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Conference Paper · March 2018

DOI: 10.1109/PERCOMW.2018.8480255

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***Abstract*— LPWAN are actually the most popular low cost, long battery lifetime, and long range communication technology for IoT applications. This paper presents a comprehensive and comparative study on three actually leading LPWAN technologies called Sigfox, LoRaWAN, and NB-IoT. We show that Sigfox and LoRaWAN excel on network capacity, devices lifetime, and cost. Whereas, NB-IoT excels on quality of service and latency. In addition, we consider application scenarios and explain which technology fits best to guide future researchers and industrials.**

Keywords—Internet of Things, Low Power Wide Area Networks, LoRaWAN, Sigfox, NB-IoT.

I. INTRODUCTION

Nowadays, Internet of Things (IoT) technologies are used in various application fields including security, asset tracking, agriculture, smart metering, smart city, and smart home [1]. IoT applications have specific requirements such as long communication range, very low energy consumption, and cost effectiveness. The widely used short communication range technologies (e.g. BLE and ZigBee) are not adapted for long transmission range requirement. Further, solutions based on mobile cellular communications (e.g. 2G, 3G, and 4G) could ensure larger transmission range, however, it deplete the device energy. Therefore, IoT applications requirement leads to the emergence of Low Power Wide Area Network (LPWAN). LPWAN technologies ensure long transmission range, low energy consumption, and low cost deployment solution. It allows up to 40 km as communication range in rural zones and 10 km in urban zones [2], up to 10 years of battery lifetime [3], less than 5$ of device cost, and less than 1$ per device per year of operator subscription cost [4]. It was particularly designed for IoT applications that require transmitting few tiny messages per day in long radio range as shown in Figure 1. These advantages have shoved various performance studies of LPWAN in outdoor and indoor environment [5-7]. As recently as early 2013, the term "LPWAN" did not even exist [8].

Many of the LPWAN technologies have arisen in both licensed and unlicensed frequency spectrum. Among them, Sigfox, LoRaWAN, and NB-IoT are today the leading emergent technologies [8-11] which involve many technical differences.

Sigfox technology was developed in 2010 by the start-up Sigfox (in Toulouse, France), from where Sigfox is both a company and a LPWAN network operator. Actually, Sigfox operates and commercializes its own IoT solution in 31 countries and still under roll-out over the world due to the partnership with various network operators [12].

LoRaWAN was firstly developed by the start-up Cycleo in 2009 (in Grenoble, France) and purchased 3 years later by Semtech (USA). In 2015, LoRaWAN was standardized by LoRa-Alliance and is actually deployed in 42 countries and still under roll-out in others countries due to the investment of various mobile operators (e.g. Bouygues and Orange in France, KPN in Netherlands, Fastnet in South Africa) [13].

NB-IoT is a LPWAN technology based on narrowband radio technology. NB-IoT is standardized by the 3rd Generation Partnership Project (3GPP). Its specification was published at Release 13 of 3GPP on June 2016. Actually, NB-IoT is under test in Europe. In December 2016, Vodafone and Huawei integrated NB-IoT into the Spanish Vodafone network and send the first message conforming to the NB-IoT standard to a device installed in a water meter. Currently, Huawei is multiplying partnerships to deploy this technology throughout the world (it was announced to be deployed in many countries on 2018). In May 2017, the Ministry of Industry and Information Technology in China announced its decision to accelerate the commercial use of NB-IoT for utilities and smart city applications.

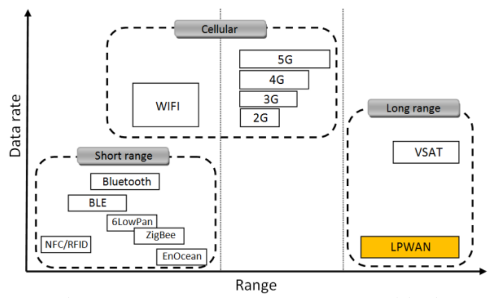

Fig. 1. Data rate vs. range: LPWAN positioning

In this paper, the technical differences of Sigfox, LoRaWAN, and NB-IoT are presented and compared in terms of physical/communication features. In addition, these technologies are compared in terms of IoT success factors such as quality of service (QoS), coverage, range, latency, battery life, scalability, payload length, deployment, and cost. Further, we consider application scenarios and explain which technology fits best.

The rest of paper is organized as follows. Section 2 describes the network topology in Sigfox, LoRaWAN, and NB-IoT. Section 3 details the technical features of these technologies. Section 4 compares them in terms of IoT factors. Section 5 explains which technology fits best for different application scenarios. Finally, section 6 discusses and concludes the paper.

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II. Network topology: Sigfox, LoRaWAN, NB-IoT

Mesh topology has widely employed for expanding the coverage of short range networks (e.g. BLE and ZigBee). However, the major disadvantage is their high deployment cost to connect huge number of devices which are geographically dispersed in a wide area range. Moreover, as data is transmitted through multi hops towards a gateway, a subset of devices are more congested than others which reduce their batteries lifetime (i.e. excessive energy consumption) and thus limit the entire network lifetime [14][15]. This limitation is surmounted in Sigfox, LoRaWAN, and NB-IoT technologies: the end-devices are directly connected to public base stations (i.e. star topology) as shown in Figure 2. Unlike mesh topology, connected end-devices do not listen to radio channel before transmitting message which ensures energy saving advantages. As base stations are always-on, they ensure immediate access to connected end-devices.

Figure 2 shows two communication way: uplink and downlink. In uplink transmission, the end-device sends messages towards base stations. Upon receiving a message, the base stations forward it to backend server (i.e. network server) using IP-based network. The network server checks authentication/authorization of messages and forward it to the application server.

Despite that LPWAN are firstly designed for only uplink transmission, downlink transmission is also available in Sigfox, LoRaWAN, and NB-IoT. If downlink transmission is required, the application server transmits a message towards the network server. The network server forwards it to the suitable base station which sends it then to the end-device.

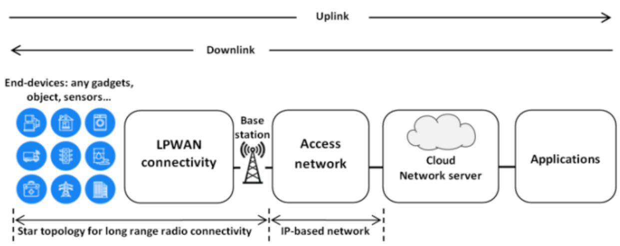

Fig. 2. Network topology of IoT deployment using Sigfox, LoRaWAN, or NB-IoT

III. Technical Differences

In this section, we highlight emerging technologies and the technical aspects of Sigfox, LoRaWAN, and NB-IoT that are finally summarized in Table 1.

A. Sigfox

Sigfox uses its patented UNB technologies and deploys its proprietary base stations deployed in various countries in the unlicensed sub-GHz ISM bands (e.g. 868MHz in Europe, 915MHz in North America, and 433MHz in Asia). The end-devices connect to these base stations using BPSK modulation in an ultra narrow band of 100 Hz at a maximum data rate of 100 bps. By employing ultra narrow band in sub-GHz spectrum, Sigfox efficiently uses the frequency band and has very low noise levels, leading to very low power consumption, high receiver sensitivity, and low cost antenna design.

Sigfox initially upheld only uplink transmission, yet later it was advanced to bidirectional communication. The downlink transmission occurs only following an uplink transmission. The number of messages over the uplink is limited to 140 messages per day. The maximum payload length for each uplink message is 12 bytes. However, the number of messages over the downlink is limited to 4 messages per day, thus all uplink message could not be acknowledged. The maximum payload length for each downlink message is 8 bytes.

Without acknowledgment capability of every uplink message, time/frequency diversity and transmission duplication are used for ensuring the uplink transmission reliability. Each end-device sends message three times through different frequency channels. Base stations could receive messages simultaneously over all channels, the end-device can thus transmit the message in randomly chosen channel which reduces the end-device complexity and reduces its cost.

B. LoRaWAN

Since 2015, a LoRa based communication protocol called LoRaWAN was standardized by LoRa-Alliance. LoRa is a patented spread spectrum technology using the unlicensed sub-GHZ band [16]. The LoRa chirp spread spectrums (CSS) modulations ensure full bidirectional communication, and the generated signal has low noise levels, enables high interference resilience, and is difficult to detect or jam [17].

LoRaWAN provides six spreading factors (SF7 to SF12) to adapt the data rate and range tradeoff. The higher spreading factor provides the longer transmission range and lowest data rate [18]. The data rate is between 300 bps and 50 kbps and the maximum payload length for each message is 243 bytes.

Using LoRaWAN, each message transmitted by an end-device is received by all base stations in the range. By exploiting this redundant reception, LoRaWAN improves the communication reliability ratio. Nevertheless, this feature requires many base stations deployment in each region which would grow the network infrastructure cost. The backend system filters the redundant reception of each message by verifying security and transmitting back acknowledgment to the end-device, and forwarding the message to corresponding application servers. In addition, reception of each message by multiple base stations avoid the handover in LoRaWAN network (i.e. if an end-device is mobile there is no handover needed between base stations). Further, this feature is exploited by LoRaWAN for localizing end-devices using TDOA-based technique.

LoRaWAN defines multiple communication classes for addressing the different latency in IoT applications:

- *Class A (bidirectional end-devices):* end-devices allow bidirectional communication where each end-device's uplink transmission is followed by two short windows for receiving downlink messages as shown in Figure 3. The uplink transmission time is scheduled by the end-device based on its own communication needs. This class is the lowest power end-device system for IoT applications that only require short downlink communication after the end-device has sent an uplink message. Downlink transmission at any other time will have to wait until the next uplink message of the end-device.

Fig. 3. Bidirectional communication between end-device and base station for LoRaWAN class A

- *Class B (bidirectional end-devices with scheduled receive slots):* in addition to the random receive windows of class A, the class B devices open extra receive windows at scheduled times. In order to open receive window at the scheduled time, end-devices receive a time synchronized Beacon from the base station. This allows the server to know when the end-device is listening.
- *Class C (bidirectional end-devices with maximal receive slots):* end-devices have nearly continuously open receive windows. This class consumes excessive energy and is defined for IoT applications with continuous energy power resources.

The next version of LoRaWAN is actually under specification by LoRa-Alliance [13]. The new expected features are: class B clarification and the temporary switching between class A and class C.

C. NB-IoT

NB-IoT is a narrowband LPWAN technology which can coexist in LTE or GSM under licensed frequency bands. NB-IoT occupies a frequency bandwidth of 200 KHz, which corresponds to one resource block in GSM and LTE transmission [19]. With this frequency bands selection, the following operation modes are possible as shown in Figure 4:
- *Stand alone operation:* a possible scenario is the utilization of currently used GSM frequencies bands.
- *Guard band operation:* using the unused resource blocks in LTE carrier's guard-band.
- *In-band operation:* using resource blocks in LTE carrier.

For the stand alone operation, the GSM carriers in the right part of Figure 4 are shown as an example in order to indicate that this is a possible NB-IoT deployment. In fact, 3GPP recommends the integration of NB-IoT in conjunction with the LTE.

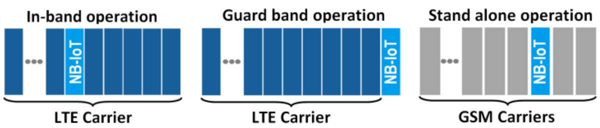

Fig. 4. Operation modes for NB-IoT

NB-IoT communication protocol is based on LTE protocol (i.e. NB-IoT reuses various principles and building blocks of LTE physical and higher protocol layers). In fact, NB-IoT reduces LTE protocol functionalities to the minimum and enhances them as needed for IoT applications. As example, LTE backend system is used to broadcast information which is valid for all end-devices within a cell. As backend system broadcasting takes resources and causes battery consumption for each end-device, it is kept to a minimum as well in its size as in its occurrence. It was optimized to small and infrequent data messages and abstain the features not required for IoT purpose (e.g. radio quality measurements, aggregation, etc). This way, the end-devices can be kept in an efficient cost and needs only a small amount of battery power.

NB-IoT allows connectivity of more than 100K devices per cell and it could be increased by exploiting multiple NB-IoT carriers. It employs QPSK modulation, Frequency Division Multiple Access (FDMA) in uplink, and Orthogonal FDMA (OFDMA) in downlink [19]. The maximum throughput rate is 200 kbps and 20 kbps in downlink and uplink respectively, with 1600 bytes of payload size in each message. As discussed in [20], NB-IoT and LTE-M technologies can achieve 10 years of battery lifetime by transmitting on average 200 bytes per day.

Actually, the improvement of NB-IoT continues with Release 15 of 3GPP. According to the 3GPP current plan, NB-IoT will be extended to include multicast services (e.g. end-device software update and messages concerning a whole group of end-devices), mobility, as well as further technical details to enhance the applications field of NB-IoT technology.

IV. Comparison Regarding IoT Factors

To choose an appropriate LPWAN technology for an IoT application, various factors have to be considered: range, coverage, device lifetime, latency, scalability, payload length, deployment, quality of service, and cost. Sigfox, NB-IoT, and LoRaWAN are compared in the following regarding these factors.

A. QoS

Sigfox and LoRaWAN employ license-free sub-GHz bands and asynchronous communication based on ALOHA protocol. They can efficiently bounce interference and fading/multi-path, however, they do not provide quality of service. NB-IoT employs licensed spectrum and LTE-based synchronous protocol which are optimal for QoS at the detriment of cost (i.e. LTE frequency band auctions are over 500 million euro per MHz [8]). Due to QoS and cost tradeoff, NB-IoT is preferred for applications that need guaranteed quality of service, while the applications that do not have this constraint should choose LoRaWAN or Sigfox.

Table 1. Overview of LPWAN technologies: Sigfox, LoRaWAN, and NB-IoT

	Sigfox	LoRaWAN	NB-IoT
Modulation	BPSK	CSS	QPSK
Frequency	Unlicensed ISM bands (868MHz in Europe, 915MHz in North America, and 433MHz in Asia)	Unlicensed ISM bands (868MHz in Europe, 915MHz in North America, and 433MHz in Asia)	Licensed LTE frequency bands
Bandwidth	100 Hz	250 kHz and 125 kHz	200 kHz
Maximum data rate	100 bps	50 kbps	200 kbps
Bidirectional	Limited / Half-duplex	Yes / Half-duplex	Yes / Half-duplex
Maximum messages/day	140 (UL), 4 (DL)	Unlimited	Unlimited
Maximum payload length	12 bytes (UL), 8 bytes (DL)	243 bytes	1600 bytes
Range	10 km (urban), 40 km (rural)	5 km (urban), 20 km (rural)	1 km (urban), 10 km (rural)
Interference immunity	Very high	Very high	Low
Authentication & encryption	Not supported	Yes (AES 128b)	Yes (LTE encryption)
Adaptive data rate	No	Yes	No
Handover	End-devices do not join a single base station	End-devices do not join a single base station	End-devices join a single base station
Localization	Yes (RSSI)	Yes (TDOA)	No (under specification)
Allow private network	No	Yes	No
Standardization	Sigfox company is collaborating with ETSI on the standardization of Sigfox-based network	LoRa-Alliance	3GPP

B. Battery life & Latency

In Sigfox, LoRaWAN, and NB-IoT, end-devices are in sleep mode the most of time as long as the application needs which reduce as much as possible the amount of consumed energy (i.e. long end-devices lifetime). However, the NB-IoT end-device consumes additional energy due to synchronous communication and QoS handling, and its OFDM/FDMA access modes require more peak current [9]. This additional energy consumption reduces the NB-IoT end-device lifetime compared to Sigfox and LoRaWAN.

Further, NB-IoT provides low IoT latency connectivity. Unlike Sigfox, LoRaWAN provides class C to handle also low bidirectional latency at the expense of increased energy consumption. Thus, Sigfox and LoRaWAN-Class-A are the best solution for latency insensitive applications. For IoT applications with low latency connectivity, NB-IoT and LoRaWAN-Class-C are the better choice.

C. Scalability & Payload length

Supporting thousands of end-devices is one of the key features for Sigfox, LoRaWAN and NB-IoT. These cellular LPWAN networks provide high scalability feature. However, NB-IoT offers the advantage of very high scalability than Sigfox and LoRaWAN. NB-IoT allows connectivity of more than 100K devices per base station compared to 50K per cell for Sigfox and LoRaWAN [18].

On the other hand, NB-IoT offers also the advantage of maximum payload length. NB-IoT allows transmission of data up to 1600 bytes. LoRaWAN allows sending in maximum 243 bytes. In contrary, Sigfox proposes the lowest payload length of 12 bytes which limit its utilization on various IoT applications that need sending large data size.

D. Coverage & Range

The coverage of an entire city using only one base station is the most Sigfox benefit (i.e. range >40 km). As example, Belgium (i.e. total surface ≈ 45000 km^2) is entirely covered by only seven Sigfox base stations [8]. In contrary, LoRaWAN has lower range (i.e. range <20 Km) that allow covering an entire city like Barcelona with three base stations.

NB-IoT has the lowest range and coverage capability (i.e. range <10 Km). It provides mainly services for end-devices which are out of reach of cellular mobile networks (e.g. indoor, deep indoor). In addition, NB-IoT is deployed only within LTE infrastructure, thus it is not adapted for regions without LTE coverage (e.g. rural zones).

E. Deployment model

The NB-IoT standardization was published on 2016, and is actually under rollout to establish its network over the world. In contrary, LoRaWAN and Sigfox ecosystems are mature and under commercialization in various countries and cities. LoRaWAN has the advantage that it is currently deployed in 42 countries versus 31 countries for Sigfox [12][13]. Although, LoRaWAN and Sigfox worldwide deployments are still in the rollout phase.

Unlike Sigfox and NB-IoT, LoRaWAN offers local network deployment (i.e. LAN using LoRa gateway) as well as public network operation via base stations. In industrial field, a hybrid operating model could be used which deploys a local LoRaWAN network in factory areas and uses the public base stations to cover the outside areas.

F. Cost

Various cost factors should be considered including spectrum (license), deployment, and end-device costs. Table 2 presents Sigfox, NB-IoT, and LoRaWAN costs.

It shows that Sigfox and LoRaWAN have an advantage in relation to cost compared to NB-IoT.

Table 2. Costs of Sigfox, LoRaWAN, and NB-IoT

	Spectrum cost	Deployment cost	End-device cost
Sigfox	Free	>4000€/base station	<2€
LoRaWAN	Free	>100€/gateway >1000€/base station	3-5€
NB-IoT	>500 M€ /MHz	>15000€/base station	>20€

In summary, each LPWAN technology has advantages in terms of different IoT factors as shown in Figure 5.

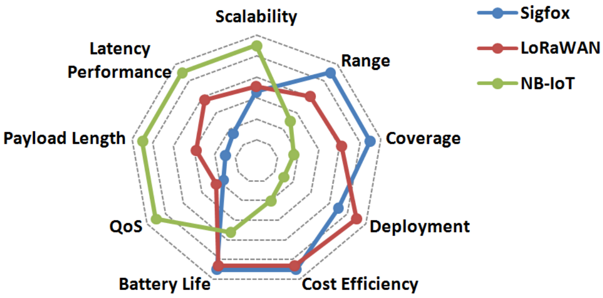

Fig. 5. Respective advantages of Sigfox, NB-IoT, and LoRaWAN

V. Application Examples: Which Technology Fits Best?

IoT factors and technical differences of Sigfox, LoRaWAN, and NB-IoT will impose which technology is suitable for each specific application. As discussed before in this paper, one technology cannot serve equally all IoT applications. In this section, various application use cases are discussed with a summary of which technology fits the best.

A. Electric metering

Electric metering was tested in [21] using LPWAN technology. In this application field, companies typically require frequent communication, low latency, and high data rate. Mostly, they do not require low energy consumption neither long battery lifetime as electric meters have continuous power source. Moreover, companies need real time grid monitoring to take immediate decisions (e.g. load, outages, and interruptions). Thus, Sigfox is inappropriate for this application since it does not handle low latency. On the contrary, electric meters can be set up using LoRaWAN-Class-C to ensure very low latency. However, NB-IoT is a better fit for this application due to the required high data rate and frequent communication. Moreover, electric meters are typically in stationary locations in densely populated areas. It is then easy to ensure NB-IoT coverage by cellular operators (LTE).

B. Smart farming

In agriculture field, long battery lifetime of sensors devices are required. Using temperature, humidity, and alkalinity sensors could significantly reduce the water consumption and improve the yield as discussed in [22]. Devices update sensed data few times per hour as the environment conditions have not radically changed. Thus, Sigfox and LoRaWAN are ideal for this application. Moreover, various farms do not have today LTE cellular coverage, thus NB-IoT cloud not be an agriculture solution in the future.

C. Manufacturing automation

Real time machinery monitoring prevents industrial production line down and allows remote control for efficiency improving. In factory automation, there are various types of sensors and communication requirements. Some applications require frequent communication and high quality of service, thus NB-IoT is a better solution than Sigfox and LoRaWAN. Other applications require low cost sensors and long battery lifetime for asset tracking and status monitoring, in this case Sigfox and LoRaWAN are a better solution. Due to this requirements variety, hybrid solutions could also be used.

D. Smart building

Temperature, humidity, security, water flow, and electric plugs sensors alert property managers to prevent damage and instantly responding to requests without having manually building monitor. The buildings cleaning and usage could also be done more efficiently. These sensors require low cost and long battery lifetime as shown in [23]. They do not require quality of service or frequent communication, so Sigfox and LoRaWAN are a better fit for this class of applications.

E. Retail point of sale terminals

Sale point systems require guaranteed quality of service since they handle frequent communication [24]. These systems have continuous electrical power source, thus there is no constraint on battery lifetime. There is also a strong requirement of low latency (i.e. long latency times limit the number of transactions that a store can make). Thus, NB-IoT is a better fit for this application.

F. Pallet tracking for logistics

Nowadays, pallets tracking to determine the location and goods condition are highly desirable in logistics. In the literature, pallet tracking was tested in [25][26] using LPWAN technology. In this application, the most requirements are device cost and battery lifetime. Pallet tracking is a good example of hybrid deployment solution. Logistics companies can have their own network so they have a guaranteed coverage in their facilities. Low cost IoT devices could be easily deployed on vehicles. Sigfox or LoRaWAN public base stations can be then used when vehicles are outside the facilities or when goods arrive at customer locations. However, LoRaWAN allows more reliable communication than Sigfox when moving at high speeds [3]. For NB-IoT, LTE network might not be available for all logistic locations, which are typically in rural areas. Due to the low cost, long battery lifetime, and reliable mobile communication, LoRaWAN is a better fit for this application.

VI. Conclusion

This paper has detailed the technical differences of Sigfox, LoRaWAN and NB-IoT, and discussed their advantages regarding IoT factors and major issues. Each technology will have its place in the IoT market. Sigfox and LoRaWAN will serve the lower device cost, very long range (high coverage), infrequent communication rate, and very long battery lifetime. Unlike Sigfox, LoRaWAN will serves also the local network deployment and the reliable communication when devices moving at high speeds. In contrast, NB-IoT will serve the higher value IoT applications that are willing to pay for very low latency and high quality of service.

Finally, it is expected that the 5th generation (5G) of mobile cellular communication will allow an all-connected world of humans and devices by the year 2020 [8], which would lead to a global LPWAN solution for IoT applications.

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