Term Paper: *Use of different Low-Power Wide Area Networks on the Internet of Things*

Chew Loh Seng
School of Computer Science and Engineering
Nanyang Technological University
Singapore, Singapore
chew0398@e.ntu.edu.sg

***Abstract*—Currently, the devices adopting the concept of Internet of Things (IoT) technology are increasing rapidly. As IoT devices require a connection to the internet, different solutions exist. One of the popular solutions is the Low Power Wide Area Networks (LPWANs). LPWAN is designed for low power consumption, long-range, and low bandwidth applications. This paper presents a comprehensive study on various LPWAN technologies, including the merits and limitations of each. The paper also covers some potential use cases, the limitations of current LPWAN technology, and the future developments required for mass adoption.**

Keywords—IoT, LPWAN, LoRa, Sigfox, LTE-M, LTE-MTC, NB-IoT, EC-GSM-IoT, M2M

I. Introduction

When Singapore announces its plan to be the world's first Smart Nation in 2014 [1], the Internet of Things (IoT) was one of the key focus areas. IoT refers to the inter-networking of everyday objects, where they are equipped with sensing, computation, and communication capabilities [7].

The Info-communications Media Development Authority (IMDA) – under its former name Info-communications Development Authority (IDA) – was looking at deploying sensors to capture and collect essential data. Attempts to make those data be anonymized, secured, managed, and shared were tested too.

FIGURE 1: DEMONSTRATION FEATURING THE AG BOX ATTACHED TO A LAMP POST [1]

At the same event, the authority showcased the "*Lamp-Post Mounted Above Ground ("AG") Boxes*" concept. Figure 1 shows the internet-connected streetlamp.

The AG Box requires external power sources and connects through the fibre backbone, thus severely limiting the potential of future IoT deployments.

The IoT is a technology shift, enabling the connection of many devices, allowing the sensing and manipulation of the physical world, as we make them smarter and connect through an intelligent network.

Unlike the AG Boxes trial, current IoT deployments aim to use minimal energy, require significantly lesser space, and use wireless communication. This would reduce the upfront and maintenance cost, thus propelling adoption in both commercial and residential environments.

As the Internet is required for deployments of IoT, different telecommunication standards were developed, with a focus on different aspects of IoT applications. Therefore, in this term paper, we will be discussing those standards, but focusing on the Low-Power Wide Area Network (LPWAN).

II. Wired vs Wireless Telecommunications

As mentioned in Chapter 1, the AG Boxes were connected through the Optical Fibre. The light signals were converted into electrical signal using Optical Network Terminal (ONT). The electrical signal follows the Ethernet protocol, a form of wired communication. However, as the current IoT implementation mainly relies on wireless communications instead, in Table 1, we will compare some commonly used network technologies.

TABLE I. COMMONLY-USED NETWORK TECHNOLOGIES

Technology	Latest Revision	Type of Network	Peak Data Rates
Ethernet	802.3bs 802.3cu	Wired Local Area Network	400Gbps
Wi-Fi	802.11ax 802.11ay	Wireless Local Area Network (WLAN)	9.6Gbps for 802.11ax 40Gbps on 802.11ay
Cellular	LTE: Release 14 5GNR: 3GPP Rel 16	Wireless Wide Area Network (WWAN)	25.065Gbps on LTE* 20Gbps on 5GNR
Bluetooth	Bluetooth 5.3	Wireless Personal Area Network (WPAN)	3Mbps

**LTE Cat 17 is currently impractical to implement, so realistic LTE peak performance is up to 3Gbps (LTE Cat 8).*

Theoretically, wired communications allow for higher throughput and can be seen as a better solution for IoT deployments. However, in practice, many IoT devices require far lower throughput. The wireless solution would also allow for rapid and large-scale deployment.

Therefore, despite being slower, and potentially less reliable, wireless communication is the preferred method of transmission.

III. About Wireless Networks

As shown in Table 1, many different wireless network technologies exist. The different technologies are suitable for different uses, and in this chapter, we will be comparing the different categories.

A. Wireless Personal Area Network (WPAN)

Bluetooth is the most used WPAN standard. The Bluetooth standard is maintained by the Bluetooth Special Interest Group (Bluetooth SIG), following the IEEE 802.15.1 standard. Currently, it is designed to cover up to a 300m radius with up to 48Mbps [4]. It operates on the ISM (Industrial, Scientific, and Medical) band, specifically on the 2.4GHz band.

B. Wireless Local Area Network (WLAN)

While the Wi-Fi standard is classified as part of a Local Area Network (LAN), it is commonly referred to as the required component to connect to the Internet (a part of the Wide Area Network – WAN). While the current Wi-Fi standard has only a slightly longer range than Bluetooth, the significantly wider bandwidth and use of Orthogonal Frequency Division Multiplexing (OFDM) resulted in significantly higher throughput, at up to 40Gbps while operating on the ISM bands [5][6]. Currently, most access points and clients use the 2.4GHz and 5GHz bands, but 6GHz, 60GHz, and sub-1GHz bands can be used if available. The Wi-Fi standard is maintained by the Wi-Fi Alliance, following the IEEE 802.11 standards.

C. Wireless Metropolitan Area Network (WMAN)

The implementation of WMAN is rather limited currently. The "Metropolitan" came from the fact that the networks are typically operating on a licensed spectrum, but the range is in between the WLAN and WWAN. One previously potential standard was the WiMAX's WirelessMAN-Advanced, for use as 4G networks. The WiMAX standard is maintained by the WiMAX Forum, following the IEEE 802.16 standards.

However, the adoption of the WirelessMAN-Advanced standard is significantly lower than the competing Long-Term Evolution (LTE) standard, as the service coverage is significantly lower. This is partially due to the use of 2.3, 2.5, and 3.5GHz for most WiMAX operators, causing weak indoor coverage due to the higher frequency (and thus, shorter wavelength). Therefore, despite the higher peak throughput of 128Mbps download and 56Mbps upload for the Mobile WiMAX standard (IEEE 802.16e-2005), as compared to 100Mbps download and 50Mbps upload for LTE Category 3 User Equipment), the real-world performance significantly lagged.

One such example is shown in Figure 2, where a video clip compared the United States' Sprint WiMAX and LTE networks in the downlink and uplink speed test.

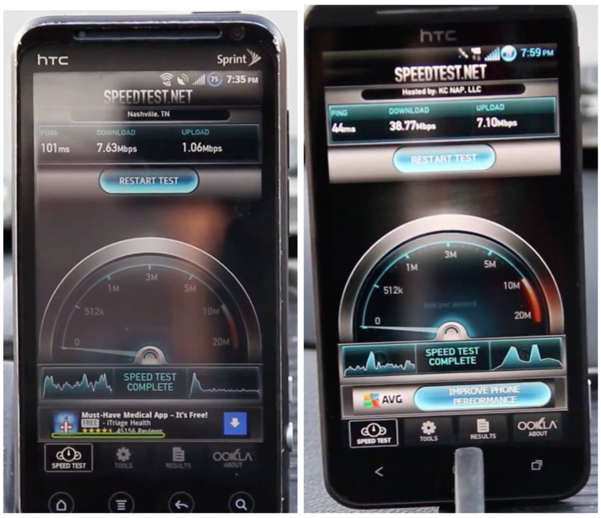

Figure 2: Snapshot of the Sprint WiMAX (left) vs Sprint LTE (right) speedtest results [18]

D. Wireless Wide Area Network (WWAN)

As mentioned in WMAN, the most common WWAN standard in use today is the LTE (Long-Term Evolution) standard, with more than 800 operators with commercial licenses worldwide [2]. Like WMAN, WWAN typically requires the relevant commercial license to operate the public cellular infrastructure, and the lease is typically limited in duration.

Unlike WMAN, implementations on WWAN can be done on sub-1GHz. Typically, during spectrum auctions, those spectrum lots are significantly more expensive [20], as the wider outdoor and deeper in-building coverage would serve more customers at lower overall capital expenditure (CAPEX) [19] despite the higher upfront cost.

Figure 3 illustrates the global trend in spectrum prices, showing that the higher price per MHz per population is typically on the coverage bands (sub-1GHz).

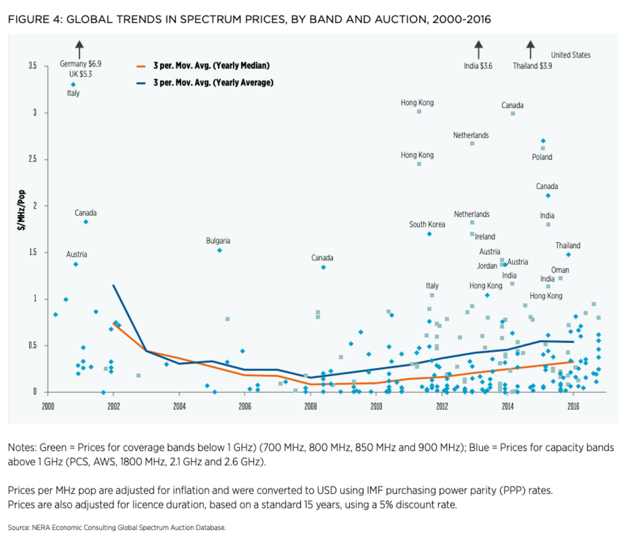

Figure 3: Spectrum Prices from 2000-2016, by bands and auctions [20]

IV. FREQUENCY ALLOCATION

As radio spectrum is a scarce resource and improper usage could render the spectrum lot and/or user equipment useless, proper spectrum allocation is required. In most countries, the government entity oversees the allocation of the radiofrequency spectrum. In the United States, the Federal Communications Commission (FCC) is in charge, while in Singapore, the IMDA governs the same spectrum.

Figure 4 shows the Singapore Frequency Allocations Chart, last updated in August 2021.

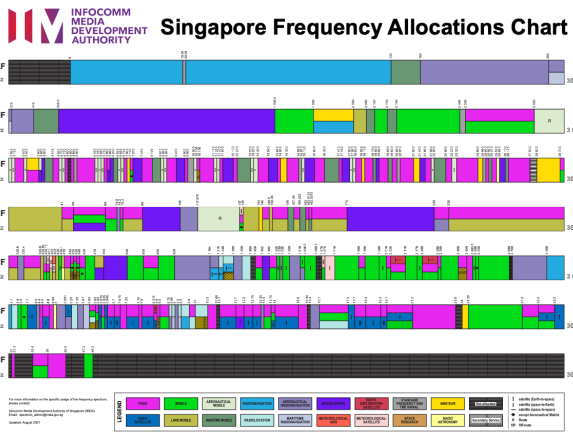

FIGURE 4: SINGAPORE FREQUENCY ALLOCATIONS CHART [3]

While each government has full control over the radiofrequency allocation in their jurisdiction, most follow the Radio Regulations set by the International Telecommunication Union (ITU) and therefore allocate spectrum lots based on the frequency bands defined. In the Radio Regulations, certain frequency ranges are reserved as the ISM radio bands, where unlicensed operations are allowed.

Therefore, most implementations of WPAN and WLAN use the ISM radio bands for localized transmission, while WMAN and WWAN typically use the licensed spectrum for regional and/or nationwide coverage. However, due to the lack of licensed spectrum lots for cellular networks, the LTE in the unlicensed spectrum (e.g., LTE-U) was proposed to off-load some data traffic from the licensed spectrum. Using LTE Carrier Aggregation enables higher throughput for the customers [28].

V. WIRELESS COMMUNICATION FOR INTERNET OF THINGS

While previous chapters focused on telecommunications for high throughput, high power devices, many IoT applications focus on low throughput, low power wireless communication. As such, different technical standards were developed recently to cater to the fast-growing IoT market. Some low-power technologies ride on the existing networks, while some were created independently. The goal is the same: low peak power draw and near-zero idle power draw.

Like Chapter 3, standards for different use-cases exist, including network coverage and data rates. In this topic, we shall discuss the classification and some of the current implementations.

A. Low-Power Personal Area Network (LPPAN)

One example of the LPPAN technology is ZigBee. Unlike Bluetooth, it focuses on creating a WPAN that uses significantly lower bandwidth, therefore it is a Low Rate – Wireless Personal Area Network (LR-WPAN). The ZigBee standard is maintained by the ZigBee Alliance, following the IEEE 802.15.4 standards. Despite that, devices on the ZigBee network cannot communicate with non-ZigBee devices. Currently, it is capable of transmission with up to 250kbps, and also operates on the ISM band [29]. However, while it typically operates on the 2.4GHz band, in some areas, it can operate on sub-1GHz bands too.

B. Low-Power Local Area Network (LPLAN)

One example of the LPLAN technology is Wi-Fi HaLow. Unlike conventional Wi-Fi, it focuses on low-bandwidth, low-power communication. Following the IEEE 802.11h standard, Wi-Fi HaLow uses the sub-1GHz band instead of the 2.4GHz, 5GHz, 6GHz, and 60GHz used in other Wi-Fi standards [8]. This allows for the range to increase significantly to an approximately 1-kilometer radius. The protocol also supports device power-saving modes and standard Wi-Fi security.

C. Low-Power Wide Area Network (LPWAN)

While LPPAN and LPLAN are ideal for communications in residential settings, they might not be practical in commercial settings, where remote sensing and control are required.

Therefore, Low-Power Wide Area Networking (LPWAN) is deployed. It is designed for large-scale, long-distance deployments. Unlike LPPAN and LPLAN, competition here is much stiffer, likely due to the economics of scale and the potentially higher profit margins led by multi-line, long-term commercial leasing contracts signed by other businesses.

In the following topics, we will be discussing some currently deployed technologies, the difference between deploying LPWAN on licensed and unlicensed spectrum, the current challenges faced, and the future developments of the technology.

VI. LPWA TECHNOLOGIES

In the Low-Power Wide Area (LPWA) industry, a few standards have been created. In this chapter, we will explore some of the emerging LPWA technologies and their implementation.

A. Example 1 - Sigfox

Sigfox is a proprietary, ultra-narrowband LPWAN technology, connecting through sub-1GHz ISM bands. It relies on the star topology, where each device is connected directly to the central network server. The Sigfox protocol uses the Differential Binary Phase Shift Key (D-BPSK) modulation to transmit messages.

As the data rate is only 100bps or 600bps – depending on the operating region – protocol overhead must be kept low to reduce the transmission period. Combining with the largest coverage in the world, the company claims that the technology consumes the least energy among the current LPWAN technologies [24].

B. *Example 2 - LoRaWAN*

Like Sigfox, the Long-Range Wide Area Network (LoRaWAN) also uses the sub-1GHz ISM bands. However, LoRaWAN claims to be an open-sourced LPWA network, but the claim has been disputed [23].

LoRaWAN is deployed in a stars-of-stars topology, as the central network server communicates with end devices through a gateway.

End devices were divided into three classes based on their needs. All three classes accept bi-directional communication.

- Class A is the default and is designed for asynchronous operations.
- Class B is designed for devices that support periodic beacons, therefore providing deterministic downlink latency.
- Class C is designed for devices that require the lowest latency, as the receiver is always on.

The trade-off is that Class C devices consume the most power, while Class A devices consume the least. Depending on the configuration, devices on the network can expect speeds of up to 50kbps.

128-bit Network Session Key and 128-bit Application Session Key have been implemented for network-level security.

Figure 6 shows the LoRaWAN network architecture.

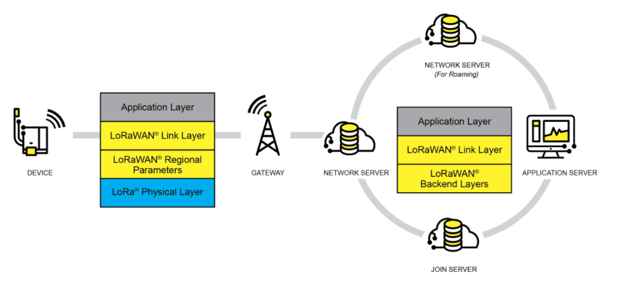

FIGURE 6: LORAWAN NETWORK ARCHITECTURE [22]

C. *Example 3 – LTE-M / LTE-MTC*

The LTE for Machine-Type Communication (LTE-MTC / LTE-M) standard comprises multiple LTE User Equipment (UE) categories, including the Cat-M1. Using the current LTE infrastructure, LTE-MTC features reduced device complexity mode and +15dB gain to extend the LTE coverage (-160dBm) [26].

Unlike Sigfox and LoRaWAN, LTE-M is a form of cellular-IoT, using the licensed radio frequency spectrum. Adopting the LTE standard, the downlink traffic uses the Orthogonal Frequency Division Multiple Access (OFDMA) and the uplink traffic uses Single Carrier Frequency Division Multiple Access (SC-FDMA) [25].

As the LTE-M supports full-duplexing, it requires significantly more power than many other LPWA networks. The trade-off is worth it if the UE requires significantly lower latency for communication. Also, features like Mobility and Voice Call over LTE (VoLTE) capability are supported, unlike most LPWANs where only simple message transmissions were allowed.

D. *Example 4 – NB-IoT*

While LTE-M requires a standalone carrier of at least 1.4MHz, the Narrowband IoT (NB-IoT) standard – also known as Cat-NB1 – can be deployed in 3 modes, as shown in Figure 5: Standalone Carrier, In-band, and LTE Carrier Guard band.

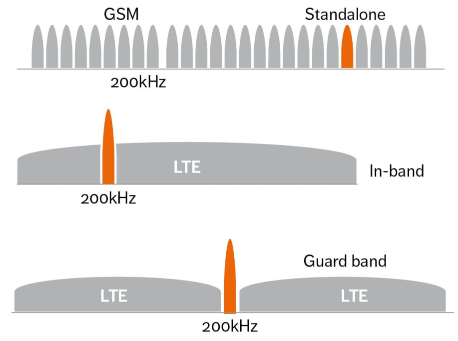

FIGURE 5: THE 3 MODES OF NB-IOT DEPLOYMENT [17]

Like LTE-M, the NB-IoT relies on the LTE infrastructure, using the same modulation techniques [25]. However, as the NB-IoT is capable of "re-farming" the guard band, the spectrum allocation reduces significantly to 200kHz. This also limits the peak throughput significantly, from 1Mbps to 250kbps [27]. Coverage is extended further, with +20dB gain compared to LTE (-164dBm) [26].

The narrowband also removed some features associated with standard cellular networks, including voice calls and cell hand-off.

E. *Example 5 – Extended Coverage GSM Internet of Things (EC-GSM-IoT)*

Unlike examples 3 and 4, EC-GSM-IoT focuses on modernizing the GSM networks (EGPRS / EDGE). Compared to the existing EGPRS/EDGE networks, the following features were adopted: up to +20dB gain for extended coverage, LTE-grade security, enhanced power efficiency, and reduced device complexity.

As the EC-GSM-IoT is an in-place upgrade on the GSM network, existing GSM/GPRS/EDGE Machine-to-Machine (M2M) terminals will not be affected while reducing cost and improving the security of newer terminals.

VII. LICENSED VS UNLICENSED SPECTRUM

For the first two technologies listed in the previous chapter, the networks were deployed on the unlicensed spectrum. In contrast, the last three technologies discussed were using the licensed spectrum. In this chapter, we will be discussing the differences between the two, focusing on the advantages.

A. *Deployment on unlicensed spectrum*

As the non-cellular IoT networks rely on the unlicensed spectrum (ISM bands), the license structure to operate the commercial network is significantly easier. Therefore, the cost to deploy is likely to be lower.

The lack of regulations also allows open sourcing to be possible. Theoretically, it would enable better security as the source codes are open for all to view and verify. Users can customize based on their requirements, eliminating unused features to further reduce power consumption.

B. *Deployment on licensed spectrum*

As mentioned, the LTE-M, NB-IoT, and EC-GSM-IoT networks were deployed on the licensed spectrum. All three technologies were standardized by the 3rd Generation Partnership Project (3GPP).

The standardization allows for interoperability between different network operators and prevents vendor lock-in. Network Security is mandatory, reducing the risk and impacts of the attacks on IoT devices [40].

Deploying on the licensed spectrum also significantly reduces the risk of interference, allowing for stricter Quality of Service (QoS) [41]. The chances of Denial of Service (DoS) attacks through network jamming are virtually eliminated, except for very specific situations.

Additionally, LTE features a standardized QoS Class Identifier (QCI), providing service differentiation. Thus, the QCI priority can be adjusted to allow some clients to transmit the data on a higher priority for a set period and on a lower priority otherwise [42].

Unlike many unlicensed spectrum players, as the three technologies are extensions of the current cellular networks, the cost to maintain the IoT networks is negligible if the existing cellular infrastructure is operational.

In fact, the Sigfox network almost went under, as it filed for bankruptcy protection in January 2022. The company cited slow adoption and COVID-19-related supply chain issues as the main issues leading to the failure [15]. Fortunately, the Singapore company UnaBiz decided to acquire the failing company in April 2022, allowing the commercial activities to continue [16].

VIII. Applications

The re-emergence of LPWAN happened because it is suitable for many smart applications. This chapter discusses some of those applications, including the advantages and limitations.

A. *Smart Meter*

A smart meter continuously monitors the power draw and reports back to the power grid. Through constant monitoring, a time-series power consumption graph can be generated for each meter. The variable pricing structure can also be adopted, encouraging off-peak usage to reduce the electrical load.

The use of cellular-IoT solutions, especially NB-IoT and EC-GSM-IoT, would allow the utility companies to upgrade the power meter with minimal reconfiguration. It also allows for constant power monitoring without actively monitoring the network load.

For example, Keppel Electric in Singapore partnered with network operator M1, using M1's NB-IoT network "to track customers' energy usage more efficiently" [30].

B. *Smart Agriculture*

Using different low-cost sensors, smart agriculture can monitor various parameters including temperature, humidity, soil moisture, and wind conditions. Those parameters are likely to be monitored periodically but not constantly. Therefore, technologies that favor low idle power consumption are preferred.

For this example, LoRaWAN and/or Sigfox should be prioritized, as both use lower power consumption during idle than their cellular-IoT counterparts [43].

C. *Last-mile delivery*

Last-mile delivery refers to the last step of the delivery process, where the parcel was delivered from the transportation hub to its destination. Typically, this process is the most expensive and hardest to resolve, as it requires labor to process and deliver parcel by parcel.

Currently, drones and self-pickup options were explored in many countries to solve this logistical problem. As those options require constant connectivity, LTE-M is the best solution available. This is especially important for deliveries using drones, as the high latency imposed by other LPWAN technologies would severely limit the remote-control capability.

IX. Limitations of LPWAN

While LPWAN is widely adopted for current IoT implementations, there are limitations to the current implementation. In this chapter, we will be discussing some of those issues.

A. *Not able to support critical IoT systems*

Many of the current deployments of LPWAN can be categorized as Massive IoT, where the IoT connected prioritize power and energy efficiency, at the significant expense of latency.

This means that the time-critical IoT applications cannot be implemented using most of the current LPWA networks. These are categorized as Critical IoT systems, as any form of failure including communications can cause catastrophic events, just like real-time systems.

Figure 7 shows some uses that are time-critical and can be enabled using Critical IoT.

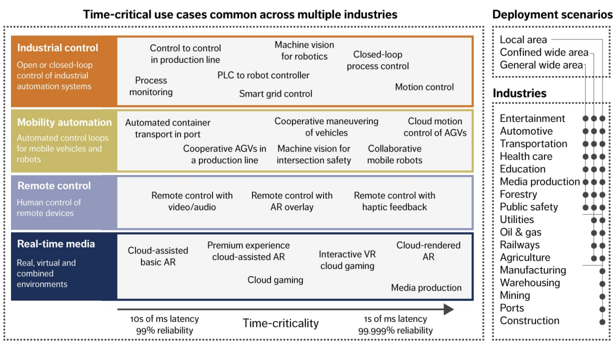

Figure 7: Time-critical use cases highlighted by Ericsson [9]

With current solutions, none of the unlicensed spectrum LPWAN standards can be adopted for Critical IoT systems. NB-IoT network is also infeasible for Critical IoT implementations. While LTE Cat-M1 can provide connectivity with a latency of 10ms [31] like existing LTE infrastructure, the latency may still be too high for certain Critical IoT systems.

LTE-Advanced Pro (LTE-A Pro), as part of 3GPP Release 13 [32], attempts to solve the issue by changing the frame structure [33], therefore reducing latency to less than 2ms in ideal situations. However, like many network upgrades, the rollout for LTE-A Pro is gradual, starting from areas with high network load. Not all operators will adopt, citing spectrum and CAPEX issues, among other reasons.

Therefore, Critical IoT systems are likely to utilize the new 5G New Radio (5GNR) – Standalone Access (SA) systems for connectivity. The 5GNR SA focuses on supporting Ultra-Reliable Low Latency Communication (URLLC), allowing for latency to be below 1ms in an ideal situation [35] while providing higher spectral efficiency than LTE systems [36].

As the Non-Standalone Access (NSA) variant of 5GNR relies on the existing LTE network for signaling [37], it is good for some Critical IoT applications.

However, as the coverage for 5GNR SA is lacking in many countries, the implementation of the Critical IoT ecosystem is likely to take a while before fruition.

B. *Scalability*

Scalability is the measure of a system's ability to dynamically increase or reduce the performance and cost as the application and system processing demand fluctuates [13].

Using the chirp spread spectrum (CSS) modulation technique and ALOHA protocol has prompted researchers to study its scalability [14]. In one of the studies, simulations found that the scalability of LoRa is rather limited due to the co-spreading sequence interference, despite having various interference mitigation measures.

As the concept of IoT is to connect as many devices as possible to the Internet, scalability is key for the LPWA networks. Therefore, for any future LPWAN technologies, scalability must be taken into consideration to ensure network stability.

C. *Network Security and Data Privacy*

As the cost of operating the cell sites could not be shared with normal users, many non-cellular LPWA players rely on funding from private investors. Therefore, with the pressure of delivering the products to the market as quickly as possible and at the lowest cost, security was typically ignored.

As the data in transit might be tapped, data privacy is also a concern. The issue is even more serious if the LPWA network relies heavily on fixed and unencrypted forms of authentication (e.g., using the MAC address to identify the user), thereby releasing sensitive information to the attack.

While most of the network security and privacy concerns mentioned in this paper involve the non-cellular IoTs, cellular IoTs are not immune to this problem too.

In fact, the European Parliamentary Research Service (EPRS) has identified 6 privacy, 6 security, and 2 ethics concerns regarding the use of 5G technology [21]. Figure 8 highlights those concerns.

Privacy concerns	Security concerns	Ethics concerns
Transboundary data flow and 5G	Network 'softwareisation' and flexibility	Lack of citizen awareness the impacts of 5G on ethic aspects
High-speed data rate	Multiconnectivity and device density	Technology and use personal data
High traffic density and location accuracy	Protocols and interoperability	
Huge number of connected devices (IoT)	Identifiers and encryption	
Internet protocol (IP)	New infrastructures and frameworks	
Privacy as open issue	Cybersecurity standards	

FIGURE 8: THE CONCERNS HIGHLIGHTED IN THE STUDY

In all, frequent network security updates must be implemented on all existing and upcoming LPWA networks.

X. FUTURE DEVELOPMENTS

In this topic, we will be discussing the future developments of LPWA networks, focusing on the headwinds and tailwinds of the technology.

A. *Future IoT growth*

Despite the IoT sector growing by 22% in 2021 [11], Forrester Research predicts that the IoT market could inhibit growth by 10-15% in 2022 [12]. The slowdown can be attributed to some factors described below.

Since 2020, the global chip shortage brought by the COVID-19 pandemic caused a cap in growth in many technology-related industries, including the edge computing and IoT sectors.

As the United States Federal Reserve projected a total of seven interest rate hikes in 2022 [10], coupled with the recent Chinese government's crackdown on technology companies [38], and the ongoing Russian war in Ukraine [39], investors are significantly more cautious when investing into disruptive technologies, including IoT.

Overall, while IoT growth is unlikely to stop, the significant delays, price hikes, and political instability could result in permanent damage to future growth.

B. *Retirement of older networks*

For non-cellular IoTs, the reduction of sales and funding and increased costs have put tremendous pressure on the players. Therefore, premature termination of the legacy non-cellular LPWA networks might happen, affecting the IoT and Machine-to-Machine (M2M) devices using the network.

For cellular IoTs, many network operators worldwide are planning to or have successfully shut down their 2G and/or 3G networks. This includes Singapore, where the GSM network was decommissioned on 1 April 2017 [34].

While the retirement of the older networks frees up the precious radiofrequency spectrum for the more efficient LTE and 5GNR networks, many 2G/3G M2M terminals were forced to upgrade. The imminent shutdown of those networks could also allow the network operators to justify not upgrading their GSM networks to support EC-GSM-IoT, compromising the security of the systems connected.

For IoT systems that rely on LTE-based networks, as many network operators focus on deploying 5GNR currently, the future remains to be seen especially in terms of security and network coverage.

XI. Conclusions

IoT and LPWAN are disruptive technologies that came about recently, each building on their existing systems. The paradigm shift from high throughput, high-capacity networks to low data-rate, long-range networks to cater to different use cases is a remarkable approach to the current IoT framework.

This paper briefly discussed different LPWAN technologies, namely: Sigfox, LoRaWAN, NB-IoT, LTE-M/LTE-MTC, and EC-GSM-IoT. Some use cases were explored regarding the few technologies covered, as well as the strengths and weaknesses of each.

In general, cellular IoT technologies are better for constant connectivity and scalability, and non-cellular IoT technologies are better for devices that require a much longer battery life.

However, the future developments of these technologies have to be closely monitored to enable quick and decisive changes whenever new challenges are addressed, even if a complete replacement of the system has to be done.

XII. References

[1] Eileen, Y. (2014, June 17). *Singapore unveils plan in push to become smart nation*. Retrieved from ZDNet: https://www.zdnet.com/home-and-office/networking/singapore-unveils-plan-in-push-to-become-smart-nation/

[2] GSA. (2022, March). *NTS Statistics – March 2022: Snapshot*. Retrieved from GSA: https://gsacom.com/paper/nts-statistics-march-2022-snapshot/

[3] Info-communications Media Development Authority, Singapore. (2021, August). *Spectrum Allocation Chart - August 2021*. Retrieved from Info-communications Media Development Authority, Singapore: https://www.imda.gov.sg/-/media/Imda/Files/Regulation-Licensing-and-Consultations/Frameworks-and-Policies/Spectrum-Management-and-Coordination/SpectrumChart.pdf

[4] Bluetooth SIG. (2021, July 13). *Core Specification 5.3*. Retrieved from Bluetooth SIG: https://www.bluetooth.com/specifications/specs/core-specification-5-3/

[5] IEEE. (2021, May 19). *IEEE 802.11ax-2021*. Retrieved from IEEE: https://standards.ieee.org/ieee/802.11ax/7180/

[6] IEEE. (2021, July 28). *IEEE 802.11ay-2021*. Retrieved from IEEE: https://standards.ieee.org/ieee/802.11ay/6142/

[7] Ali, N., Saleem, R., Angelina, P., Mesut, G., & Behnam, D. (2018, December 3). *Low-Power Wireless for the Internet of Things: Standards and Applications*. Retrieved from IEEE Access: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8528458

[8] Wi-Fi Alliance. (n.d.). *Wi-Fi CERTIFIED HaLow*. Retrieved from Wi-Fi Alliance: https://www.wi-fi.org/discover-wi-fi/wi-fi-certified-halow

[9] Fredrik, A., Joachim, S., Ali, Z., Lisa, B., & Y.-P. Eric, W. (2020, June 2). *Critical IoT connectivity: Ideal for time-critical communications*. Retrieved from Ericsson: https://www.ericsson.com/49ba0b/assets/local/reports-papers/ericsson-technology-review/docs/2020/critical-iot-connectivity.pdf

[10] Pound, J. (2022, March 16). *New Federal Reserve projections show six more rate hikes this year*. Retrieved from CNBC: https://www.cnbc.com/2022/03/16/new-federal-reserve-projections-show-six-more-rate-hikes-this-year.html

[11] Wegner, P. (2022, March 30). *Global IoT market size grew 22% in 2021 — these 16 factors affect the growth trajectory to 2027*. Retrieved from IoT Analytics: https://iot-analytics.com/iot-market-size/

[12] Onag, G. (2021, November 18). *Chip shortage will hinder IoT growth by 10% to 15% in 2022*. Retrieved from Future IoT: https://futureiot.tech/chip-shortage-will-hinder-iot-growth-by-10-to-15-in-2022/

[13] Gartner. (n.d.). *Definition of Scalability*. Retrieved from Gartner Information Technology Glossary: https://www.gartner.com/en/information-technology/glossary/scalability#:~:text=Scalability%20is%20the%20measure%20of,application%20and%20system%20processing%20demands.

[14] Orestis, G., & Usman, R. (2017, April). *Low Power Wide Area Network Analysis: Can LoRa Scale?* Retrieved from IEEE Xplore: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7803607

[15] Lunden, I. (2022, January 27). *Sigfox, the French IoT startup that had raised more than $300M, files for bankruptcy protection as it seeks a buyer*. Retrieved from TechCrunch: https://techcrunch.com/2022/01/27/sigfox-the-french-iot-startup-that-had-raised-more-than-300m-files-for-bankruptcy-protection-as-it-seeks-a-buyer/

[16] Morris, A. (2022, April 22). *IoT player Sigfox finds saviour with UnaBiz*. Retrieved from Mobile World Live: https://www.mobileworldlive.com/featured-content/top-three/iot-player-sigfox-finds-saviour-with-unabiz

[17] Sara, L., Joakim, B., Erik, W., & David, H. (2016, April 25). *NB-IoT: a sustainable technology for connecting billions of devices*. Retrieved from Ericsson Technology Review: https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/nb-iot-a-sustainable-technology-for-connecting-billions-of-devices

[18] wwjoshdew. (2012, August 14). *Sprint WiMax [EVO3D] vs 4G LTE [EVO4GLTE] 38MB/s DOWNLOAD!!* Retrieved from YouTube: https://www.youtube.com/watch?v=PcKmisujJH4&ab_channel=wwjoshdew

[19] Ashutosh, J., & Debashis, S. (2017, September 27). *Techno-Economics Behind Provisioning 4G LTE Mobile Services over Sub 1 GHz Frequency Bands*. Retrieved from Springer Nature: https://link.springer.com.remotexs.ntu.edu.sg/chapter/10.1007/978-3-319-67235-9_17

[20] Richard, M., Bruno, S., & Hans-Martin, I. (2017, February). *Effective Spectrum Pricing: Supporting better quality and more affordable mobile services*. Retrieved from GSMA: https://www.gsma.com/spectrum/wp-content/uploads/2017/02/Effective-Spectrum-Pricing-Full-Web.pdf

[21] Carmela, O., Luigi, B., Antonio, C., Riccardo, S., Emanuela, T., & Andrea, I. (2022, March). *Privacy and security aspects of 5G technology*. Retrieved from European Parliamentary Research Service: https://www.europarl.europa.eu/RegData/etudes/STUD/2022/697205/EPRS_STU(2022)697205_EN.pdf

[22] LoRa Alliance. (n.d.). *What is LoRaWAN® Specification*. Retrieved from LoRa Alliance: https://lora-alliance.org/about-lorawan

[23] Paultre, A. (2020, February 7). *How Open-Source is the LoRaWAN IoT Community?* Retrieved from Embedded Computing Design: https://embeddedcomputing.com/technology/open-source/linux-freertos-related/how-open-source-is-the-lorawan-iot-community

[24] Sigfox. (n.d.). *Sigfox*. Retrieved from Sigfox: https://www.sigfox.com/en

[25] Electronics Notes. (n.d.). *LTE OFDM, OFDMA SC-FDMA & Modulation*. Retrieved from Electronics Notes: https://www.electronics-notes.com/articles/connectivity/4g-lte-long-term-evolution/ofdm-ofdma-scfdma-modulation.php

[26] Singapore Telecommunications Limited. (2018). *Brochure - IoTConnect*. Retrieved from Singapore Telecommunications Limited: https://www.singtel.com/content/dam/singtel/business/globalservices/Featured%20Articles/brochure-iotconnect.pdf

[27] Ullerstig, S. (2019, February). *Know the difference between NB-IoT vs. Cat-M1 for your massive IoT deployment*. Retrieved from Ericsson: https://www.ericsson.com/en/blog/2019/2/difference-between-nb-iot-cat-m1

[28] Ran, Z., Miao, W., Zhongming, Z., Xuemin, S., Liang-Liang, X., & Lin, C. (2015, July 6). *LTE-unlicensed: the future of spectrum aggregation for cellular networks*. Retrieved from IEEE Xplore: https://ieeexplore.ieee.org.remotexs.ntu.edu.sg/document/7143339/authors#authors

[29] Imran, A., & Atif, S. (2018). *Zigbee Protocol*. Retrieved from ScienceDirect:

https://www.sciencedirect.com.remotexs.ntu.edu.sg/topics/engineering/zigbee-protocol

[30] M1 Limited. (2018, March 23). *M1 partners Keppel Electric to offer new power options*. Retrieved from M1 Limited: https://www.m1.com.sg/about-us/news-releases-archive/2018/m1-partners-keppel-electric-to-offer-new-power-options

[31] Nokia. (2016, November 29). *The evolution of LTE-Advanced: LTE-Advanced Pro*. Retrieved from YouTube: https://www.youtube.com/watch?v=iU1IZVUnGS4&t=1s&ab_channel=Nokia

[32] 3rd Generation Partnership Project. (2015, September 17). *Release 13*. Retrieved from 3GPP: https://www.3gpp.org/release-13

[33] Nokia Networks. (2015, December). *LTE-Advanced Pro - Pushing LTE capabilities towards 5G*. Retrieved from Nokia Networks: https://www.3g4g.co.uk/4_5G/4_5G_Nokia_LTE-A_Pro_white_paper_Dec2015.pdf

[34] Infocomm Media Development Authority. (2017, March 27). *2G Services to Cease on 1 April 2017*. Retrieved from Infocomm Media Development Authority: https://www.imda.gov.sg/news-and-events/Media-Room/Media-Releases/2017/2g-services-to-cease-on-1-april-2017

[35] Petar, P., Jimmy, N. J., Marko, A., Cedomir, S., Elisabeth , C. d., Kasper, T. F., & Alexandru-Sabin, B. (2019, August). *Wireless Access in Ultra-Reliable Low-Latency Communication (URLLC)*. Retrieved from IEEE Transactions on Communications: https://ieeexplore.ieee.org.remotexs.ntu.edu.sg/stamp/stamp.jsp?tp=&arnumber=8705373

[36] 5G Networks. (2021, February 8). *Spectral Efficiency : 5G-NR and 4G-LTE compared*. Retrieved from CableFree Networks: https://www.5g-networks.net/5g-technology/spectral-efficiency-5g-nr-and-4g-lte-compared/

[37] Ekström, H. (2019, July 11). *Non-standalone and Standalone: two standards-based paths to 5G*. Retrieved from Ericsson: https://www.ericsson.com/en/blog/2019/7/standalone-and-non-standalone-5g-nr-two-5g-tracks

[38] Qu, T. (2022, March 14). *China tech crackdown: Beijing to tighten regulation on internet platforms that profit from teenage users*. Retrieved from South China Morning Post: https://www.scmp.com/tech/policy/article/3170401/china-tech-crackdown-beijing-tighten-regulation-internet-platforms

[39] Al Jazeera and News Agencies. (2022, February 24). *Russian forces launch full-scale invasion of Ukraine*. Retrieved from Al Jazeera and News Agencies: https://www.aljazeera.com/news/2022/2/24/putin-orders-military-operations-in-eastern-ukraine-as-un-meets

[40] Marshall, P. (n.d.). *LoRa or Cellular for IoT: Which is the Right Choice for You?* Retrieved from Eseye: https://www.eseye.com/iot-explained/lora-vs-cellular-for-iot/

[41] Infocomm Media Development Authority. (n.d.). *QoS standards for 4G services*. Retrieved from Infocomm Media Development Authority: https://www.imda.gov.sg/-/media/Imda/Files/Regulation-Licensing-and-Consultations/Licensing/licenses/Compliance-to-IDA-standards/QoS-standards-for-4G-services.pdf

[42] You-Chiun, W., & Song-Yun, H. (2015, November 10). *Service-differentiated downlink flow scheduling to support QoS in long term evolution*. Retrieved from Elsevier: https://www.sciencedirect.com.remotexs.ntu.edu.sg/science/article/pii/S1389128615004053

[43] Ritesh Kumar, S., Priyesh Pappinisseri, P., Rafael, B., & Maarten, W. (2020, August 25). *Energy Consumption Analysis of LPWAN Technologies and Lifetime Estimation for IoT Application*. Retrieved from Multidisciplinary Digital Publishing Institute: https://www.mdpi.com/1424-8220/20/17/4794