Telecommunication Systems
https://doi.org/10.1007/s11235-019-00557-9

# A survey on low-power wide area networks for IoT applications

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## Abstract

We are on the entry of the exponential advancement of the internet-of-things (IoT) due to the quick development of internet-connected smart-objects. As the number of connected smart-objects increase, IoT will continue to advance by providing connectivity and interactions between the physical and the cyber world. This connectivity is characterized by low throughput, delay sensitivity, small and wide coverage, low power consumption, low device, etc. Which explains the emergence of low power wide area network (LPWAN). LPWAN technologies are an alternative promising connectivity solutions for Internet of Things. However, the lack of an overall LPWAN knowledge that present a comprehensive analysis of LPWAN technologies is presently constraining the achievement of the modern IoT vision. In this paper, we begin with a detailed analysis of the conventional high power long-range network technologies that considers IoT applications and requirements. We further point out the need for dedicated low power wide area technologies in IoT systems. In addition, we analyse the technical specification based on the PHY and MAC layers of the technologies that are already deployed, or likely to be deployed. The focus is to incorporate both standard and proprietary technologies in our study. Furthermore, we present the modelling techniques and performance metrics that are adopted in LPWAN networks analysis. Finally, challenges and open problems are presented. The main contribution of this study is that it provides an enhanced summary of the current state-of-the-art of LPWAN suitable to meet the requirements of IoT, while uniquely providing LPWAN's modelling techniques, performance metrics and their associated enablers.

**Keywords** Internet of things · Cellular networks · Sensors · Wireless sensor networks · Standards · Analytical models

## 1 Introduction

Over the last decade, we witnessed the advancement of a wide number of technologies, such as sensors, actuators, cloud computing and many more. This has been accompanied by the emergence of many new type of cheaper small wireless devices (smart-objects/things/end-nodes) evolving towards the internet of things (IoT). The realization of IoT is achieved by merging data-oriented applications and massive number of device-oriented smart-objects that have identifiable addresses in order to provide intelligent services that are enabled by the internet and its related technologies [1,2]. Smart-objects/end-nodes represent different functions/wireless devices, such as sensors, actuators, tags, and increasingly mobile devices. Each smart-object is seen as an edge-node that belongs to cyber physical environment and is envisioned to have a number of use cases that will foster different types of applications [3–5] such as seen in Table 1. Through IoT, smart-objects will be merged with the internet, enabling the interaction between human and smart-objects, or interaction between smart-objects normally known as machine-to-machine (M2M) communication. This shows that M2M communication is a subset of IoT systems, hence all M2M will be referred to as IoT.

Unfortunately, the development of IoT systems is facing challenges in all protocol stack layers. The greatest challenge is networking due to the fragmented market with diverse range of products and standards from different companies. This is taking in consideration the number of smart-objects, their location, their battery lifetime, their data efficiency [6] and security [7,8]. There is still no ideal network connectivity solution, which explains the reason behind the different types of network connectivity technologies available in the market. Since the IoT idea mostly depends on the wireless technologies for it to be fully realised, this paper limit

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**Table 1** The different service sectors of IoT systems and their associated description

| Service sector | Description |
|---|---|
| Smart buildings | IoT service will enable effective energy management of both public buildings and private homes. This will be achieved through different mechanism, such as using thermostats to control air conditioners based on the user's needs and habits |
| Energy management | Use of smart IoT-based systems will be useful in ensuring that generators and private homes as application group have an optimised power consumption management system |
| Construction management | IoT-based smart systems enables the construction of new in application group such as process, control and automation. This will allow rapid manufacturing of new products through the communication between smart objects and controlling or monitoring systems |
| Smart vehicle and logistics | Smart vehicles have started to revolutionize terrestrial, aeronautical and maritime traditional transportation. This is ground, air, sea, road and railroad vehicles can be remotely controlled, and be provided effective security |
| Market | Stores and hospitality companies can develop an easy supply chain management systems. Where cinema theatres, fuel stations and supermarkets can be enabled to highly secured and easily managed. |
| Public safety and security | IoT will play a vital role in case of emergencies, where it will enable fast detection of threat to the public and its environments. |

IoT network connectivity to wireless technologies [9,10]. The conventional IoT system is based on multi-hop short-range transmission technologies, formerly used for wireless personal area networks (WPAN), and wireless local area networks (WLAN). Short-range transmission technologies include ZigBee, Bluetooth and many more technologies [11–17].

However, WPAN and WLAN are limited in their application, due to their small coverage areas and network topologies known for their energy efficiency. IoT systems have a further technological requirement beyond short-range. The requirements extend to that of long-range technologies. This prompts the realization that future IoT network connectivity landscape will be a heterogeneous network. Both short-range and long-range transmission technologies will be deployed either in different or same geographical space. These long-range technological requirements include ubiquitous coverage, low energy consumption. It further includes low costs, low data rates, and high capacity of devices per access-node (base station/ gateway/ access point) [18].

The recent emergence of innovative communication technologies and the associated advancement of smart-objects have made it possible to introduce low power wide area network (LPWAN). These networks are seen as potential candidates for IoT network connectivity technologies based on wide area networks [19]. This is not meant to replace WPAN, WLAN networks or cellular networks, rather to complement them, since IoT will be based mostly on multi-tier access networks [20–25]. There is an anticipation of LPWAN networks to play a very big role in connecting IoT systems. However, there still exist a lot of open questions or challenges with the implementation of LPWAN networks for IoT [21–26]. There is an ongoing debate on the best long-range technology that should support the IoT. There is a long list of the already existing technology that will be studied in this paper. This study will investigate the different LPWAN standards and technologies that will support IoT, and their associated open challenges.

To the best of our knowledge, this is the first LPWAN review to include LPWAN associated modelling techniques, performance metrics, and presenting their enablers. Moreover, this review further conduct a comprehensive technical analysis of a wide number of LPWAN technologies, some have been addressed in previous studies, while others have not been thoroughly addressed. Xiong et al. [27] introduced typical LPWAN machine-to-machine application scenarios and further presented a LPWAN prototype system. However, only two network connectivity technologies are presented and compared. On the other hand, Sergey et al. [28] conducted an extensive survey on the IoT network connectivity landscape, with particular attention to cellular based wide transmission range solutions employing 3GPP LTE technology. Raza et al. [29] presents the design goals and techniques of LPWAN, while surveying the a number of LPWAN technologies and standards. Centenaro et al. [30] introduced the overview of the LPWAN model, accompanied by technological interpretations. The authors further discuss the importance of introducing LPWAN networks as compared to short range technologies. Specifically, the discussion is on exploring the advantages of LPWAN in unlicensed spectrum.

The remainder of the paper is organised as follows. In Sect. 2, we discuss the existing long-range IoT connectiv-

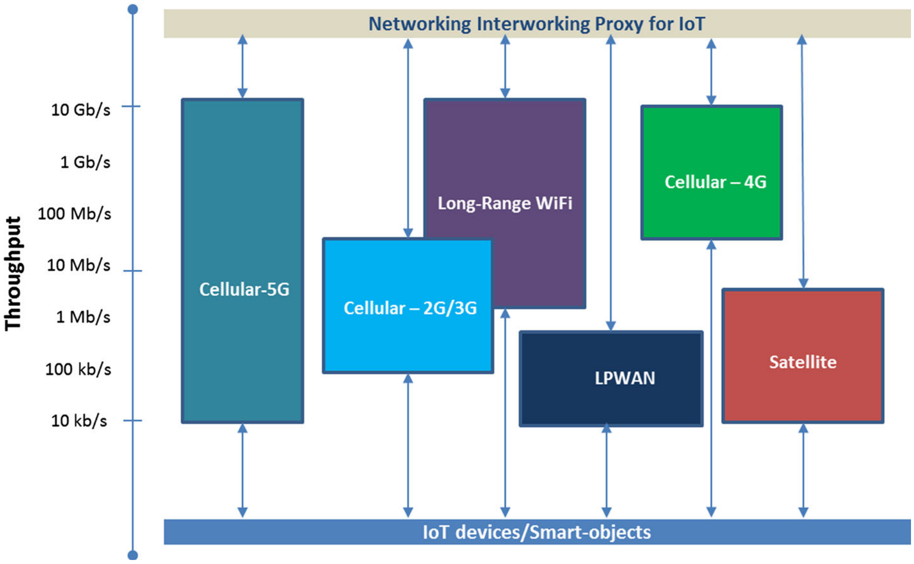


**Fig. 1** Throughput characteristics of wireless long-range IoT networking connectivity techniques

ity technologies. In Sect. 3, we introduce the concept of LPWAN technologies, its requirements and present the fundamental features of LPWAN. In Sect. 4, we further introduce and discuss the current LPWAN technologies in the market. While in Sect. 5 and 6, we analyse the technical specifications of both the LPWAN's standards and proprietary technologies, respectively. Then in Sect. 7, we present a comparative analysis between standard and proprietary LPWAN technologies. In Sect. 8, we introduce the different modelling techniques and performance metrics that are used in evaluating LPWAN networks. In Sect. 9, we present the current existing challenges and open problems in the topic of LPWAN technologies. Finally, we provide the conclusions.

## 2 Wireless long-range IoT network connectivity technologies

IoT includes a large number of wireless network connectivity technologies (radio technologies) amongst the large pool of wireless technologies. In most cases, radio technologies can be classified into two classes (short-range and long-range radio technologies). The current IoT market is saturated by short-range transmission technologies (example: Bluetooth, ZigBee, RFID, and others). However, as stated, they don't satisfy all the IoT network connectivity requirements. This is partly because of the technological limits in ability to support the current diverse and complex IoT applications and environments. Furthermore, there have been business model concerns on the deployment of short-range radio technologies. Hence the observed emergence of alternative long-range radio technologies as seen in Fig. 1. These long-range radio technologies are divided into the following radio technologies: Long-Range 802.11 WLAN; Cellular, LPWAN and Satellite technologies [31]. The advantage about some of these technologies is their existing coverage footprint and their long range capabilities. However, they still don't satisfy all the IoT network connectivity requirements. In this section we discuss the existing long range technologies except the LPWAN as it will be discussed later.

### 2.1 Conventional long range 802.11 WLAN

Wireless local area network (WLAN) market is consistently experiencing an exponential growth in adoption. Most private homes and offices use 802.11 WLAN technology and their deployment is being extended to outdoor environments. However, current 802.11 WLAN networks (excluding the 802.11ah standard) cannot support IoT based smart-objects. This is firstly because of the absence of energy efficient methods. Secondly, the lack of 802.11 WLAN to support low data rates applications. 802.11 WLAN technologies are a medium range technology with the potential of being a long range technology when power is increased and directional antennas are employed [32]. Thirdly, poor performance in supporting low battery consumption as compared to other emerging technologies [33]. This explains the introduction of the 802.11ah standard, which will be discussed in the next section.

### 2.2 Conventional cellular networks

Conventional cellular networks, such as 1G (first generation), 2G (second generation), 3G (third generation) and fourth generation/4G, such as Worldwide Interoperability for Microwave Access (WIMAX) and Long Term Evolution (LTE) were originally designed for human-to-human (H2H) communication. This has contrasting requirements

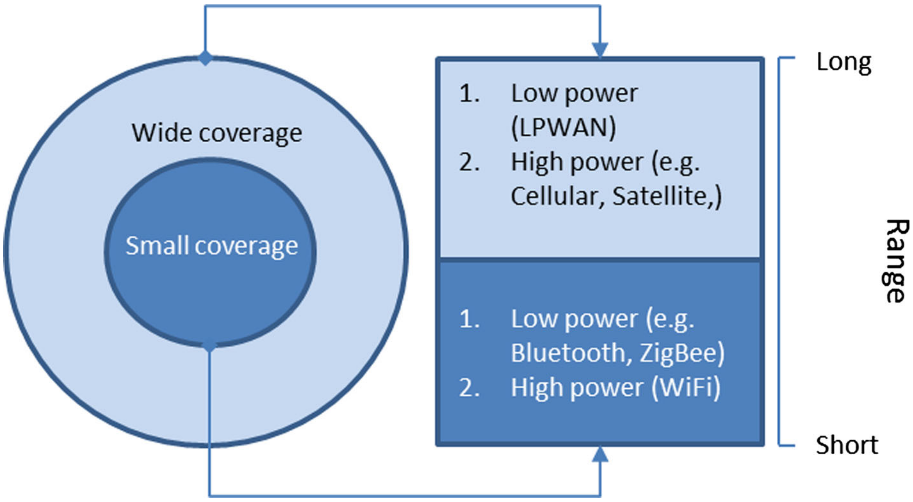


**Fig. 2** A battery life and range analysis for IoT network connectivity technologies

to that of IoT communication. Nevertheless, current cellular system have a sufficient coverage footprint, positioning cellular systems as potential contender for providing matured IoT system. Research initiatives from cellular community are investigating way to optimize the existing cellular system for IoT requirements. These initiatives have resulted to a number of proposals of cellular standards enabling IoT network connectivity [34].

### 2.3 Satellite

Satellite networks have the capability to be one of the prominent network connectivity technologies for IoT. Especially when considering their dominant long-range transmission capability. The recent improvements in satellite technology have eliminated some wrong claims on the use of satellite, especially concerning their reliability and latency. The coverage of satellite networks is almost 99.9 %, which ensured a very high reliability characteristic [35]. However, satellite systems still require the consideration of evolutionary techniques to reduce power consumption enabling them to meet IoT requirements [36].

## 3 Requirements and enablers for IoT network's long-range connectivity

This section provides a basic understanding of the IoT network's long-range requirements, this specifically refers to the type of LPWAN needed to support IoT applications.

LPWAN networks are long range networks that are mostly characterised by a star topology. LPWAN networks provide a direct connection of smart-objects to the access-node, which is also responsible for providing bridging to the internet. Furthermore, LPWAN's architecture is designed to enable wide area coverage and the ability to provide service to smart-objects located in intolerant or severe environments [30]. The architecture of these networks is designed to support IoT applications that require low power consumption, long range and low bandwidth. Furthermore, to ensure connectivity to nodes deployed in very harsh environments.

### 3.1 LPWAN IoT requirements

The following are the requirements for LPWAN in order to enable their support for IoT deployments:

#### 3.1.1 Low power consumption/long battery life

IoT devices are expected to have a long life time (low power consumption) without any human interaction. Mesh topologies have been employed in many technologies, especially in short-range systems. However, mesh network topology is associated with a high number of deployment cost. Moreover, the requirement of mesh networks to hop data to multiple nodes, can lead to more some nodes consuming their battery faster, reducing the lifetime of a network. LPWAN network technologies are recommended to adopt a star network topology as means to enable a low power consumption characteristic, while achieving long range transmissions or wide coverage area (see Fig. 2) [29]. This is in contrast with some of the competing long-range technologies and small coverage area or short-range technologies. Furthermore, the activity level per smart-object should be required if there is a need to send or receive data. Otherwise, it should be on the sleeping mode. Reciprocally, there is a need to adopting non-synchronised or a star network configuration enabled by ALOHA medium access method. Lastly, the transmission power should be limited to around 25 mW in order to achieve the Low-Power in the LPWAN network. These techniques are expected to enable a battery life time of at least 10 years [37].

### 3.1.2 Extended coverage

IoT is expected to exponentially grow in the wide-area applications such as smart cities, power grid management, water network management [4,5] and many more, requiring long-range transmission solutions. LPWAN's wide-area coverage (averagely radius above 10 km in rural and between 2 to 5 km in urban) is vital in many IoT applications [30]. Such as smart meters [15], where they are often in the basements of buildings behind concrete walls. Furthermore, other applications such as elevators or conveyor belts can either be indoor or outdoor applications. This demand LPWAN networks to be able to extend their coverage to indoor environments through walls and floors. This extended coverage means the network infrastructure deployment should be nationwide, requiring the ease of adding infrastructure and smart-objects. In principle it means there is a need for protocols to align to certain standards in order to increase the availability of smart-objects and enable seamless network connectivity [38].

### 3.1.3 Low device cost and deployments cost

LPWAN adopted techniques are mostly a trade-off, which is between cost, data rate and deployment cost [39]. Economic constraints are usually the barriers to high adoption of technology. The devices and network deployments should be low, proportionally the cost the smart-object should be low with no sim card requirement. Furthermore, the network should be easy installable with minimum maintenance. The costs are also influenced by the complexity, hence the need for low complexity of the hardware and software of the smart-objects [29].

### 3.1.4 Ubiquitous communication and massive number of devices

One of the key characteristics of IoT and its network connectivity through LPWAN is that it should be available anywhere and anytime (ubiquitous) [40]. However, being ubiquitous is one thing, but also the ability to connect massive number of devices is a big requirement, especially given that IoT connected devices will exceed the subscription of cellular networks. It is further expected that the density of the connected devices will not be uniform, which implies the need to be able to simultaneously connect a massive number of devices.

### 3.1.5 Security and privacy

One of the treat to IoT adoption is the issue of security and privacy, hence the importance for any LPWAN to address the two issues of security and privacy. This is vital in ensuring that LPWAN networks to be developed can enable a plethora of services for IoT services [41,42]. The LPWAN based security will assure the authenticity of the access-node in the network. Other security measures can be implemented in the application layer, but that is beyond this survey. The following issues should be assured in most LPWAN, they form part of the IoT security requirements [42,43]:

- Confidentiality: this item is useful in assuring that access is given to authorised smart-objects.
- Integrity: Useful for assuring that the data accessed is complete, accurate and without manipulation.
- Accountability: LPWAN networks should assures users that all smart-objects owners are responsible for all actions.
- Auditability: The LPWAN should enable constant monitoring of all communication or actions taking place in their networks.
- Non-repudiation: The network should have the ability to record occurrence and non-occurrence actions.
- Privacy: The LPWAN should obey the privacy policies and enabling individuals to control their personal information.

## 3.2 Enabling technologies and driving factors

This subsection presents the technologies that can be adopted by LPWAN in order to deal with the IoT demands. Furthermore, the discussion includes their need and their role or potential role in LPWAN networks. This is vital in aiding the current research efforts and highlighting the challenges that need to be addressed.

### 3.2.1 Software defined networks and network virtualization

The expected exponential growth of traffic generated by smart-objects in the IoT networks as compared to human generated traffic requires intelligent, efficient, secure and scalable networks. In order to address the LPWAN and IoT associated needs, the operators are required to invest towards adopting the use of Software defined networking (SDN) and Network Virtualization as potential enabling technologies [44]. On one hand, SDN is achieved by adopting a centralised network approach, while logically separating the traditional forwarding devices into control plane from the data plane. The control plane is responsible for executing logical procedure supporting network protocols. On the other hand, the data plane is responsible for executing the forwarding of packets on the most suitable interface towards the intended destination. SDN's separation of the forwarding device enables the network to use the network optimally through intelligent traffic routing methods, hence mitigating the burden on the network posed by the data onslaught of IoT [45,46].

On the other hand, Network Virtualization is concerned about the abstraction of the basic infrastructure where virtual networks with fluctuating architecture may be developed in order to satisfy diverse service requirements [47]. ETSI Industry Specification Group proposed Network Function Virtualization as a Network Virtualization solution responsible for virtualizing the network functions that we previously carried out by some proprietary dedicated hardware. NFV is a network architecture concept that enables the decoupling of the network hardware and software, enforcing network services to operate on commodity cloud computing style platforms. It is projected that through Network functions virtualization (NFV), innovation will soar in deploying new services with less risk, service delivery will be made easy, entry barrier will be minimised, and the network cost will be reduced through infrastructure sharing and automation [48,49].

The two concepts of SDN and NFV were developed independently in their original state. However, recent development has shown that the two concepts complement each other through their common goals and similar technical methods. Hence, the recent development that includes the integration of SDN with NFV, enabling various network control and management goals that exploit the advantage of both SDN and NFV technologies [50]. The advancement of LPWAN is thwarted by the inherent challenges that they possess. There is a lot of work that is seeks to address the current challenges. However, there is not yet a holistic solution as each focuses on a specific problem in isolation. The SDN and NFV approach to LPWAN is envisaged to potentially solve some of the challenges. One of the requirement that SND and NFV will help achieve is IoT ubiquity, which it will achieve through its ability to intelligently route traffic, ensuring that the network resources are optimally utilised [46]. However, the traffic flow of LPWAN is low throughput, while SDN and NFV increases the computational efforts as algorithmic complexity increases. Hence, there is work addressing these challenges within the SDN community. Such as the work by Xiaodong et al [51], where the authors suggest an efficient forwarding scheme that employs a forwarding scheme that enables a trade-off between the control traffic overheads and the bandwidth overheads. In a nut shell, SDN is envisioned to be an enabler of quicker reaction to access-node, higher utilization of the accessible resources and faster deployment of updates in networking [52].

Furthermore, SDN and NFV are expected to be infused with wireless sensor networks (WSN), where WSN is expected to play a significant role in IoT. WSN is based on the IEEE 802.15.4 standard, which specifies the Physical (PHY) and Medium Access Control (MAC) layers for low-power, low-bit-rate communications [53], which makes it similar to LPWAN except for network topology and the coverage range. The infusion of SDN and WSN gives rise to Software Defined Wireless Sensor Network (SDWSN). SDWSN is a new emerging paradigm for a low-rate network such as LPWAN. SDWSN is a good approach to improve efficiency and sustainability of WSNs and to foster interoperability with other networks. The authors of [6] highlights the various inherited challenges associated with WSN and discuss the important of SDN in WSN and how most prevalent and critical WSN problems can potentially be addressed by SDN. WSN management and SDN techniques that could improve the management of WSN have been discussed in [54,55]. This further shows the significant role SDN and NFV is expected to play in changing networking at large.

### 3.2.2 Dynamic spectrum management

As IoT adoption grows, it relates to the requirements for service level agreement (SLA). This growth is further proportional to deploying a number of base station or nodes or gateways, which is related to spectrum requirement. There SLA requirements might not be satisfied through unlicensed bands, which has challenges in supporting the required Quality of Service (QoS). In regard to this challenge, exploring White Spaces (WS) may be a valuable alternative. Especially considering that other bands cannot be used, it makes spectrum a scarce resource as there are many services already occupying the current usable bands [56]. It is therefore imperative to realize the importance of adopting use of WS, which is a method of sharing the spectrum. This is moving away from the legacy spectrum management. It is achieved by allowing flexibility in spectrum management, allowing new users and uses such as LPWAN network connectivity for IoT and other. The optimal sharing mechanism is the dynamic spectrum sharing. Dynamic spectrum sharing is equivalent to flexible (opportunistic) spectrum sharing [57]. The adoption of dynamic spectrum management comes with the ability to support the massive number of devices and the ability of network provider to achieve the required coverage extension.

### 3.2.3 Intelligence

A typical IoT architecture can be grouped into four subsystems: smart-objects; access-point; network; cloud. IoT has a requirement that has not well being addressed, this is enabling the smart-objects to be intelligent to filter and manage data before forwarding it to the cloud. Contrary, most of the smart-objects are not suitable for internet network connectivity, which explains their inability to process and send data to the cloud. This inability further decrease energy efficiency and enhance resource misuse, which is one of the described LPWAN requirement of low power consumption. There is a need for intelligence to aid in decision making. Such as the computing intelligent introduced at the network edges for controlling data, managing data, and network resource.

The intelligence incorporated includes a regressive admission control (REAC). The REAC's use is complemented by intelligent scheduling and queueing algorithms for network performances. This ensures that resources are optimally used and the congestion is well controlled and prevented Distributed Antenna Systems [58].

### 3.2.4 Energy harvesting

Energy harvesting technologies is a promising enabling technology; this is because supplying adequate energy for smart-objects in IoT networks is still a challenge. Energy harvesting has the ability to enable the realization of zero power requiring (self-sustaining) wireless devices, which is necessary for achieving low power consumption. Energy harvesting methods includes thermal, solar, kinetic and wireless RF energy sources [59–61]. Through energy harvesting, LPWAN technologies can even achieve enhanced (far beyond what the literature shows) battery lifetime.

### 3.2.5 Green technologies

LPWAN as an IoT connectivity technology is expected to enable the fusion of sensing and wireless communication. Communication is claimed to be responsible for 2% to 4% of the current total carbon footprint [62]. According to ABI research, there are more than 40 billion forecasted smart-objects to be connected to IoT networks by 2020 [63]. The number of smart objects is predicted to contribute 75% of the future growth of end user devices from 2014 to the end of the decade. Proportionally, the carbon footprint is going to increase dramatically and IoT will contribute a lot in this carbon footprint. The current LPWAN technologies are not equipped to deal with this issue. Hence it is vital that the current LPWAN networks be enabled to reduce its carbon footprint, which will ensure its sustainability in future network requirements. This implies the need to analyse the LPWAN lifetime by minimizing its total power consumption and carbon footprint, while ensuring that the desired application performance and reliability are not degraded. Therefore, the need is for enabling technologies for green LPWAN (GLPWAN), which will enable sustainable LPWAN networks. The LPWAN or GLPWAN will allow smart-objects to connect to the cloud in an energy efficient manner. One method of enabling GLPWAN is developing cloud computing with efficient energy consumption methods [64–66].

## 4 Low power wide area network technologies

It has been realised that in order for LPWAN to be able to meet the above mentioned requirements, system designers should focus on improving both the physical (PHY) layer and medium access control (MAC) layer [27]. LPWAN are mostly suited for on/off type applications with only few messages per hour.

### 4.1 LoRa and LoRaWAN

#### 4.1.1 Description and advantages

This is a wireless technology developed by Semtech as a LPWAN technology, a solution for IoT network connectivity problem. LoRa promises to meet the IoT requirement for LPWAN, such as wide area coverage or long-range transmission capability, low battery life consumption, and secure data transmission.

LoRa technology is estimated to provide a superior coverage to that of existing cellular networks. The superior coverage is enabled by the technology's sub-gigahertz radio bands operation (109 MHz, 433 MHz, 866 MHz and 915 MHz). Furthermore, LoRa is a physical layer techniques, specifically, a modulation method derived from chirp spread spectrum. It is this modulation method that enables the long-range feature of LoRa. These modulations allow multiple data rates through the adjustability of the bandwidth and the spreading factors. Hence, most operators have opted to adopt and augment LoRa into their existing networks. LoRa's plug and play feature into existing networks is another reason behind the wide adoption by existing and new operators. LoRa is a proprietary solution, LoRa works together with the LoRaWAN protocol, which is an open source communication protocol and a system architecture for networking. LoRaWAN has the highest impact in controlling the battery lifetime, network capacity, quality of service, security, and many other applications served by the network. It further has a star-of-stars topology. It is subdivided into four subsystems: the application server, network server, gateways and smart-objects (see Fig. 3) [41].

#### 4.1.2 Disadvantage

LoRa uses a Carrier Activity Detection (CAD) to detect an incoming transmissions. However, CAD is not efficient as there are cases where it detect a signal that uses a wrong spreading factor, while it cannot be decoded. False detection increase the energy consumption, which is against the requirements of IoT applications [67]. Furthermore, LoRa uses the typical LoRaWAN that assume a 20 byte packet size being sent by each node per approximately 17 min rate and with a data extraction rate that is greater than 0.9 requirement, which can support a maximum of nodes. This is not enough for some of the IoT applications, especially smart building deployments [68].

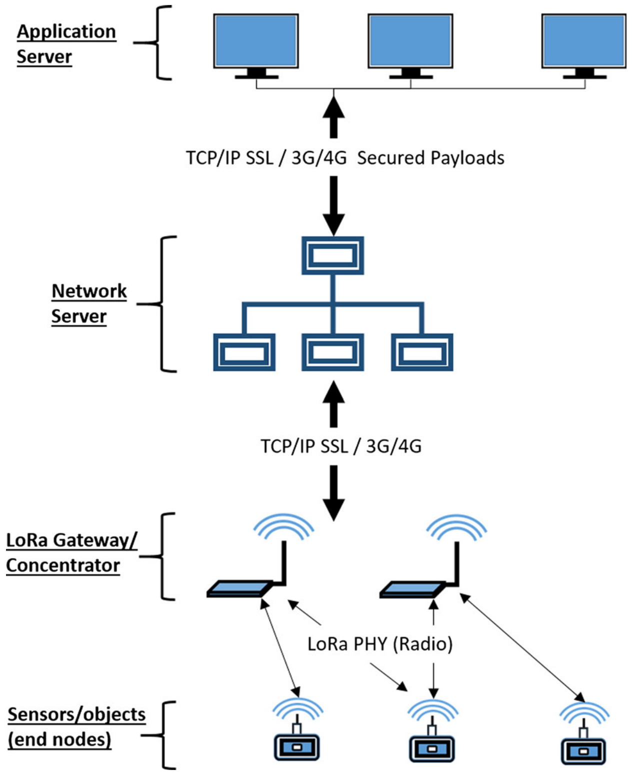


**Fig. 3** LoRa/LoRaWan network architecture for IoT communication [41]

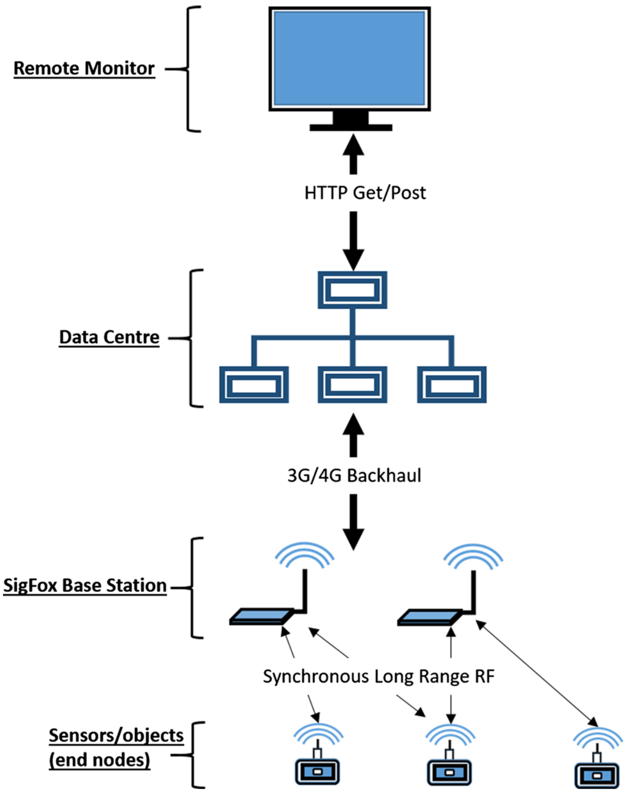


**Fig. 4** SigFox network architecture for IoT communication [18]

## 4.2 SigFox

### 4.2.1 Description and advantages

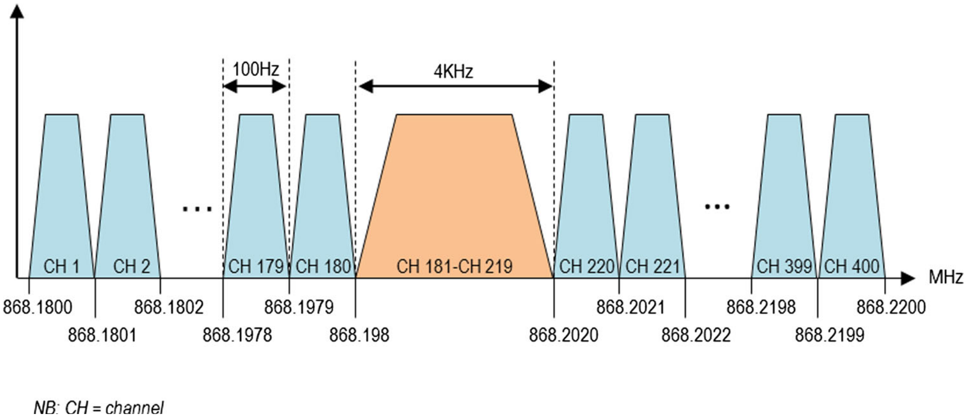
Sigfox is one of the first proposed technologies for LPWAN. It was founded in 2009, with its approach based on the network topology of cellular networks (see Fig. 4), except that it provided low bandwidth, and low throughput. This is achieved through the adoption of the ultra-narrowband wireless modulation. Furthermore, Sigfox make use of 100 Hz bandwidth for uplink and 600 Hz for downlink for every signal transmission, which is associated with low noise susceptibility [18]. Low noise susceptibility enable SigFox to have a high reception rate for even very low received power signal [69]. Initial Sigfox release was only one directional communication system; however, the recent release supports a bidirectional communication. It further has the ability to handle millions of smart-objects per concentrator/gateway. Semtech claims that the technology has coverage of 30 km to 50 km in less dense environment (rural areas) and 3 km to 10 km in dense environments such as urban areas. In order achieve these long ranges, Sigfox is equipped to operate at 868 MHz spectrum in Europe and 915 MHz in the U.S., bands with good propagation characteristics and less costly because of being unlicensed band.

The 868 MHz (868.180–868.220) spectrum band is sampled into 400 channels of 100 Hz. Channel 181 to 219 are not used as seen in Fig. 5. This channel bandwidth size is able to support 12 bytes payloads for uplink and 8 bytes for downlink transmission. Sigfox further supports protocol overhead of 26 bytes. The technology adopts different modulations schemes for uplink (BPSK using 100 bps on a 100 Hz channel) and downlink (GFSK at 500 bps on a 600 Hz channel). The uplink transmission is conducted in a multiple of three per message in order to ensure that the message is delivered successfully to data centre [18,31,69].

### 4.2.2 Disadvantage

The challenge with Sigfox is that its downlink is constrained as a result of the blocking and duty cycle contravention at 868 MHz ISM band. The duty cycle limitation of the utilised sub band is one percent, which imply that transmission is limited to less than 36 s per hour. When considering other factors, such as the 6 s time on air per package, it implies that SigFox is limited to six messages per hour with a payload of 4, 8, or 12 bytes [70]. On the other hand, SigFox is not completely bidirectional LPWAN technology. Originally, it was a connectivity technology limited to only an uplink communication. SigFox allows downlink messages to always precede uplink messages.

**Fig. 5** SigFox channelization [69]



## 4.3 Weightless

### 4.3.1 Description and advantages

Weightless is a name of both a group, Weightless Special Interest Group (Weightless SIG) and Weightless technology. Weightless technology is a promising contender in long-range wireless network connectivity for IoT applications and LPWAN solution. Its transmission range (50 km+ in rural and 2 km+ in urban areas) and low transmission power of 17 dBm qualifies it as a LPWAN technology. It is designed to operate in sub-gigahertz spectrum. This is both the licensed and unlicensed spectrum bands [71,72].

Weightless technology has three standards: Weightless-W; Weightless-N; and Weightless-P. All this three standards are Open Standards. Their network architecture is similar between the three Weightless standards; however, they have different respective specific use cases.

Firstly, Weightless-W was the first to be developed with specification for it to operate in TV whitespace spectrum. It offers an excellent signal propagation characteristic and consequently a long range transmission. Weightless-W offers an average data rates from 1 to 10 Mbps with flexible packet size and data rates. This standard allows both acknowledgement and non-acknowledgement of the message from the access point. The standard has a shared secret key used for security measures in the smart-objects. On the other hand, the server has an encryption capability [71].

Secondly, the Weightless-N is the second standard to be developed. Weightless-N is going to be developed under the low throughput networks (LTN) developed by ETSI [73]. Weightless-N operates on the sub-gigahertz spectrum for mainly Industrial, Scientific and Medical (ISM) purposes. It adopts a star network topology/architecture with an ultra-narrow band technology from nWave (a Network solution, hardware and software provider). Its design is based on time division duplexing (TDD) and a differential binary phase shift keying (DBPSK) digital modulation scheme [71]. Weightless-N further uses modulations scheme within narrow frequency bands. It is aggregated with frequency hopping algorithms, enabling Weightless-N to possess an effective interference mitigation capability. The disadvantage is its one way communication capability. Thirdly and lastly, Weightless-P is the latest to be released. It will provide full acknowledgement in both direction as a bidirectional communication technology. It is the most costly of the three weightless standards. Weightless-P adopts GMSK and Offset-GPSK modulation, which is responsible for ultra-low energy consumption and link quality improvement [71].

The general weightless technology has a capability of supporting variable spreading factors. It further supports low power devices with low data rates. Weightless technologies differential features are: their Global Open standard; Range minimum of 2 km; 3–10 years Battery Life depending on the technology; $2 for module network connectivity; and Spectrum Flexibility [71].

### 4.3.2 Disadvantages

The Weightless-N standard's number of total message copies can be increased up to 8 for IoT applications with high quality of service requirement. This and other unspecified reasons results to a maximum message rate of Weightless-N to only one message per minute at a data rate of 100 bps [74].

Weightless-W uses TV white spaces only, which is not allowed in most countries. The challenge with Weightless-P is its shorter range as compared mostly with Weightless-N and shorter battery lifetime [75].

## 4.4 Ingenu random phase multiple access

### 4.4.1 Description and advantages

Ingenu Random Phase Multiple Access (Ingenu-RPMA) is a wireless network connectivity technology based on a combination of state of the art technologies designed specifically and exclusively for wireless machine-to-machine communication (IoT systems). The key capability of Ingenu-RPMA is its immense capacity (about 80 MHz of spectrum availability proportional to 60 to 1300 more devices per access-node) and scalability [76]. The scalability is claimed to be unlimited, a very useful feature required for IoT network connectivity. The technology enables high data rates (624 kbps uplink and 156 kbps downlink) than most LPWAN technologies and the trade of are on the high transmission power. Its spectrum operation is 2.4 GHz band, with high propagation loss as compared to sub-gigahertz based technologies. Lastly, Ingenu-RPMA is a bidirectional communication technology [77,78].

### 4.4.2 Disadvantages

Ingenu-RPMA operate in the ISM band (2.4 Ghz) radios systems. This band is an unlicensed band used for consumer and commercial WiFi and WLAN applications as well as for commercial Radio Frequency Identification (RFID) and Supervisory Control and Data Acquisition (SCADA) applications. Especially the 2.4 GHz band is one of the highly used frequency band with the highest probability of being crowded. This implies the range of a signal is limited because of the transmit power allowed, which implies the need for many intermediate nodes. Consequently increasing the cost (deployment, operating and maintenance cost).

## 4.5 Narrowband fidelity

### 4.5.1 Description and advantages

Narrowband fidelity (NB-Fi) is a LPWAN network connectivity solution designed and developed by WAVIoT. It was developed specifically for low power and wide area IoT communication. It differentiates itself by its robust and reliable characteristics, fast deployment, large ranges, long battery life, low cost deployment and low hardware cost. Fast deployments are achieved by a less complicated network design. The range achieved by this technology is superior to most LPWAN technologies, with a minimum effective range of 16 km in urban environments and 50 km in rural environments. This technology employs its channel allocation on the server, with a full duplex gateway based on bidirectional software defined radio (SDR). NB-Fi uses three equal sectors in an omni-directional plane [79].

### 4.5.2 Disadvantages

NB-FI uses a 100 Hz band, which has a higher requirements on the RF crystal. Where a frequency error on the RF crystal results to an offset on the programmed RF frequency that can fall outside the channel, making it difficult to be correctly decoded.

## 4.6 Dash 7

### 4.6.1 Description and advantages

DASH7 is an open source standard of ultra-low power mid-range network connectivity technologies for IoT. It is developed to operate within the sub-gigahertz band. This is because the ISO 18000-7's default parameters of the active air interface communication at 433 MHz. The technology is based on a MAC and Presentation layer using strict methods of data elements. Its development can be groups into five concepts: The BLAST; D7AP data elements; D7AP sessions; and a D7AP physical communication properties [80,81].

### 4.6.2 Disadvantages

The DASH7 standard uses an advanced encryption standard (AES) in order to ensure confidentiality of data link layer, while it lack security measures in the network layer. This is a problem because the use of AES is not compatible with low power devices, implying that DASH7 is not optimal it its power consumption. There is a need for a light weight cyphers to enhance the battery consumption while ensuring confidentiality in DASH7 networks [82].

## 4.7 Cellular for IoT

### 4.7.1 Description and advantages

The recent observed high rate of IoT deployment corresponds to an evolution of IoT network connectivity requirements. Consequently, the cellular community is undergoing its own standard evolutions to address the IoT needs through new additional techniques to improve the network performance. The challenge with current cellular standards and technology design is their disregard to IoT applications. The terminologies used in cellular communities for IoT network connectivity is M2M and within 3GPP is known as machine-type communications (MTC) [31,83]. There are about four separate standards developed and undergoing development by the cellular community: extended coverage GSM IoT (EC-GSM-IoT); Long term evolution for MTC (LTE-MTC); Narrowband IoT (NB-IoT); and 5G based MTC.

**EC-GSM-IoT for 2G networks** Extended coverage GSM IoT (EC-GSM-IoT) is a technology enabled by new techniques to evolve the existing 2G cellular networks to be a LPWAN solution. It is an evolution of GSM designed for IoT applications, with high capacity, long range, low energy consumption, and low complexity capabilities. The current GSM network can be upgraded to EC-GSM-IoT through software deployment, which is capable of increasing the transmission range of the system and can accelerate market penetration. Ericsson, Orange and Intel have completed trials of EC-GSM-IoT, with the anticipation to launch the first commercial EC-GSM-IoT network in 2017 [84].

**LTE enhancements for MTC** LTE and LTE-advanced employs OFDM/OFDMA, which enables the scaling of the bandwidth according to diverse needs. An LTE enhancement for MTC (eMTC) is based on LTE technologies, meaning that the same LTE nodes can be used. Fortunately, the usage of LTE nodes does not restrict the eMTC from achieving a long lifetime of at least 10 years and a reduced modem costs. eMTC is realised through the reduction of the data rates from LTE CAt1 to CAtM. This is vital for cost reduction of LTE technology. The enhancement brought to CAt0 by adopting half duplex resulted to CAtM1 referred to as eMTC. eMTC provides an alternative from EC-GSM-IoT. eMTC is based on 4G technology, while EC-GSM-IoT is based on 2G technology. The constraint against developing a 3G based LPWAN is its short battery life and high modem cost. eMTC is expected to be commercially available by 2017 [85].

**NB-IoT** The narrowband IoT (NB-IoT) is a narrowband radio technology that can be classified as a LPWAN technology. This technology can be deployed in three methods: in-band by using normal LTE resource block of 180 kHz; within a guard-band of an existing LTE resource block of 180 kHz; as a stand-alone using specific bands allocated for it, like re-farming a GSM channel of 200 kHz. The technology can be achieved through the physical layer signals and channels such as an Evolved Packet Core based power saving mode [86,87].

**LTE-Advanced Pro** LTE-Advanced Pro or the 5th Generation (5G) cellular standard's overall goals are now developed. However, the technical performance requirements for the radio system are still under development. Both eMTC and NB-IoT pave the way for 5G or are a bridge to massive IoT capabilities envisioned in 5G, but are not 5G standards. Especially when considering that both eMTC and NB-IoT are being rolled out already while 5G standard is fully develop, it make it hard to refer it as a 5G standard. Nevertheless, 5G systems is forecast to be able meet a number of future networks requirements. Such as diverse services, diverse device classes, diverse deployment types, diverse environments, and diverse mobility levels [86]. Diverse service refers to the different services including broadcasting, multicasting, mobile broadband and etc. Diverse device classes is more concern about the variety of devices with capability to operate without human interaction (example: smart-objects) to human dependant devices (smartphones and other user equipment). Diverse deployment types present the concept of heterogeneity of access-points (example: femtocell, picocell, microcell and macrocells). Diverse environments are mainly about the density of access-points or density of smart-objects or mobile devices for H2H communication. Diverse mobility levels are an old topic in cellular communication. Hence 5G is expected to satisfy the requirements of both static and mobile smart-objects and mobile devices. Some of the highlighted expected capabilities of 5G will meet the LPWAN requirements, such as: capacity/user-rates of more than 1000 times; latency, reliability, coverage (ubiquitous penetration of 5G access-points), mobility, massive number of devices at a level of 10 to 100 times more connected devices (smart-objects and mobile devices), cost/energy consumption (10 times more lower energy consumption) [83,88].

### 4.7.2 Disadvantages

One main challenge with most of the cellular based IoT connectivity technologies is their use of licensed spectrum, which is overloaded with traffic. Hence the industry is increasingly leveraging unlicensed spectrum to opportunistically offload some if not most of their traffic load. There are other disadvantages associated with the individual cellular technologies, but will be included in the analysis later in this paper.

## 4.8 Low-power 802.11 WLAN

### 4.8.1 Description and advantages

As much as conventional 802.11 WLAN standards were not originally designed for IoT, however the needs now exist. Hence, IEEE 802.11 AH Task Group (TGah) was formed in 2010, which was responsible for specifying an unlicensed sub-gigahertz wireless local area network (WLAN) standard to meet current and future IoT requirements. The standard resulted to the LP-802.11 WLAN or IEEE 802.11AH, which supports a wide range of applications and a large number of devices. LP-802.11 WLAN is a simple, robust and efficient solution in the ISM band that supports a long-range transmission with appropriate energy efficiency mechanisms. Furthermore, LP-WiFi promises a superior quality of service as compared to the IoT network connectivity by cellular networks. The LP-802.11 WLAN is expected to operate on the Sub-1 GHz, which has good propagation characteristics and a typical range of 100 meters to 1 Km with corresponding data rate of 0.15–4 mbps in a one hop topology [89].

### 4.8.2 Disadvantages

This technology has a limited coverage range interim of 0–1 km, sometime to 1.5 km. This is not good enough for LPWAN requirement. Furthermore, more disadvantage are discussed later in this paper during the competitive analysis.

## 5 Technical specifications of standard based LPWAN technologies

Most of the LPWAN technologies have a lot in common, like adopting the Star topology. While most might adopt the same network topology, however their performance is not the same. Some are proprietary technologies, while others are standard based technologies. In this subsection we conduct an analytical comparison of the standard based LPWAN technologies related to their technical specifications.

### 5.1 Physical layer specifications

Table 2 shows the main physical specifications for standard based LPWAN technologies: Weightless; Dash7, IEEE 802.11AH; eMTC; EC-GSM-IoT; and NB-IoT. 3GPP's 5G specification is not included as it is still under development. These specifications are useful in giving a developer a basis to determine whether a standard is viable for their preferred applications or not. This analysis adopted the framework that subdivide the PHY layer into modulation, data rate, transmission mode, and channel coding, which can be discussed within channelization and transmission mode [90].

#### 5.1.1 Channelization analysis

The available sub-1 GHz ISM bands are unique per given country, while the licence bands are fixed. IEEE 802.11ah, Weightless, and Dash7 have different bands of operation, making it easier for different countries with different frequency planning to adopt these different standards. Dash7 has channelization plan in ISM 433 MHz with channel width of 25 kHz and 200 kHz, which enables achievement of different rates ranging from 13 to 200 kbps.

Weightless channelization is different for the different standards, in Weightless-W, it is very dynamic as it uses TV white spaces, with a specific channel width of 5 MHz and consequently achieving data rates of 1 kbps to 1 Mbps depending on the link budget. While Weightless-N uses a fixed ultra-narrow channel width of 200 Hz, enabling it to achieve data rates of 20 to 100 kbps depending on the link budget. Weightless-P and IEEE 802.11 have a very good channel plan for global deployment. Weightless-P adopt a fixed channel width of 12.5 kHz to achieve data rates of 200 bps–100 kbps, using different channels (169/433/470/780/868/915/923MHz). This is responsible for the ability to ease of adoption from different regions and countries. The channel plan of IEEE 802.11ah is as shown in Fig. 6. IEEE 802.11ah offers different data rates through carrier aggregation. For example, see Fig. 7 that depicts the carrier aggregation in IEEE 802.11ah. There are about 26 number of 1 MHz channels with 2 pilot sub-carriers and 24 data sub-carriers per OFDM symbol.

For higher data rates, the channel width is increased through carrier aggregation, resulting to different channel width of 2 MHz, 4 MHz, 8 MHz and 16 MHz between 902 MHz and 928 MHz. This carrier aggregation is achieved through the adjacent narrow channel width. It should be noted that most countries have different regulations, resulting to different maximum achievable carrier aggregation channel [91].

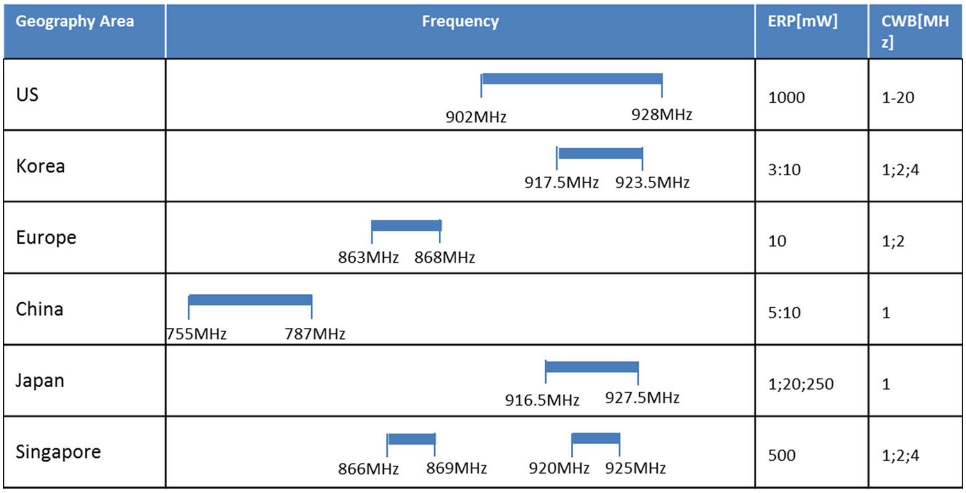
Weightless-P, Weightless-N, and all the 3GPP standards operate on the licensed band and their employment require the involvement of an operator, consequently increasing their entry barrier.

#### 5.1.2 Transmission mode analysis

Dash7 is mostly characterised by non-overlapping normal rate channels using 2-GFSK modulations. The GFSK modulation is most popular in low-power wireless communication because of its constant-envelope property. This is further aided by its fewer requirements for linearity on the power amplifier in the transmitter, which is 10 dBm at 433 MHz and 27 dBm at 868/915 MHz [92]. IEEE 802.11ah adopts BPSK corresponding to minimum receiver of $-98$ dBm, QPSK and QAM modulation with minimum receiver sensitivity of $-72$ dBm. This shows that IEEE 802.11ah is a scalable standard that can offer a variety of data rates and communication ranges through adopting different parameters. Weightless standard as mentioned previously has three different versions which adopt different modulations techniques. Weightless-W adopts 16QAM and offset-BPSK coupled with spreading code of up to 1024, resulting to a wide range of link budgets. This is the location of the smart-object can be in different environments such as indoors and outdoors with a transmit power of 17 dBm. Offset-BPSK has been shown to degrade the bit error rate, which might demand more on power transmission as a trade-off [93]. Weightless-P uses GMSK modulation and QPSK, where GMSK is unique from both Weightless-W and IEEE 802.11ah and is known for its power efficiency and suitable for narrowband communication due to its constant envelop [94]. On the other hand, Weightless-N adopts the use of DBPSK and an associated transmit power of 17 dBm, similar to the other weightless standards.

**Table 2** Physical layer specifications of LPWAN standards

| Attribute | DASH7 | IEEE 802.11ah | Weightless-W | Weightless-P | Weightless-N | 3GPP: eMTC | 3GPP: NB-IoT | 3GPP: EC-GSM |
|---|---|---|---|---|---|---|---|---|
| Operation frequencies | Sub-GHz (433, 868, 915 MHz) | Below 1 GHz, excluding<br>TV white spaces | TV white spaces,<br>470–790 MHz | Sub-GHz (169/ 433/ 470<br>/780/ 868/ 915/ 923 MHz) | ISM Sub-GHz EU,<br>868 MHz US, 915 MHz | Licensed 700–900 MHz | Licensed 700–900 MHz | Licensed 800–900 MHz |
| Channel width | 25/200 kHz | 1/ 2/ 4/ 8/ 16 MHz | 5 MHz | 12.5 kHz | UNB 200 Hz | 1.08 MHz | 180 kHz | 200 kHz |
| Tx power | 433 MHz: +10 dBm<br>868/915 MHz: +27 dBm | 1 mW to 1 W | 17 dBm | 17 dBm | 17 dBm | 20 (UL), 23 (DL) dBm | TBD (UL), 23 (DL) dBM | 23 (UL), 33 (DL) dBm |
| FEC | Convultional encoding | Convultional encoding & LDPC | Convultional encoding: rate 3/4 or 1/2 | Convultional encoding: rate 3/4 or 1/2 | Convultional encoding: rate 3/4 or 1/2 | Yes | Yes | Yes |
| Modulation | GFSK | BPSK, QPSK, QAM | 16-QAM, offset-BPSK | GMSK & offset-QPSK | DBPSK | 16QAM | pi/2- BPSK or pi/4- QPSK | GMSK/ 8PSK |
| Frequency hopping | Yes |  | Yes | Yes | Yes | Yes | Yes |  |
| Range | 0–5 km | 0–1 km | > 5 km | > 2 km | >5 km | < 11 km | < 15 km | <15 km |
| Data rate | 55–200 kbps, a proposal for 55 kbps | 150 kbps–86 Mbps | 1 kbps–10 Mbps | 200 bps–100 kbps | 30–100 kbps | 1 Mbps for DL & UL | 50 kbps (DL) & 50 kbps | 70 kbps (GMSK) & 240 kbps (8PSK) |



| Geography Area | Frequency | ERP[mW] | CWB[MHz] |
|---|---|---|---|
| US | 902MHz 928MHz | 1000 | 1-20 |
| Korea | 917.5MHz 923.5MHz | 3:10 | 1;2;4 |
| Europe | 863MHz 868MHz | 10 | 1;2 |
| China | 755MHz 787MHz | 5:10 | 1 |
| Japan | 916.5MHz 927.5MHz | 1;20;250 | 1 |
| Singapore | 866MHz 869MHz<br>920MHz 925MHz | 500 | 1;2;4 |

**Fig. 6** IEEE 802.11ah global channelization

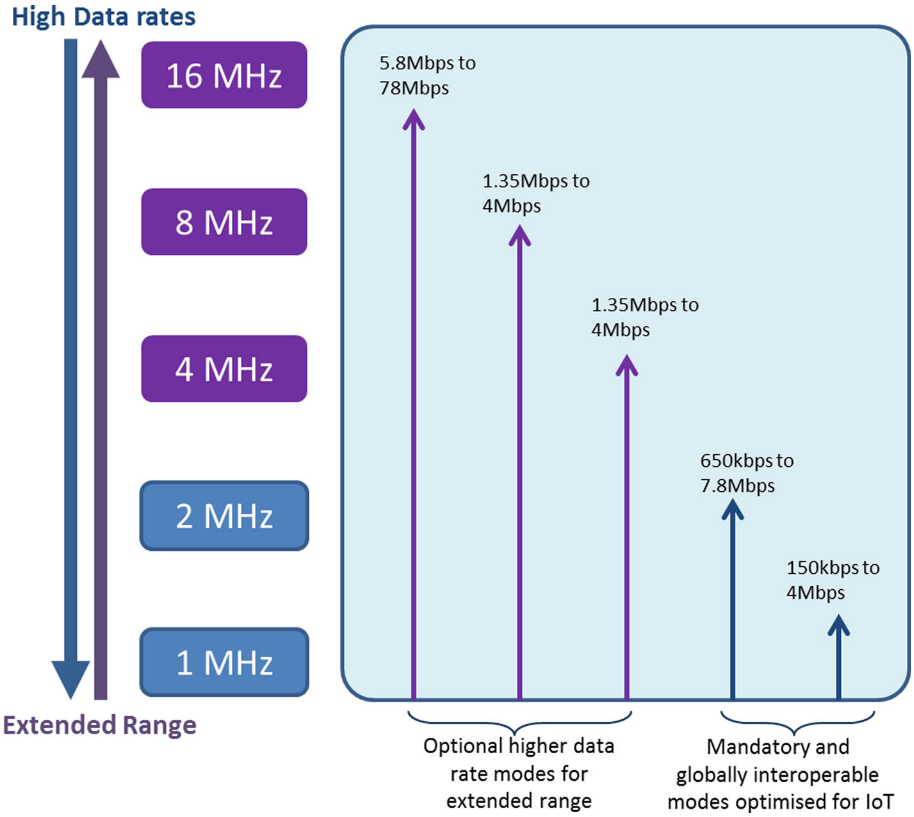


**Fig. 7** Carrier aggregation in IEEE 802.11ah

## 5.2 MAC layer specifications

Most of the MAC layer specifications for the different LPWAN standards are included in Table 3. This included the analysis of the medium access methods, and throughput capabilities. Again this is useful for technology development and selection of the best standard that suits a user's need or operator's needs. Dash7 support automated scanning scheme. The scanning scheduling scheme is used to identify background or foreground frames. The scheduler checks the energy levels during the background scan and if the threshold is met, then a sync word is detected. The foreground scanning is contrary to the background in that it starts with the sync word detection first before identifying the energy levels. The standard further uses collision avoidance together with the CSMA process. This the same with the IEEE 802.11ah, except that IEEE 802.11ah has ALOHA with PCA as well. Also, Weightless-N uses ALOHA. ALOHA random access scheme is useful for short message transmission. This is especially useful in networks that use a shared channel when propagation delay is larger than the message transmission time, since smart-objects are not required to sense before transmission. This

**Table 3** MAC layer specifications of LPWAN standards

| Attribute | DASH7 | IEEE 802.11ah | Weightless-W | Weightless-P | Weightless-N | 3GPP: eMTC | 3GPP: NB-IoT | 3GPP: EC-GSM |
|---|---|---|---|---|---|---|---|---|
| Topology structure | Start, tree, node-to-node | Star, tree | Star, with multi-hop relay capability | Star | Star | Star | Star | Star |
| Channel access method | CSMA /CA | CSMA /CA, CSMA /CA with PCA | TDMA / FDMA | TDMA / FDMA | Slotted ALOHA | OFDMA / SC-FDMA | OFDMA / SC-FDMA | CDMA |
| Traffic priority | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

makes ALOHA a good random access for LPWAN technologies, when considering that their simple implementation is behind the simple transceiver design, consequently reducing the technology cost.

Weightless-W and Weightless-P adopt the TDMA and FDMA access scheme [95]. NB-IoT and eMTC adopt the use of OFDM and SC-FDMA. This technologies makes is easier to use MIMO systems in other to mitigate the interference experienced and improve the data rates that can be supported. EC-GMS-IoT make use of the CDMA access scheme, which is still not energy efficient as compared to OFDM and still reduce the number of smart-object that can be connected. This enables the making scalability of EC-GSM-IoT to be lower than that of NB-IoT and eMTC.

## 6 Technical specifications of proprietary based LPWAN technologies

In this subsection we present the analysis of proprietary LPWAN technologies related to their technical specifications. The proprietary technologies studied in this research include Ingenu RPMA, Sigfox, NB-Fi and LoRa as seen in Tables 4 and 5. However, it should be noted that LoRa technology is a proprietary technology, while its LoRaWAN protocol is a standard. For this study, consideration is only given on the LoRa technology than LoRaWAN.

### 6.1 Physical layer specifications

In this subsection, we present a Physical layer analysis of four proprietary technologies as presented in Table 4. The proprietary technologies considered in this work include Ingenu RPMA, SigFox, NB-Fi and LoRa. Our analysis will be divided into the number of the proprietary technologies considered in this work.

#### 6.1.1 Channelization

Ingenu RPMA has defined the channelization based on 2.4 GHz, an ISM band available globally. The 2.4 GHz is available as a continuous band in every country, except that it is an over allocated band by many technologies due to its unlicensed requirement. This band provides a frequency spectrum of 100 MHz band, while Ingenu RPMA uses a fixed channel width of 1 MHz. Consequently, there are about 40 channels available with 1 MHz buffer channels to each side. Ingenu RPMA uses a channel width that is wider than most of the LPWAN technologies and achieving data rate of more than 40 kbps in uplink and 20 kbps in downlink. SigFox uses a fixed channel width of 100 Hz in sub-1 GHz (868 MHz in Europe and 902 MHz in US). The challenge with this chan-

**Table 4** Physical layer specifications of LPWAN proprietary technologies

| Attribute | Ingenu RPMA | SigFox | NB-Fi | LoRa |
|---|---|---|---|---|
| Operation frequencies | ISM 2.4 GHz | Sub-1 GHz ISM: 868 MHz EU, 902 MHz US | Sub-1 GHz ISM: 868 MHz | Sub-1 GHz ISM |
| Channel bandwidth | 1 MHz | 100 Hz | 100 Hz | 125/250 kHz (UL) & 125 kHz (DL) in EU, 125/500 kHz (UL) and 500 kHz (DL) |
| Tx power, dB | 21 (UL), 27 (DL) | 14 (UL), 27 (DL) | 14 (UL), 27 (DL) | 14 (UL), 27 (DL) |
| EC | Yes | | | |
| Modulation | D-BPSK | BPSK | D-BPSK | CSS |
| Range | 15 km | 10 km (urban),<br>50 km (rural) | 0–16 km (urban)<br>> 50 km (rural) | 5 km (urban),<br>15 km (rural) |
| Data rate | 624 kbps UL, 158 kbps DL | 100 bps (UL), 600 bps (DL) | 10–100 bps | 980 bps–50 kbps |

**Table 5** MAC layer specifications of LPWAN proprietary technologies

| Attribute | Ingenu RPMA | SigFox | NB-Fi | LoRa |
|---|---|---|---|---|
| Topology structure | ypcal Star, tree supported with RPMA | Star | Star, with multi-hop relay capability | Star |
| Channel access method | RPMA (CDMA-like) | ALOHA | TDMA/ FDMA | ALOHA |
| Traffic priority | | Yes | Yes | |
| Packet length | 6 bytes to 10 bytes | 12 bytes (UL), 8 bytes (DL) | | Up to 250 bytes |

nel is its limit in other countries as other countries have those bands allocated for other services.

Sigfox achieves low data rates (100 bps in uplink and 600 bps downlink) as compared to Ingenu RPMA. NB-Fi adopts a channel width of 100 Hz and uses sub-1 GHz of 868.8 MHz (applicable mostly in Europe), which is also a limiting factor in other countries that already having this band occupied. This technology supports the lowest data rates (between 10 and 100 bps) between the two presented proprietary technologies. Lastly, LoRa uses a channel width of 125 kHz in different Sub-1 GHz bands. This is useful for the different ISM band per regions or countries. The European frequency band is 867–868 MHz, for North America is 902–928 MHz, for China is 470–510 MHz, for Korea and Japan is 920–925 MHz, and for India is 865–867 MHz. In Europe, LoRa uses ten channels, where 8 of them are multi data rates (250 kbps to 5.5 kbps) channels. The other two remaining channels use LoRa channel and FSK channel, with data rates of 11 kbps and 50 kbps, respectively.

#### 6.1.2 Transmission mode analysis

The Ingenu RPMA, SigFox and NB-Fi proprietary technologies uses one transmission mode and the same DBPSK modulation technique. LoRa uses two transmission modes in uplink, while still one transmission mode is used on the downlink. These different modes of LoRa are associated with chirp spread spectrum (CSS) composing of spreading factors of 6–12 and code rate of 1–4, which has superior transmission range while maintaining a reasonable low power characteristic. The channel width is scalable with a constant power envelope, reducing cost of technology implementation.

### 6.2 MAC layer analysis

This subsection discusses the MAC layer specifications that are highlighted in Table 5. All the proprietary technologies support the star network topology, which is recommended for LPWAN as cost and energy efficient topology. In a star topology, each smart-object communicates directly with the access-node or gateway. This is responsible for latency reduces the latency time and the multi-hop overheads are not required. However, NB-Fi has a multi-hop or mesh like topology as well in addition to the star configuration that it supports. However star topology is not as reliable as the multi-hop topology, since in a case the access-node is non-functional, meaning network unavailability. When it comes to channel access, different techniques are adopted. Both LoRa and SigFox adopts ALOHA as a channel access. This implies that the smart-object has to ‘switch-on/wake-up’ to synchronise with the network and scan for messages. During synchronization and scanning, a lot of energy is consumed, hence reducing the battery lifetime. NB-Fi uses TDMA or FDMA as a channel access scheme. This requires simple receiver design. The Ingenu RPMA on the other hand adopts the use of CDMA variation channel access. The use of CDMA is not bandwidth limited as compared to TDMA and FDMA, however interference limited. The capacity of Ingenu RPMA can be elevated through frequency reuse. The packet size requirement of Ingenu RPMA is the least packet size of 6 bytes as compared to the other proprietary technologies, while LoRa has the longest packet size at 250 bytes.

## 7 Comparative analysis between standard and proprietary LPWAN methods

The LPWAN technologies analysed in this study can be classified into two groups, proprietary and standard. This implies that in other cases you will get full specifications of the LPWAN technology, while in other cases the technology has to perform more than a specific performance requirement. Proprietary based LPWAN technologies have an advantage through their early market entry. Furthermore, proprietary LPWAN have a potential for more adoption provided a standard is developed amongst the proprietary vendors. Network operators under normal circumstances will favour proprietary LPWAN technologies due to their low deployment and maintenance cost. However, the disadvantage is the less business proposition it offers to developers due to their lack of standards among proprietary vendors [96]. On the other hand, standards provide a fierce competition to proprietary based LPWAN with their business appeal to already established vendors for cellular systems. Contrary, standards have less market impact because of their late market arrival. However, due to their business proposition, their market impact is envisioned to increase. Furthermore, standard based LPWAN offers the following advantages: quality, interoperability, efficient and well organised development, robust deigns, and cost effective development. In the history of wireless communications, open standards are always favoured to win the market race [96,97].

## 8 Modelling techniques and performance metrics

There are different tools that can be used for LPWAN modelling purposes. In this sections, we limit our discussion to two of the most commonly used modelling techniques in LPWAN: Cooperative Differential Game Theory, and Evolutionary Game Theory [98,99]. We begin our discussion by introducing the mostly used performance metrics in the modelling of LPWAN. This section gives a solid foundation to address similar problems in future studies.

## 8.1 A performance metric

There is a number of metrics that are useful, such as: reliability, low latency, mobility support, scalability, roaming support, low module cost and service level agreement (SLA) support. However, for the purpose of this document we limit our discussion to the mostly vital metrics for LPWAN. The metrics of our discourse are coverage, power consumption and interference susceptibility. They are based on the, rate, ubiquity, signal propagation and channel.

### 8.1.1 Coverage

The coverage of a node has two important metrics: coverage probability and the rate coverage. The coverage probability is determined by the probability to find a smart-object having the received signal (signal to noise ratio) above a certain minimum required signal. This is determined by taking a random set of smart-object in the expected coverage area. The coverage probability is also known as the success probability. Through the coverage probability one can determine the outage probability, which is the probability that the received signal is below the minimum required signal.

Another form of determining good coverage not only for LPWAN but for most wireless networks is the rate coverage. The rate coverage is useful in determining if the throughput of a smart-object and the node link, meets the minimum throughput. This is achieved by randomly taking a throughput link for either uplink or downlink or both links at the same time to determine if the throughput achievable meets the minimum required [100,101]. Both coverage probability and rate coverage are dependent on the channel characteristics, interference and receiver noise level. LPWAN is mostly divided into ultra-narrow band and spread spectrum techniques. When considering ultra-narrow band communication, the coverage at a Line of Sight is limited by the noise level as shown below [102]:

$$NL = 10 \times log_{10}\left(3.98 \times 10^{-21} \times NF \times B\right) \tag{1}$$

where $NF$ represents the noise figure of the receiver and $B$ represents the equivalent noise bandwidth of the signal, while $NL$ represents the noise level in *dBm*. The noise floor when considering the ultra-narrow bandwidth communication with a bandwidth of around 100 Hz, the noise floor is given by the following:

$$NFl = 10 \times log_{10}\left(3.98 \times 10^{-21} \times NF\right) \tag{2}$$

On the other hand, the signal to noise on the free-space condition is given by:

$$SNR = log_{10}\left(\frac{P_d}{P_n}\right)^{10} = T + 132 - log_{10}\left(\frac{r}{\lambda}\right)^{20} \tag{3}$$

where $P_d$ is the power of the desired signal, $P_n$ denotes the power of the background noise, $T$ is the transmit power, $r$ is the range of the signal and $\lambda$ represents the wavelength of the transmitted signal. The attainable range for ultra-narrow band communication technologies is around 63 km of coverage radius [102].

### 8.1.2 Interference susceptibility

Another parameter of interest in LPWAN is the interference susceptibility of a technology. Interference occurs there is simultaneous co-channel transmission from two or more source or from adjacent-channel transmission from two or more sources. The interference observed by the LPWAN contributes to the system capacity of the LPWAN network. However, the system capacity of the spread spectrum based LPWAN is affected differently from the ultra-narrow band based LPWAN. Ultra-narrow band based LPWAN partition its bandwidth to different narrowband in order to enable multi access capability. Spread spectrum based LPWAN technologies use spreading sequence as a mechanism to give access to multi smart-objects. The capacity of the ultra-narrow band based LPWAN is given by the following equation:

$$E = \sum_{n=1}^{N} C_n = \sum_{n=1}^{N}\left[\frac{B}{N} log_2\left(1 + \frac{P_n}{\frac{B}{N} \times N_0 + I_{ne}}\right)\right], \tag{4}$$

where the total bandwidth $B$ is split between $N$ smart-objects, the received signal power by smart-object $n$ or access-node from smart-object $n$ is given $P_n$, whose capacity is represented by $C_n$. The interference experienced by either device is denoted by $I_{ne}$ from co-channel based external communication technologies, which corresponds to an AWGN $BN_0/N$ [103].

On the other hand, the capacity of the spread spectrum based LPWAN is based on the smart-object or access-node that transmit information that is spread across the whole bandwidth by:

$$C_n = B \times log_2\left(1 + \frac{P_n}{BN_0 + \sum_{i=1, i\neq n}^{N} I_i + I_{ne}}\right) \tag{5}$$

where the total bandwidth $B$ is not partition as in ultra-narrow band LPWAN, the difference is that there is a new interference that come from the other smart-objects, denoted by $\sum_{i=1, i\neq n}^{N} I_i$.

### 8.1.3 Low power consumption

Almost all the smart-objects in the IoT networks will be battery-powered; hence the need to ensure that energy efficiency is enhanced in these networks. Furthermore, since changing batteries is costly and one of the requirements for IoT is minimal device cost. The energy efficiency/low power consumption is computed as a ratio of achievable rate to the energy costs to achieve the rates [104,105]. In general the actual energy consumption depends on both the transmit power and the packet size. Yi $atal$. presented an energy efficient or low power consumption model in a form of a topology control algorithm for low power network, which includes LPWAN networks as well, see [105] for the whole detailed model.

## 8.2 Modelling techniques

The advancement in IoT has its own challenges such as the need for central resource allocation in IoT associated with a large number of smart-objects. These smart objects are expected to independently make their own decisions and perform tasks without human interaction. This will results to a high computational cost and immoderate overheads required for information acquisition. These challenges render distributed resource management as an important feature to future IoT systems including LPWAN. Game theory is a suitable technique when it comes to analysis of interactive decision situations for complex interaction among rational entities [106]. Especially, given that rationality requires complete compliance to a strategy in case of perceived results. However, conventional game theory methods are not adequate to model large scale systems, even though they have been useful in cellular networks and other networks. This is due to its susceptible to analytical complexity, slow convergence and excessive overhead caused by information exchange [99]. The literature is exploring non-traditional game theory, such as evolutionary games, mean field games, minority games, mean field bandit games, and mean field auctions [99]. As much as some of the traditional game theory models are not used, the cooperation differential game theory is adopted for modelling energy-bandwidth efficiency trade-off in the Internet of Things networks (see [98]). In this subsection we present the basis of evolutionary games and cooperation game theory.

### 8.2.1 Cooperative differential game theory

Cooperative differential game model can be used for energy efficiency and optimal usage of other resources usage while maintaining acceptable performance. The modelling is achieved by classifying different services offered through a specific access-node as a resource. The goal is to identify an optimal mapping between the services (resource) and the smart-objects. The final result of the optimization is acquired by finding the grand coalition's condition. The grand coalition is used to determine the standard dynamic programing problem responsible for minimising the sum of all cost. The grand coalition is further used for determining both the feedback Nash equilibrium and intermediate coalitions [98,107]. The IoT systems composed of the access-node and smart-objects. Through the smart-object's functions the access-node builds a platform for smart-objects to access different services (resource) of interest. The focus in this illustration is on optimizing the energy efficiency in the access-node. In order to achieve that, two definitions are presented for the illustration optimization problem:

**Definition 1** An IoT network can compose of $X$ number of access-nodes, where $X \in [1, x]$ and $x \in Y$. The quality of the access-points to serve $Y$, can be separated into two groups. The first group is concern about the number of fundamental services $Z, Z \in Y$. The second group is concern about the number of additional services:

$$\sum_{a=1}^{X} f(t), f(t) \in Y \tag{6}$$

provided that $q(0) = q$, where it represents the probability of failure in providing service to the smart-object.

**Definition 2** The cost of providing service depends on a number of resources, however for this illustration we only focus on power consumption. Access-node $a$, the power consumption is given by

$$R(f_a(t)) = \kappa\{[f_a(t) - \widetilde{f_a(t)}]\}^2 \tag{7}$$

where $\kappa$ is a constant factor and $[f_a(t) - \widetilde{f_a(t)}]$ represents the additional services provided by access-node $a$. The goal of the game is to minimize the utility function of the power consumption cost, this optimization problem results to the following:

$$min_{x_a} K(x, q) = \int_0^{\infty} R(f_a(t)) e^{-\varphi t} ds \tag{8}$$

subject to the constraint given by (7) [98].

### 8.2.2 Evolutionary game theory

Evolutionary game theory is another form of non-cooperative game. It uses the same conventional non-cooperation game theory formulation. However it differs by its inclusion of the concept of population and its trial and error process. It is best described as a set of players (access-nodes, smart-object, and etc.) partitioned into two groups of different populations, a set of strategies per player, associated player payoff for choosing a specific strategy, and a solution per player. The population's players have the same set of strategies; their responsibility is to avoid other populations strategies. The population can either be finite or infinite number of players. The game is always played between populations not the players [108].

Once the evolutionary equilibrium is reached, it is then that the game can be put to an end. This is contrary to the Nash equilibrium used in conventional non-cooperative game theory. The vital feature of an evolutionary game is its ability to record the unpredicted interaction amongst the players of the population. Where a subset is capable to determine the behaviour of other subsets known as players, and make the best decision based on the determination capability and its knowledge. It is through this feature that it can give an optimal solution while keeping the stability by evolutionary equilibrium. Evolutionary game theory can be used in networks for network selection, which is another topic in IoT. It can be further used for balancing power consumption of all devices [108,109].

An example of an evolutionary game theory formulation for balancing power consumption per smart-objects includes the definition of the players. *Players* refers to services selection for a component in an application. Secondly, the definition of the *population function*, which denotes the set of players that selects services from the same candidate set. Thirdly, it is the description of the *set of actions*, which refers to a specific decision taken by a player. The different services that the *player* can take corresponds to the *set of action* that a can be taken. Fourthly and lastly, the definition of the *payoff function*, its vitality is its ability to reflect the motivation of a *player*. The *player's* goal is to minimize its power consumption of a specific service. A *player's* payoff function depends on *set of actions* and the *set of actions* of other *players*. Assuming that the remaining power of smart-object $S0_s$ is given by $RP_s$ and the related approximate calculation of the battery lifetime is $t_s$. Given that the service selected is $s_s^u$ from s smart-object $SO_s$, the resulting *payoff function* $PF_{s,w,v}^u$ of *player* $p_{w,v}u$ is given by

$$PF_{s,w,v}^u = \frac{RP_s}{\sum_u e_s^u + \tau_s}, \tag{9}$$

where $\tau_s$ is the static power consumption rate given that there is no service selected on the smart-object and $\sum_u e_s^u$ denotes the dynamic power consumption rate, which is equal to the total power consumption rate of al selected services on $SO_s$. The rest of the model is presented in [105].

## 9 Challenges and open problem

The significant impact of LPWAN on IoT in terms of coverage and support of different application has attracted the attention of researchers and practitioners. LPWAN amongst other network connectivity technologies such as ZigBee, Bluetooth and etc. are the main players envisioned to be part of the heterogeneous networks in IoT network connectivity. However, it is vital to identify the challenges faced by LPWAN technologies, such as interference management, massive access scheme, optimal coexistence scheme, and energy efficient schemes. This subsection presents the different challenges and open problems that needs the attention of the research community in order to avoid counter-productive in LPWAN development.

**Coexistence** There is less research on the effect of coexistence of the different LPWAN in the sub-1 GHz. Most of the different LPWAN standards and proprietary technologies use different channel access methods, consequently resulting to a high number of packet collisions. Other studies provide an insight in the introduction of collision in asynchronous channel access of non-harmonised carrier sense access.

**Massive Access Scheme** This type of schemes have been proposed in the literature, such as the cognitive-cdma with the ability to increase spectral efficiency [77]. However, they have not been extensively investigated for LPWAN. Especially, given that there is shortage of the spectrum resource and the lack of continuous frequency band. In the 2.4 GHz ISM band there is a continuous band, however the band is heavily occupied [110].

**Energy Efficiency** The cause of energy inefficiency in IoT is mostly imputed to communication/connectivity, processing and sensing. There are wide efforts proposed in providing solution to energy inefficiency of IoT network connectivity technologies. In communication it will be best to identify optimal energy efficient solution, such as the best sleep mode schemes that can be implemented within a specific duty cycle while requiring less energy to wake up. Zhang at al. [111] presents an integrated energy efficient. The uniqueness of this proposed method is its ability provide solutions for both wired and wireless systems. The reason behind this approach is based on the IoT requirement for heterogeneous network configuration. Furthermore, this method is ubiquitous in the sense that it enhance the energy efficiency of both wired or wireless based. There are other alternative to LPWAN's finite battery life. This is exploration of energy harvesting techniques as presented in earlier section of this study. The upper-hand of energy harvesting techniques is their OPEX reduction capability.

**Interference Management** In order for LPWAN to have an optimal performance, many research questions still remain to be resolved. One of those questions in finding the best method to address interference issue. LPWAN is affected by inter-symbol, co-layer and cross-layer interference. The use of omnidirectional antennas results to high multipath effects and high scattering, which results to inter-symbol interference.

This can be mitigated by either MIMO systems, directional or/and smart antennas. However, more studies still need to be conducted in order to identify optimal way of integrating these improvements in the current LPWAN technologies. Co-layer and cross layer interference, causes significant degradation in the network performance. This is even more so for unlicensed LPWAN technologies such as LoRA, SigFox, Ingenu RPMA, NB-FI and Weightless. These technologies operate in ISM bands, making then susceptible to interference. Furthermore, the access scheme being adopted by a specific LPWAN technology determines the level of interference susceptibility. These challenges require interference mitigation schemes that are aligned with LPWAN requirements, such as low-complex and enhance battery lifetime while considering IoT.

**Theoretical Models** During this study it was established that the competition is still open between the different LPWAN technologies. This shows the need to further analyse the different technologies and determine their enhancement magnitude. Consequently, there is a need for a specific theoretical model that can be employed in LPWAN analysis. Especially, given that LPWAN use short packets communication, it makes it difficult to use conventional cellular models and other broadband theoretical models. As most of this technologies are based on long packet size, which is completely different to LPWAN technologies.

**Management of Massive smart-objects** IoT networks, including LPWAN are inherently going to accommodate a massive number of smart-objects. The massive number of smart-objects place will place an overload of the LPWAN networks due to the limitation of resource such as power, spectrum and susceptibility to interference. Hence the need for efficient resource management techniques, consequently LPWAN network performances will be degraded. Resource management includes spectrum allocation, power control, interference management, backhaul resource allocation, and allocation of storage [99]. Game theory have been used a lot to develop efficient resource management techniques. However, game theories are insufficient for LPWAN network optimization because of the immense overhead as a result of information acquisition, slow convergence to equilibrium, inefficiency of equilibrium in terms of social welfare, excessive computation complexity and theoretical complexity of characterizing equilibrium. These are the reasons behind the need to explore some non-conventional game theoretical models that fit the large scale IoT networks more appropriately.

There is also a need to optimize the current LPWAN technologies to address the need for Internet Protocol version 6 (IPv6), as current LPWAN nodes don't support IPv6 [112]. IPv6 is the successor to Internet Protocol version 6 (IPv4), which is expected to enable simultaneous internet connection to approximately $3.4 \times 10^{38}$ (340 trillion trillion trillion) devices and people in the world because of its 128 bits address. The adoption of IPv6 is necessary for ensuring the support for the current massive deployment of IoT devices and the forecasted future devices to be deployed. Re-emphasises the need to intensify more research in this area of IPv6 adoption for LPWAN.

**Security** Most of the currently existing security measures depend on cryptographic algorithms. Cryptographic algorithms employ the use of elliptic curve cryptosystems (ECCs) for basic building blocks to secure the communication in the IoT. The challenge is that these systems are susceptible to intrusion due to the development of quantum computers. Hence the need for development of new security measure that address the quantum computing world. A survey is presented in [113], where it presents the research direction in quantum resistant security models or crypto systems. There is a requirement for more research that will investigate and develop techniques with the ability to secure both classic and quantum based attacks.

Another important feature is the use of IPv6, because of its ability to run end-to-end encryption. Both encryption and integrity-checking comes as standard component for current virtual private networks (VPNs). Consequently, reducing attacks. There are many other related security challenges that can be enabled by adopting IPv6 [114].

**Other** Most technical development are now requiring a set of new research topics that focus on issues such as new business models, ecosystems, and consumer-centric aspects. The research community needs to address issues such as IoT application development, utilization of semantics, geolocation [115], privacy, and trust. However, we did not deal much with some of this topic in this paper. Another topic of interest is quality of service (QoS), which is necessary because of the high probability for congestion in IoT networks because of the huge anticipated traffic. An increase in congestion is proportional to an increase in packet loss rate. There is a need for a lightweight context-aware congestion control (CACC) mechanism that will enable IoT networks to mitigate the consequences of traffic congestion.

## 10 Conclusion

In this paper we present the appealing IoT connectivity solution for long-range connectivity, low-power consumption, low network cost and low throughput known as LPWAN. LPWAN technologies are an alternative solution to short-range IoT connectivity solutions. It has been shown that LPWA network connectivity technologies both the standards and proprietary technologies have a market in IoT applications and can be able to dedicate their services to IoT and M2M applications. Furthermore, LPWAN can provide connectivity services to IoT applications such as smart buildings, energy management, health monitoring, transportation and public safety. These services require a low throughput in order to be able to allow the transmission of high number of small messages. LPWAN meets these requirements and further manages to allow surveying a large number of smart-object in a wide area.

In this paper we managed to present common knowledge and new insight of LPWAN technologies and were presented as follows. The discussion began with the presentation of the background in IoT systems, which was followed by the discussion of the existing long-range IoT connectivity technologies. The aim was to identify other competing technologies that can be investigated in terms of their limitation and their prospect augmentation capability to LPWAN. The new trend in adopting long-range connectivity networks makes this LPWAN a trending research issue. The concept of LPWAN technologies is discussed and suggested as a potential solution for long-range IoT connectivity. Furthermore, the multiple current LPWAN technologies are discussed and evaluated.

Based on the technical systems specifications, the Physical layer and the MAC layer are vital components and require theoretical quantification. Hence, we presented some modelling and performance metrics for LPWAN technologies. The goal is to provide researchers in the field of LPWAN based IoT connectivity to develop theoretical models and to obtain basic understanding of LPWAN technologies. The paper is concluded by discussing the identified challenges and open problem that require the attention of the research community and the potential prospect solutions.

## 11 Appendix

Table 6 depicts all the acronyms used in this paper.

**Table 6** Definitions of all acronyms used in the paper

| Abbreviation | Defination |
|---|---|
| 3GPP | 3rd generation partnership project |
| 5G | Fifth cellular generation |
| BPSK | Binary phase-shift keying |
| CDMA | Code division multiple access |
| DBPSK | Differential phase-shift keying |
| eMTC | enhanced-MTC |
| EC-GSM-IoT | Extended coverage-GSM-IoT |
| FDMA | Frequency division multiple access |
| GFSK | Gaussian frequency-shift keying |
| GMSK | Gaussian minimum-shift keying |
| GSM | Global system for mobile communications |
| H2H | Human-to-human |
| IoT | Internet of things |
| IPv4 | Internet protocol version 4 |
| IPv6 | Internet protocol version 6 |
| ISM | Industrial, scientific and medical |
| LPWAN | Low power wide area networks |
| LTE | Long term evolution |
| LTN | Low throughput networks |
| M2M | Machine-to-machine |
| MAC | Media access control |
| MTC | Machine-type communications |
| NFV | Network functions virtualization |
| NB-IoT | Narrowband-IoT |
| NB-Fi | Narrowband fidelity |
| OFDMA | Orthogonal frequency-division multiple access |
| OFDM | Orthogonal frequency-division multiplexing |
| OPEX | Operational expenditure |
| PHY | Physical |
| QoS | Quality of service |
| QAM | Quadrature amplitude modulation |
| QPSK | Quadrature phase-shift keying |
| REAC | Regressive admission control |
| RPMA | Random phase multiple access |
| SC-FDMA | Single-carrier FDMA |
| SDN | Software defined networks |
| SDR | Software defined radios |
| SDWSN | Software defined wireless sensor networks |
| SIG | Special interest group |
| TDD | Time division Duplexing |
| TDMA | Time division multiple access |
| TV | Television |
| WiMAX | Wireless interoperability for microwave access |
| WLAN | Wireless local area networks |
| WPAN | Wireless personal area networks |
| WS | White space |
| WSN | Wireless sensor networks |

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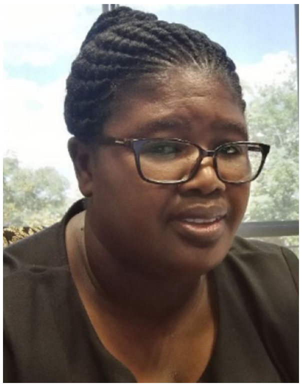

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