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Recent advances, challenges and future trends for the applications of Low Power Wide Area Networks (LPWANs) technologies in underground mines

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ABSTRACT

Technologies such as the Internet of Things (IoT), Industrial IoT (IIoT), Industrial Communication Systems (ICS), Machine-to-Machine (M2M) Communication, Extended Reality (XR), Blockchain, Artificial Intelligence (AI) and the 4th Industrial Revolution (4IR) are becoming an integral part of the future of underground mines with applications in health and safety, productivity, energy efficiency and cost optimisation. These technologies rely heavily on their efficiency to establish seamless wireless connectivity to perform optimally. For a long time, underground mines relied on the short to medium range network systems such as the wireless fidelity (Wi-Fi), Zigbee, Bluetooth and ultrawide bandwidth (UWB) for data transmission. However, in typical underground mining environments, these technologies suffer from limited range, poor line-of-sight (LoS), signal fading and multipath effects, they consume more power and are relatively high-cost systems. Around the 2010s, Low Power Wide Area Network (LPWAN) communication systems were revitalised and emerged to overcome these challenges. These technologies are characterised by wide area coverage, low power consumption and operate at low cost. However, this is achieved at the expense of reduced data rates. This allowed the LPWAN technologies to thrive in a number of industries operating on surface and outdoor environments. These technologies have also succeeded in indoor environments due to their good penetration through walls. Recently, they are gaining good traction in the mining industry including underground mines. However, very little is known about their successes in underground mines. This study examines and provides a status update of the current and some emerging LPWAN technologies.

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1. Introduction

Technology has become a key driver for economic growth and has revolutionised functions such as productivity and efficiencies across industries. Technologies such as the Internet of Things (IoT), Industrial IoT (IIoT), Industrial Communication Systems (ICS), Machine-to-Machine (M2M) Communication, Extended Reality (XR), Blockchain, Artificial Intelligence (AI) and the 4th Industrial Revolution (4IR) have become an integral part of modern life. These technologies have transformed human lives and our ways of doing things. These technologies continue to grow at an exponential rate and remain at the centre of the IoT ecosystem of telecommunications. These

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technologies, at their core, rely heavily on their efficiency of to transmit signals at the required quality and strength in order to establish seamless wireless connectivity. This is required for communication between smart devices to help revolutionise industries and enabling organisations to make faster, efficient and intelligent decisions. Studies show that the number of devices that will come online, connect and communicate with one another, is expected to reach between 40 billion by 2030, with an estimated economic global impact of $11.1 trillion [1]. This will also be influenced by the continued growth in economies and populations.

For many years, wireless communication systems have been a success and worked very well on surface and/or outdoor environments. This can be attributed to the availability of systems such as the global positioning system (GPS), the global navigation satellite system (GNSS), and cellular networks. These systems are characterised by good coverage, higher positioning or localisation accuracy and precision, higher data rates, higher throughput, low latency, etc. However, the GPS, GNSS and cellular networks do not thrive in indoor environments, and fail completely in extreme environments such as underground mines where line-of-sight (LoS) can be extremely limited. Their signals cannot penetrate significant distances through the earth's overburden to reach underground environments. The satellite networks are complex to design, deploy, and operate, with high energy requirements [2]. The cellular network technologies, which includes 2G (second generation), 3G (third generation), 4G (fourth generation) (or LTE) and GPRS (General Packet Radio Service), provide relatively wide coverage at high data rates, but require high capital and running costs due to their high power consumption and extensive infrastructure requirements. But there was an increasing demand for wireless communication systems suitable for indoor environments including buildings and underground mines. This was particularly motivated by the realisation that people spend up to 80% of their time in indoor environments working or performing other activities (e.g. gyms, shopping centres and malls, libraries, museums, cinemas, etc.) [3]. Furthermore, in underground mines, the Mine IoT (MIoT) has become an integral part of the health and safety of personnel, and productivity and cost optimisation. The MIoT has a role in applications such as environmental conditions monitoring, two-way voice, text or data communication, people tracking, fire detection and localisation, asset and machines tracking, fleet management and dispatch, process control and automation, big data for business continuous improvement, etc. To date, short range communication systems such as Bluetooth, Radio Frequency Identification (RFID), Near Field Communication (NFC) and Ultrawide Bandwidth (UWB); and medium range systems such as wireless fidelity (Wi-Fi) and Zigbee have predominantly been used in underground mines to provide the MIoT connectivity. However, they can only be operated in small-scale network applications due to their limited range.

In the 2010s, an influx of Low Power Wide Area Network (LPWAN) wireless communication technologies was realised across many industries. The LPWAN technologies are a group of licenced and unlicensed, long range and wide area coverage, low power consumption and long battery-life and low cost, but low data rates wireless communication protocols. This includes LoRa/LoRaWAN, Sigfox, NB-IoT (Narrowband Internet of Things), NB-Fi (Narrowband fidelity), DASH7 (D7AP), Telensa, LTE (Long Term Evolution) Cat-1, LTE Cat-M (Category-M), Weightless-W/N/P, Platanus, RPMA (Random phase multiple access), Z-Wave, Wize, ELTRES, Adaptrum, Symphony Link, Qowisio, EnOcean, 6LowPan, WiMAX, LiDar, Wi-SUN (Wireless Smart Utility Network), IQRF, MIOTY (My Internet of Things), Starfish, Rotating Polarization Wave (RPW), Amber Wireless, SNOW (Sensor Network Over White Spaces), Helium, Amazon Sidewalk, Wi-Fi Halow (IEEE 802.11ah), RedCap (Reduced Capability), etc. The LPWAN technologies are communication protocols developed and standardised by special interest groups (SIGs) such as the 3GPP (3rd generation partnership project) Group, the LoRa Alliance, DASH7 Alliance, Ingenu, Weightless SIG, IQRF Alliance, Wi-SUN Alliance, etc. Although the LPWAN technologies became more popular in the 2010s, their history dates back to the late 1980s [4,5]. During those times, the LPWAN systems were mainly used for low-speed data-only applications. The main uses were sales automation, fleet tracking, email and messaging services. They still covered about 65% of the United

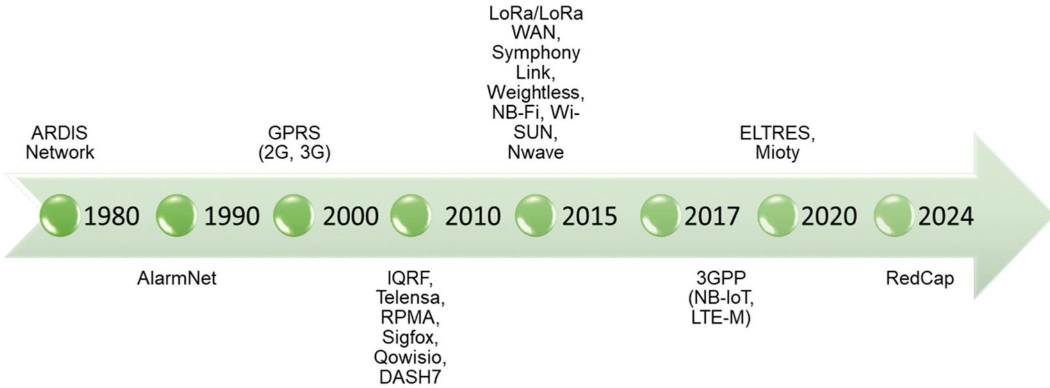

Figure 1. Evolution of the LPWAN technologies.

States of America's urban areas with their 900 mHz frequency [4]. Figure 1 provides timelines of the evolution and introduction of the LPWAN technologies.

The LPWAN technologies were mainly designed and developed for outdoor environments to provide connectivity in remote areas with good LoS but limited infrastructure such as remote and rural areas. Due to their low data rates, they can transmit signals for significant distances, reaching 10–50 km in rural and/or remote areas and 5–10 km in urban areas [6]. In urban areas, their range is often limited due to poor LoS caused by tall buildings and other structures. Figure 2 is a comparison or benchmark of the LPWAN technologies against the short and medium range wireless communication technologies, cellular networks and satellite networks by transmission range, and data rates and power consumption.

The various types of wireless communication protocols can be further categorised or grouped in various forms. Based on the transmission range, data rates, power consumption and cost of system, four classes or categories of the wireless communication systems can be grouped as depicted in Figure 3. The four categories can assist end-users in deciding on the appropriate communication system and to distinguish the different requirements.

Lately, the LPWAN technologies have started gaining traction in underground mining applications. This has been fuelled by their characteristics of low power consumption and wide range which have numerous advantages and potential benefits for underground mining applications. In underground mines, the LPWAN systems can be used for a wide range of application in both health and safety, and productivity. This study compares the competitiveness of the LPWAN standards to the short and medium range protocols, and identify gaps and opportunities for future applications of the LPWANs in underground mines.

1.1. LPWAN modulation techniques

To achieve wide area coverage and long range, the LPWAN technologies make use of modified and reduced capabilities. The uniqueness of these protocols lies on the type of modulation techniques. This improves bandwidth utilisation, receiver sensitivity, simplified network architecture, advance signal error correction techniques, energy efficiency, resilience and robustness against noises and interferences, etc. The modulation techniques play a huge role in the design of the LPWAN technologies by distributing the transmitted signals over a wider bandwidth or narrowing the frequency of the signals [7]. This allows more energy to be dedicated and conserved for each bit or symbol that is being transmitted. Even without increasing the sensitivity of the receivers, these systems can accurately decode or demodulate long transmission weakened signals without incurring any errors [8]. This is because the signals are encoded at very low to ultra-low bandwidth,

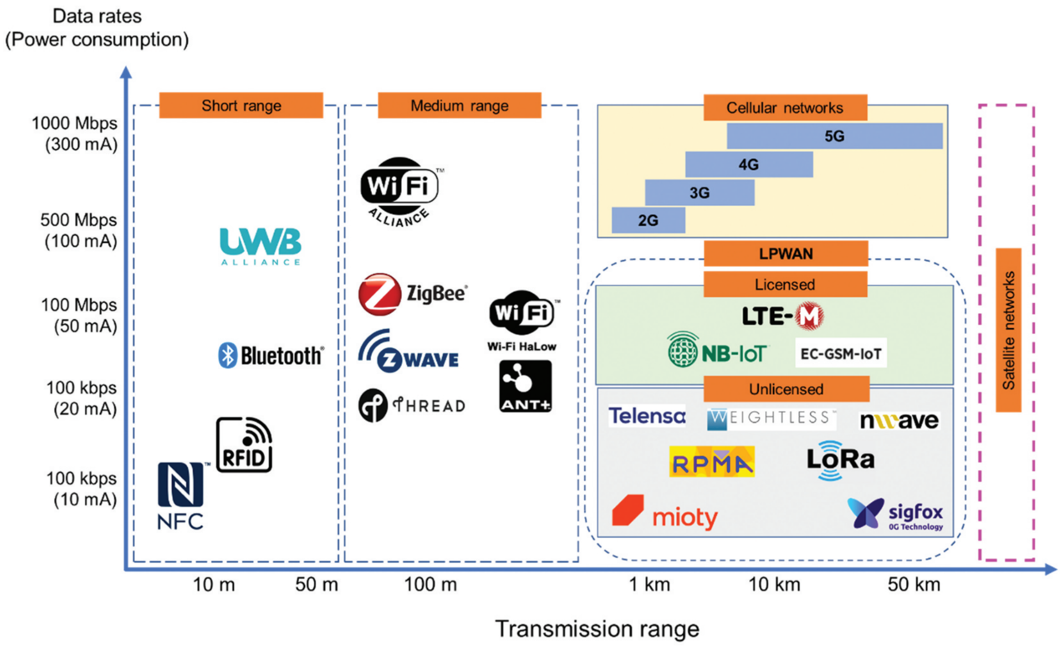

Figure 2. Comparison of wireless communication systems.

generally anything less than 25 kHz and thereby achieving a good link budget (dB). Due to the continuously increasing demand and competition for spectrum, spectrum sharing is utilised as a technique to strike a balance between parameters such as the coverage, time and frequency. This is done to overcome challenges related to spectrum scarcity, collisions and interferences. As such, Cognitive Radio (CR) capacity has become an imperative factor in the deployment of LPWAN technologies operating in the similar frequency bands [9,10]. For wireless protocols, this can be done by one of the four spectrum sharing management techniques which includes spectrum sensing, spectrum allocation, spectrum access and spectrum hand-off [11]. Overall spectrum optimisation and utilisation can be achieved through an efficient sharing of the spectrum using multiple links for narrow bands. In this case, each carrier signal in the transmission process is assigned a very low band to operate alone. This reduces noises and interferences on the signals, which reduces the complexity to decode signals by the receiver and the required cost [8]. The LPWAN technologies are mainly grouped into the Ultra-Narrow Band (UNB) and the Spread

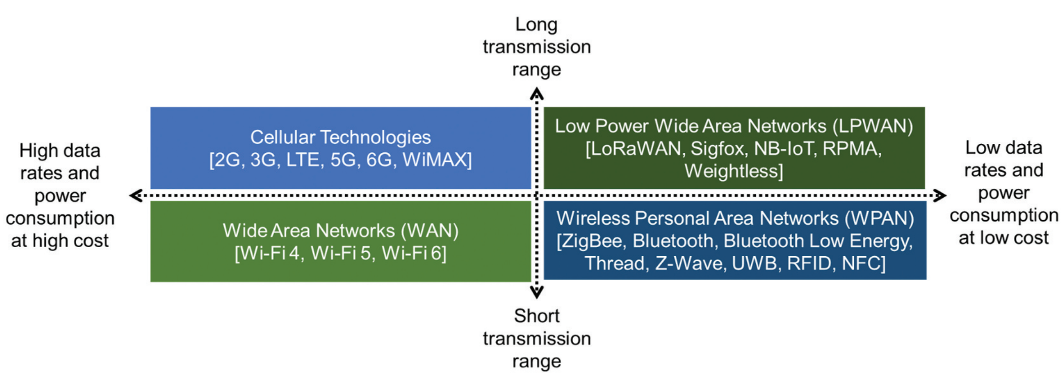

Figure 3. Categories of the wireless communication systems by data rates and range.

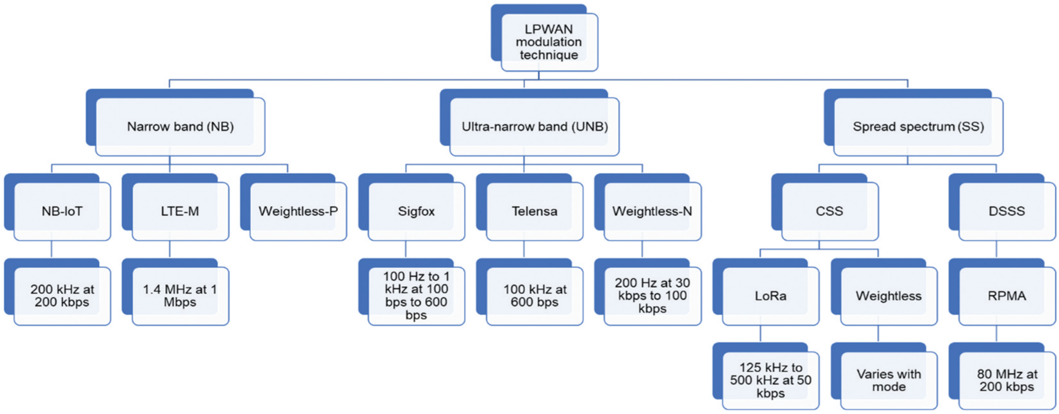

Figure 4. Classification of LPWANs by modulation technique – NB, UNB and SS.

Spectrum (SS) according to their modulation technique in their wireless communication physical (PHY) layer (Figure 4) [12]. The UNB is more applicable for transferring data with small bandwidth for small uplink traffic, while the SS is suitable for transferring data over a wider frequency band. The SS modulation technique is further divided into the Chirp Spread Spectrum (CSS) and the Direct Sequence Spread Spectrum (DSSS) variations. LPWANs like LoRa/LoRaWAN are examples of the CSS modulation technique [13–15]. The SS spreads the signal being transmitted over a larger bandwidth using wideband. The signal is multiplied a chirp signal to spread its bandwidth, beyond the bandwidth of the original signal [16]. This reduces the impact of noises and interferences before the signal is compressed back to its original bandwidth at the receiver. Increasing the bandwidth reduces the error rate over long transmission distance. The UNB offers less data rates compared to the SS. Some examples of the UNB includes Sigfox and Telensa, while examples of the SS include LoRa and RPMA [12]. The CSS model used in the LoRa/LoRaWAN allows an efficient decodification of the received signal strength below the noise floor. This is due to the signal's resilience against pathloss, multipath and fading effects, the Doppler effect, and other possible interferences [17]. The channel bandwidth of the UNB technique tends to be higher than that of the SS modulation technique, but the UNB requires complex signal processing and extra synchronisation at the receiver.

Although the UNB and CSS techniques are both compliant with the LPWAN requirements of low power and wide coverage, they also have their own advantages and disadvantages [12]. The UNB modulation is suitable for low data rates and wide coverage, and can support many devices. On the other hand, the CSS technique is suitable for increased throughput but with reduced transmission range. The CSS technique requires an active network to retain its settings in order to eliminate the for a higher spreading factor [18]. The SS techniques makes the signals more robust and thus less sensitive to noises and interferences. This will result in an increase of the throughput of the devices farther from the base station nodes. However, the performance of the network can be further affected by the presence of additional networks operating within the same frequency band. But this affects heterogenous networks mostly due to their low signal power and thus increasing collisions and noise floor [19]. But also, an increase in the modulation orders requires an increase in the signal processing capabilities. The wide range of LPWAN technologies from various alliances has also necessitated specific deployment architectures for connectivity route of their devices based on the applications intended. The different and unique architectures are designed based on the number of layers of connectivity between end devices, base stations, and their transmitter or receiver antennas. Typically, the architectures will have anything between two to four, and up to seven layers [20,21]. These layers are made up of functions such as network connectivity infrastructure, information processing, sensing and applications. The network can be configured from low complexity design and simple topologies such as linear, ring and bus; to more complex topologies such as the star or star-on-star, tree, mesh, cellular, point-to-point (P2P), point-to-multipoint (P2MP) or hybrid. This is based on the deployed number of end devices, and how they establish communication with one another and the required base stations, via a dedicated gateway. A single base station can be used in the network to service all the connected end devices. Sometime multiple base stations can be deployed to share the services of the end devices. This will be based on design factors such as co-existence, integration, interoperability, scalability and capacity of the LPWAN network. The star, mesh and cellular are the prominent, common and preferred topologies for LPWAN technologies [22,23]. The star topology, where one gateway connects with all the nodes, has an edge over the mesh topology [24]. The star topology is usually faster and reliable due to its single-hop connectivity route while the mesh network may experience delays due to multi-hops between routers before reaching its gateway. The star topology is essential for networks where energy efficiency and conservation are desired to increase battery life. A majority of the available LPWANs achieve long range communication by forming the star topology. In this case, the end devices communicate with the base stations in a direct link. Alternatively, the mesh network topology, consisting of a connection of the base stations, sensors, and sensor-cum-routing nodes, can connect via a gateway. All the nodes are allowed to connect with each other directly, forming multiple routes, which allows all node to cooperate in distributing or sharing data in the network. Its advantages include multiple route options, simultaneous transmissions, ease of scalability, and self-healing capabilities. The cellular topology is versatile and supports mobility. The topologies by router, relay or hybrid, and a survey of their potential application in various scenarios [25]. This includes router-based topologies (router-devices, router-gateway or router-devices-and-gateway) and relay-based topologies (relay-devices, relay-gateway or relay-device-and-gateway). For example, LoRa operates on a star-of-stars array. Its connected devices can transmit information to whichever gateway is available within its range based on the ALOHA as MAC layer. In this case, connectivity between end devices and the gateways is not via a direct link. The gateway merely forwards the message to a network server using a traditional Internet protocol (IP) connection.

The type of topology should be designed with care as it can have an influence on the achievable range, power consumption requirements, and the available infrastructure. But some of the LPWAN technologies are infrastructure-less, some require minimal infrastructure and some capitalise on pre-existing cellular infrastructure. The type of topology applicable can also be dictated by the type of environment and its properties. For example, underground mines are extremely confined and made of long tunnels which can significantly restrict certain types of topologies based on complexity and power requirements. This is based on the route in which end devices connect to different gateways, continue to connects to a network server, and then connect to the application server. The applications server forms the interface between the users and applications and is used for processing and analysing the collected data and information. The network server is responsible for administering the entire system and end devices by collecting and processing network and transfers the information to the application servers. The end devices are responsible for collecting the data measured from the environment, and transmitting the data to the gateways, and then the network server. The end devices could also be located in different cloud clusters which connect directly to the gateways through a back-haul. Some topologies are composed of end devices that connect directly to a gateway, but then reroute to a server before arriving at an application server. The gateways are responsible for transmitting the collected data to the specific end devices. The end devices receive instructions or service functions for their applications through the network servers.

1.2. LPWAN standardization

More commonly, the LPWAN can be categorised in the 3GPP group and the non-3GPP group of technologies (Figure 5). The 3GPP is one of the different standard development organisations

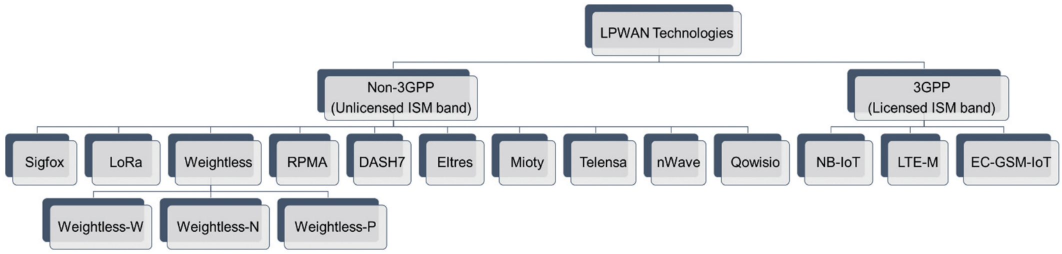

Figure 5. Categorization of the 3GPP group and the non-3GPP group of LPWAN technologies.

(SDOs) which also include the IEEE 802.15.4, European Telecommunications Standard Institute (ETSI) and Internet Engineering Task Force (IETF). The 3GPP wireless communication protocols are developed to operate over the licenced frequency band. Some of the common LPWANs technologies which are standardised by the 3GPP group include the LTE Cat 1, LTE-M, NB-IoT and EC-GSM-IoT. The 3GPP group mainly operates three licenced LPWAN technologies which are LTE-M, NB-IoT and EC-GSM, but can also include 5 G. The 3GPP group was established in 1998 to develop 3 G mobile standards, produce Technical Specifications and Technical Reports [26]. These technologies are evolving from its current cellular networks but seek to address the current IoT and M2M challenges. The 3GPP LPWAN protocols are infrastructure-based. However, the bigger goal was to retain, maximise and re-use the existing cellular network infrastructure [27]. The non-3GPP technologies includes the unlicensed technologies such as Sigfox, LoRa, RPMA, Weightless, DASH7, Telensa, etc. The 3GPP group standards operate in three different streams, which include Radio Access Networks, Services and Systems Aspects, and Core Network and Terminals [27]. The 3GPP group standardisation was formed to support the existing cellular networks such as 3 G in 2001 with frequencies between 400 MHz and 3 GHz providing about 2 Mbps on average, 4 G (LTE) in 2008 providing up to 1 Gbps, 5 G in 2018 and now 6 G anticipated for 2029. The 3GPP group has since been continuously evolving, modifying and optimising its networks to be less complex, to consume low power, to have a long battery life, to extended coverage and to operate at low cost. This is to address some of the current IoT and M2M challenges.

1.3. The future of LPWAN technologies

Even though there are so many emerging LPWAN standards, the LoRaWAN, Sigfox and NB-IoT seem to be ahead of the rest in terms of applications and deployment in general. They have remained the most prominent of all LPWANs in the market over the last few years [28]. The NB-IoT technology differs from the two in its capabilities of low latency, payload length and scalability. The NB-IoT technology has an edge over the Sigfox and LoRa systems. Overall, the number of devices that will connect the IoT, IIoT, M2M and AI ecosystem is predicted and projected to reach 75 billion by 2025 [29]. Some reports suggest that the IoT market will only reach 40 billion connections by 2033. This will be dominated by short range systems such as Wi-Fi at 73%, followed by cellular networks at 7.5 billion devices connected. The use of LPWANs is projected to reach 5.3 billion connected devices by the year 2030 with an anticipated growth from USD 14.31 billion to USD 704.95 billion between 2023 and 2030, at a compound annual growth rate (CAGR) of 74.50% [30,31]. The market growth for LPWAN technologies is aligned to the increasing demand for long-range communication in smart cities. NB-IoT is expected to lead LPWAN connections by 43%, followed by LoRa at 41%, Sigfox at 9%, LTE-M at 4% and the rest making up the remaining 3% in 2025, and a similar trend can be expected until the 2030s but with LTE-M expected to overtake Sigfox [32]. By the look of things, the LPWAN technologies are growing at a fast rate and could surpass the current projections. While the IoT and M2M technologies are shaping the future of connected devices, they come with cybercrime problems. This crime is projected to cost up to $ 24 trillion by 2027 invested in security measures against data breaches and unauthorised accesses [33]. This is particularly due to the growing security threats to the IoT, IIoT, AI, M2M and 4IR in general. The key security requirements for these technologies include authorisation, confidentiality, integrity, privacy, authentication, availability and non-repudiation [34,35]. Similar security threats exist for the LPWAN communication protocols. For example, an exhaustive state-of-the-art research study on the security measures around the LPWAN technologies is conducted [36,37]. Their study mainly focused on: (a) security requirements and their implementation including factors such as authentication, encryption, access control, and key management; (b) categorisation of attacks and threat modelling; (c) attacks documentation by examining the underlying vulnerabilities exploited, outlining potential consequences and discussing countermeasures proposed to mitigate these attacks; and (d) security enhancements proposed to address vulnerabilities in each network; (e) the integration of LPWANs with other cellular networks such as 5 G and the consequent security challenges. Several studies have surveyed and investigated the applications of the LPWAN standards in surface and outdoor environments. But often the IoT of the LPWANs is best described by industry and application. These applications are mainly classified into four IoT industry classes, which includes appliances, industries, public, and personal [38–41]. These applications are in wide range of industries in both the public and private sectors, as summarised in Figure 6 [42–54].

While the LPWANs have seemingly been a success in the industries and applications mentioned in Figure 6, they have also worked well in indoor environments [55]. Lately, these technologies are gaining traction in underground mines in the MIoT. The Mine IoT (MIoT) is based on a three-layered architecture comprised of the application server, network server and end-devices [56]. However, it can be mentioned that very little has been published on the applications of LPWAN systems in underground mines when compared to other sectors and industries. There is also a need to study, understand and predict the behaviour of the LPWAN signals as has been done for the short and medium range systems (i.e. Wi-Fi, Zigbee, etc.) [57–60]. Although the LPWAN technologies brought in some robust solutions, it is prevalent that several factors and challenges can still affect the functionalities and performances of these systems underground. Although these systems have been extensively surveyed, we continue to see further developments, improvements and more application options. This necessitates continuous evaluations of recent trends and developments. The cost-effectiveness of these systems has been one of their point of attraction [61]. To assess the feasibility and cost-effectiveness of implementing LPWAN technologies, considerations should

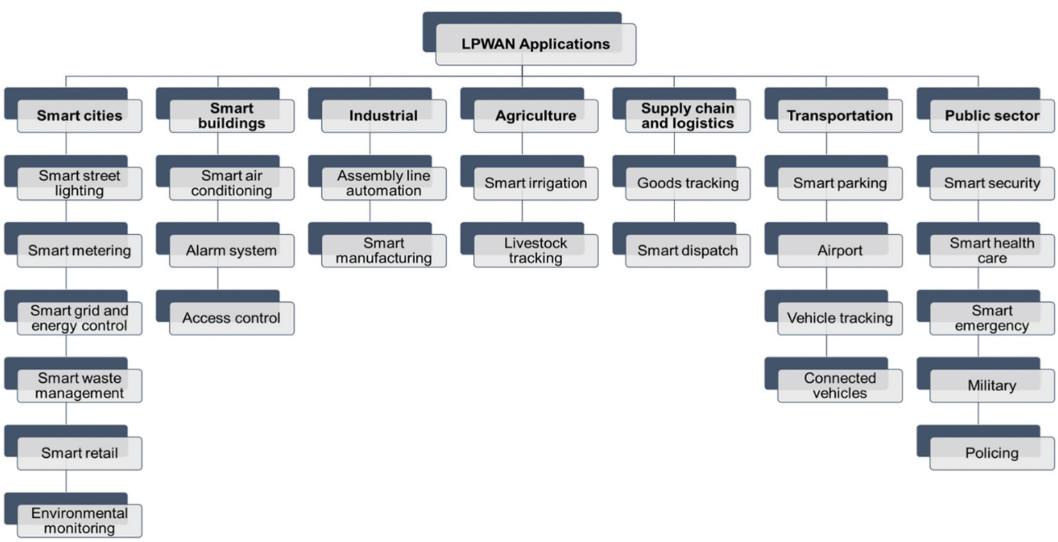

Figure 6. Industries and applications of LPWAN.

include equipment cost, installation cost, licencing and spectrum cost, site establishment and lease cost, power cost, transmission installation cost, transmission cost, and the operational and maintenance costs. These costs will vary according to the geolocation, extent of project and market or number of connected devices.

2. Wireless communication in underground mines

One of the major challenges of wireless communication systems is their susceptibility to suffer from signal fading challenges due to pathloss (attenuation and LoS obstructions), multipath (reflection, diffraction and scattering) and signal strength fluctuations. These challenges are even greater in underground mining environments. We have since seen extensive research being focused on modelling the channel for the propagation of signals. These models attempt to predict the behaviour of the transmitted signals, from a transmitter to the time it reaches a receiver, and also estimate receiver power. The performances of wireless communication systems rely on their efficiency to transmit signals between a transmitter and receiver at the required bandwidth. The transmission efficiency depends on the link budget or power budget, which accounts for all possible losses and gains. The link budget is essential for predicting the success of a communication system and is given by Equation 1 [62]. Understanding the link budget is important for determining or measuring the required transmitter power necessary to meet SNR requirements based on the desired transmission range and data rates and also to compare coverage capability between any two wireless technologies. An increase in the link budget improves the transmission range and its ability to penetrate deep into buildings or underground environments. It has also been extensively used to compare the capabilities of different LPWAN technologies to provide good wireless communication [63,64]. If the link budget is poor, the signals often get swallowed by the noises and no information can be retrieved at the receiver node. This will assess whether a signal will be strong enough to overcome losses and interferences and reach its target.

$$\begin{aligned} Link\ budget = {} & Transmitted\ power + Transmitter\ gain - Pathloss - Interference\ margin \\ & - Receiver\ gain - Receiver\ sensitivity \end{aligned} \tag{1}$$

From the link budget, the received power (P_{rx}) together with all associated gains due to the antenna design should be able to overcome the total losses and interferences that can degrade the signals. The antenna received power in the channel of the communication system can be calculated from Equation 2 [65].

$$P_{rx}(dBm) = P_{tx}(dB) + \sum Gains(dB) - \sum Losses(dB) \tag{2}$$

Similarly, the performances of the LPWAN systems can be compared by their link budget. The link budget is one of the most critical factors to consider when designing and optimising wireless transmission systems. The importance of the link budget is to ensure clear and reliable communication. The analysis of the link budget is more complex for the uplink transmission than downlink [66]. Clearly, a larger link budget is required for long-range transmission as signals naturally attenuate over long distances. Equation 2 can be further expanded to Equation 3 to cater for all the possible losses in a typical wireless communication system. The transmitter power depends on factors such as the transmit antenna gains (G_{tx}), receive antenna gain (G_{rx}), transmission losses (L_{tl}), free-space pathlosses ($L_{Pathloss}$) as well as factors such as receiver sensitivity, noises and interferences, and channel effects as demonstrated in Figure 7.

$$P_{rx} = P_{tx} + G_{tx} + G_{rx} - L_{rx} - L_{tl} - L_{Pathloss} \tag{3}$$

The LPWAN technologies suffer more from free-space losses or pathlosses due to their long-range and wide-range transmissions. Due to this reason, the LPWANs will rely heavily on a good receiver sensitivity. Sensitivity can be described as the receiver's capacity to decode, understand and encrypt

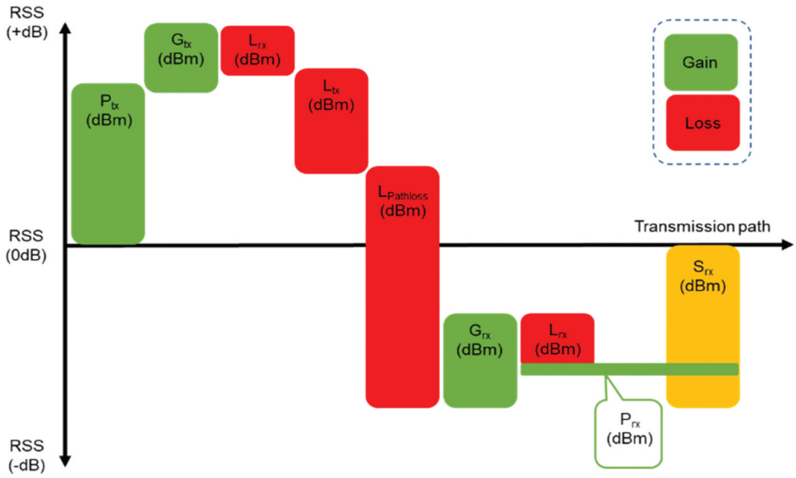

Figure 7. LPWAN technologies link budget computation and analysis.

a weak signal. To establish communication, the receiver power should equal or exceed the receiver sensitivity. Increasing the receiver sensitivity requires more power consumption, but this can improve the range [67]. The sensitivity parameter is important for improving signal power and its responsiveness, and thereby improving the range. However, this extends the packet duration. LPWAN technologies have sensitivity of about −142 dBm [68]. A majority of the LPWAN technologies ranges between −156 dBm and −172 dBm but will typically average around −160 dBm [17]. The link budget is typically the same for uplink and downlink, but can differ according to the loss parameters. In general, the UNB-based LPWAN protocols provide a higher link budget. This is achieved by encoding their signals using the UNB modulation technique where each carrier signal is compressed to 100 hz. The link budget does not only assess the quality of communication in terms of received signal strength (RSS), data rates or bandwidth but can also be used to predict the achievable range for the wireless communication systems. Distance is one of the factors affecting signal strength as the signals start to break-up into replicas and spread in different directions, thus weakening the strength or quality of the transmitted signals. To mitigate signal strength fading and losses due to distance, repeaters can be installed to boost the signal. Further away from the transmitter, the transmission of radio wave is given by the Friis Equation in the far-field [69]. From the link budget equation, the maximum range (d) can be determined from Equation 4 for a given path attenuation rate (A_{Path}) and receive antenna sensitivity (S_{rx}) [65]. The required receiver sensitivity of LPWAN protocols can also be determined from the available link budget.

$$d = \frac{P_{tx} + G_{tx} + G_{rx} - S_{rx}}{A_{Path}} \tag{4}$$

Equation 5 is used to calculate the RSS at a distance (d) from a transmitter, considering the transmitter power, the gains of the transmitter and receiver, the signal wavelength (λ) with a frequency (f), and the overall distance apart between the transmitter and receiver [70].

$$P_{rx} = \frac{P_{tx} G_{rx} G_{tx} \lambda^2}{(4\pi)^2 d^2} \tag{5}$$

$$P_{rx} = \frac{P_{tx} G_{rx} G_{tx}}{1} \left(\frac{\lambda}{4\pi d}\right)^2$$

Where by:

$$\lambda = \frac{c}{f} \; with \; c = 3x10^8 m/s$$

Other signal power losses include losses due to factors such as pathloss, shadowing and multipath fading. When incorporating pathloss ($P_{Pathloss}$), fading losses (P_{Fading}) and other losses (P_{Other}), the received power can be rewritten by Equation 6.

$$P_{rx} = P_{tx} G_{rx} G_{tx} \left(\frac{1}{P_{Pathloss} P_{Fading} P_{Other}} \right) \tag{6}$$

Whereby, pathloss is given by Equation 7:

$$P_{Pathloss} = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) \tag{7}$$

This Equation 8 can be rearranged to measure the transmission distance:

$$d = \frac{1}{\frac{4\pi}{\lambda} \sqrt{\frac{P_{tx}}{P_{tr} G_{rx} G_{tx}}}} \tag{8}$$

The channel and propagation models should overcome the underground environments. However, this necessitates special considerations of the transmission requirements of the channel capacity in relation to the required range and data rates. The channel capacity (C), defined as the maximum rate of transmission, can be calculated from the Shannon's Channel Capacity Theorem is given by Equation 9 [71].

$$C = (B) \log_2 \left(1 + \frac{S}{N} \right) \tag{9}$$

Whereby:

B = channel bandwidth (Hz)
S = signal strength (watts)
N = noise power (watts)

From the Shannon's Channel Capacity Theorem, it can be seen that the signal-to-noise ratio (SNR) has an influence on the quality of the signals. Wireless communication systems tend to experience higher attenuation rates in underground mines than they do on surface or outdoor environments. Underground mines are known to introduce additional losses and distortions on signal strength [72]. These factors and challenges are generally absent on surface and outdoor environments, making it easier to propagate signals for longer distances and higher bandwidth. But underground mines incur additional losses due to wall roughness, smaller tunnels, confined workings, curvatures and obstructions due to frequently moving personnel and machinery [73]. For example, in underground mines, the propagation of signals can be significantly affected by the type of rock and its properties and the dimensions of excavations. Some of these factors are not factored in the standard Friis model. Although the Friis equation is generally not applicable for complex environments in its standard form, it provides the basis of channel modelling for wireless communication. This model is often preferred over other models such as the Fresnel model [74–76]. Therefore, these factors must be incorporated in order to obtain better estimate of the link budget to ensure reliable wireless communication for the proposed system. The link budget is then used to estimate the transmission distance and data rates at that point. The achievable data rate by distance can be affected by factors such the SNR and the signal-to-interference-plus-noise ratio (SINR) interferences. The SINR depends on the distance from the base station and the floor noise and thus can be described as the ratio of the power of a signal of interest to the the sum of the interference power and the power of additional background noises [77]. The SINR is a more accurate method to measure the quality of signal at a particular distance. This is because it considers the noise floor or ambient noise in that specific environment. There is also a need to evaluate the relationship between SINR and RSSI with an increase in distance. Figure 8 is a demonstration that the SINR decreases with distance.

Equation 2 –9 have been extensively applied in propagation models to predict the RSS for wireless communication systems. This has been used to study and predict the behaviour of signals between the transmitter and receiver at the cost of signal fading factors. The signal propagation equations are more accurate for free-space and outdoor environments where signal propagation is uninterrupted or distorted. In wireless communication systems, signal fading occurs mainly due to multipath (reflections, refractions, diffractions and scattering), shadowing (LoS obstruction), path-loss, and due to the radio frequency channel properties and external interferences and noises [78–80]. The propagation of signals in underground mining environments can be extremely challenging compared to surface, outdoor and some indoor environments. For example, underground mines are generally comprised of environmental conditions and objects that can affect the propagation of signals. This can include objects and obstacles such support pillars, rough walls, moving and stationary machines and personnel, water accumulation, gases, continuous curvatures, confined tunnels and sharp corners and confined excavations and tunnels. These factors lead to signal strength fluctuations, degradation, attenuation, distortions, bit error, low coverage, reduced data rates and throughput, resulting in poor and unreliable communication. This is mainly due to the effects of the underground mine environments such as geometry, range, obstacles and wall roughness. The harsh conditions of underground mines have necessitated the need for adaptive channels and signal propagation models. Signal attenuation and pathloss occur over the distance traveled by

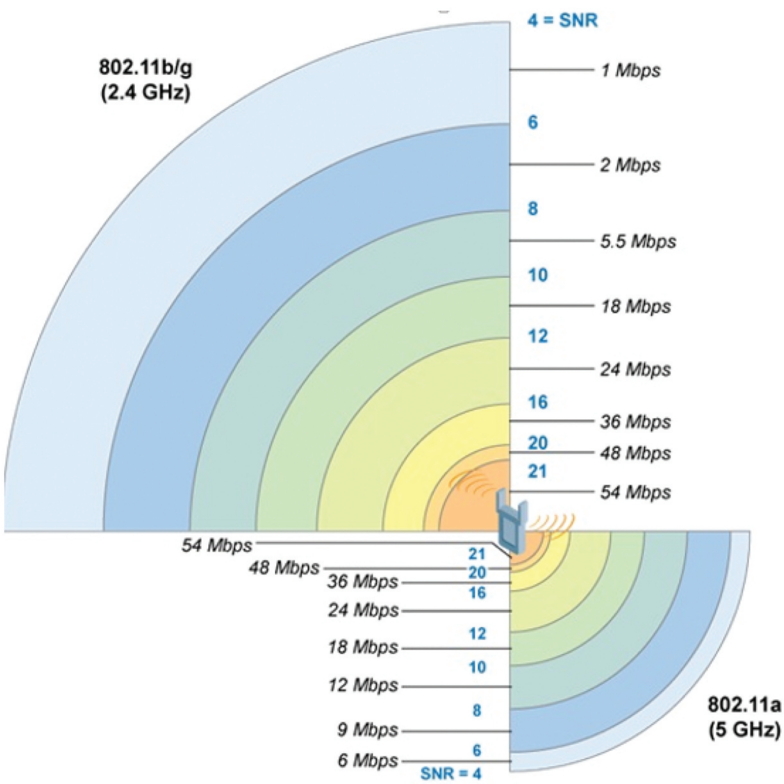

Figure 8. Change or reduction in data rates with SNR and distance [77].

the signals between the transmitter and the receiver. The quality of signals received can be further affected by external, environmental or electrical noises and other interferences during transmission. Naturally, underground mines are comprised of a network of tunnels and excavations of different sizes and shapes. These excavations and tunnels may be of different gradients and curvatures which can affect the propagation of signals. There are significant differences in the behaviour of signals in straight and curved tunnels [65]. The curved tunnels presented more challenges than the straight tunnels. This emphasised the need to study and understand the behaviour of signals inside a mine. Forooshani et al. [81] created signal attenuation models in which an attenuation constant will be equal to zero in a vacuum. Previous models assumed that mine tunnels were smooth walls, which is not always true. In addition, the environmental conditions of underground mines are worsened post-accident, and this can further affect the propagation of signals. Highly unstable ground conditions can result in falls of ground causing damages to infrastructure. Collapsed tunnels can affect signal propagation and affect signal waveguide. Humidity may also be as high as 99% in the tunnels, which can cause an increase in the rate of attenuation and signal degradation. Pathloss increases as the distance between the transmitter and receiver increases. Increase in heat in the environment can cause the ionisation of air, and this can significantly affect the quality of the signal. Degradation of communication signals may be caused by the tunnels of the mine acting as low-loss dielectric mediums at certain frequencies. As such, the propagation of signals from a transmitter to a receiver appears to be the biggest challenge facing communication systems underground mines being humid, dusty, consisting of corrosive water, gases and are naturally dynamic, poor visibility, rubble accumulation, flooding and blockages along haulages [82] in Figure 9.

3. Low Power Wide Area Network (LPWAN) technologies

The LPWAN technologies emerged as solutions to the challenges experienced by the commonly used short and medium range communication systems. They provide long range and wide area coverage, consume less power (long battery life), have good scalability, support mobility, etc. However, their low data rates remain the one major disadvantage. Even so, they enable better propagation range, better penetration in buildings and other obstacles. Nonetheless, the low data rates are not ideal for certain application requirements such as full-duplex voice communication and live video streaming or transmission. The LPWAN protocols have good capacity and scalability to support and connect as many devices. They are mainly used to connect devices with low power requirements such as sensor tags, actuators and controllers. To date, a number of LPWAN

Figure 9. Typical post-accident conditions in an underground mine [82].

protocols have entered into the market. This includes the 3GPP Group protocols – NB-IoT [83–89], LTE-M, LTE-Cat1, and EC-GSM-IoT [90–94], LoRa [95,96], Sigfox [97–100], Weightless [101], Nwave [102], DASH7 [103,104], RPMA [105,106], Telensa [107], Mioty [108–110], ELTRES [111], NB-Fi [112–115] and IQRF [116–119]. Further information and specifications of the LPWAN standards in Table 2 were consolidated from numerous publications [120–145].

3.1. LTE-M Cat-1

LTE-M Cat-1 is category 1 of the 4 G and LTE (long term evolution) cellular networks modified and optimised with reduced bandwidth and communications demands to meet the requirements of LPWAN standards. It is also known as LTE Cat 1Bis but with a single receive antenna. It is part of the Release 8 of the 3GPP standards [90–94]. In comparison to the LTE Cat M1 and the LTE Cat M2 protocols, it provides broadband global coverage, roaming, medium data speeds and low power consumption. With the low power consumption, its battery life can be optimised to more than 5 years. The LTE-M Cat-1 was built and modified from the existing LTE and 4 G standards which replaced the 3 G wireless broadband standard as part of the 3GPP's Release 8 in 2008. The 5 G standard can achieve up to 2.5 Gbps of download data speeds, and 1.25 Gbps upload data speeds with a latency less than 1 ms [146]. On the other hand, 4 G networks can reach up to 1 Gbps download speed and 500 Mbps upload speeds with about 50 ms latency [146]. LTE Cat-1 is a medium data speed LTE standard, slightly faster than the LTE-M standard and consume lesser power with its higher bandwidth, up to 20 MHz for full-duplexing. However, it consumes slightly higher power than its counterparts NB-IoT and LTE-M. Its range is also slightly shorter than that of LTE-M and NB-IoT. But its main point of attraction is the medium speed of up to 5 Mbps uplink and 10 Mbps downlink which can support video streaming. It is one of the most cost-efficient of the LTE category but still with full mobility IoT applications, low late`ncy (typically in the range 10–100 ms), continuous data streaming and voice support.

3.2. LTE-M

The LTE-M LPWAN protocol is the LTE-Machine-to-Machine, also known as LTE-eMTC (enhanced Machine-Type Communication) or LTE Category-M1. It is also part of the 3GPP Group standard-based technology that operates in the licenced LTE spectrum range of 700–900 MHz [90–94]. LTE-M was introduced alongside NB-IoT as part of the 3GPP Group Release 13 in 2016. It was mainly developed to modify and optimise the characteristics of LTE to support LPWAN requirements. This was done by lowering its data rates to increase the coverage range of the cellular LTE technology, with low power consumption. But its bandwidth is slightly higher than that of NB-IoT. This was to maintain slightly higher data rates with secured transmission, while power consumption was slightly higher. Its higher bandwidth enables good data rates and throughput. Based on its LTE resemblance, it can leverage from the pre-existing infrastructure of the LTE network. It was developed to provide both real-time communication and non-real-time communication with its variable or adaptive data rates. But low latency is its main drawback compared to cellular technologies and has since been used for deferred traffic applications. The LTE-M protocol makes use of a 16-bit Quadrature Amplitude Modulation (QAM) modulation technique. This technique is based on the star topology. LTE-M also uses the Frequency Division Multiple Access/ Orthogonal FDMA (FDMA/OFDMA) as a media access control (MAC) layer. The 3GPP LPWAN cellular technologies were specifically designed to conserve battery power with devices lasting over 10 years. Its data rates can range between 10 kbps to a maximum of 1 Mbps depending on the environment at 1000-byte payload capacity in both uplink and downlink directions. The reduced complexity of the LTE-M technology reduces its costs significantly but limiting its communication to half-duplex. It has capacity to support over 100 000 devices from a single base station. Several optimisation and modifications have been trialled to improve its coverage.

3.3. NB-IoT

NB-IoT is also a licenced LPWAN technology operated by the 3GPP Group and currently the most prolific of the 3GPP Group of cellular networks and was also part of the Release 13 standard [90–94]. It operates over the licenced frequency bands of 700 MHz–900 MHz (sub-GHz) where there are no limitations on the duty cycle. However, this will depend on the spectrum licencing regulations and policies within a specific region [126]. Similar to LTE-M, NB-IoT was developed as a modified and optimised version of the LTE protocol with reduced data rates and low power capabilities. NB-IoT was developed to compete with the likes of Sigfox and LoRa for long-range transmissions. It was developed with a small bandwidth for its data transmission. It has the capability to replace the GSM carrier standard (200 kHz bandwidth) or integrate into LTE carrier standard (180 kHz bandwidth). Therefore, the NB-IoT can operate over existing LTE infrastructure within only upgrades in its software. The NB-IoT protocol was designed based on the UNB modulation to provide extended coverage, conserved and long battery life, deployment flexibility and less complexity at low cost. Data transmission is only limited to the QPSK or BPSK only. Yet, this protocol can co-exist with the 3GPP licenced spectrum as LTE and GSM, but slightly modified to achieve the LPWAN capabilities [24]. The narrow bands are essential for the reduced power consumption [85]. This allows conservation of battery life to over 15 years. The narrow frequency bands allow extended coverage in remote and urban areas. Although it is within the 3GPP Group standards, it is not compatible with the 3 G network technology but can co-exist with the likes of 4 G and LTE. This allows it to leverage from the existing LTE infrastructure. NB-IoT can be deployed in one of three modes for enhanced flexibility (Figure 10) – the In-band (which is assigned a block within the LTE carrier signal and support uplink and downlink), the Guard-band (which is assigned a block in the guard band of LTE carrier signal), or the Stand-alone (in which the signal itself act as a dedicated carrier and occupying the 200 kHz bandwidth) depending on the availability of infrastructure. NB-IoT can achieve up to 200 kbps (downlink) and 20 kbps (uplink) using a 1600-byte maximum payload size. Its low power consumption improves its battery life to more than 10 years. It has a transmission capacity of 200 bytes per single day and can support more than 100 000 devices per base station.

3.4. EC-GSM-IoT

The EC-GSM-IoT, Extended Coverage (EC) – Global System for Mobile Communication (GSM) for IoT, is a licenced LPWAN protocol developed by the 3GPP Group as a part of the Release 13

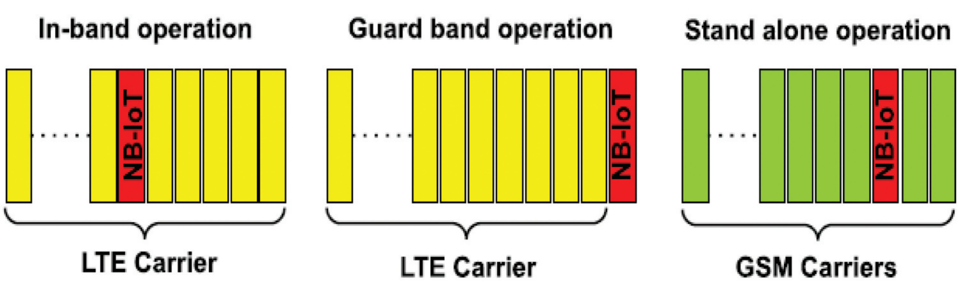

Figure 10. NB-IoT operational modes [24].

[90,91]. This protocol operates in the 800–900 MHz (sub-GHz) frequency band. It was mainly designed to extend coverage in comparison to the traditional GSM network. This allows it to leverage on the existing infrastructure of the GSM and GPRS technologies for enhanced connectivity, increased coverage, improved security and improved energy efficiency. This is based on its ability to support the Gaussian Minimum Shift Keying (GMSK) and 8-Phase-shift keying (PSK) modulation techniques [126]. With these modulation schemes, EC-GSM can achieve 70 kbps or 240 kbps at its 200 kHz per channel throughout its 2.4 GHz frequency band [24]. This enables the EC-GSM to extend the coverage of eGPRS by 20–23 dB with a link budget between 154 and 164 dB [24]. This technology differs from NB-IoT and LTE-M in that it is based on enhanced GPRS (or eGPRS) for improved scalability and reducing complexity purposes. The EC-GSM-IoT has a wireless communication channel of 200 kHz, similar to NB-IoT, it provides improved coverage, long battery life, high capacity and low complexity [147]. Based on application requirements, it makes use of the extended Discontinued Reception (eDRX) technique to further optimise and conserve battery life according to the number of inactivity periods [45].

3.5. LoRa/LoRaWAN

LoRa/LoRaWAN is an LPWAN proprietary PHY layer based on the CSS modulation techniques for data transmission where all the chirps have the same duration. It is patented and commercialised by the Semtech Corporation and has existed since 2014 operating over the unlicensed sub-GHz Industrial, Scientific and Medical (ISM) band [148]. It operates on the 868 MHz frequency in Europe, 433 MHz in Asia and 915 in North America [148]. Since its introduction into the market, it is vastly growing across a number of countries around the world and has a number of applications in various industries. LoRa provides bidirectional communication with deep indoor penetration capabilities. LoRa/LoRaWAN signals are not severely affected by noises and interferences making it less susceptible to jamming attacks [149]. The LoRa communication system has data rates that range between 50 and 300 bps depending on the spreading factor (SF) and channel bandwidth (BW). This system is able to achieve a longer transmission at the expense of the data rates based on the SF choice. The SFs are able to adapt the system to an optimal data rate range. LoRa base stations are able to receive simultaneous messages transmitted through different SFs between 6 and 12 [148]. In comparison to the likes of Sigfox, LoRa can achieve a maximum of 243 bytes payload length for a single message. In a LoRa communication system, all base stations are able to receive the message transmitted by an end device. This configuration increases the redundancy of the system. Increasing redundancy requires an increased number of base stations to be deployed. In this case, multiple base stations can receive the same message based on the time difference of arrival (TDOA) localisation algorithm. In a star-of-stars topology, the transmitted messages are received all the base stations within the range. Accuracy is thus achieved through time synchronisation between the base stations. With the possible configurations of multiple base stations, message handover is not necessary as each base station would have received that message. LoRa has a high resilience and robustness against interferences [150]. A LoRa/LoRaWAN network can be configured based on factors such as SF, BW, Coding Rate (CR), or Data Rates (R_{bit}), transmitter power and the carrier frequency (CF). These parameters have an influence on energy consumption, throughput, range and robustness against interferences and noises [151–157]. The transmitter power for LoRa is typically between 4 and 20 dBm. The CF for LoRa can be permuted in increments of 61 hz, ranging from 137 MHz to 1020 MHz. Obviously, this will depend on the number of chirps, which are typically limited to 860 and 1020 MHz [158].

3.5.1. LoRa spreading factor (SF)

The SF can be described as the ratio of the symbol rate (R_{symbol}) and the chirp rate. The SF parameters control the permutations of how the chirps are spread and is used to determine the number of bits and chirps contained in a symbol. The number of chirps generated per second is equal to the BW whereby a symbol occupies the whole BW. The BW represents the width of frequencies within a transmission band. The sensitivity (S_{rx}) of a receiver can be improved by lowering the BW, but this will also reduce the data rates. The number of chirps per symbol (N) for LoRa is given by Equation 10, the number of chirps is given by Equation 11 and the symbol rate by Equation 12:

$$1 symbol = 2^{SF} chirp \tag{10}$$

$$N = 2^{SF} \tag{11}$$

$$R_{symbol} = \frac{BW}{2^{SF}} \tag{12}$$

A higher or an increase in SF indicates a longer symbol duration and therefore will result in a reduction in the data rates. An increase in the SF reduces the speed of the signal by half. This will double the transmission period and therefore the power consumption. For example, the SF for LoRa is generally within the range 6 to 12 for the BW of 125 kHz, 250 kHz and 500 kHz for both uplink and downlink, while the chirp length ranges from 128 to 4096 [149]. An increase in SF increases receiver sensitivity and chirp length but decreases bit rate. Receiver sensitivity depends on the chosen SF whereby a higher SF results in a longer transmission range [128]. A higher BW reduces sensitivity. A lower SF decreases the SNR which decreases the sensitivity, resulting in a reduced transmission range with a reduced air-time of the packet [159]. The receiver sensitivity can thus be calculated based on the BW, noise figure gain (NF) and the SNR power, given by Equation 13.

$$S_{rx} = -174 + 10\log(BW) + NF + SNR \tag{13}$$

3.5.2. LoRa coding rate (CR)

Coding rates is used as a representation that every useful bit is encoded by the number of transmission bits. By reducing the CR, there will be an increase in the air-time, resulting in low data rates. The CR performs error detection and correction by applying the forward error correction (FEC) code incorporated in a packet before transmission to provide security and robustness against noises and interferences [160]. LoRa PHY makes use of four coding rates; 4/5, 4/6, 4/7, and 4/8 [159]. An increase in the CR improves immunity but this will result in an increase of the ToA and power consumption. With n ranging from 1 to 4, the CR can be calculated from Equation 14.

$$CR = \frac{4}{4+n} \tag{14}$$

3.5.3. LoRa data rates

Data rates or modulation bit rate, in bits per second (R_{bit}), can be defined as the rate at which bits of data are transmitted from one point to the other. Often, the modulation bit rate is influenced by the BW, SF and CR; given by Equation 15 and Equation 16.

$$R_{bit} = SF\left(\frac{BW}{2^{SF}}\right)(CR) \tag{15}$$

$$R_{bit} = SF\left(\frac{BW}{2^{SF}}\right)\left(\frac{4}{4+n}\right) \tag{16}$$

3.5.4. Air-time or time-on-air (ToA)

ToA refers to the transmission duration time of a LoRa symbol (T_{symbol}) in seconds, given by Equation 17. This parameter is measured from the time it takes a symbol to propagate from a transmitter to a receiver. A higher BW result in shorter air-time. The longer the ToA in a transmission, the longer it takes to transmit a packet of data. This makes it easier to demodulate the packet data and less receiver power required. Therefore, an improved sensitivity and communication link budget are achieved.

$$T_{symbol} = \frac{2^{SF}}{BW} \tag{17}$$

3.5.5. Transmitter power

The required transmitter power for a LoRa network ranges from 2 to 20 dBm, with incremental steps of 1 dB. But the transmitter power in a network can be reduced when there are few devices. This requires resource optimisation where the total energy per useful bit of the network is minimised [17].

3.5.6. Packet structure

The packet structure configuration for LoRa is demonstrated in Figure 11. It consists of fixed preamble symbols, packet header (which is optional), a payload, and a payload cyclic redundancy check (CRC) [161]. An optimised packet design is essential for the network's resilience against noises and interferences, and for good scalability.

The preamble symbol consists of:

- 8 fixed symbols,
- 2 synchronisation symbols, and
- 2.25 start frame delimiter (SFD) symbols

The packet header:

- Contains data such as payload length and CR,
- It can discard invalid headers using a cyclic redundancy check (CRC),
- It has a maximum error correction code rate (4/8),
  The payload:
- Contains the actual transmitted data

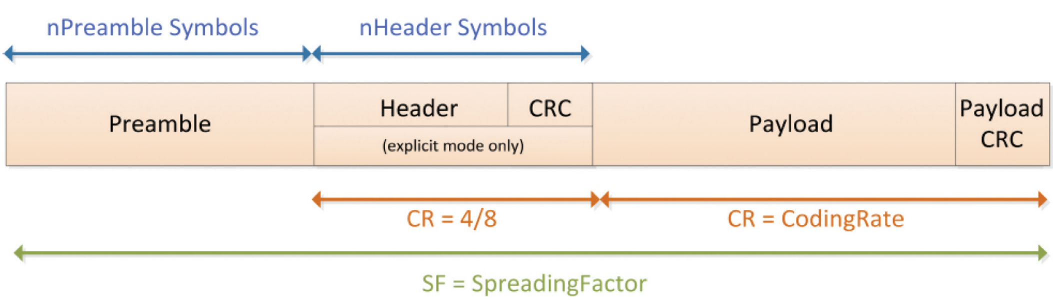

Figure 11. LoRaWAN packet structure [148].

Optional payload CRC:

- Protects the integrity of the transmitted data

Packet duration:

- LoRa packet duration is the sum of the duration of the preamble ($T_{preamble}$) and the transmitted packet payload ($T_{payload}$), given by Equation 18.

$$ToA = T_{preamble} + T_{payload} \tag{18}$$

Table 1 is a summary of the LoRaWAN PHY layer parameters and their values [149,158,162]. The air-time is based on a 20-byte per packet and CR of 4/5.

Table 1. LoRa PHY layer core parameters and values.

SF	BW (kHz)	Maximum payload (bytes)	Chirps or Symbols	Sensitivity range (dBm)	SNR	Bit rate (bps)	Air-time (ms) 11-byte payload	Range (km)
7	125	242	128	−123	−7.5	5470	61	2
8	125	242	256	−126	−10	3125	103	4
9	125	115	512	−129	−12.5	1760	185	6
10	125	51	1024	−132	−15	980	371	8
11	125	51	2048	−134.5	−17.5	537	741	11
12	250	51	4096	−137	−20	293	1320	14

3.6. Sigfox

Sigfox is also an unlicensed LPWAN PHY and MAC layer protocol based on the 868 MHz in Europe, 915 MHz in North America and 433 MHz in Asia frequency ISM bands [97–100]. It is capable of utilising its frequency band efficiently due to its UNB at 100 hz. It is mainly used for applications that require low data rates. Its low data rates and bandwidth allow it to overcome noises interferences during transmission. Sigfox makes use of the Binary PSK (BPSK) and the Differential Binary PSK (DBPSK) modulation techniques, with a low-complexity narrowband modulation. These slow modulation techniques allow long range of more than 10 km in urban areas at bitrate of 100 bps and more than 50 km in remote rural areas. Due to its reduced data rates, Sigfox consumes very low power its high receiver sensitivity. Sigfox can reach a maximum throughput of 100 bps and this makes it a relatively low-cost system. Although initially designed as an uplink-only system, it has since evolved into a bidirectional system with the introduction of downlink communication. The uplink transmission has a limitation of 140 messages in a single day at a 12-byte maximum payload length (uplink). The downlink messages are only limited to 4 per day at an 8-byte payload length. Clearly, not all the uplink messages will be supported for downlink communication. The issue of unsupported uplink messages not being acknowledged has been resolved using time and frequency diversity together with the duplication of transmission. In this case, a single message is transmitted over three different channels for multiple time occasions. For example, the 868 MHz frequency band is divided into 400 orthogonal channels of 100 hz in which 40 of them remain unused and reserved. This allows all the base stations to receive messages simultaneously from all channels while the end devices must randomly select a channel in which they can transmit. This has resulted in a simplified end device design at a low cost. It offers low security due to a 16-bit encryption. One of its essential characteristics include high spectral efficiencies, less complexities in implementation, low data rate for long transmission, and less expensive transceiver implementations [153]. Figure 12 is a demonstration of a typical Sigfox architecture.

Table 2. Comparison of LPWAN technologies.

LPWAN	LTE-M Cat-1 (Release 8)	LTE-M (eMTC) (Release 13)	EC-GSM-IoT (Release 13)	NB-IoT (Release 14)	LoRa	Sigfox	Weightless-W/N/P	NB-Fi
Standardization	3GPP	3GPP	3GPP	3GPP	LoRa Alliance	Sigfox Company	Weightless SIG	Russian Federal Agency
Origin	USA	USA	USA	USA	France	France	UK	Russia
Founded or official launch	2009	2016	2016	2017	2015	2009	2012	2019
Topology	Star	Star	Star	Star	Star, mesh, star-on-star	Star	Star	Star, mesh
Frequency spectrum	Licensed LTM bands	Licensed LTM bands	Licensed LTM bands	Licensed LTM bands	Unlicensed ISM bands	Unlicensed ISM bands	Unlicensed ISM bands	Unlicensed ISM bands
Deployment model and proprietary or open-source	Operator-based, limited, full stack	Operator-based, limited, full stack	Operator-based, limited, full stack	Operator-based, limited, full stack	Private and pen-standard, physical (PHY) layer	Proprietary PHY and MAC layers, no open-source	Open-standard	Private, open-standard
Frequency spectrum band	400 MHz, 700 – 900 MHz, 1700 – 1900 MHz, 2100 MHz, 2500 – 2600 MHz	700 – 900 MHz, 1700 – 2100 MHz	800 MHz, 900 MHz	400 MHz, 600-900 MHz, 1400 MHz, 1500 MHz, 1700 – 2100 MHz	868 MHz Europe, 915 MHz North America, 433 Asia	868 MHz Europe, 915 MHz North America, 433 Asia	915 MHz, Sub-GHz	868 MHz Europe, 915 MHz North America, 433 Asia
Modulation technique	16-QPSK, OFDMA	QPSK, OFDM	GMSK, 8-PSK, TDMA, FDMA	BPSK, QPSK, SC-FDMA (downlink) OFDM (uplink)	SS, CSS, TDOA, VSF	RSSI, BPSK, DBPSK, UNB (uplink), GFSK (downlink)	Narrowband, GMSK, PSK, 16-QAM, BPSK, QPSK	UNB, DBPSK (uplink), BPSK (downlink)
Channel bandwidth	20 MHz	1.4 MHz, 5 MHz	200 kHz, 600 kHz	200 kHz, 180 kHz	125 kHz, 250 kHz, 500 kHz	100 Hz (600 Hz for FCC regions)	200 Hz, 12.5 kHz, 5 MHz	25 – 50 Hz, 600 Hz, 25 600 Hz
Data rates, maximum peak data rates	10 Mbps downlink and 5 Mbps uplink	1 Mbps (uplink and downlink), 1 – 4 Mbps (downlink), 7 Mbps (uplink)	350 bps to 70 kbps (GMSK), 240 kbps (8PSK)	200 kbps, 127 kbps (downlink), 150 – 250 kbps (uplink)	300 bps, 50 kbps	100 bps, 600 bps, 1000 bps	30 kbps, 100 kbps, 10 Mbps, 24 Mbps	50 bps, 400 bps, 3 200 bps, 25 600 bps
Adaptive data rates	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Maximum messages per day	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	144 (uplink), 4 (downlink)	Varies for N/P/W version, unlimited	20 Mbit per base station per day for 3 minutes (uplink), 100 000 per base station (downlink)
Range	40 km	1 km (urban), 10 km (rural)	20 km	1 km (urban), 10 km (rural)	5 km (urban), 20 km (rural)	10 km (urban), 50 km (rural), 1 000 km LoS	5 km	10 km (urban), 40 km (rural)
Latency	50 – 100 ms	10 – 20 ms	700 ms – 2 s	1.6 – 10s	2 – 10s	1 – 30s	1 – 10s	1.5 – 5 s

(*Continued*)

Table 2. (Continued).

LPWAN	LTE-M Cat-1 (Release 8)	LTE-M (eMTC) (Release 13)	EC-GSM-IoT (Release 13)	NB-IoT (Release 14)	LoRa	Sigfox	Weightless-W/N/P	NB-Fi
Maximum coupling loss or link budget	155.7 dB (+23 dB)	160 dB (+15 dB)	164 dB (+20 dB)	164 dB (+20 dB)	157 dB	153 dB	155 dB	174 dB
Maximum payload length (packet size)	100 to 1 000 bytes	1 000 bytes	160 bytes	1 600 bytes	243 - 250 bytes, user-based	12 bytes (uplink), 8 bytes (downlink)	10 to 20 bytes	8 to 20 bytes per packet, 240 bytes for a group of packets
Connections capacity (possible devices per node)	More than 20 000	More than 80 000 per cell	More than 50 000 per gateway or cell	More than 52 000 per gateway	More than 1 million per gateway (uplink), 100 000 (downlink)	More than 1 million per gateway	Unlimited	More than 2 million, up to 4.3 billion devices in a single network
End node roaming	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sensitivity	-123 dBm	-132 dBm uplink and downlink	-121 dBm downlink	-141 dBm downlink	-137 dBm uplink and downlink end nodes, -142 dBm gateways	-142 dBm uplink, -130 dBm downlink	-124 dBm	-148 dBm (uplink and downlink)
Transmitter power	23 dBm	20 dBm	23 – 33 dBm	14 – 23 dBm	13 – 30 dBm (uplink) and 27 dBm (downlink)	For 100 bps - 14 dBm (uplink) and 27 dBm (downlink) For 600 bps – 22 dBm (uplink) and 30 dBm (downlink)	15 – 17 dBm	14 – 27 dBm
Transmitter power consumption	100 – 490 mA	380 mA	152 – 1 228 mA	74 – 220 mA	28 mA	10 – 50 mA	49 mA	44 – 250 mA
Receiver power consumption	20 mA	54 mA	66 mA	46 mA	10 mA	10 mA	13 mA	12 mA
Sleep mode power	1.5 – 1.7 uA	1.4 – 8 uA	10 uA	3 - 8 uA	1 - 2 uA	1.3 uA, 6 - 100 nA	4 uA	1.5 uA
Battery life	5 – 10+ years	10+ years	5 – 10+ years	10+ years	10+ years	15+ years	10+ years	20+ years
MAC layer	RRC	FDMA, OFDMA	GSM MAC, CDMA	LTE, SC-FDMA (uplink), OFDMA (downlink)	Unslotted ALOHA	TDMA, Unslotted ALOHA	Slotted ALOHA	Tailored
Localization or location support	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

(*Continued*)

Table 2. (Continued).

LPWAN	LTE-M Cat-1 (Release 8)	LTE-M (eMTC) (Release 13)	EC-GSM-IoT (Release 13)	NB-IoT (Release 14)	LoRa	Sigfox	Weightless-W/N/P	NB-Fi
Mobility	Supported – full mobility speed to stationary and handover	Supported (full mobility and handover)	Supported	Not supported (limited to fixed)	Supported	Not supported	Not supported	Supported
Interference immunity	Medium	Low to medium	Medium	Low	High	Very high	High	High
Security	Yes	Yes	Yes	Yes	Yes	No built-in	Yes	Yes
Co-existence	Yes	Yes	Yes	No	Yes	No	Yes	Yes
Scalability	High	High	High	High	Low	Low	Low	High
Bidirectional	Full	Full	Full	Yes	Yes	Limited	Yes	Yes
Duplex scheme	Full-duplex	Full and Half-duplex	Half-duplex, Full-duplex	Half-duplex	Half-duplex	Half-duplex	Half-duplex	Full-duplex for base stations and Half-duplex for devices
Number of channels or orthogonal signals	1 channel per carrier	1 channel per carrier	124 channels	1 channel per carrier	10 in Europe, 64-72 North America	360	Multiple	1024 channels
Authentication and encryption	3GPP AES 128-256 bit	3GPP AES 128-256 bit	GSM encryption (A5/1, A5/3)	3GPP AES 128-256 bit	AES-128 bit	AES-128 bit	AES 128–256 bit	Magma, XTEA/AES-256 bit
Cost (in relation to each other)	Moderate to high	Moderate to high	Moderate to high	Low to moderate	Low	Very low	Low	Low to moderate
Key applications	Environmental conditions monitoring, telematics, smart retail, automation, smart surveillance, connected vehicles, IIoT, and smart healthcare.	Asset tracking, smart homes and cities, environmental condition monitoring, smart metering, wearables, smart logistics, smart healthcare, and IIoT.	Smart metering, asset tracking, environmental conditions monitoring, smart agriculture and smart farming, and IIoT.	Smart metering and environmental conditions monitoring, smart grid, smart agriculture and farming, and IIoT.	Smart buildings and cities, automation, and environmental conditions monitoring.	Asset tracking, smart buildings and cities, and environmental conditions monitoring.	Smart metering, smart cities and buildings, automation and IIoT, asset tracking, and environmental conditions monitoring.	Smart cities (smart grid and utilities, environmental monitoring, safety and security), smart agriculture, smart retail and warehouse management, smart alarms, smart gas metering, and smart water metering.

(*Continued*)

Table 2. (Continued).

LPWAN	LTE-M Cat-1 (Release 8)	LTE-M (eMTC) (Release 13)	EC-GSM-IoT (Release 13)	NB-IoT (Release 14)	LoRa	Sigfox	Weightless-W/N/P	NB-Fi
Advantages	Good data rates, wide coverage, leverage of existing LTE networks, lower latency and low power.	Low latency transmission, higher data rates, real-time transmission, high mobility.	Large and wide coverage, leverages existing GSM infrastructure, low power consumption and long battery life.	Long range, low power consumption, indoor penetration, interoperable with cellular networks, reliable connectivity, low cost, and high capacity.	Long range coverage, low power consumption, and they can support large number of devices at a low cost.	Long range coverage, low power consumption and low cost.	Large and wide area coverage, low power consumption, long battery life and low cost.	Energy efficiency, long and wide coverage, higher spectral efficiencies, incorporates AI and machine learning algorithms and higher sensitivity.
Disadvantages	Higher power consumption compared to the LPWAN technologies.	Higher power consumption and higher cost.	Limited data rates, restricting use to low-data-rate applications, lower global support and adoption.	Relies on cellular networks, low data rate, limited mobility, and higher latency.	Limited data rates and low positioning accuracy.	Limited bandwidth and data rates, low precision and low frequency updates.	Lower ecosystem adoption compared to other LPWAN technologies and complex infrastructure deployment due to low commercial availability.	Small volumes of data, low data transmission speed and higher latency.

LPWAN	Nwave	DASH7 (D7AP)	RPMA	Telensa	Mioty	Eltres	IQRF
Standardization	Weightless SIG	DASH7 Alliance	Ingenu	Telensa or Signify	Mioty Alliance	Sony, NEC and Orix	IQRF Alliance
Origin	UK	USA	USA	UK	Germany	Japan	Czech
Founded or official launch	2010	2009	2008	2005	2019	2019	2004
Topology	Star	Star, tree, node-to-node	Star, tree	Star, tree	Star	Star	Mesh, star, tree
Frequency spectrum	Unlicensed ISM bands	Unlicensed ISM bands	Unlicensed ISM bands	Unlicensed ISM bands	Unlicensed ISM bands	Unlicensed ISM bands	Unlicensed ISM bands
Deployment model and proprietary or open-source	Proprietary, full stack	Private	Proprietary, no open-source, full stack	Mix, full stack	Open-standard	Proprietary	Proprietary

(*Continued*)

Table 2. (Continued).

LPWAN	Nwave	DASH7 (D7AP)	RPMA	Telensa	Mioty	Eltres	IQRF
Frequency spectrum band	Sub-GHz	433 MHz, 868 MHz, 915 MHz	2.4 GHz	868 MHz Europe, 915 North America, 433 Asia	Sub-GHz ISM bands (868 MHz Europe, 915 MHz North America)	Sub-GHz, 923 MHz to 928 MHz Japan, 868 MHz in Europe, 915 MHz North America	868 MHz Europe, 915 North America, 433 Asia
Modulation technique	UNB	2-GFSK	SS, RPMA-DSSS (uplink), UNB 2-FSK (downlink), CDMA	UNB 2-FSK	OFDM	BPSK (pi/2)	FSK, GFSK
Channel bandwidth	UNB, 100 Hz per communication channel	25 – 200 kHz	1 MHz	100 kHz	200 kHz	200 kHz	20 kHz, 100 kHz
Data rates, maximum peak data rates	100 bps	200 bps, 10 kbps (uplink), 60 kbps (downlink)	20 kbps (downlink), 78 kbps (uplink) 624 kbps	62.5 bps (uplink), 500 bps (downlink)	50 bps, 128 kbps	80 bps	1.2 - 115 kbps, 256 kbps
Adaptive data rates	No	No	Yes	No	Yes	No	Yes
Maximum messages per day	20 messages per day	Unlimited	350,000 messages per day	100 messages per day	1.5 million messages per day	Unlimited	1 message per hour, 40 920 messages per day per gateway
Range	10 km (urban), 30 km (rural), 2030 in LoS	1 – 2 km (urban), 2 - 5 km (rural)	5 km (urban), 20 km (rural), 500 km LoS	5 km (urban), 10 km (rural)	10 km (urban), 15 km (rural)	100 km	1 km, 10 km LoS
Latency	1 – 10s	700 ms – 2s	2 – 10s	1 – 10s	700 ms	393 ms – 10s	400 ms – 1 s
Maximum coupling loss or link budget	153 dB	140 dB	177 dB	154 dB	155 dB	157 dB	135 dB
Maximum payload length (packet size)	12 bytes header, 220 bytes payload	256 bytes	6 bytes to 10 000 bytes	6 500 bytes	250 bytes (downlink), 245 bytes (uplink)	128 bytes	100 – 128 bytes
Connections capacity (possible devices per node)	More than 1 million per gateway	Unlimited	More than 500 000 per cell	Up to 5 000 per base station or telecell, more than 500 000 per server	More than 1 million per gateway or network	95 625 slots per channel	More than 240 devices in the network (1 Coordinator + 239 Nodes)
End node roaming	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sensitivity	-135 dBm	-110 dBm uplink and downlink	-137 dBm	-139 dBm	-135 dBm	-144 dBm	-106 dBm
Transmitter power	14 – 20 dBm	10 – 27 dBm	21 – 30 dBm	14 – 20 dBm	13 – 20 dBm	14 dBm	11 dBm (optional maximum)

(*Continued*)

Table 2. (Continued).

LPWAN	Nwave	DASH7 (D7AP)	RPMA	Telensa	Mioty	Eltres	IQRF
Transmitter power consumption	Unspecified	30 mA	Unspecified	Unspecified	23 – 26 mA	30 mA (20 – 25 mW to 100 mW)	8.3 – 25 mA
Receiver power consumption	Unspecified	15 mA	Unspecified	Unspecified	5.4 – 65 mA	1:00 AM	1.4 – 2.8 mA
Sleep mode power	Unspecified	1 – 2 uA	Unspecified	Unspecified	0.7 uA	0.6 uA	1 - 2.3 uA, 1.7 uA, 100 nA
Battery life	10+ years	10+ years	15 – 20+ years	8+ years	20+ years	20+ years	7 – 20+ years
MAC layer	Slotted ALOHA	CSMA-CA,	CDMA, RPMA-DSSS	Slotted ALOHA	CMAC	24-bit cyclic redundancy check (CRC) and 32-bit MAC-protocol-ID (MID)	IQRF MAC, TDMA
Localization or location support	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mobility	Supported	Supported	Limited	Not supported	Supported	Supported	Supported
Interference immunity	High	High	High	High	High	Low LDPC Forward Error Correction	High
Security	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Co-existence	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Scalability	High	Moderate	High	Yes	Yes	High	Moderate
Bidirectional	No	Yes	Yes	Yes	Yes	One-way	Yes
Duplex scheme	Half-duplex	Half-duplex	Half-duplex	Half-duplex	Half-duplex	Half-duplex	Half-duplex
Number of channels or orthogonal signals	1 channel per carrier	Multiple	40 channels, 1200 signals per channel	Multiple	2 channels	23 in Asia, 17 in Europe, 25 in North America	189
Authentication and encryption	AES-128 bit	AES-CCM	AES-128 bit	AES-128 bit	AES128 bit, 32-bit cipher-based message authentication code (CMAC)	128-bit encryption-based block cipher ISO/IEC 29192-2 "CLEFIA"	AES-128 bit
Cost (in relation to each other)	Moderate	Low	Medium	Low	Moderate	Low to moderate	Moderate to high

(*Continued*)

Table 2. (Continued).

LPWAN	Nwave	DASH7 (D7AP)	RPMA	Telensa	Mioty	Eltres	IQRF
Key applications	Smart parking, smart buildings and cities, smart waste management, and environmental conditions monitoring.	Asset tracking, smart logistics and transport, smart agriculture and livestock farming, automation and IIoT.	Asset tracking, utilities, smart cities, smart grid, smart agriculture, connected cars, oil and gas industries, environmental conditions monitoring, and fleet management.	Smart street lighting, sparking, smart cities, and environmental conditions monitoring.	IIoT, smart metering, smart cities, smart buildings, smart logistics, smart agriculture, smart health, smart consumer and retail, and toll management.	Logistics – trucks, drones and pallets, environmental monitoring, disaster detection, infrastructure monitoring, smart agriculture and farming, people tracking and rescue, and outdoor sports tracking.	Smart building automation, smart cities, smart agriculture and farming, and smart logistics.
Advantages	Long and wide area coverage, low power consumption and high scalability.	Long and wide area coverage, low power consumption, real-time data transmission, and low latency, high mobility and high scalability.	Long range and wide coverage, high capacity, good penetration in building and good security.	Long and wide area coverage, low power consumptions, and high scalability.	High interference resistance, high scalability, and high capacity.	Very large and wide area coverage, ultra-low power, and high mobility.	Mesh networking enables longer-range coverage through relays, low latency and low power consumption.
Disadvantages	Less widely adopted and complex network infrastructure.	Not popularly used and lack adoption, lower range compared to other LPWAN technologies, requires more power and constrained applications.	Not popularly used, lack adoption, high power consumption compared to other LPWANs, operates in the 2.4 GHz band – suffer from interferences.	Limited focus on broad IoT applications, lower data throughput compared to other LPWAN technologies.	Fairly new and still emerging, limited widespread deployment and slightly higher complexity compared to the other LPWAN technologies.	Fairly new and still emerging with limited adoption especially outside Japan or Asia.	Limited global adoption and commercial infrastructure, less suitable for large-scale, long-distance deployments compared to other LPWAN technologies.

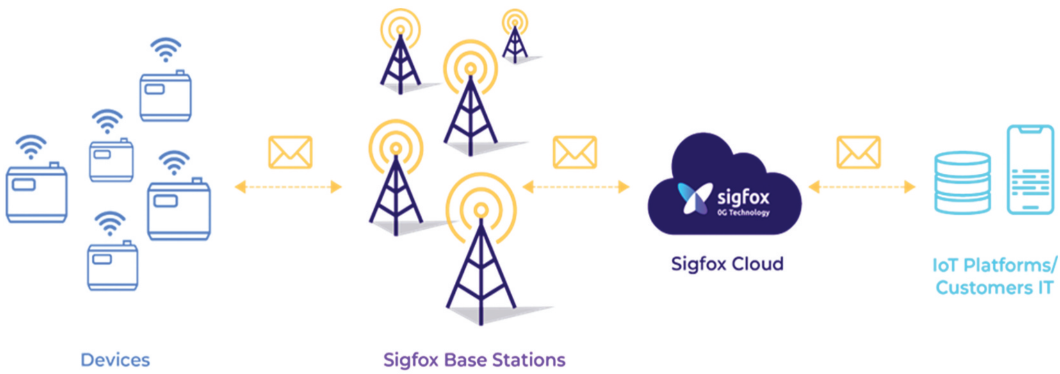

Figure 12. Sigfox architecture [97].

3.7. Weightless W/N/P

Weightless is an open standard LPWAN protocol comprised of three versions including W, N and P. These protocols were all introduced by the Weightless Special Interest Group (SIG) to provides low power wide area network coverage. The three LPWAN protocols, Weightless-W, Weightless-N and Weightless-P operates in both licenced and unlicensed sub-GHz frequency band [101]. Each of these three versions have their own unique characteristics, advantages and disadvantages. Weightless-N operates in the unlicensed ISM band and is based on the Nwave technology. It uses the narrow band scheme but only supports unidirectional communication between transmitters and receivers. It is capable of transmitting up to 3 km. For a transmitter power of 17 dBm, it can reach up to 100 kbps of data rates. The Media Access Control (MAC) protocol of Weightless-N is based on slotted ALOHA. Weightless-P is the latest LPWAN protocol to be introduced by Weightless-SIG. It was developed as a non-proprietary PHY layer communication technology based on the Platanus technology. Platanus belongs to the M2COMM. It uses both the GMSK and the QPSK modulation techniques. It fully supports bi-directional communication between transmitter and receiver. Weightless-P has the least communication range amongst the Weightless SIG protocols. It can only manage approximately 2 km. It also has the shortest battery life in comparison to Weightless W and N. Weightless-P spreads its spectrum into steps of 12.5 kHz narrow channels. Each channel provides up to 200 bps to 100 Kbps data rates. It can, however, support bidirectional communication with the appropriate software upgrades [128].

3.8. NB-Fi

NB-Fi (Narrowband Fidelity) is a relatively new LPWAN technology developed by WAVIoT for IoT, IIoT and M2M applications [112,163]. It operates on the unlicensed sub-GHz frequency ISM bands to provide wide area coverage at low power consumption. It is an open-source and full-stack protocol with 7 seven PHY layers. One of its key features is the ability to support a large number of devices (up to 4.3 billion devices with a single network) using the star-of-stars topology. This also allows it to have good scalability. It uses the narrow band modulation scheme with 1 000 channels in 50 kHz range. The 50 kHz bandwidth is used for uplink message while 100 kHz is used for downlink. This allows it to reach up to 30 km in rural areas and up to 10 km in urban areas. NB-Fi supports secure bidirectional communication between its connected devices for uplink and downlink messages with equal link budget with high noise immunity. It uses neural network and AI techniques for the optimisation of its spectrum utilisation. A typical NB-Fi architecture is described in Figure 13.

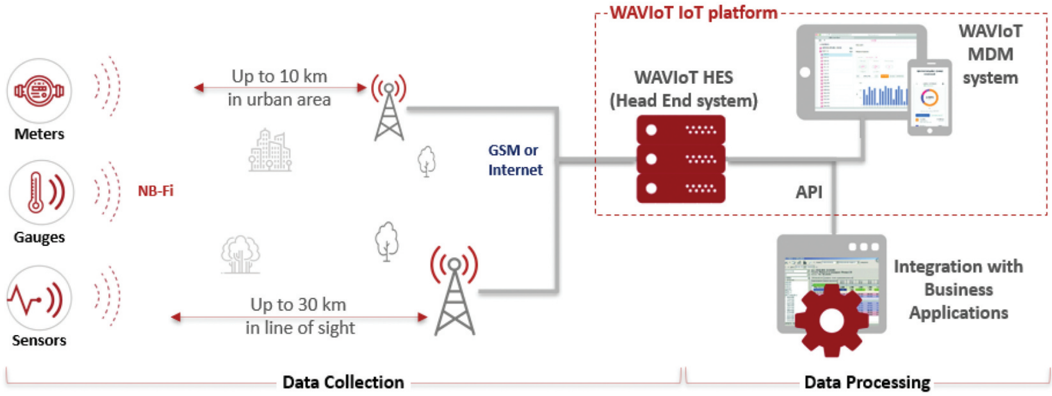

Figure 13. NB-Fi architecture [112].

3.9. Nwave

Nwave is another LPWAN technology developed by Nwave operating on the unlicensed sub-GHz frequency ISM band [102]. It is shares similar characteristics as the Weightless LPWANs, and often used interchangeable. The Nwave system is primarily developed for smart parking and car counting solutions in smart buildings, corporate offices, in airports, shopping malls and universities, but also widely used in smart health care and smart manufacturing [102]. Its main purpose is to help drivers identify parking space and then park their cars securely, quickly and efficiently. This is done by guiding drivers to available parking spaces in real-time. It makes use of the UNB modulation scheme to provide wide coverage at low power consumption. It can also support a higher density of connected nodes using the star topology. Nwave can only achieve up to 100 bps data rates and supports mobility. It can reach up to 7 km with battery life of more than 10 years.

3.10. DASH7

The DASH7, also well known as Dsah7, D7A, or D7AP is an open standard protocol operating in the sub-1-GHz ISM frequency band, developed and introduced by the DASH7 Alliance [103,104]. It operates as an open source communications protocol to cater for wireless sensor network applications in various industries. This wireless protocol operates on the 433 MHz, 868 MHz and 915 MHz unlicensed ISM frequency bands. DASH7 has its roots in the military logistics but has since evolved and penetrated a wide range of industries with a wide range of applications. DASH7 is capable of enhanced reliability providing bidirectional communication with low latency and good scalability. It is able to achieve these capabilities using the P2P, star or the tree topologies rather than a mesh network. With its low data rates, it can penetrate buildings and obstacles, achieving more than 2 km in outdoor environments.

3.11. RPMA

RPMA, a proprietary LPWAN technology developed by INGENU, formerly known as On-Ramp Wireless. It is based on a PHY layer to provide low cost, low power consumption, robust, reliable and bi-directional communication [105,106]. Its bi-direction communication incorporates a slight link asymmetry for the uplink and downlink. For the uplink, nodes transmit to the base station, while the downlink allows the base stations to spread the signals using the Code Division Multiple Access (CDMA) modulation technique. The CDMA also enhances its security measures and resilience against interferences. But in general, RPMA is based on the SS modulation scheme operating on the globally available 2.4 GHz frequency band based on random phase multiple access (i.e. RPMA) direct sequence SS (i.e. DSSS) [106]. It does not rely on the better propagation properties of the sub-GHz frequency band like most LPWAN protocols. Rather, it takes advantages of, and leverages from the rules and regulation in place for the 2.4 GHz frequency band. This includes benefits such as reduced duty-cycle which enables the system to achieve long-range and wide area coverage. The RPMA communication system operates at an increased power consumption rates compared to most LPWAN technologies. It leverages its capabilities from the unlicensed frequency spectrum with relaxed regulations. RPMA nodes can share the same transmission slot, which would be acquired from the downlink frame's time and frequency [128]. Even multiple transmitter can transmit on the same slot. The RPMA architecture makes use of adaptive data rates. Its devices are able to select optimal SF according to the downlink signal strength. This is because the base stations are allowed to receive all SFs and delay times.

3.12. Telensa

Telensa is an open-source standard proprietary LPWAN communication protocol based on the sub-GHz frequency ISM frequency band, 868–869.6 MHz in Europe and 910–925 MHz globally [107]. Telensa is predominantly and well known for its applications for smart street lighting in smart cities [107]. It uses the UNB modulation scheme to provide long range at low power consumption rates. It was developed as a low throughput protocol based on the ETSI standards. This allows Telensa to easily integrate and be interoperable with other wireless communication system operating on the same frequency range standards. To date, over 2.5 million street lights have been connected in more than 400 smart cities around the globe [107]. This is over 150 networks of infrastructure deployment. A Telensa base station can connect up to 5 000 devices. Its range can stretch for more than 16 km with good scalability capabilities.

3.13. Mioty

The Mioty LPWAN protocols was developed and standardised by the Mioty Alliance to address some of the IoT challenges [108,110,164]. It operates over the unlicensed sub-GHz ISM bands (868 MHz in Europe, and 916 MHz in North America and is based on the ETSI TS 103,357 TS UNB standards. This technology requires a bandwidth of 200 kHz for two channels but does not require any network synchronisation. At this bandwidth, it is capable of achieving up to 250 bytes (downlink) and 245 bytes (uplink). Its main advantages or significant contributions was to provide a highly reliable and scalable IoT, high capacity and density, and mobility solution. Mioty is based on the Telegram Splitting Multiple Access (TSMA) modulation technique which helps enhance its reliability and signal transmission efficiency. The TSMA splits the transmitted data packets in simplified smaller packets. The data packets carried by the TSMA can therefore be transmitted in smaller sub-packets at the PHY layer sensor level. Various frequency bands are used to transmit the sub-packets at different time intervals. This helps avoid packet collisions over the wide frequencies. Mioty makes use of a robust FEC technique in which the receiver requires only 50% of the radio bursts in order to demodulate the received signals.

3.14. ELTRES

ELTRES is one of the latest and emerging LPWAN technologies developed by Sony to meet the IoT requirements [111]. It was targeted an IoT applications with long range and low power requirements. Its main features include one of the highest transmission range of up to 100 km (LoS) at speeds of up to 100–120 km per hour. This allows it to support high mobility devices. ELTRES has a very low power consumption with a long battery life. One of its unique features is the built-in GNSS receiver, but this makes it suitable for outdoor and unobstructed LoS. A typical ELTRES architecture based on the Sony IoT ecosystem is described in Figure 14. There is very limited work and case studies published on the deployment and application or user cases of ELTRES to date.

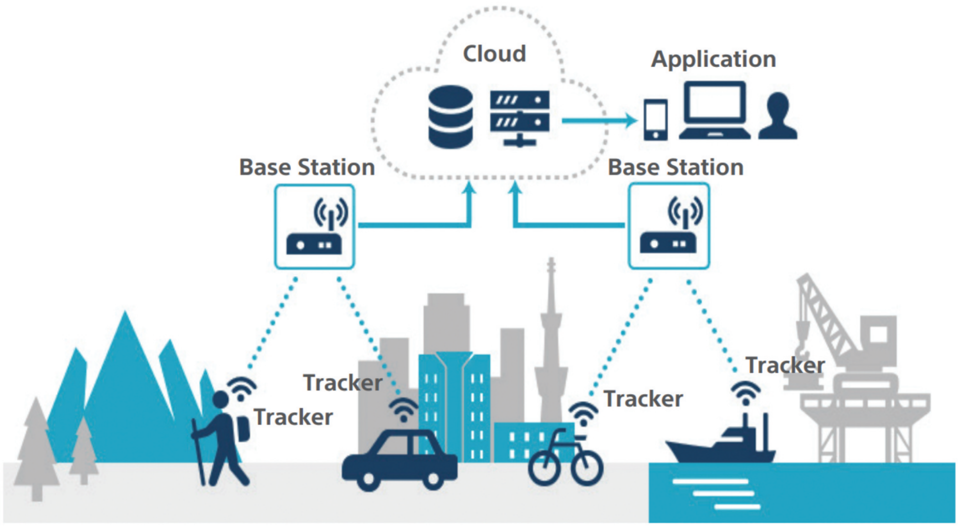

Figure 14. ELTRES architecture [111].

3.15. IQRF

IQRF is a proprietary wireless mesh network based LPWAN protocol based on the unlicensed sub-GHz ISM frequency bands [116–118]. It was initially established in 1991 by MICRORISC but officially introduced in 2004 in various countries around the world. It operates is an unlicensed frequency band and therefore does not incur any carrier fees. It was specifically developed to provide low to ultra-low power consumption operations, low data rates, low traffic volumes and can well integrate with products from various producers. Its ultra-low power consumption gives it a lifetime battery using a mesh network topology. The IQRF protocol has the capability to support up to 239 end devices with a single base station. It makes use of the GFSK modulation technique to slow down its data rates and maintain resilience against interferences. It transmits and receive at ultra-lower power, enabling it to cover several square kilometres in outdoors environments, and few square kilometres in indoors environments. The IQRF LPWAN technology makes use of two transmission modes which include the networking and non-networking modes. Each of the two modes has specific user cases according to requirements. For example, the networking mode, based on a mesh network with a single coordinator and 239 nodes, is suitable for complex networks. It is mainly used for communication with multiple nodes. The non-networking mode is mainly used for single and/or multiple peer-to-peer communication. It does not incorporate a centralised coordinator in the network. Communication can take place in one of 62 channels within a 100 kHz bandwidth. Some of its successful applications are smart parking, heating automation, building automation, smart street and industrial lighting, battery life monitoring system, smart inventory management, telemedicine, remote data acquisition, etc. A typical IQRF architecture design is demonstrated in Figure 15.

But there are much more LPWANs to cover in details in this study. There have been newly developed protocols with promising future and competitive capabilities. For example:

- **Helium**: Helium, which can typically achieve a higher network density than the likes of LoRa, has a unique advantage of a decentralised network model. It utilises blockchain technology to incentivise the growth of a network and its security measures [165].
- **Amazon Sidewalk**: Amazon Sidewalk is another LPWAN protocol developed for smart consumer services and automation of smart home devices [165].

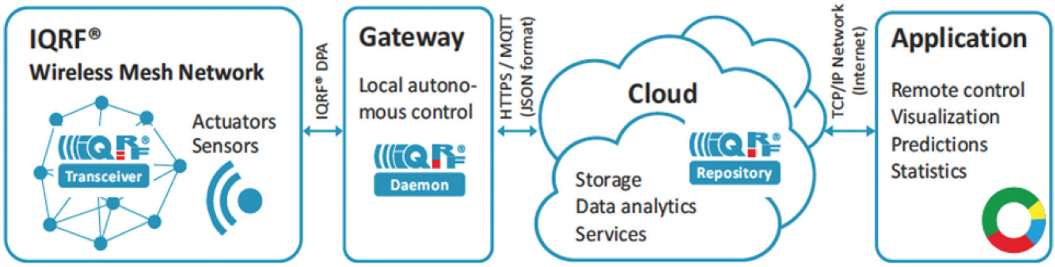

Figure 15. IQRF architecture [116].

- **Qowisio**: Qowisio provides dual-mode networks with its low power cellular network allows for the IoT to transmit at very low volumes of data several times per day at a very low cost [166]. The Qowisio technology combines their own proprietary UNB technology with that of LoRa in its deployment. offers a wide range of connected devices that can be easily integrated into IoT solutions.
- **SNOW**: Another emerging LPWAN is SNOW with PHY layer design that takes scalability limitations to the next level [167–171]. Its scalability increases with an increase in the availability of TV spectrum. It makes use of wide channels splits with equal spectra. Each sensor has a half-duplex narrow band white space radio with all devices connected to the base station and the other way.
- **RPW**: RPW is expected to grow significantly over the coming years with a great potential [172–174].
- **RedCap**: RedCap, referred to as the Fifth Generation Reduced Capability, 5 G RedCap or simply RedCap, is one of the latest LPWAN technologies introduced. It is part of the Release 17 and 18 of the 3GPP Group in 2022, and operates on the licenced spectrum and shares the same frequency bands as the likes of LTE, but very similar to the 5 G technology. This allows it to leverage from the existing infrastructure of protocols such as the LTE and 5 G technology. It was mainly introduced to provide a balance between 5 G network capabilities while operating at the LPWAN standards by providing wide area coverage, low data rates, low power consumption and low cost. But it is desired for its ability to provide a good balance between coverage, power consumption and data rates. It reduces costs and complexity by reducing the number of receivers and transmitters, bandwidth, processing capabilities and uses half-duplex scheming, but also to support medium range transmission based on narrowband channels [175]. In the Release 17, the bandwidth was down-scaled from 100 MHz to 20 MHz while maintaining the same frequency with reduced data rates [176]. The bandwidth is further reduced to 5 MHz in the Release 18 [176]. The initial release of 5 G was mainly focused on the enhanced mobile broadband (eMBB), ultra-reliable low latency communication (uRLLC), and mMTC. But the RedCap protocol can now bridge the gap between these technologies and allows a modified solution that caters for LPWAN applications as illustrated in (Figure 16) [177,178]. But its capabilities are slightly higher data rates than some of the 3GPP group protocols such as NB-IoT and LTE-M. However, it comes at higher costs due to spectrum acquisition and licencing fees, infrastructure capital investment (CAPEX), and the typical operational costs (OPEX). Even though it is costlier than most LPWAN protocols, it is lower than 5 G due to the reduced capabilities. For example, the reduction in the bandwidth for the Release 17 resulted in 33% cost reduction, and a significant reduction in its complexity [176]. It uses the a similar PHY layer and MAC layer as LTE-M and NB-IoT, but a different RRC and application layer. RedCap is well known for its strong security measures. It can share the same frequency band with LTE and 5 G, but without experiencing any interferences. This is achieved using the 256-QAM and 64-QAM, and the DQPSK modulation techniques [120,179,180]. These modulation techniques are more efficient (QAM) and provide

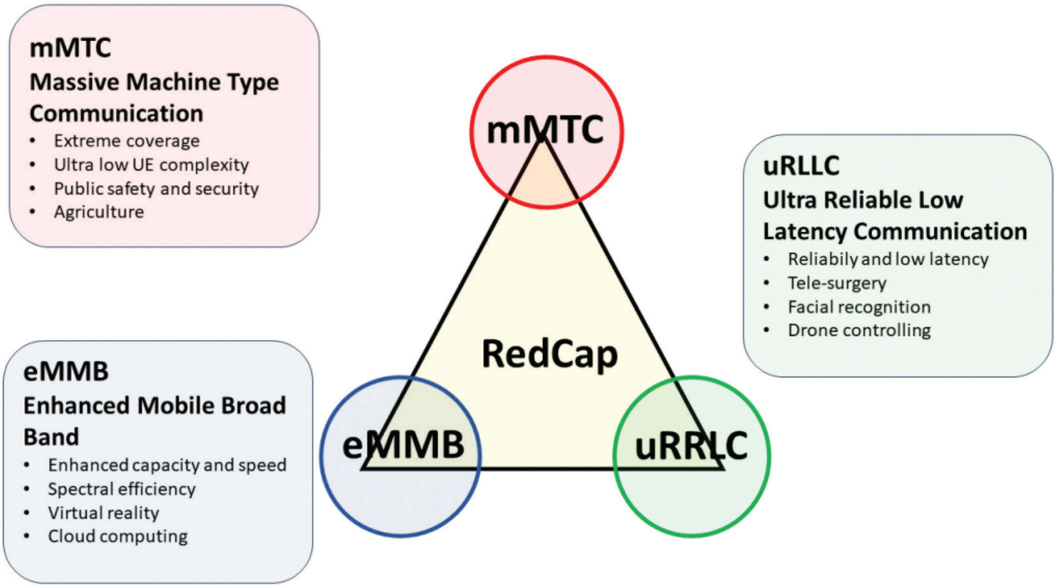

Figure 16. RedCap technology positioning among mMTC, eMBB, URLLC [177].

better immunity to noise and interference (DQPSK). The modulation scheme is reduced from a 64-QAM standard to a 16-QAM for uplink and from 256-QAM to 64-QAM for downlink, and thereby lowering the signal processing capabilities and requirements [176]. Its latency ranges from 500 to 5 ms [181]. However, this means that it will consume slightly more power. It is capable of up to 220 Mbps (downlink) and 120 Mbps (uplink) data throughput, with peak data rates of 10 Mbps [175]. RedCap can compete with the likes of 4 G, which rely on near real-time data communication. Communication can be achieved in both the half-duplex and full-duplex modes. Handover between different cells is well supported and maintains connectivity when devices hop between base stations. Some of the interesting research with regards to RedCap includes work being done to integrate it with the low orbiting satellite networks [176]. RedCap is predominantly used for applications such as smart cities and buildings, asset tracking, smart agriculture, smart manufacturing, smart health care and vehicle telematics.

4. Performance measure and criteria

There are many ways in which the LPWAN technologies can be compared for applicability, suitability and selection purposes. The comparison and selection of the LPWAN technologies can be based on performance measure metrics. These parameters are also critically important for design considerations of these technologies. Several authors have emphasised the need to consider a performance evaluation criterion for applications requirements [7,44,120,126,174,182].

4.1. Coverage

The LPWAN technologies are well known for their long range and wide area coverage. It can be quantified as a measure of distance (m/km), area (m^2) or volume (m^3) of the transmitted signals [60]. Coverage has a direct impact on the scalability, deployment flexibility and costs of the systems [120]. Multiple base stations are required to extend coverage, which increases the cost and complexity. Long range is ideal for remote and rural areas, while short to medium range system are deployable for indoor environments. This requires efficient signal transmission and deep penetration capabilities. However, wide area coverage comes at the expense of frequency and bandwidth. Coverage can be affected by obstructions such as tall buildings and trees in urban areas. But, at lower frequencies, the signals can travel through obstructions. Most of the LPWAN protocols rely on their sub-GHz frequency for improved signal transmission and quality. The lower frequency signals are less susceptible to attenuation, fading and multipath effects. Therefore, the range will differ according to the environment. Therefore, system design factors for optimum coverage include the signal fading and multipath effects, the number and configuration of the base stations and topology, modulation scheme, transmitter power, link budget, SNR, SINR, frequency bandwidth, data rates, etc. Coverage can be improved by simply increasing the number of base stations. But the LPWAN protocols in the unlicensed ISM band are limited in their transmitter power and duty cycles due to regional regulations.

4.2. Data rates and throughput

Data rates and throughput are amongst the crucial measures of the performances of communication systems. They determine the speed, efficiency and quality of the communication. Higher data rates and throughput are required for seamless and real-time communication for both uplink and downlink. This helps enhance user experience and decision-making efficiency [120]. But, the LPWAN technologies are characterised by low data rates due to their narrow bandwidth. The issue of low data rates is one of the areas of future focus for LPWAN systems in order to reach more applications and capabilities [44]. Data rates depend on the bandwidth and channel capacity. If the bandwidth is high, the bit rate tends to be high whether adequate digital communication technologies are employed. Often, a trade-off between data rates, range and power consumption come into effect. Low data rates are capable of long-distance transmission of lower payloads and deep penetration. On the other hand, throughput describes the actual amount of data transmitted and received in a defined period of time while data rates can be measured by the maximum amount of data or information that can be transmitted and delivered per unit time, normally in seconds (bit rate). Throughput is based on the MAC layer while data rates are based on the PHY layer. Various modulation schemes can be applied to maintain or improve data rates and throughput. Typically, the cellular licenced protocols (LTE-M, LTE-M Cat1, RedCap, etc.) have better data rates than the unlicensed protocols (Sigfox, LoRa, NB-IoT, etc.) [126].

4.3. Latency

Latency is a measure of the delay with which the required information reaches the end user. It provides the time delay during the transmission of packets from end devices to base stations. It determines the degree to which real-time communication can be obtained. The lower the latency, the better it is to real-time communication. LPWANs such as NB-IoT and LTE Cat M1 have low latency compared to the unlicensed technologies such as LoRa and Sigfox [126].

4.4. Traffic requirements

The LPWAN technologies have traffic requirements to meet in their networks based on delays, jitter and packet. This should consider the number of transmissible messages and their sizes in a channel. LPWANs like LoRa, RPMA, and Mioty are built to support multiple channels and this allows them the capability to handle high traffic volumes, while the likes of NB-IoT, LTE-M and Sigfox have low traffic due to their single channel at a time.

4.5. Scalability

Scalability refer to the ability of a system to enable multiple functions and maintain its standard operability performances and reliability even with an increase in the number of connected devices. It can be improved by increasing base stations, end devices and gateways while coping with the traffic requirements. This design considerations of the modulation schemes, adaptive data rates, spectrum utilisation, channel capacity, payload size and MAC layer are crucial for scalability. For example, the UNB modulation technique has higher scalability capabilities than SS. One of the important requirements for the LPWAN technologies is their capability to support a large number of end devices at the same time. They are required to support 100 000 to over 1 000 000 devices per cell. The LPWANs operating in licenced bands have better scalability capabilities [126]. The cellular LPWANs systems exhibit very high scalability and are capable of supporting millions of devices per cell.

4.6. Energy efficiency, power consumption and battery life

The LPWAN technologies are developed for long battery life service (in the order of over 10–15 years) due to their low to ultra-low power consumption. Power efficiency is directly linked to transmitter power (dBm), transmitter and receiver power consumption (mA), transmission time and the required data rates. The LPWAN systems are designed with sleep and deep sleep modes to further conserve more energy and increase battery life using duty cycling in the gateways. This increase the time before the system has to be recharged or replace its battery, and thus reducing costs. The low power consumption is also a benefit in terms of permissibility requirement in gassy underground mines. However, lower power consumption comes at the expense of latency and data rates or throughput. Battery life can be improved by increasing the number of uplink base station to improve uplink throughput which reduces the total transmission time. In some of the LPWAN systems, the transmitter power can be adjusted to meet the link budget and range requirements. However, this will increase power consumption and thereby reducing battery life. But the link budget does not necessarily increase with an increase in transmitter power consumption. Typically, the cellular or licenced network systems tend to consume more power than those operating in the unlicensed bands due to their higher infrastructure complexity [126]. Typically, LTE-M and NB-IoT have higher consumption than the likes of LoRa, Sigfox, and Weightless. In addition, network topology and modulation schemes are other factors affecting power consumption. The star topology, where the end devices connect directly to the base stations, is often a preferred choice for reduced deployment costs and power consumption, in comparison to the tree and the mesh networks.

4.7. Cost effectiveness

The costs associated with LPWAN systems include capital investment (infrastructure establishment), licencing costs, deployment costs, operating costs, service and maintenance costs. One of the simplest ways of reducing costs is reducing complexity. Additional cost benefits can also be realised if the system has a long life span. The total cost of system should include planning, implementation, operation and maintenance and service [120]. LoRa units cost about $ 6 for an end-device, $ 110 per gateway and $ 1 080 per base station; Sigfox cost $ 3 per end-device and $ 4 300 per base-station; and NB-IoT cost $ 22 per end-device, $ 16 000 per base-station, and $ 550 million per MHz [38]. DASH7 gateways can cost anything from $ 100 to $ 1 000 per base station, while NB-IoT can reach up to $ 1 500 [126]. Low-cost LPWAN technologies include NB-IoT, LoRa, Sigfox, Weightless, Telensa, and Nwave, while LTE-M, LTE Cat-1, RPMA are costlier due to the required infrastructure and cellular dependency. For LPWAN technologies, significant costs are saved by the long-life batteries due to their low power consumption and reducing infrastructure intensity. Frequency costs are also reduced in the unlicensed LPWANs. In addition, the UNB modulation scheme does not require expensive transceiver designs in comparison to the SS which additional processing gains on the transceiver.

4.8. Authentication, immunity, privacy and security

These parameters are related to the control and management of information, maintaining its integrity and protecting its history. This is due to the increasing cybersecurity risks of malicious jamming attacks, eavesdropping and packet sniffing. These risks are particularly higher when transmitting information over long distances on-air [44]. The risk is even higher for the unlicensed frequency bands. For wide coverage, more security measures are required. The essential security measures and attributes include authorisation, authentication, trust, availability, confidentiality, data security, access control and non-repudiation. The LPWAN systems use the UNB and SS modulation techniques to prevent interferences. Robustness against interferences is even better when incorporated with FEC techniques [126]. Most of the LPWAN technologies support Advanced Encryption Standard (AES) in a symmetric block cipher encryption for security. This makes them suitable for IoT applications without any threats. Additional end-to-end authentication and privacy methods such as Subscriber Identification Module (SIM) can be introduced to strengthen security measures, but at a higher cost due to design complexity [44].

4.9. Co-existence

The network provided by the LPWAN systems should be able to handle heterogeneous devices and operate seamlessly over crowded networks. Due to the growing IoT, most LPWANs will be deployed in close proximity and this may necessitate co-existence. The performance of the current LPWANs is degraded by co-existence [44]. RPMA and Mioty excel in co-existence due to their interference tolerance mechanisms, while Sigfox tends to perform worse in crowded radio environments.

4.10. Accuracy and precision

The LPWAN technologies have also been extensively used for applications such as tracking people, machine, assets, goods, and livestock. This requires positioning accuracy and precision. Accuracy can be defined as the measure of degree of deviation of the estimated location from its actual or true position. The accuracy measure provides an indication of how close the measured or computed location is to the true position. The higher the accuracy the lesser the error or deviation from the truce location. However, coverage has a direct influence on accuracy. Wide coverage can reduce the level of positioning accuracy. With the long-range capabilities of the LPWAN systems, positioning accuracy can be an issue. Precision provides the repeatability of a specific measurement of the estimated location. It gives an indication of the reliability of the location even when the surrounding environment conditions have changed. This parameter is closely linked to accuracy and resolution but it is distinct to the standard deviation in distance location error rather than to the mean distance error. A measured location can be found to be not precise but a precise location always yields high accuracy.

4.11. Availability

Availability refers to the amount of time over the total time that the system can be used at its design performance. For example, low availability for a positioning system is anything less than 95%, average availability at 99% and high availability is at 99.9% [183].

4.12. Adaptiveness, responsiveness, flexibility and mobility

Adaptiveness is associated with the capabilities of a system to maintain high performance with changing environmental conditions. This parameter can reduce the need for repeated calibrations of the system. Responsiveness is a measure of how quick the system can perform its function or instructions. Flexibility refers to the ability of the system to respond to reconfigurations.

4.13. Complexity

The complexity of a system refers to the amount of hardware and software requirements to the overall functionality of the system. Although low complexity is desired, the hardware and software are increased to improve the effectiveness of the system and thus its complexity. At some point, accuracy and costs are not enough to justify the complexity of the system.

4.14. Reliability and robustness

Reliability and robustness focus on the system's resistance to incur transmission errors and resilience against interferences during transmission. Interferences can be caused by electrical noises, intra-networks or self-interferences. Reliability can also be described as an indication of the degree of the dependability on the entire system. The need for reliability is to ensure accurate communication. This parameter measures the percentage of the system meeting its accuracy threshold. For example, RPMA, NB-IoT and LTE-M show high immunity to interference. Sigfox and Nwave have lower immunity compared to the most. Robustness can be seen as the measure of a positioning system to remain operational and provide accurate locations even when the surround conditions are unfavourable such as in the underground mining environments. In particular, with high complexity systems, damages to the hardware or software components can cause the system to fail. But poor reliability can also affect the maximum achievable data rates by the system.

4.15. Quality of service (QoS)

Lastly, the Quality of Service (QoS), is evaluated to measure the overall performance of a system [128]. The QoS combines all the metrices to obtain an overall best performing system based on parameters such as latency, bidirectional communication, data rates, throughput, wide coverage and range, low cost, low power consumption, etc. Its purpose is to obtain a balance between the various parameters based on the application requirements by conducting trade-offs. But the different PLWANs are designed and developed with specific purposes. Overall, the licenced LPWANs (NB-IoT, LTE-M, EC-GSM-IoT, etc) tend to have a better QoS than the unlicensed technologies [24]. LoRa, NB-IoT and Sigfox stand out for low power consumption, low cost, and high scalability, making them ideal for massive IoT applications. RPMA and Mioty offer robust interference immunity and scalability, though they may be more complex and costlier to deploy. LTE-M and LTE Cat-1 provide higher data rates but come with higher costs and power consumption. This comparison provides a solid foundation for evaluating which LPWAN technology suits different use cases, especially in large-scale deployments like smart cities or industrial monitoring systems.

4.16. Comparison of the different LPWAN technologies

A combination of parameters or performance measures can then be used to compare the LPWAN technologies based on user needs. The comparisons must be based on a defined performance criterion for the specific application. For example, in Figure 17, the technologies are compared by data rates and transmission range. Various applications and environments may necessitate different

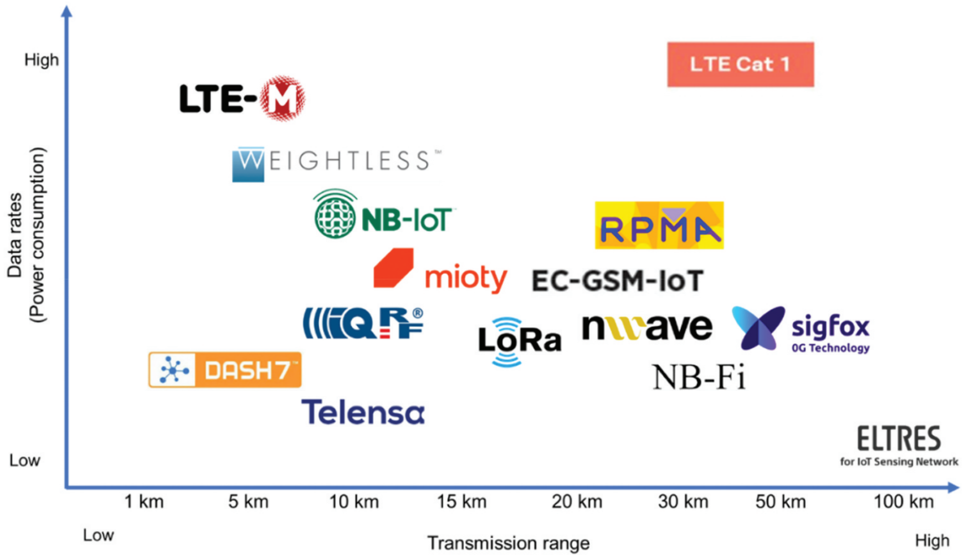

Figure 17. Comparison of LPWAN technologies.

combinations for performance measures. But typically, the licenced LPWANs can achieve higher data rates but at a higher cost and higher power, while the unlicensed achieve lower data rates at low cost, low power, and good scalability.

5. Underground mining applications

To date, there has been very little adoption of the LPWAN technologies in underground mines, and the mining industry in general when compared to other industries. LoRa has gained significant traction in various applications in the mining industry. There has also been some reported user-cases for LPWANs such as DASH7, NB-IoT, Mioty, Sigfox, Weightless and Wi-Fi Halow (Table 3). However, no work has been reported on the use of LPWANs such as LTE-M, Telensa, Nwave, IQRF, RPMA, etc. This can be attributed to the fact that some of these technologies are still emerging and require some design considerations to adapt to the harsh conditions of underground mines. But Mekki et al. [140] predicted that the LPWAN technologies will dominate the applications of wireless communication systems. Unlike the short and medium range protocols which rely on high-speed, high-bandwidth connectivity, the LPWANs perform optimally with intermittent transfers of small data packets. This could be a limiting factor in some of the underground applications. Hence, research has moved in direction of studying the propagation models and link performances of the LPWAN technologies in the underground mining environments. This has been done for DASH7 [10,185] and LoRa [57, 184, 193, 221–224]. Overall, LoRa seems to be well accepted in underground mines. Table 3 is a compilation of the currently applications of some of the LPWAN technologies in underground mines, open-cast mines or surface areas, and the oil-and-gas industry.

6. Challenges, opportunities and the future in underground mines

While the LPWAN technologies are promising to be an important contributor to the MIoT, they are also faced with a number of challenges and limitations in their applications. Some of these challenges could be due to the uncongenial nature of the underground mining environments compared to surface and outdoor environments or just technical. This has necessitated the need

Table 3. Applications of LPWAN technologies in the mining industry.

LPWAN	Underground mining applications	Technology implementation stage	Country or mine in use	References
LoRa, DASH7	Real-time tracking of personnel and localization of personnel during normal work hours and during emergencies to aid and enhance the rescue trapped or lost personnel. This will help ensure the safety of personnel by tracking their real-time locations, providing last detected positions of trapped miners and last detected direction of movement (node-to-node).	Laboratory and field tests in an underground coal mine	China, Pakistan	[56,185–191]
Unspecified LPWAN	Personnel physical health status prediction, tracking and monitoring (fatigue, physical and mental) through the collection and monitoring of vital signs, physiological characteristic data and movement state data in advance during work or shift hours.	Design concept for underground coal mine	China	[192]
Unspecified LPWAN	Using LPWAN technologies to manage, facilitate, arrange and organize work shift patterns and schedules for workers for underground mining operations to improve work coordination. This can also help with fatigue management.	Design concept for underground coal mine	China	[192]
LoRa	Increase level of automation in underground mines through functions such as real-time tracking and monitoring of mine assets, equipment and machines. This is to ultimately remove people from the hazardous areas underground.	Measurements collected from an underground Block Cave gold mine	Australia	[193]
LoRa	Pathloss modelling of LoRa signal propagation in underground mining environments to enable seamless connectivity for productivity optimization features or functions such as fleet management and dispatch system for production and efficiency optimization.	Measurements collected from an underground Block Cave gold mine	Australia	[193]
LoRa	General connectivity and wireless communication in underground mines including real-time two-way voice, text or data transmission.	Prototype development and simulations	India, Canada	[57,194,195]
LoRa	Real-time tracking of mine assets and continuous monitoring system to manage their fleet and heavy equipment.	System implemented in an underground mine and quarry	United States of America, Canada	[56,196]
LoRa	Real-time detection, monitoring of environmental or atmospheric parameters or ambient conditions including dust levels, air pollution levels, air velocity, humidity, air pressure, temperature, exposure to noise levels and ground vibrations.	Prototyped development and underground testing (Mines A and B) in different tunnels	India	[185,197,-198]
LoRa	Early warning and alert system for emergency evacuation of miners.	Underground testing of a prototype	India	[199]

(*Continued*)

Table 3. (Continued).

LPWAN	Underground mining applications	Technology implementation stage	Country or mine in use	References
LoRa	Monitoring and detection of concentration of harmful, unsafe or explosive gases such as Methane (CH_4), Carbon Monoxide (CO), Sulphur dioxide (SO_2), Nitrogen dioxide (NO_2), Hydrogen Sulphide (H_2S), fires and smoke levels, and providing early warning and evacuation during emergencies.	Prototype development and underground coal mine testing	India	[196,197,199–207]
DASH7	Events localization in underground mines such as falls of ground, distressed and falling miners (lying horizontal on the floor) through the detection and identification of abnormal changes.	Field tests conducted in an underground coal mine	Pakistan	[185]
NB-IoT, DASH7	Real-time environmental monitoring and detection of atmospheric gases such as the deficiency of vital gases such as oxygen (O_2), concentrations or buildup of explosive gases such as CH_4, acetylene (C_2H_2) and hydrogen (H_2), toxic and acidic gases such as carbon dioxide (CO_2), SO_2, nitrogen oxides (NOx), CO and H_2S, as well as exposure levels of respirable concentration of dust.	Tests in an underground coal mine	India, Pakistan	[56,185,203,208]
DASH7	Environmental and atmospheric conditions control and automation.	Prototype development and underground coal mine testing	Pakistan	[185]
LoRa	Robotics for underground mining missions during emergencies and rescue.	Concept developed for an underground mine and testing	Australia	[209]
LoRa	Mine goaf detection and monitoring, and spontaneous combustion detection, prevention and control within the goaf area.	System deployment and testing in an underground longwall coal mine	Kongzhuang underground coal mine, China	[210]
LoRa	Underground conveyor belt remote control and monitoring, detection of rips and activation of emergency remote shut down.	Implemented system – case studies	Underground mines	[58]
Mioty	Mine climatization control, asset tracking, environment monitoring, waste management, cost optimization, predictive maintenance, equipment utilization and workflow automation.	Fully developed system available in the market	Developed in Sweden	[58,211]
LoRa	Underground blasting and remote explosives detonation, and explosives control. A LoRa multi-hop system is used for initiating and detonating charged explosives.	System design, development and testing underground	Newcrest's Cadia mine, New South Wales	[56,212]
Sigfox	Mining shaft monitoring for continuous real-time monitoring of changes in shaft to reduce the effort for on-site inspections.	System installed and in operation	Germany	[213]

(*Continued*)

Table 3. (Continued).

LPWAN	Underground mining applications	Technology implementation stage	Country or mine in use	References
LoRa, NB-IoT, Sigfox, Weightless and Wi-Fi HaLow	Mine monitoring devices down mineshafts for wearable safety technology, remote mines and improving hazardous conditions and water metering systems.	System deployment and operating in underground mines	Australia, New Zealand, Brazil	[214]
LPWAN	**Surface areas or open-cast mining applications**	**Technology implementation stage**	**Country or mine in use**	**References**
LoRa	Slope monitoring in an open-cast mine. Slope conditions data is obtained in real-time and transmitted over long distances to the workers to enable emergency evacuation.	System architecture design, development and deployment in an open-cast mine	India	[215,216]
LoRa integrated with Wi-Fi	Real-time landslide monitoring for early warning in risk prone areas.	Prototype design, development and testing	India	[217]
NB-IoT and LoRa	Blast induced waves, ground vibrations and air-blast measuring and monitoring due to drilling and blasting.	Prototype design, development and testing	India, China	[218,219]
LoRa and Sigfox	Monitoring and prevention of thermal events in mining waste disposal sites and landfills.	Prototype development and testing	Czech Republic	[220]
LPWAN	**Oil and gas industry applications**	**Technology implementation stage**	**Country or mine in use**	**Reference**
LoRa	Monitoring of leakages in pipelines, monitoring of corrosion, and integrity issues by measuring data on pressure, temperature, and flow rates. Enabling monitoring, remote control and automation systems to optimize production systems and processes. Monitoring of worker safety in hazardous environments by detecting environmental conditions such as temperature, gas levels, and motion, and provide emergency evacuation alert features in real-time.	System implementation cases studies	United States of America, Canada	[196]

to evaluate their potential challenges, risks and hazards, but also their emerging opportunities and future trends. This can help improve their performances, adaptability and adoption for optimised future applications in underground mines.

6.1. Major drawbacks

The LPWAN technologies are characterised by low to very low data rates. This is at the expense of the long-range transmission and the low power consumption. The low data rates are the main drawback of these technologies as they limit the possibility for features such as real-time communication or data transmission, co-existence, mobility, scalability, and security. With the limited data rates, functions such as video streaming and full-duplex bidirectional voice communication are difficult to achieve and sometimes not feasible. In addition, the LPWAN technologies are characterised by higher latency due to their low data rates and duty cycle. The latency is higher than that of the short-range systems such as Wi-Fi and ZigBee. Again, this affects high-speed transmission functions such as real-time communication. Most of the LPWAN technologies operate in unlicensed frequency bands and this limits their capability to co-exist with other wireless systems. These technologies also face data integrity concerns due to their weaker encryption and security measures in the unlicensed frequency bands. This makes them vulnerable to attacks and threats such as jamming, unauthorised access, etc. The technologies are also vulnerable to interferences and malicious attacks due to the lack of standardisation. In certain cases, overlapping frequency bands can cause signal interferences over the long transmission distance on-air. Like any other wireless communication systems, the LPWANs can also suffer from signal fading due to pathloss, attenuation and multipath effects due to the complex geometry of underground mines and LoS obstructions. This can lead to signal degradation and thus resulting in poor connectivity, reduced reliability and range.

6.2. Potential risks and hazards in underground mines

The implementation of communication systems is often guarded against the possibility of igniting explosive gases, especially in the gassy underground coal mines. The same is required for the LPWAN technologies. However, the LPWAN technologies are characterised by low power consumption which reduces the risk of igniting explosive gases or causing underground fires. To further minimise this risk, the use of intrinsically safe units and flame-proof infrastructure components should be considered. To date, no study has indicated any gas explosion and underground fire incidents related to the LPWAN technologies. In addition, depending on the scale of deployment, underground mines may be required to develop and implement battery management strategies and procedures for the disposal of old depleted batteries from the LPWAN units. Further considerations should be taken with regards to the heat load added to the atmosphere by the batteries used by the LPWAN units. From the literature, no study has highlighted any potential hazards related to electromagnetic radiation caused by the LPWAN technologies.

6.3. Future trends and opportunities in underground mines

There are numerous potential applications of the LPWAN protocols in underground mines. These applications have benefits such as improved productivity, enhanced health and safety, improved cost-effectiveness, energy efficiency, process optimisation, etc. The potential applications of the LPWANs should be designed and incorporated into a network architecture based on the user-requirements. The deployment of the LPWAN technologies requires strategic placement and installation of robust, reliable, and cost-effective nodes or sensors throughout the mine, where coverage is required. During design and deployment, the complexity of the system should also be kept as low as possible for energy efficiency and reduced costs. The LPWAN protocols can also be integrated with other communication systems such as Wi-Fi or ZigBee. This can further reduce deployment costs and energy requirements. In addition, other systems such as Blockchain technology can be integrated to improve the performances of the system, enhance data integrity, security and immunity through its decentralised platform. Figure 18 is an example of an architecture that can be deployed underground with a number of opportunities for future applications of the LPWANs.

Personnel tracking and localisation are amongst the safety features that can be provided by the LPWAN technologies in underground mines (e.g. LoRa, NB-IoT, DASH7, Sigfox, Mioty, Weightless, Wi-Fi Halow, etc). This is required to account for the whereabouts of miners during shift hours. The tracking data becomes useful for localisation of miners during emergencies. This requires strategic placement of the gateways in the areas where coverage is required. However, positioning accuracy and precision could be a concern due to their long-range transmission and wide coverage in confined spaces. The LPWAN technologies have already been deployed and extensively used for environmental conditions monitoring applications in underground mines

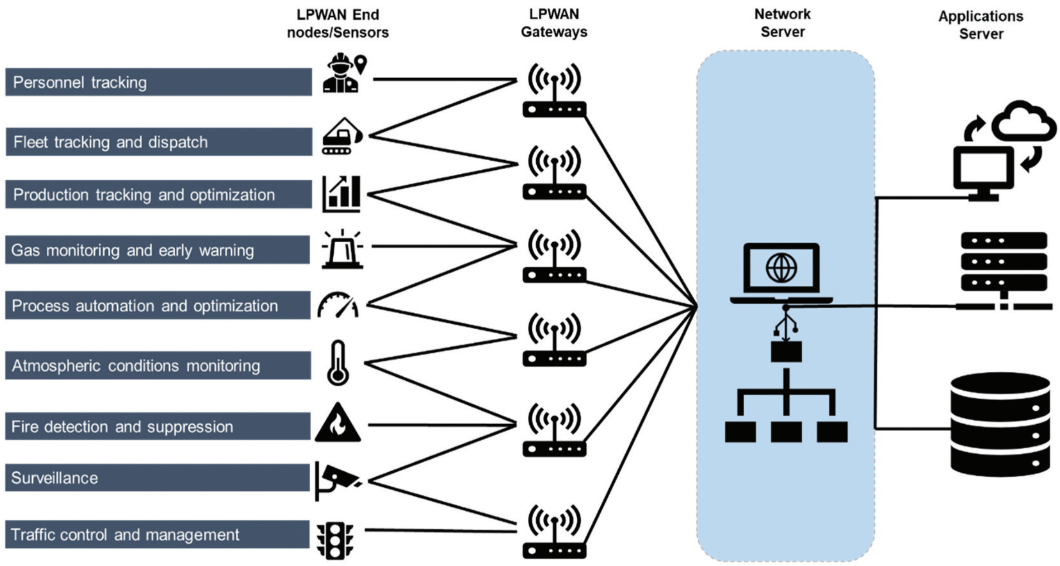

Figure 18. Ideal LPWAN architecture for underground mines.

(e.g. LoRa, NB-IoT, etc). This enables underground mines to detect and measure the concentration of gases, and control atmospheric conditions in real-time. In addition to environmental parameters monitoring, the mines have a legal requirement to measure and monitor gases underground. This can help the mines ensure compliance with regulatory requirements but also prevent the risks of gas explosions and exposure of employees to harmful or toxic gases. The LPWAN technologies have been used to trigger alerts of abnormal events and provide early warning. The control room and management can be immediately notified of the arising risk and the hazardous situation underground in real-time. This can enable management to efficient take the necessary immediate action to mitigate risks and deploy rescuers as quickly as possible. The LPWAN technology can also enable wearable devices for real-time monitoring of the vital signs of personnel, and relay any anomalies to the control room. Further research can be directed on applications in exploration and geological mapping in remote areas due to their range capabilities. For productivity and cost optimisation, LPWAN-enabled sensors can be installed to track and monitor the productivity of machines in real-time, for productivity optimisation data collection and dispatch optimisation (e.g. LoRa, NB-IoT, etc). This will help the mine with production planning and optimisation, and thus enable efficient asset utilisation. This can ultimately improve productivity and production rates, operational efficiencies, minimised downtime and reduce operational costs. The LPWAN sensors can also be integrated to the machine mechanisms to collect, monitor and analyse data on the machine availability and utilisation factors, idling time, fuel levels and engine temperature, predict the health status of engines, and predictive maintenance. The sensors can be further used for collision avoidance and proximity detection applications. The collected data and analysis can play an important role in the automation of processes and activities, remote control of machines. LPWAN technologies like LoRa, NB-IoT, RPMA, Sigfox and DASH7 can be used for inventory management of machines spare parts, explosives and accessories, and day-to-day consumable material to prevent shortages and production delays.

6.4. Deployment cost analysis

While the technology is promising to be an integral part of the future of underground mines, there is also a need to assess the cost benefit of implementing the technology in underground mines. This can be conducted based on the methodology followed in [61], where a feasibility analysis was used to evaluate the cost-effectiveness of different LPWAN protocols in different scenarios. Similarly, a cost structure or framework can be developed to evaluate return on investment for various deployment scenarios in a typical underground mine setup. This should consider the scale of the operation, production rates, number of employees, types and number of machines and equipment, etc. The total cost of ownership (ToC) can be determined from the required capital investment (i.e. infrastructure and equipment purchase, spectrum and licencing, etc.) and operational expenses (i.e. electricity consumption, services, maintenance, battery replacement, etc.). This can then be used to assess the feasibility of implementation in terms of net present value (NPV), payback, etc.

7. Conclusions

The LPWAN technologies are already a game changer for many industries operating in the world of IoT, IIoT, M2M, Blockchain, XR, 4IR and AI. These technologies have been growing, maturing and succeeding in industries such as agriculture, construction, smart manufacturing, smart cities, public spaces, etc. The performances of these technologies depend on the efficiency to transmit and receive signals between connected smart devices and this has been well achieved in outdoor environments. However, there is still a limited adoption of the LPWAN technologies in underground mines. This study has shown that the LPWAN technologies can be used for a wide range of applications in underground mines with benefits in mine health and safety, productivity, cost-effectiveness and overall efficiencies. Various types of LPWAN technologies with different capabilities and limitations have been identified and evaluated for their applicability in underground mines. These technologies are capable long range and wide area coverage and low power consumption at low cost, but at the expense of limited data rates. However, there has been some successes from the limited work done to date on the application of LPWAN for wireless communication in underground mining environments. These characteristics make the LPWAN technologies a promising and suitable choice for the harsh underground mine environments. This suggests a promising avenue for the LPWAN technologies to thrive in the harsh environments of underground mines. The LPWAN technology are characterised by low data rates which is the major setback for the technology. The low data rates can limit high-bandwidth and high-speed functions such as real-time communication and video streaming. Their limited mobility, scalability and immunity to noise are some aspects that still require engineering attention to suit underground mining environments. Further considerations can be focused on the deployment, operations and maintenance of these technologies. The LPWAN technologies can contribute significantly in modernising underground mines.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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