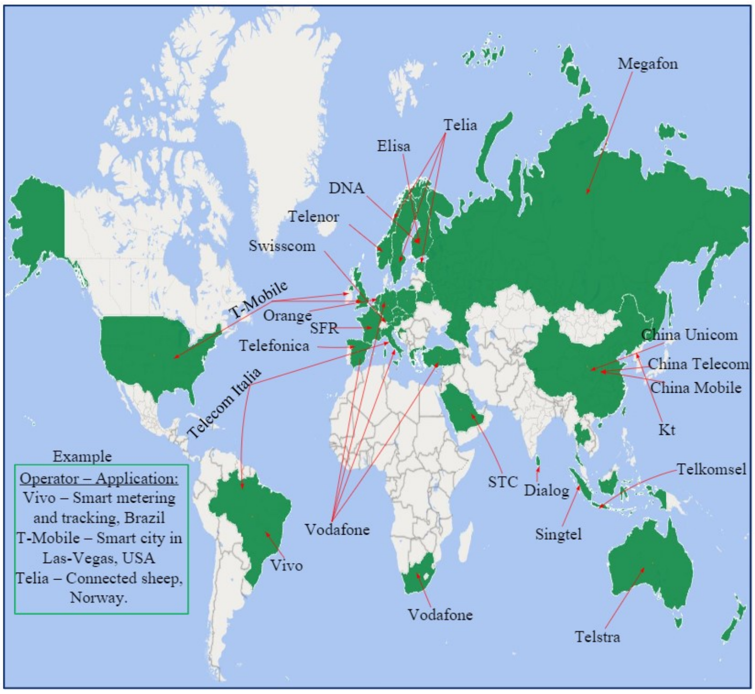

Figure 6. Global NB-IoT deployment. Reproduced with permission from Collins Burton Mwakwata, Narrowband Internet of Things (NB-IoT): From Physical (PHY) and Media Access Control (MAC) Layers Perspectives, *Sensors*; published by MDPI, 8 June 2019 [21].

Table 4. NB-IoT network configurations: the coverage level corresponds to NPRACH configurations.

NB-IoT Features	Values
NPRACH Detection threshold	40 dB
NPDSCH Repetition and TBS	1 and 3
UL Subcarrier spacing	1
Subcarrier	15 KHz
NPDCCH	8
NPUSCH subcarrier	12
Frequency carrier	Band 28
Bandwidth	180 KHz
Receive power	−15 dBm
Transmit power	−3 dBm
Sample rate	30

5.2.3. NB-IoT Positioning Accuracy

Positioning accuracy is an enhancement of the NB-IoT network that could increase the application of NB-IoT across different sectors. Positioning accuracy is a vital aspect of IoT and applicable to most use cases such as asset tracking, environmental monitoring, wearable, and smart agriculture. The NB-IoT release 13 on which the test was based can only associate the UE to the serving cell. Release 14 and other higher release standards provide enhanced serving cell identity (SCID) measurement and observed time difference of arrival (OTDOA), which are more reliable options of obtaining the UE position more accurately. The time advance (TA) eCID is a round-trip measurement (initial round trip time (iRTT)) between the eNodeB and the UE, measured as 48.5 µs, for sending 44 bytes of data through a 5744-window size. The value was used to compare the UE position to the serving cell. The OTDOA uses the measurement of the time-of-arrival (ToA) on the set of a DL narrowband positioning reference signals (NPRSs) from a set of time-synchronised eNodeBs serving the UE. In LoRaWAN, the time-of-difference arrival (TDoA) and received signal strength indicator (RSSI) are two methods of determining IoT module position. It is important to state that the methods discussed above do not require the use of Global Positioning System (GPS) or Assisted Global Positioning System (AGPS) which would make IoT devices more complex, expensive, and power hungry [67].

5.2.4. NB-IoT Mobility Enhancement

NB-IoT device mobility is limited by the radio resource control (RRC), which is able to re-establish connection with an appropriate cell when a UE moves out of a cell coverage area through cell selection. The connection re-establishment is achieved through the user plane data support. The handover feature is not supported in release 13, and mobility creates issues such as radio communication link failure when a UE moves from one serving cell to another. Release 13 only supports stationary UEs, while release 14 supports low-mobility UEs [65]. Mobility, on the other hand, is an inherent feature of LoRaWAN and the impact of mobility on LoRa communications is the reduction in the packet delivery ratio. A mobility analysis does not apply under this scenario since the UE and LoRa gateway are within a single location (see Figure 3). However, in [68], it was observed that the message size and mobility degrade the LoRa signal propagation and even further in urban areas where high-rise buildings would make the light of sight more difficult to achieve. Applying the NB-IoT for remote monitoring applications presents coverage, low cost, high connection, and other benefits. We identified the following challenges of deploying the NB-IoT:

- The availability of IoT networks such NB-IoT will depend on the mobile network providers' offering and government regulatory frameworks;
- Most available cellular IoT devices are based on 3GPP release 13. There is a significant gap that exists in the implementation of new technology features and the technological process;
- To a certain degree, the security and privacy of the NB-IoT solution can rely on the robust security features of LTE. NB-IoT data within the LTE environment is encrypted

except for connections between the application and cloud server where other security mechanisms such as TLS can be considered;

- For scalability reasons, NB-IoT modules need to support the IPv6 addressing scheme.

5.3. LTE-M

LTE-M stands for long-term evolution for machines and is predominantly designed for low cost, deep coverage, and long-lasting battery-powered IoT devices. It is an industrial IoT technology designed for enhanced machine-type communication (eMTC) specified in the 3GPP studies provisioning different LTE categories: Cat-0 in release 12, Cat-M1 in release 13, and Cat-M2 in release 14. It is one of the cellular IoT connectivity options that was first introduced in the 3GPP release 13 standardisation. Similarly to NB-IoT, LTE-M was introduced to support massive IoT deployments of low-complexity devices with deep coverage for UEs in the hard-to-reach locations. The summary of the improvement in the subsequent releases includes positioning accuracy, multicast support, higher data rate, reduced overhead for UEs and control channel signalling, longer battery life, quality channel, coexistence with other radio technology, enhanced use cases, and quality reporting to the network. LTE-M relies on the existing LTE infrastructure and design actions such as a software upgrade in the base station. LTE-M data rates are higher than LoRa and NB-IoT networks for both the uplink and downlink channels. LTE-M may be more widely adopted with more connectivity opportunities for smart city applications in developing countries. In most implementations, LTE-M and NB-IoT support data transmission at a maximum coupling loss (MCL) of 156 dB in a 1.4 MHz bandwidth and 164 dB in a 200 kHz bandwidth, respectively, [50]. Previous mobile technologies before 3GPP standardisation are not suitable for massive machine-type communication (mMTC) because of the high cost and power consumption of IoT modules. One deployment strategy of NB-IoT and LTE-M networks is by a software upgrade to an existing GSM or LTE-based station. As shown in Figure 6, this opportunity is only being taken in Europe, the United States, and other countries with a few trials happening in Africa. Vodacom deployed the 3GPP release 13 cellular NB-IoT in South Africa through the Vodaworld campus laboratory to facilitate the development of NB-IoT-related applications. Vodacom launched NB-IoT (LTE Cat-NB1) on the B8(900 MHz) band in November 2017 [69]. In Nigeria, the mobile telephone networks (MTN) launched NB-IoT (LTE Cat-NB1) on the B8(900 MHz) band in the 2018 trial. With Huawei's CloudAIR 2.0 spectrum sharing innovation, MTN overlapped NB-IoT and LTE in the 900 MHz band [70]. In Kenya, prepared gas services have been made possible by Safaricom NB-IoT (LTE Cat-NB1) deployed on the B20 (800 MHz) band [71].

5.4. 5G and LPWAN Integration

The Fifth Generation Cellular Network (5G) is the most recent cellular IoT standardisation effort. The 5G development agenda was not to replace cellular LTE IoT technology as it has dominated the IoT market but to meet the growing demand for network capacity and coverage. 5G is projected to reach 3.5 billion subscriptions in 2026—exclusive of IoT—according to the 2020 Report by Ericsson [72]. In the same report, the 2026 IoT connection outlook based on NB-IoT and LTE-M was estimated to account for 45% of mobile IoT deployment. Hence, they were left out in the first 5G new radio (NR) release since MTC is already offered in LTE [73]. In 3GPP release 15, LTE could offer reliability as high as 99.99%. However, to meet the LPWAN needs in terms of 5G standards, 3GPP added features that allow cellular LPWAN to be seamlessly integrated into 5G with provisions for potential coexistence enhancement to be considered. The NR frequency band, numerology, beamforming, and duplex mode features are research areas of interest when integrating MTC into NR. Network slicing, network sharing, and machine learning are other research areas of interest to determine a secure means of leveraging the public network infrastructure to deploy 5G private networks [30].

5G is suitable for low latency applications. The ultra-reliable and low-latency (uRLLC) teleprotection and remote access services in utility networks are examples of the benefits of using 5G to complement other LTE technologies. In the 3GPP release 16 and above, 5G NR is being evaluated to support the IoT deployment in the unlicensed spectrum and the possibility of achieving integrated access backhaul (IAB) and unified non-terrestrial networks based on satellites to scale network coverage to hard-to-reach locations. The International Telecommunication Union (ITU) has since 2018 established a focus group to drive a vision beyond 5G by formulating the requirements of network 2030 and beyond [74].

6. LoRaWAN and NB-IoT Implementations

The contribution of this paper is two-fold. The LoRaWAN and NB-IoT testbed is implemented to demonstrate their capabilities and to measure and analyse the performance of QoS parameters under testing.

6.1. Design of a LoRaWAN Testbed

The LoRaWAN implementation is based on a star network topology, separated into its front-end and back-end, as shown in Figure 3. The Things Network (TTN) is an open LoRaWAN platform that runs server infrastructure as a service. The Pysense node joined the Fipy gateway in the Over the Air Activation (OTAA) mode added to TTN through the TTN application programming interface (API) with limited time on-air of 10 messages in the downlink and 30 s duration per device per day. A hypertext transfer protocol (HTTP) web application interface and database is integrated with the LoRaWAN application server to display TTN data. LoRaWAN private infrastructure may deliver close to 846 s/day time on-air as specified in the LoRa Alliance specifications. This reflects the potential challenges of applying LoRaWAN protocol to different applications of different performance requirements sharing the same network resources. Private LoRaWAN platforms will be needed if the requirements of latency, reliability, and transmission patterns of different IoT applications in developing countries are to be satisfied, though as an alternative to licensed spectrum IoT solutions such as NB-IoT and LTE-M.

6.2. Design of an NB-IoT Network

In our recent publication, we demonstrated the design and implementation procedure of the NB-IoT testbed [8]. The NB-IoT testbed specification includes a LimeSDR (LMS7002M) that generates the standard LTE core MME and eNB physical signals from the same CPU that runs Ubuntu Intel Core i7-8550U at 4 GHz, Ubuntu 16.04 xenial OS, 32G RAM, and x86_64-bit kernel. A multiple-input–multiple-output (MIMO) transceiver was based on field-programmable radio frequency (FPRF) for integrated circuit digital signal processing (DSP). The eNB has a 30.72 MHz reference clock, 780.500 MHz DL frequency, 725.500 MHz UL frequency on band 28 (DL EARFCN = 9435), filter order of 4, filter bandwidth of 5MHz, a real pole first order filter of 2.5 MHz, and a transmit and receive sample rate of 1.92 MSps. The NB-IoT node device is the Fipy and Pysense expansion board programmable in the Visual Studio Code and Atom and supports NB-IoT, LTE-M, SigFox, LoRa, Wifi, and Bluetooth IoT wireless technologies. Figure 7 shows our testbed in operation with illustrations on the functionalities and Table 4 shows the parameters' configurations. With this, sensors could then be strategically positioned in various regions to monitor water quality and air pollution levels and the data collected transmitted to IoT cloud platform for analysis.

A similar study that routed LoRaWAN traffic through EPC demonstrates that licensed and unlicensed LPWAN technologies can be integrated and served by a single network core [12]. Such integration is very relevant given the emerging theoretical studies on deploying NB-IoT on the Sub-1 GHz unlicensed band that complies with the Federal Communication Commission (FCC) and European Telecommunication Standards Institute (ELTSI) regulatory requirements [75,76]. The MulteFire Alliance (MFA) specification presents an opportunity to utilise LTE in unlicensed, shared, and large bandwidths in the global unlicensed 5G spectrum bands to lower the cost of deploying private LTE networks. However, in this scenario, our contribution lies in demonstrating the real-world performance of a licensed NB-IoT technology for IoT application using the same end device that was evaluated in the LoRaWAN Things Network platform. An integrated gateway and network core, as shown in Figure 8, then becomes a novel deployment alternative in an environment where cellular network occupies more than 99% of coverage such as the telecommunications services market share of technologies as deployed in Nigeria [35].

Figure 7. LPWAN network in operation.

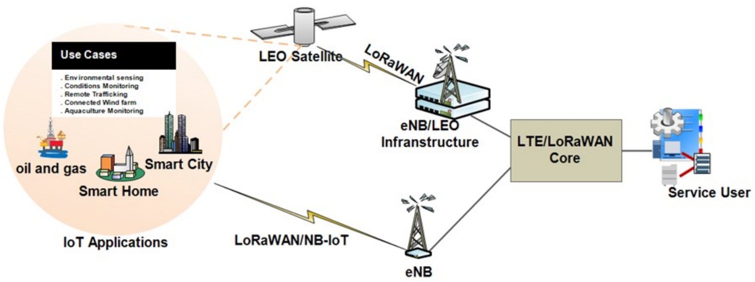

Figure 8. LPWAN integrated architecture.

A multi-standard approach can be adopted where, for instance, a cellular IoT device can support more than one cellular network standard. Multi-radio access network (Multi-RAN) technology will allow multiple LPWAN technologies to be integrated and separated based on use case requirements. Hybrids of WiFi and LoRaWAN [77], and LoRaWAN and NB-IoT [23] are a few of the multi-RAN technologies proposed for global IoT connectivity. These will, however, come with increased processing, memory and energy consumption requirements. The increased device complexity means an increase in the cost of building applications and support infrastructure.

7. Network Performance Analysis: NB-IoT vs. LoRaWAN

Similarly to other IoT networks, NB-IoT network performance is evaluated based on data latency, throughput, battery utilisation, and security. In summary, we present the general NB-IoT testbed performance in the in-band mode of operation that uses the LTE PRBs as specified in the 3GPP release 13 164 dB MCL. However, the general performance mostly differs regardless of any standard assumptions, depending on the mode of operation, the IoT device specifications, and the eNB and MME implementations. The many performance results, as presented in the 3GPP TR 45.820 [78], and in [5,79] are theoretical in light of the limited practical NB-IoT test network performance results. In [44], field testing was performed using different test equipment and was based on simply evaluating the performance of RF coverage and MNO's signal quality. The results of our NB-IoT and

LoRa test networks is presented based on battery life, throughput, security, and latency QoS parameters. While quantifying the power consumption of the testbed, two approaches were used, namely the RTT of a PING request and the transmission of certain data sizes. With the testbed configured with a high NPDCCH repetition rate of 8 and a low coding rate in the case of NB-IoT to increase the detection rate, the power consumption analysis was considered robust. An average delay that was inclusive of the RRC transmission was obtained for TCP transmissions between the UE and server located within the same location. The equivalent average power peaks are shown in Figure 13.

7.1. Latency

As expected, NB-IoT experiences a higher delay than the LTE network due to the transmission pattern of the downlink control information and data being sent via the downlink control and shared channels, respectively. The coverage capacity of the NB-IoT network depends on several factors such as the RF link budget, antenna gain, transmission power, and the target is to achieve a high data rate at 164 dB MCL through an adequate performance of LTE or GSM physical channels. For instance, this would mean a 90% narrowband primary synchronisation signal (NPSS) and narrowband secondary synchronisation signal (NSSS) detection rates with high synchronisation accuracy to meet the latency requirement of 10 s, and also, the NPRACH timing advance of 3 µs. The latency target of the NB-IoT network performance during RRC connection procedure and data rate transmission is to deliver 10 s. The stateful nature of the LTE uplink and downlink transmissions increases the data overhead. The TCP retransmission timeout (RTO) of 244 ms occurred following a 44 bytes transmission segment. The latency in the uplink and downlink channels, as presented, is the sum of the time spent in the synchronisation, resources reservation, data transmission, and reception processes. The latency between the eNB and MME clients, as shown in Figure 9 varies from 6 µs to 50 ms. As observed, the message size does not directly impact the delay, although it does increase the energy consumed as the UE has to wait for message acknowledgement in successful transmission. In the LoRaWAN platform, we considered latency as the duration between when the data are sent by the Fipy and received by the web server. For sending 16 bytes of data in a custom format to the web server per day, for every experiment, between 2 s and 3.5 s latency was measured between when the data were sent and received by the web application. In the LoRaWAN, with a packet length of 20 bytes in class A mode, 2 s was needed for packet re-transmission. However, the success rate of every transmission was above 50%.

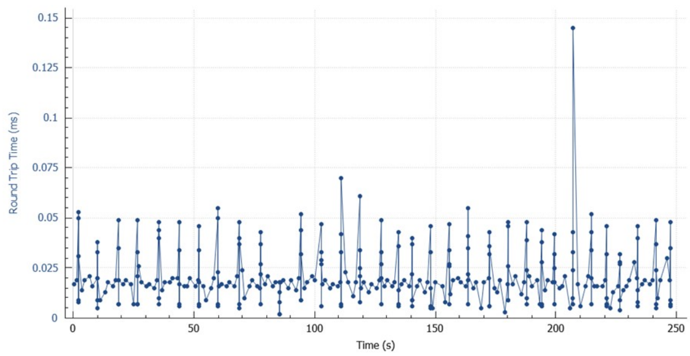

Figure 9. Round-trip time between the LTE eNB server and client.

7.2. Throughput

Data transfer technologies, as specified in the 3GPP documentation, such as multiple-input–multiple-output (MIMO) and carrier aggregation, provide a higher data transfer rate and high-speed packet access networks in LTE. The test results for bidirectional data transfer show the uplink and downlink data throughput in LMS7002M for sending a 44 bytes TCP message. For the in-band mode of operation, a maximum of 1.57 kbps and 1.59 kbps was obtained for the uplink and downlink channels, respectively. It is important to note that the performance of the network could be improved if a different UE is used and the number of lost packets is reduced. The actual data throughput for NB-IoT is usually a fraction of the theoretical maximum. The category of UE, network cell bandwidth configuration, and mode of transmission play an important role in achieving good NB-IoT network performance. In the case where a single UE is attached to an NB-IoT network, it can make use of the full available link capacity for transmission. The highest signal level is required for high data rate transmission and aspects such as fading, link loss, line of sight, noise and interference from other base stations could degrade the signal level. For sending between 29 and 48 bytes, as shown in Figure 10, the average throughput varied between 115 bps and 264 bps between the UE (192.168.3.2) and the server (192.168.3.1). Figure 11 compares throughput, latency, and bitrate in the uplink and downlink transmissions, for the same payloads. In LoRaWAN, the size of the data sent to and received from the TTN is 16 bytes, with a LoRaWAN overhead of 14 bytes. The size of the LoRa payload is one of the features that determine the transmission time. For a 20 byte LoRaWAN packet, with a separation distance of 3 m between the Pysense node and the Fipy gateway, to prevent saturating the receiver amplifier, an estimated on-air time of 31.024 ms was obtained for an SF of 7, a BW of 125 kHz, a data rate of 5, and an indicative bit rate of 5470 bits/s. As a single channel gateway, when the distance is increased, the transmission time increases, resulting in reduced throughput and an increase in bit error rate.

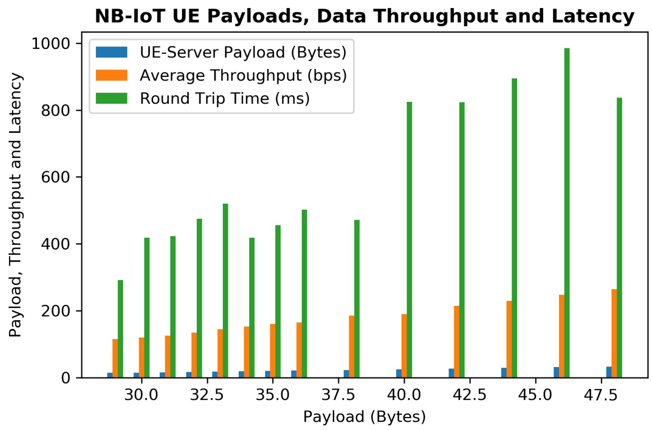

Figure 10. NB-IoT throughput and latency for data UE–server payloads. Note that the server-to-UE transmissions is a constant value of 15 bytes with a constant DL and UL bitrate of 396 and 436 and a number of transmissions within 3 and 5, respectively.

As shown in Figure 12, for every transmission window as shown in Figure 13, a maximum data throughput of 264 bits/s is achieved by the UE which is far below the average throughput established between the LTE eNB server and the client server. During periodic ping requests of 48 bytes between the UE and the network, an average round trip time (RTT) of 655.84 ms was recorded due to the high repetition rate in the subframes. A high repetition rate was expected in NB-IoT networks where signal propagation is inefficient.

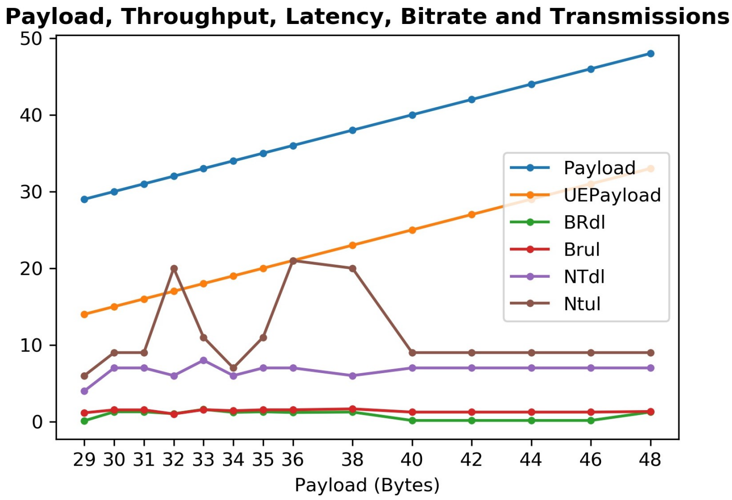

Figure 11. NB-IoT downlink and uplink bitrates for in-band modes of operation. NTdl and Ntul are the number of transmissions in the downlink and uplink channels, respectively, while BRdl are Brul is the bitrate in the downlink and uplink channels, respectively. In the event of retransmissions, the latency increases, as shown in the Ntul spikes between 40 and 48 bytes of data payload in Figure 10.

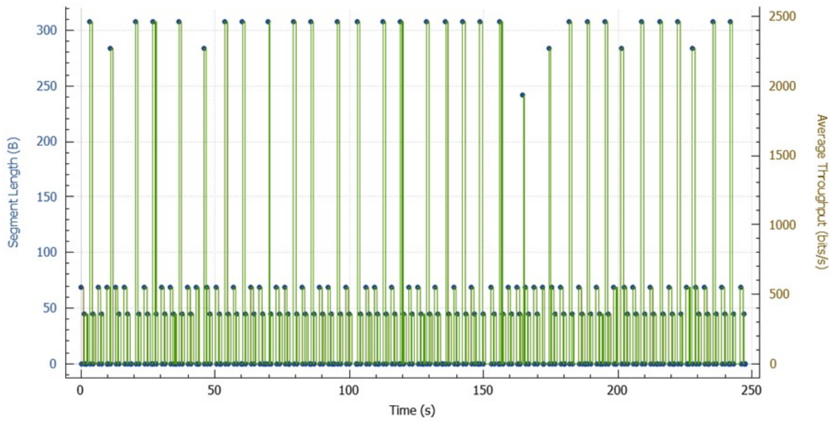

Figure 12. Average throughput between the LTE eNB server and MME client. Maximum and minimum throughput of 308 and 45 bytes, respectively, for the round-trip time in Figure 9.

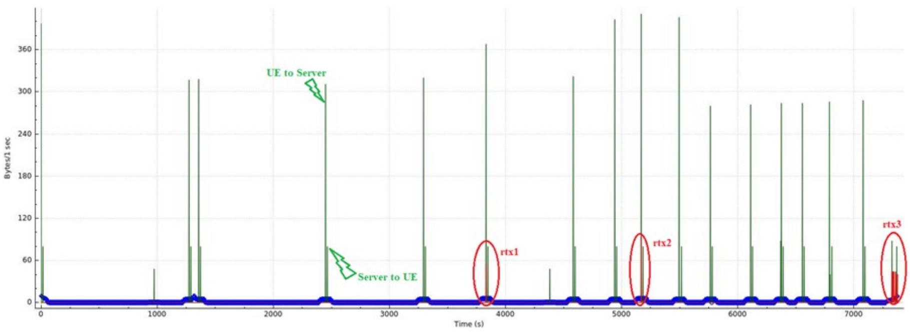

Figure 13. NB-IoT data throughput for successful interval transmissions for a maximum of 7 packets/s. Retransmissions (rtx 1, 2 and 2) occurred in a few of the transmissions' windows and courses' spikes in the number of packets that increased the maximum number of packets to 9 packets/s. At 50 bytes (rtx3) of data payload, the successful transmission rate decreased and, in most cases, resulted in unsuccessful transmission.

7.2.1. Battery Life

The energy consumption of IoT devices is use case-dependent and is mainly influenced by several protocol-specific factors such as hardware synchronisation, the OFDM modulation scheme, network coverage levels, high message repetitions, software, and application capabilities [24]. The energy consumption target of NB-IoT devices according to the 3GPP release 13 standard is 10 years when operated between 20 dBm and 23 dBm. This requirement includes devices that are battery powered, non-rechargeable and used in the most difficult terrains. The power consumption analysis is one way of computing the battery life of IoT modules. The comparison of power consumption analysis of Fipy module in NB-IoT and LoRa networks is based on the USB power meter. It is important to note that the timing resolution of the power meter is a critical requirement and may affect the following results presented in Table 5. As Fipy is a release 13 standard, its radio components remain turned off once registered to the NB-IoT network except when there is scheduled data transmission. At this point, the UE is in an idle state, and the channel is monitored for any handover procedure using paging signals. The eDRX included in the higher 3GPP standardisation is to allow UEs to stay in a sleep state for up to T413 (413.3 days) to save more energy. For every packet's transmission, bursts of power consumption are observed in the CPU and NB-IoT power transmission measurements in Figure 14.

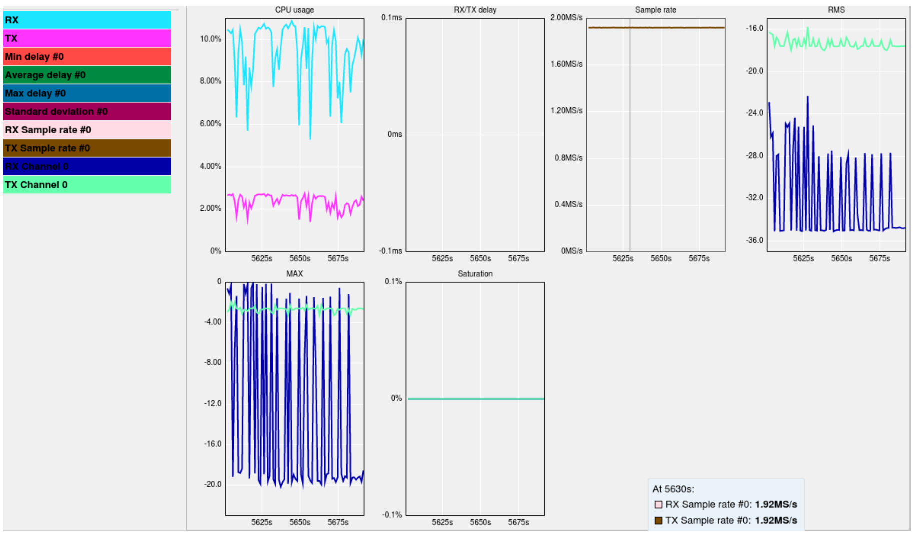

Figure 14. NB-IoT CPU receive and transmission channels' power consumption.

Table 5. NB-IoT vs. LoRaWAN average power consumption, latency, and throughput.

Features	NB-IoT	LoRaWAN
Joining network	3 mAh	1 mAh
Uplink message (44 bytes)	1.8 mAh	100 µAh
UE class	Cat NB1	A
Data rate (20 bytes)	0.6–4 bps	
Frequency	28 Mhz	EU868 MHz

Since the Fipy was not battery powered and to keep the tests' duration to a reasonable period, the evaluation of battery life was limited to the RRC connection procedure and data transmission. With an average of 3 mAh needed to reconnect the NB-IoT module to the network, an uplink message consumed an average of 1.8 mAh for 44 bytes of data at 3.3 vs. the regulated output voltage. For instance, this deviates by a high margin from the 100 µAh measured for uplink messages in LoRaWAN. As concluded in [30], based on ideal conditions, the 10-year lifetime in NB-IoT can be met if 24 h data transmission intervals are implemented and lowering the time scale to 2 h becomes unrealistic at 146 dB MCL. The mode of operation does not impact the uplink transmission, a major determinant of power consumption reduction. In release 14, where a power class of 14 dBm enables the use of smaller cell batteries in new NB-IoT deployment, more efficient power consumption is expected. This improvement over release 13 helps reduce the power amplifier (PA) drain current which negatively affects the UL coverage and the maximum coupling loss (MCL) to 155 dB. An example is that of the Fipy NB-IoT module, a release 13 device that supports 20 and 23 dBm power classes. As shown in Figure 14, without transmissions, the −20.4 dB and −2.72 dB full scale is the maximum power, −35.5 dB and −17.7 dB root mean square (RMS) full-scale value, and 8.40% and 2.72% CPU power for the transmit and receive channels, respectively. During transmissions, an average of −5.68 dB and −2.99 dB full scale was the maximum power, −31.4 dB and −17.1 dB RMS was the full-scale value, 6.32% and 1.85% was the CPU power for the transmit and receive channels, respectively. This shows that the NB-IoT consumed more power than LoRaWAN due to its complicated communication procedure, irrespective of the PSM and eDRX power saving modes. A greater part of the energy was drawn during the synchronisation, joining, and connected state of the UE.

In the LoRaWAN test, the IoT module (Fipy is used as the LoRa gateway and LoRa Node) and the test parameters include a coding rate of 4/5, 125 kHz bandwidth, class A, and a spread factor (SF) of 7. The SF influences the power consumption level since it determines the time it takes radio links to transfer data. The LoRa network gateways are diverse, as a receiving gateway can become a serving gateway. This reduces end devices' power consumption since devices closer to the edge can become gateways. The asynchronous nature of the LoRaWAN allows UE to sleep as often as desirable based on the class of configuration. To achieve an instant downlink communication, the IoT device must be configured as a class C, and scheduled transmission modes in classes B and A is recommended for efficient power consumption. In both networks, allowing more frequent data transmission would reduce the battery lifespan. The total energy required to perform a single test procedure in LoRaWAN was measured as 1 mAh. Similarly, the uplink transmission for LoRa consumed approximately 100 µAh, which is far lower than 1.8 mAh consumed in NB-IoT network. This shows that LoRa is more power efficient than NB-IoT and should be considered as a primary deployment option for extremely low data applications. To achieve a reduction in energy consumption in LoRaWAN such as water quality monitoring, the transmission should be scheduled based on use case.

7.2.2. Security

NB-IoT security capabilities are based on the radio access, network core, and user data encryption of an LTE system. As detailed in our previous study on the security of IoT networks [7], LTE-based technologies use encryption, authentication, and integrity protection mechanisms to provide data, and access and non-access stratum signalling confidentiality, integrity and availability between the UE and core network, the UE and radio network (RN), respectively. In our network, as shown in Figure 15, the MME uses NAS signalling security commands to secure UE and MME messages.

```
21:44:44.414 [NAS] -  0065 UE auth OK
21:44:44.414 [NAS] DL 0065 EMM: Security mode command
        0000:  37 b4 1a 06 40 00 07 5d  02 00 04 f0 f0 00 00 c1  7...@..]........
        0010:  4f 08 c2 89 07 0c f9 79  42 21                    O......yB!
        Protocol discriminator = 0x7 (EPS Mobility Management)
        Security header = 0x3 (Integrity protected with new EPS security context)
        Auth code = 0xb41a0640
        Message type = 0x5d (Security mode command)
        Selected NAS security algorithms = 0x02 (EEA0, EIA2)
        Replayed UE security capabilities:
          0xf0 (EEA0=1, 128-EEA1=1, 128-EEA2=1, 128-EEA3=1, EEA4=0, EEA5=0, EEA6=0, EEA7=0)
          0xf0 (EIA0=1, 128-EIA1=1, 128-EIA2=1, 128-EIA3=1, EIA4=0, EIA5=0, EIA6=0, EIA7=0)
          0x00 (UEA0=0, UEA1=0, UEA2=0, UEA3=0, UEA4=0, UEA5=0, UEA6=0, UEA7=0)
          0x00 (Spare=0, UIA1=0, UIA2=0, UIA3=0, UIA4=0, UIA5=0, UIA6=0, UIA7=0)
        IMEISV request = 1
        Hash MME:
          Length = 8
          Data = c2 89 07 0c f9 79 42 21
```

Figure 15. UE security capabilities.

Security is also an important part of LoRaWAN, primarily in terms of ensuring an authenticated connection, integrity protection, and confidentiality are present in the communication process. Three layers of security are common in the LoRaWAN: device; network; and application security. Device security ensures that only authenticated IoT device connection attempts are accepted by the network. For NB-IoT, the network and application layer security ensures the authenticity of nodes and the confidentiality of data, respectively. To deliver confidentiality in LoRaWAN, in this scenario, LoRa messages should be encrypted using AES, an encryption algorithm supported in IoT modules such as the Fipy. Due to the limitations of release 13 UEs in carrying out successful transmissions at 50 bytes as shown in Figure 13, we will present the evaluation of these security mechanisms using higher standard UEs in future work. Security techniques contribute a substantial data overhead which will be better processed using IoT devices with higher processing power. The security of IoT networks could in many cases be improved by implementing security measures such as locally performing server tasks where possible, to reduce exposure of data to external servers and the internet; ensuring messages are content length-padded to prevent the disclosure of side information through the length of messages; ensuring that suitably strong keys are used, and generated from high-quality random numbers; security keys loaded on the end device in a protected area of memory; along with other good security practices recommended for LPWANs [36].

8. Limitation and Future Research Directions

The following is by no means an exhaustive account of the challenges and future research directions in the field of NB-IoT and LoRaWAN. Nonetheless, we focused on realising the above results of the performance of LoRaWAN and NB-IoT using one eNB and two UEs, as the same approach could applied to cellular LTE-M and other unlicensed LPWANs. LoRaWAN and NB-IoT were selected since they have both gained research and industrial interest with their wide coverage, low-power consumption, good security, and low cost. By introducing additional UEs and eNBs to our testbeds, a better understanding of a larger IoT network performance can be achieved, but we will explore this further in our future work. Although the NB-IoT experiment was performed based on 3GPP release 13, new features have been introduced to the standard release 16, as discussed in Section 5.2.1. The UE used can only support standard release 13 due to a gap between NB-IoT standardisation and manufacturing. Similarly, LoRaWAN was performed in TTN version 2, latency, and other QoS presented could be enhanced when performed in TTN version 3.

As an improvement to this study, packet losses due to signal propagation challenges should be considered when planning IoT networks, especially in challenging environments. Link quality is essential in this type of wireless network to determine the type of service deployed in a particular environment and the packet losses. Refer to [25] for the propagation losses' comparison of NB-IoT and LoRaWAN due to transmissions in underwater, underground, and metallic surfaces. NB-IoT is also faced with roaming problems when the service is to be deployed on a global scale. This means that deploying NB-IoT in more than one country will require the ability to establish international commercial roaming agreements with local carriers, produce NB-IoT carrier-specific modules, and create robust SIM and network management systems to provide cross-border IoT services. Based on the Deutsche Telekom and Vodafone NB-IoT roaming trial, it remains challenging to take an NB-IoT module with Deutsche Telekom SIM and use it in another country's NB-IoT carrier, such as T-Mobile in the United States [80].

Since NB-IoT and LoRaWAN will be deployed in challenging environments, continuous improvements will also be required in data security, self-configuration/organising/healing, cloud and edge computing capabilities, resource mapping and air interface. NB-IoT services are primarily provided by the mobile network operators (MNOs) using their available infrastructure with a decision on the business implications and technical alterations to be made at the base station. However, it is also possible to provide clean slate NB-IoT services but at a higher cost. The air interface is one of the optimisation challenges in the in-band deployment of NB-IoT in an LTE network. It makes use of the core LTE design features such as channel coding, uplink and downlink frequency division access, data rate matching, interleaving, etc. For the efficient coexistence of NB-IoT inside an LTE carrier, orthogonality to the LTE signal must be protected when mapping NB-IoT to LTE resources. The UE needs to be designed to automatically detect the deployment mode and subsequently identify LTE resource blocks. Similarly, to achieve scalability in LPWANs, new LPWAN modules should incorporate adequate memory, processing power, and bandwidth.

9. Conclusions

In this paper, we presented the sustainable opportunities that licensed and unlicensed LPWANs could offer with regard to IoT development in developing countries and compared LoRaWAN and NB-IoT in terms of power consumption, security, latency, and throughput perspectives. With Nigeria as a case study, we discussed the practical challenges and opportunities of deploying LoRaWAN and NB-IoT technologies. The real-world performance/power measurements, as presented herein, show that NB-IoT and LoRaWAN have the potential to drive the realisation of SDGs in developing countries through, for example, the provision of effective asset tracking and environmental monitoring solutions. However, the increased energy efficiency of LoRaWAN suggests that when the QoS requirements of a licensed solution are not required, LoRaWANs could offer savings in a like-for-like deployment, albeit at a reduced QoS. However, the test results proved that on average, NB-IoT could outperform LoRaWAN in terms of data throughput, latency, and security. On the other hand, the roles that the current GSM and LTE MNOs will play to facilitate licensed IoT penetration in developing countries is considered, specifically in the context of challenges in reaching some locations were also presented. The important features of NB-IoT 3GPP standard releases 14, 15, and 16 were discussed; while the performance of release 13 was demonstrated in our testbed, we showed the specific performance of the testbed on power consumption, data throughput, latency, and security of the network as four network features for facilitating NB-IoT for other use-cases. New experimentation capabilities, as introduced in our testbed, allowed the LoRaWAN integration and present evidence of spectrum needs, power utilisation, latency, data rate, and security to guide deployment decisions. These are essential in determining the reliability of LPWAN, and understanding how LPWAN options may help to meet service requirements such as NB-IoT, which guarantees data delivery but at higher energy costs. In contrast, the duty cycle regulations and ISM signal interference affects the reliability and maximum per-device throughput of LoRaWAN, with the benefits of consuming less energy and being cheaper to deploy.

Potential Benefits and Drawbacks of Integrated LPWANs

- Wider Range of Applications—When multiple LPWANs such as LoRaWAN and NB-IoT are supported and integrated on a single IoT device, the effective coverage area will be that of the LoRaWAN and NB-IoT. Though switching between multiple technologies causes an increase in energy consumption due to the cost of the IoT modules and computational overhead increase, it has the potential to rapidly increase the IoT footprint in developing countries as the networks can be extended using a single gateway. IoT devices can dynamically switch between the LPWANs available. The optimisation of the circuit and components' design could improve the cost, energy, and data overhead challenges.
- Improved Reliability—An integrated LoRaWAN and NB-IoT network guarantees message delivery. This means a more robust and intelligent network that can periodically switch technology types based on message sizes and QoS requirements. NB-IoT is for more frequent transmissions while LoRaWAN is for less sensitive and periodic data transmissions.
- Improved Latency—The availability of more than one LPWAN option for message delivery increases the opportunity to spread IoT data over multiple technologies based on the criticality of the application, payload size, and power source. Depending

on the application, variable message sizes can be efficiently and reliably sent. For instance, indoor transmissions can be performed using NB-IoT [81].

- Reduced Cost—The cost of deploying NB-IoT is generally higher than LoRaWAN. NB-IoT operates in licensed spectrum, and the costs of acquiring the spectrum and base stations limits the deployment of private cellular networks. However, when studies on NB-IoT in the unlicensed band become successful [75,76], it will be less expensive and power-efficient to design IoT modules to support multi-radio access technologies, while operating in unlicensed bands.

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Abbreviations

The following abbreviations are used in this manuscript:

μLLC	Ultra-Reliable and Low Latency
3GPP	Third Generation Partnership Project
5G NR	Fifth Generation New Radio
5G	Fifth Generation Cellular Network
ADR	Adaptive Data Rate
API	Application Programming Interface
ATU	International Telecommunication Union
B2B	Business to Business
B2C	Business to Consumer
CapEx	Capital Expenditure
CRASA	Communication Regulators' Association of Southern African
CSS	Chirp Spread Spectrum
EC-GSM-IoT	Extended Coverage Global System for Mobile Communication
EDGE	Enhanced Data Rates for GSM Evolution
EDT	Early Data Transmission
eNB	Evolved Node B
eDRX	Extended Coverage Mode
GDP	Gross Domestic Product
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
HTTP	Hypertext Transfer Protocol
IAB	Integrated Access Backhaul
IoE	Internet of Everything
IoT	Internet of Things
ITU	International Telecommunication Union
LEO	Low Earth-Orbiting

LoRa	Low Range
LoRaWAN	Low-Power Wide Area Network
LPWA	Low-Power Wide Area
LTE	Long-Term Evolution
M2M	Machine to Machine
MCL	Maximum Coupling Loss
MME	Mobility Management Entity
MNO	Mobile Network Operator
MTC	Machine Type Communication
NB-IoT	Narrowband Internet of Things
NPSS	Narrowband Primary Synchronisation Signal
NSSS	Narrowband Secondary Synchronisation Signal
NPDCCH	Narrowband Physical Downlink Control Channel
NPRACH	Narrowband Physical Random-Access Channel
NCC	Nigerian Communications Commission
OTAA	Over-the-Air Activation
OpEx	Operational Expenditure
PRACH	Physical Resource Access Channel
PRB	Physical Resource Blocks
QoS	Quality of Service
RA	Radio Access
RAN	Radio Access Network
RRC	Radio Resource Control
RF	Radio Frequency
ROI	Return on Investment
RTT	Round-Trip Time
SIB	System Information Block

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