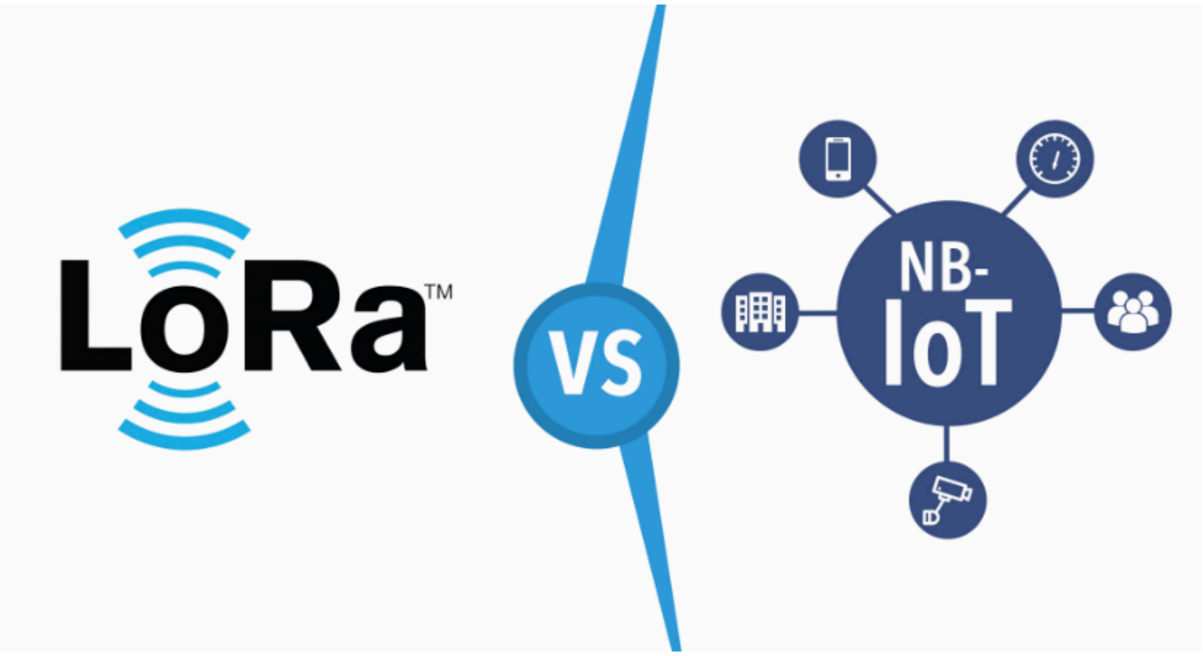
ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ

UNIVERSITY OF PIRAEUS



Master Thesis Subject

Internet of things, LoraWan VS Nb-Iot

Student: Nikolaos Konstas

Supervision:
Associate Professor Ms.Angeliki Alexiou

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Abstract:

Internet of things (IoT) changes significantly the requirements for connectivity, mainly with regards to long battery life, low device cost, low deployment cost, extended coverage and support for a massive number of devices. Driven from these requirements, several different cellular and non-cellular low power wide area network (LPWAN) solutions are emerging and competing for IoT business and the overall connectivity market. Motivated by this, in this thesis, we review and compare the pros and the cons for 2 specific LPWANs,LoraWan and Narrowband IoT, as well as, we discuss their suitability for different IoT applications. Finally, we will simulate the LoraWan with the help of Matlab platform and compare it to a an existing simulation of Narrowband IoT,to see the differences.

Το Internet of things (IoT) πρόκειται να αλλάξει τις απαιτήσεις για συνδεσιμότητα καθώς και την ανάγκη για μεγαλύτερη διάρκεια μπαταρίας, χαμηλό κόστος συσκευών, χαμηλό κόστος παραγωγής, αυξημένη κάλυψη και υποστήριξη για έναν πολύ μεγάλο αριθμό συσκευών. Οδηγούμενοι από τις παραπάνω απαιτήσεις διάφορα κυψελοτά και μη κυψελοτά χαμηλής ισχύος ευρείας κάλυψης δίκτυα, εχουν πάρει θέση στην αγορά.

Σε αυτή την διπλωματική αναλύουμε και συγκρίνουμε 2 τεχνολογίες οι οποίες δείχνουν ότι θα παίξουν σημαντικό ρόλο στα επόμενα χρόνια. Συγκρίνουμε λοιπόν το LoRaWan με το Narrow-Nand IoT. Συγκρίνουμε τα αρνητικά και τα θετικά της κάθε τεχνολογίας καθώς και την χρησιμότητα τους σε διάφορες εφαρμογές. Τέλος γίνεται η προσομοίωση μέσω του προγράμματος Matlab και συγκρίνουμε τα αποτελέσματα της προσομοίωσης.

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1 Low Power Wide Area Networks(Lora)

1.1 Introduction

During the last decades, wireless communications have been a subject of much hype, due to their increasing integration in everyday life. As a result, they have evolved significantly from early voice systems to today's highly sophisticated integrated communication platforms that provide numerous services, which are used by billions of people around the world. The internet of things (IoT) is considered as the next revolution of communications, which will play a significant role in improving the efficiency of the human, natural and/or energy resource management, as well as in optimizing the production processes. As a consequence, by 2020, it is expected that approximately 26 billion IoT devices will serve the global population.

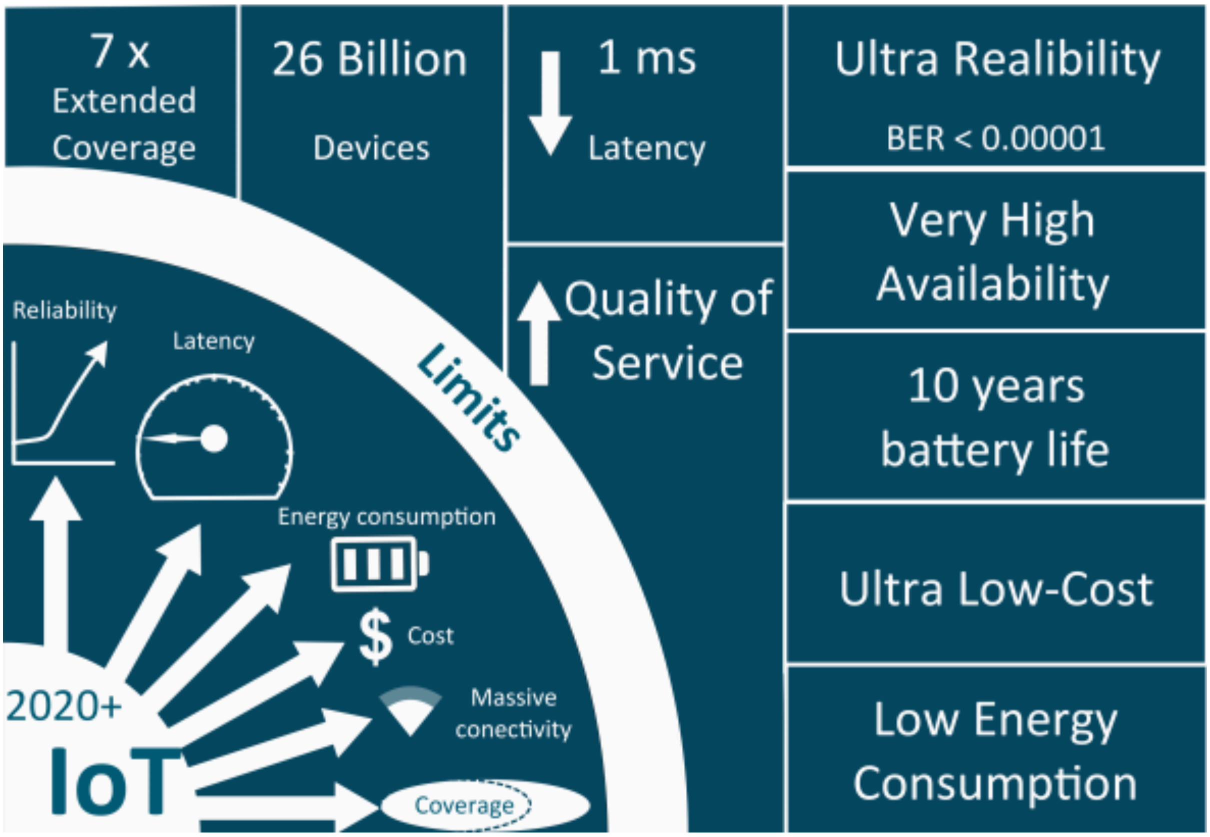


Fig. 0. Applications of LPWA technologies across different sectors

On the other hand, as IoT systems evolve, we are comforting more and more inherent limitations, preventing further performance improvements. Therefore, it is necessary to develop the appropriate technologies, which meet those requirements.

Since recently, there was no economical, flexible, and reliable technology for the connection of the IoT devices in the network. Traditional solutions, such as short-range wireless networks, e.g.Bluetooth, ZigBee, Z-Wave, wireless local area networks (WLANs), e.g. wireless fidelity (WiFi), HiperLAN, and cellular networks, e.g., global system for mobile communications (GSM), long-3term evolution (LTE), etc., even though they allow the wireless connection of the IoT devices in the network, they are usually of high cost, high energy consumption, high complexity and low reliability approaches. As a result, the technology of low power wide area networks (LPWANs) has been recently developed. LPWANs are considered excellent candidates for IoT applications,since they promise high energy efficiency, low power consumption and high coverage capabilities.

1.2 Introduction To Low Power Wide Area Networks

The Internet of Things (IoT) promises to revolutionize the way we live and work. It could help us in overcoming the top global challenges due to population explosion, energy crisis, resource depletion, and environmental pollution. To realize this vision, *things* need to sense their environment, share this information among themselves as well as with humans to enable intelligent decision making for positively affecting our entire ecosystem. Due to this promise, an interest in IoT is phenomenal. Multiple independent studies have forecasted a rampant growth in volume and revenue of IoT and Machine-to-Machine (M2M) industry in the next ten years. Number of connected M2M devices and consumer electronics will surpass the number of human subscribers using mobile phones, personal computers, laptops and tablets by 2020 [1]. Moving forward, by 2024, the overall IoT industry is expected to generate a revenue of 4.3 trillion dollars [2] across different sectors such as device manufacturing, connectivity, and other value-added services. Recent improvements in cheap sensor and actuation technologies along with an emergence of novel communication technologies are all positive indicators, supporting the forecasted trends.

Low Power Wide Area (LPWA) networks represent a novel communication paradigm, which will complement traditional cellular and short-range wireless technologies in addressing diverse requirements of IoT applications. LPWA technologies offer unique sets of features including wide-area connectivity for low power and low data rate devices, not provided by legacy wireless technologies. Their market is expected to be huge. Approximately one fourth of overall 30 billion IoT/M2M devices are to be connected to the Internet using LPWA networks using either proprietary or cellular technologies [3].

Figure 1 highlights variety of applications across several business sectors that can exploit LPWA technologies to connect their end devices. These business sectors include but not limited to smart city, personal IoT applications, smart grid, smart metering, logistics, industrial monitoring, agriculture, etc.

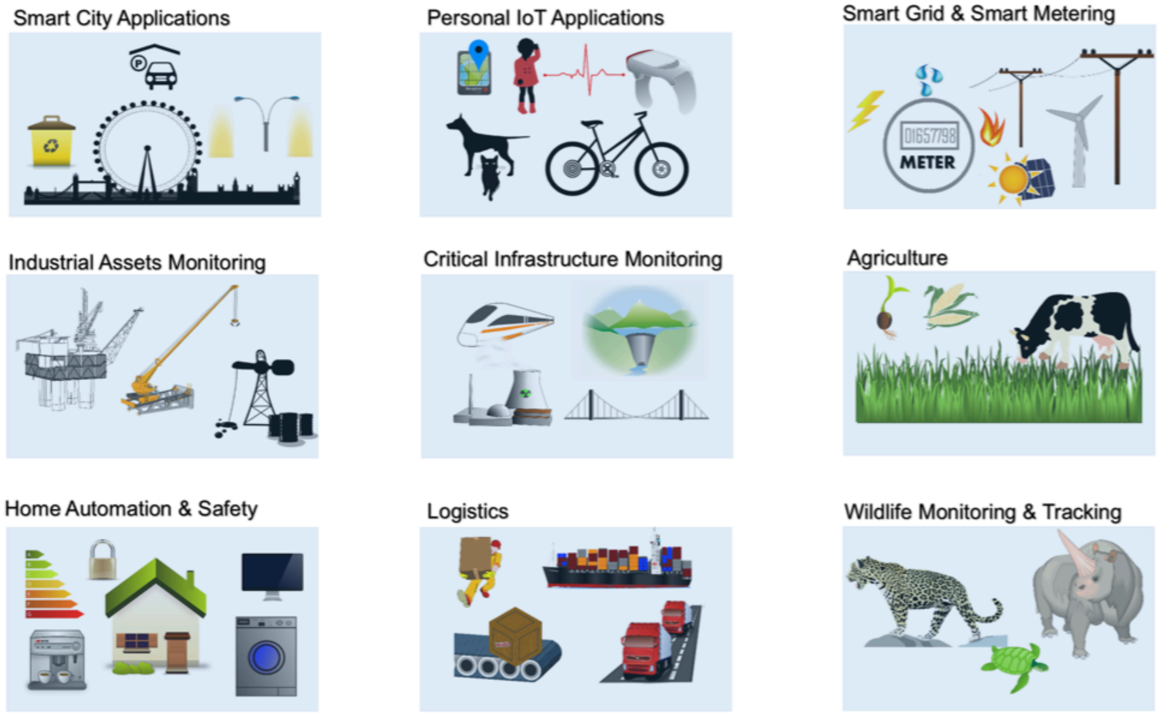


Fig. 1. Applications of LPWA technologies across different sectors

1.3 Importance Of Low Power Wide Area Networks

LPWA networks are unique because they make different tradeoffs than the traditional technologies prevalent in IoT landscape such as short-range wireless networks e.g., Zig- Bee, Bluetooth, Z-Wave, legacy wireless local area networks (WLANs) e.g., Wi-Fi, and cellular networks e.g. Global Sys- tem for Mobile Communications (GSM), Long-Term Evolution (LTE) etc. The legacy non-cellular wireless technologies are not ideal to connect low power devices distributed over large geographical areas. The range of these technologies is limited to a few hundred meters at best. The devices, therefore, cannot be arbitrarily deployed or moved *anywhere*, a requirement for many applications for smart city, logistics and personal health [4]. The range of these technologies is extended using a dense deployment of devices and gateways connected using multihop mesh networking. Large deployments are thus prohibitively expensive. Legacy WLANs, on the other hand, are characterized by shorter coverage areas and higher power consumption for machine-type communication (MTC).

A wide area coverage is provided by cellular networks, a reason of a wide adoption of second generation (2G) and third generation (3G) technologies for M2M communication. How- ever, an impending decommissioning of these technologies [5], as announced by some mobile network operators (MNOs), will broaden the technology gap in connecting low-power devices. In general, traditional cellular technologies do not achieve energy efficiency high enough to offer ten years of battery lifetime. The complexity and cost of cellular devices is high due to their ability to deal with complex waveforms, optimized for voice, high speed data services, and text.

For low-power MTC, there is a clear need to strip complexity to reduce cost.With a phenomenal range of a few to tens of kilometres [6] and battery life of ten years and beyond, LPWA technologies are promising for the Internet of low-power, low-cost, and low-throughput things. A very long range of LPWA technologies enables devices to spread and move over large geographical areas. IoT and M2M devices connected by LPWA technologies can be turned on *anywhere and anytime* to sense and interact with their environment instantly. It is worth clarifying that LPWA technologies achieve long range and low power operation at the expense of low data rate (typically in orders of tens of kilobits per seconds) and higher latency (typically in orders of seconds or minutes).

Therefore it is clear that LPWA technologies are not meant to address each and every IoT use case and caters to a niche area in IoT landscape. Specifically, LPWA technologies are considered for those use cases that are delay tolerant, do not need high data rates, and typically require low power consumption and low cost, the latter being an important aspect. Such MTC application are categorized as Massive MTC [7] in contrast to Critical MTC [7] applications that require ultra-low latency and ultra high reliability.

The latter are definitely out of the remit of LPWA technologies because their stringent performance requirements such as up to five nines (99.999%) reliability and up to 1-10 ms latency cannot be guaranteed with a low cost and low power solution. While LPWA technologies, for this reason, are not suitable for many industrial IoT, vehicle to vehicle (V2V), and vehicle to infrastructure (V2I) applications [8], they still meet the needs of a plethora of applications for smart cities, smart metering, home automation, wearable electronics, logistics, environmental monitoring etc. (see Figure 1) that exchange small amount of data and that also infrequently. Therefore, appeal of LPWA technologies, although limited by its low data rate, is still broad. This is the reason why LPWA technologies generated so much interest after the proprietary technologies such as SIGFOX [9] and LoRa [10] hit the market.

1.4 Low Power Wide Area Networks Technologies

At this moment, there are several competing LPWA technologies, each employing various techniques to achieve long range, low power operation, and high scalability. The LPWAN heavyweights are LoRa and SigFox. However, a few others, like Ingenue and Weightless are definitely worth a look. To start, let's explore what the heavyweights have to offer[11]:

LoRa, has gained momentum in Europe, where there are already deployed coverage areas. It requires the use of a radio chipset from Semtech, so it's not an open standard.

Pros:

- Great industry support and partners, including Cisco, IBM Microchip Technology, KPN, IMST, and more.
- Comparatively decent bandwidth (for LPWAN, you're not going to be streaming YouTube clips here)
- Security: AES CCM (128 bit) encryption and authentication

Cons:

- Not an open standard
- You can only use vendors approved by Semtech
- Private networks are difficult/impossible on LoRa
- Difficult validation/acknowledgement protocols and high error rates
  Limited downlink capability

Sigfox is an other major big contender that is also already deployed. SigFox also has strong industry support from partners like Texas Instruments, Silicon Labs, and Axom.

Pros:

- SigFox has deployed with a lot of traction in Europe and San Francisco
- There is no receiver circuitry, so less power is required.
- Longer range, achieved at the cost of slower modulation, making SigFox ideal for simple metering applications

Cons:

- Not an open standard
- US architecture is different from what has been deployed in Europe due to the transmission length mandated by the FCC, so testing may not be as robust.
- Minimal security (16 bit encryption)
- No downlink communication
- Potential for higher RF interference

Ingenu has been slower to market than SigFox or LoRa because its spent a lot of time and effort developing the full LPWAN technology stack. Ingenu was a founding member of the iEEE 802.15.4k task group, working on low-energy infrastructure monitoring, so they are strong on the fundamentals.

Pros:

- Architecture development with superior uplink and downlink capacity, compared to other LPWANs.
- Higher link budget than LoRa or SigFox, providing greater, and more robust, area coverage
- International compatibility with operation at 2.4 GHz.

Cons:

- Increased interference from WiFi, Bluetooth, and buildings with 2.4 GHz operation
- Shorter battery life due to higher processing power

Weightless is another sub-1 GHz LPWAN, operating in the unlicensed spectrum. I'm particularly fond of it because it's the only open-standard in that space, and I love the potential that offers for new applications. There are three standards, N, W, and P. You can balance cost against speed and extensive feature sets to choose which is best for your system.

Pros:

- Options for low-speed sensor networks (N), or adaptive rate private networks (P)
- Uplink and downlink capability (P, W)
- Good range in urban environments (2-5+ km)
- Co-exists with other RF technologies with minimal interference using advanced demodulation

Cons:

- TV white space spectrum is required for Weightless W
- Battery life ranges from 2-10 years, depending on the standard

Several other options exist but have yet to gain much traction. These include LTE-M, IEEE P802.11AH (a low power wifi option), and Dash7. In order to deploy an IoT device, you need an LPWAN to be readily available, so these aren't great choice yet.
In the next paragraps we will study 2 of these technologies LoraWan and Nb-Iot.We will see the advantages and disadvantages of each technology.

2

LoRa-Wan Network

2.1 What is LoRaWan?

LoRaWAN defines the communication protocol and system architecture for the network while the LoRa® physical layer(Figure 2) enables the long-range communication link.The protocol and network architecture have the most in influence in determining the battery lifetime of a node, the network capacity, the quality of service, the security, and the variety of applications served by the network.

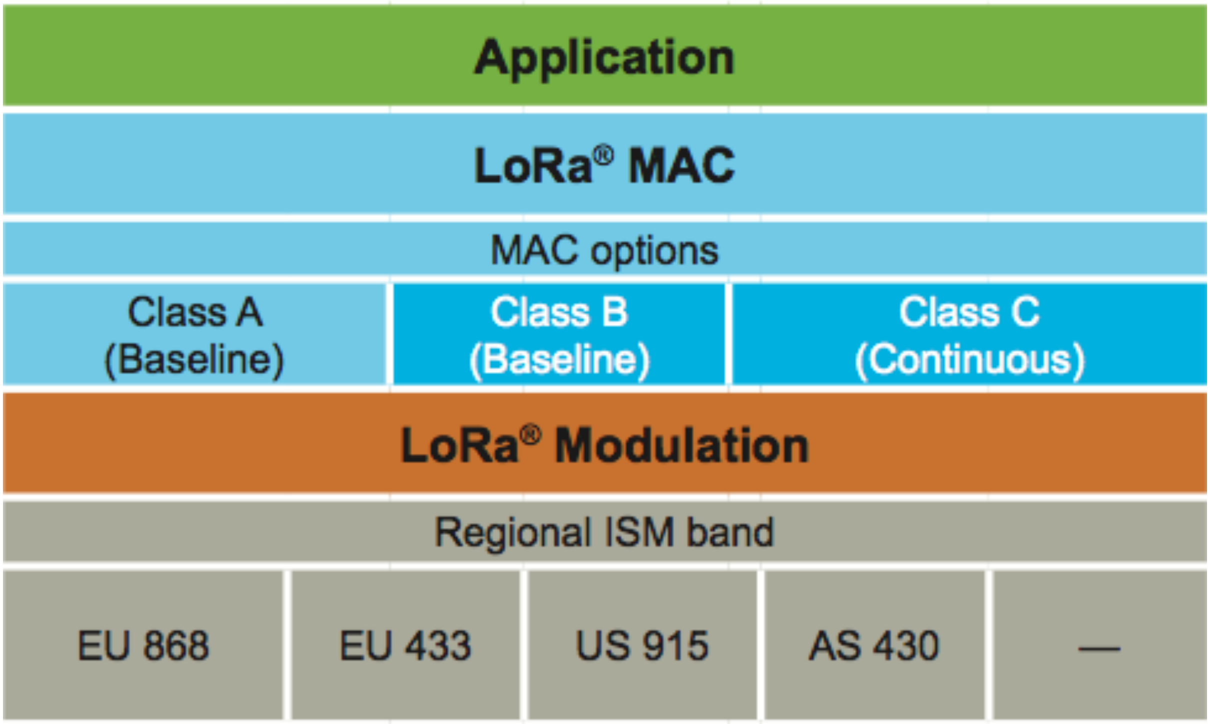


Figure 2. LoRaWan Description In Layers

2.2 Network Architecture

Many existing deployed networks utilize a mesh network architecture. In a mesh network, the individual end-nodes forward the information of other nodes to increase the communication range and cell size of the network. While this increases the range, it also adds complexity, reduces network capacity, and reduces battery lifetime as nodes receive and forward information from other nodes that is likely irrelevant for them. Long range star architecture makes the most sense for preserving battery lifetime when long-range connectivity can be achieved.

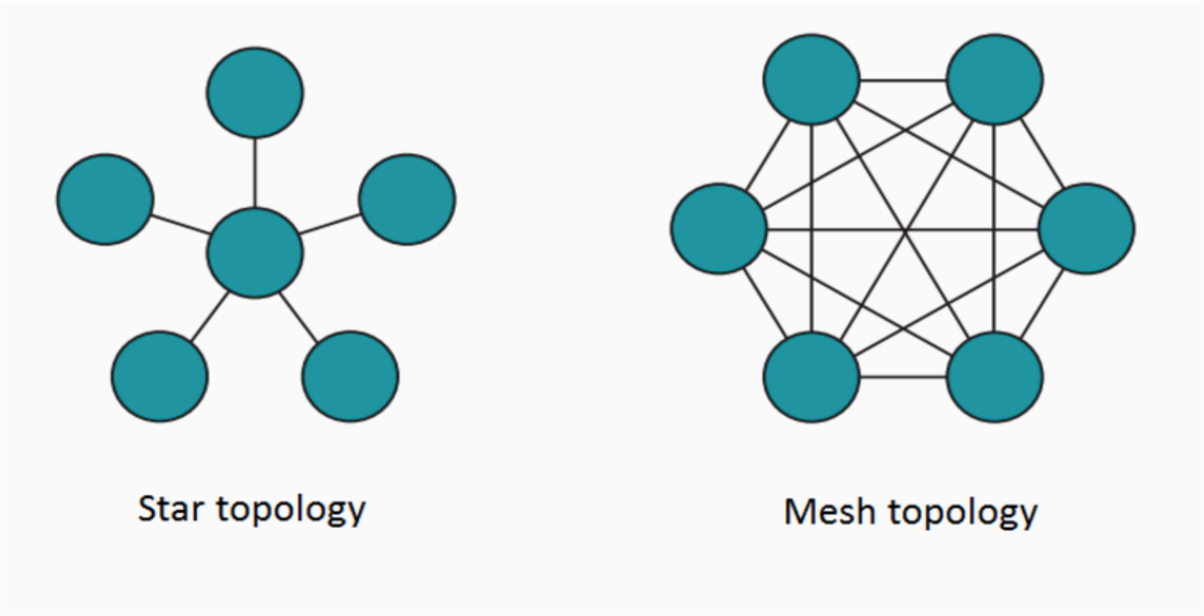


Figure 3. Star VS Mesh Topology

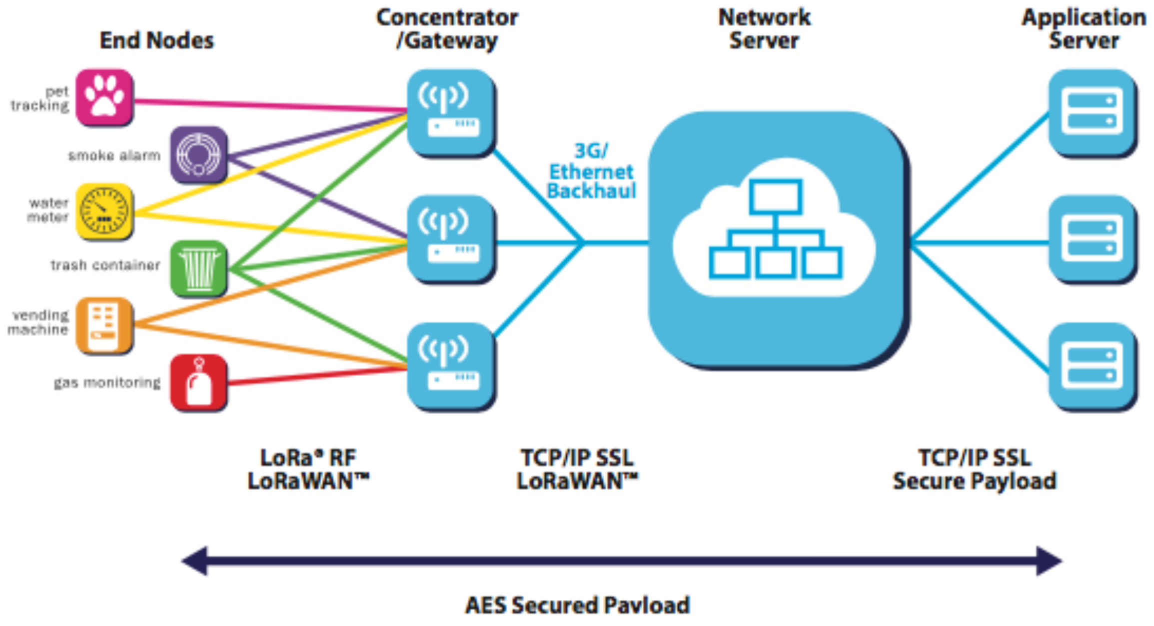


Figure 4. LoRaWan Network architecture

In a LoRaWAN network nodes are not associated with a specific gateway. Instead, data transmitted by a node is typically received by multiple gateways. Each gateway will forward the received packet from the end-node to the cloud-based network server via some backhaul (either cellular, Ethernet, satellite, or Wi-Fi).

The intelligence and complexity is pushed to the network server, which manages the network and will filter redundant received packets, perform security checks, schedule acknowledgments through the optimal gateway, and perform adaptive data rate, etc. If a node is mobile or moving there is no handover needed from gateway to gateway, which is a critical feature to enable asset tracking applications–a major target application vertical for IoT.

2.3 Battery Lifetime

The nodes in a LoRaWAN network are asynchronous and communicate when they have data ready to send whether event-driven or scheduled. This type of protocol is typically referred to as the Aloha method. In a mesh network or with a synchronous network, such as cellular, the nodes frequently have to ‘wake up’ to synchronize with the network and check for messages. This synchronization consumes significant energy and is the number one driver of battery lifetime reduction. In a recent study and comparison done by GSMA of the various technologies addressing the LPWAN space, LoRaWAN showed a 3 to 5 times advantage compared to all other technology options.

2.4 Network Capacity

In order to make a long range star network viable, the gateway must have a very high capacity or capability to receive messages from a very high volume of nodes. High network capacity in a LoRaWAN network is achieved by utilizing adaptive data rate and by using a multichannel multi-modem transceiver in the gateway so that simultaneous messages on multiple channels can be received. The critical factors effecting capacity are the number of concurrent channels, data rate (time on air), the payload length, and how often nodes transmit. Since LoRaWAN is a spread spectrum-based modulation, the signals are practically orthogonal to each other when different spreading factors are utilized. As the spreading factor changes, the effective data rate also changes. The gateway takes advantage of this property by being able to receive multiple different data rates on the same channel at the same time. If a node has a good link and is close to a gateway, there is no reason for it to always use the lowest data rate and fill up the available spectrum longer than it needs to. By shifting the data rate higher, the time on air is shortened opening up more potential space for other nodes to transmit. Adaptive data rate also optimizes the battery lifetime of a node. In order to make adaptive data rate work, symmetrical up link and down link is required with sufficient downlink capacity. These features enable a LoRaWAN network to have a very high capacity and make the network scalable. A network can be deployed with a minimal amount of infrastructure, and as capacity is needed, more gateways can be added, shifting up the data rates, reducing the amount of overhearing to other gateways, and scaling the capacity by 6-8x. Other LPWAN alternatives do not have the scalability of LoRaWAN due to technology trade-offs, which limit downlink capacity or make the downlink range asymmetrical to the uplink range.

2.5 Nodes Classes

End-devices serve different applications and have different requirements. In order to optimize a variety of end application profiles, LoRaWAN utilizes different device classes. The device classes trade off network downlink communication latency versus battery lifetime. In a control or actuator-type application, the downlink communication latency is an important factor.

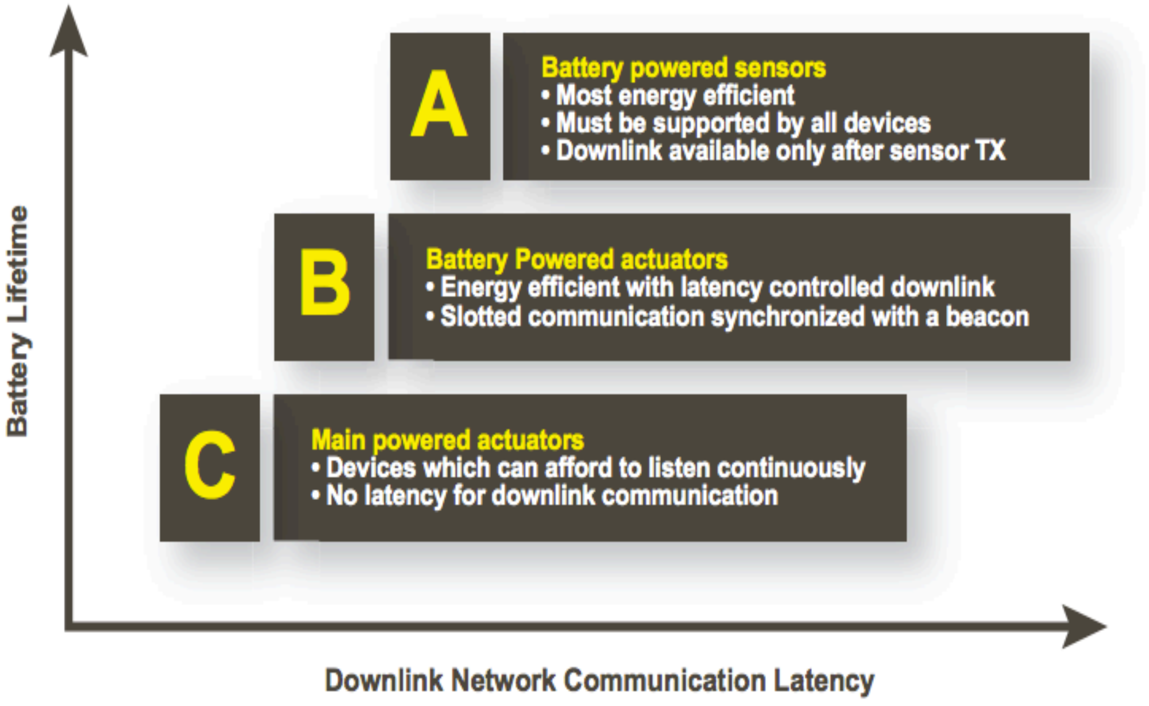


Figure 5. LoRaWan Nodes Classes

- Bi-directional end-devices (Class A): End-devices of Class A allow for bi-directional communications whereby each end-device's uplink transmission is followed by two short downlink receive windows. The transmission slot scheduled by the end-device is based on its own communication needs with a small variation based on a random time basis (ALOHA-type of protocol). This Class A operation is the lowest power end-device system for applications that only require downlink communication from the server shortly after the end-device has sent an uplink transmission. Downlink communications from the server at any other time will have to wait until the next scheduled uplink.

- Bi-directional end-devices with scheduled receive slots (Class B): In addition to the Class A random receive windows, Class B devices open extra receive windows at scheduled times. In order for the end-device to open its receive window at the scheduled time, it receives a time-synchronized beacon from the gateway. This allows the server to know when the end-device is listening.

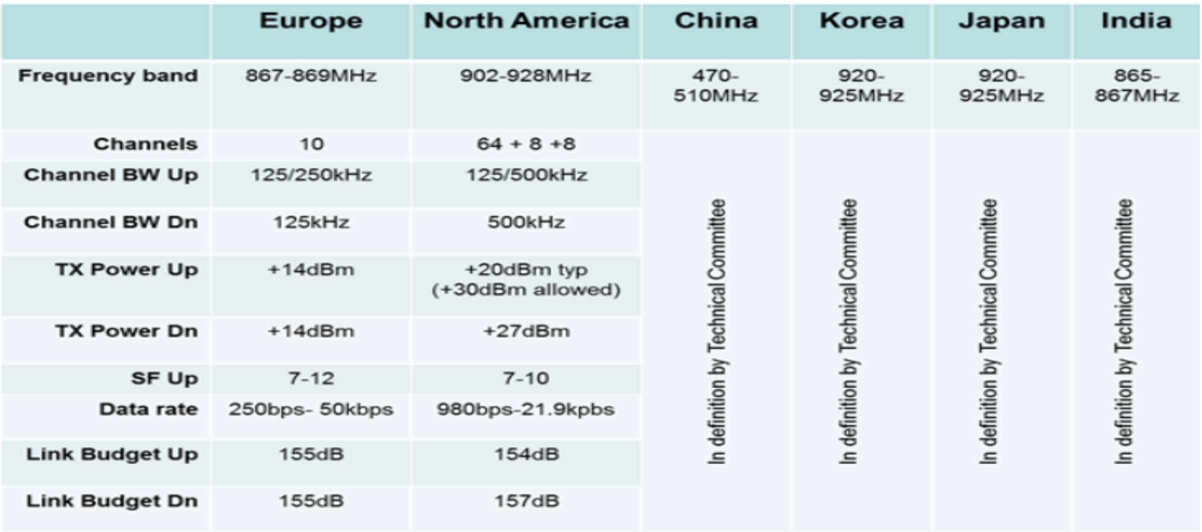
- Bi-directional end-devices with maximal receive slots (Class C): End-devices of Class C have almost continuously open receive windows, only closed when transmitting.

2.6 Security

It is extremely important for any LPWAN to incorporate security. LoRaWAN utilizes two layers of security: one for the network and one for the application. The network security ensures authenticity of the node in the network while the application layer of security ensures the network operator does not have access to the end user's application data. AES encryption is used with the key exchange utilizing an IEEE EUI64 identifier. There are trade-offs in every technology choice but the LoRaWAN features in network architecture, device classes, security, scalability for capacity, and optimization for mobility address the widest variety of potential IoT applications.

2.7 LoRaWan Specification

The LoRaWAN specification varies slightly from region to region based on the different regional spectrum allocations and regulatory requirements.LoRaWAN specification for Europe and North America are differenced, but other regions are still being defined by the technical committee. Joining the LoRa Alliance as a contributor member and participating in the technical committee can have significant advantages to companies targeting solutions for the Asia market.



	Europe	North America	China	Korea	Japan	India
Frequency band	867-869MHz	902-928MHz	470-510MHz	920-925MHz	920-925MHz	865-867MHz
Channels	10	64 + 8 +8	In definition by Technical Committee	In definition by Technical Committee	In definition by Technical Committee	In definition by Technical Committee
Channel BW Up	125/250kHz	125/500kHz				
Channel BW Dn	125kHz	500kHz				
TX Power Up	+14dBm	+20dBm typ (+30dBm allowed)				
TX Power Dn	+14dBm	+27dBm				
SF Up	7-12	7-10				
Data rate	250bps- 50kbps	980bps-21.9kpbs				
Link Budget Up	155dB	154dB				
Link Budget Dn	155dB	157dB				

Figure 6. LoRaWan Regional Specification

- LoRaWAN for Europe

LoRaWAN defines ten channels, eight of which are multi data rate from 250bps to 5.5 kbps, a single high data rate LoRaWAN channel at 11kbps, and a single FSK channel at 50kbps. The maximum output power allowed by ETSI in Europe is +14dBM, with the exception of the G3 band which allows +27dBm.There are duty cycle restrictions under ETSI but no max transmission or channel dwell time limitations.

- LoRaWAN for North America

The ISM band for North America is from 902-928MHz. LoRaWAN defines 64, 125kHz uplink channels from 902.3 to 914.9MHz in 200kHz increments. There are an additional eight 500KHz uplink channels in 1.6MHz increments from 903MHz to 914.9MHz. The eight downlink channels are 500kHz wide starting from 923.3MHz to 927.5MHz.The maximum output power in North America 902-928MHz band is +30dBm but for most devices +20dBm is sufficient. Under FCC there are no duty cycle limitations but there is a 400msec max dwell time per channel.

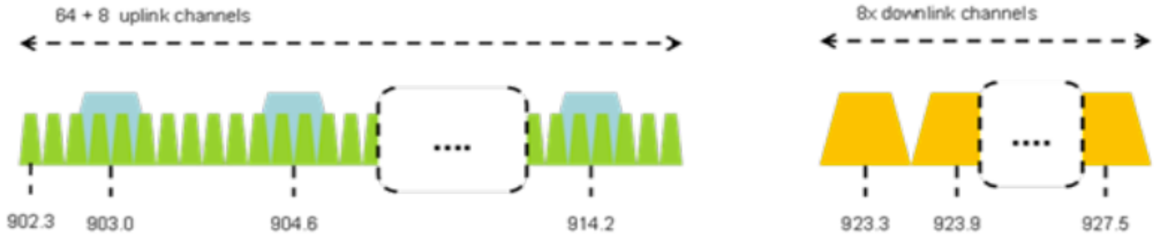


Figure 7. LoRaWan downlink channels

3 NarrowBand IOT (NB-Iot)

3.1 Introduction to NarrowBand Iot

The mobile industry has developed and standardised a new class of low power wide area (LPWA) technologies that help network operators to tailor the cost, coverage and power consumption of connectivity for specific IoT applications.

NarrowBand IoT (**NB-IoT**) is a one of these Low Power Wide Area Network (LPWAN) radio technology standard that has been developed to enable a wide range of devices and services to be connected using cellular telecommunications bands. NB-IoT is a narrowband radio technology designed for the Internet of Things (IoT), and is one of a range of Mobile IoT (MIoT) technologies standardized by the 3rd Generation Partnership Project (3GPP)[13].

It can be deployed in three different operation modes [14] stand-alone as a dedicated carrier, [15] in-band within the occupied bandwidth of a wideband LTE carrier, and [16] within the guard-band of an existing LTE carrier. In stand-alone deployment, NB-IoT can occupy one GSM channel (200 kHz) while for in-band and guard-band deployment, it will use one physical resource block (PRB) of LTE (180 kHz). The design targets of NB-IoT include low-cost devices, high coverage (20-dB improvement over GPRS), long device battery life (more than 10 years), and massive capacity (greater than 52K devices per channel per cell). Latency is relaxed although a delay budget of 10 seconds is the target for exception reports. Since NB-IoT is expected to adopt a design based on existing LTE functionalities, it is possible to reuse the same hardware and also to share spectrum without coexistence issues. In addition, NB-IoT can simply plug into the LTE core network. This allows all network services such as authentication, security, policy, tracking, and charging to be fully supported.

3.2 Downlink transmission scheme

The downlink of NB-IoT is based on OFDMA with the same 15 kHz subcarrier spacing as LTE. Slot, subframe, and frame durations are 0.5 ms, 1 ms, and 10 ms, respectively, identical to those in LTE. Furthermore, slot format in terms of cyclic prefix (CP) duration and number of OFDM symbols per slot are also identical to those in LTE. In essence, an NB-IoT carrier uses one LTE PRB in the frequency domain, i.e. twelve 15 kHz subcarriers for a total of 180 kHz. Reusing the same OFDM numerology as LTE ensures the coexistence performance with LTE in the downlink. For example, when NB-IoT is deployed inside an LTE carrier, the orthogonality between the NB-IoT PRB and all the other LTE PRBs is preserved in the downlink.

3.3 Uplink transmission scheme

The uplink of NB-IoT supports both multi-tone and single- tone transmissions. Multi-tone transmission is based on SC- FDMA with the same 15 kHz subcarrier spacing, 0.5 ms slot, and 1 ms subframe as LTE. Single-tone transmission supports two numerologies, 15 kHz and 3.75 kHz. The 15 kHz numerology is identical to LTE and thus achieves the best coexistence performance with LTE in the uplink. The 3.75 kHz single-tone numerology uses 2 ms slot duration. Like the downlink, an uplink NB-IoT carrier uses a total system bandwidth of 180 kHz.

3.4 Deployment options

NB-IoT may be deployed as a stand-alone carrier using any available spectrum exceeding 180 kHz. It may also be deployed within the LTE spectrum allocation, either inside an LTE carrier or in the guard band. These different deployment scenarios are illustrated in Fig. 8. The deployment scenario, stand-alone, in-band, or guard-band, however should be transparent to a user equipment (UE) when it is first turned on and searches for an NB-IoT carrier. Similar to existing LTE UEs, an NB-IoT UE is only required to search for a carrier on a 100 kHz raster. An NB-IoT carrier that is intended for facilitating UE initial synchronization is referred to as an anchor carrier. The 100 kHz UE search raster implies that for in-band deployments, an anchor carrier can only be placed in certain PRBs. For example, in a 10 MHz LTE carrier, the indexes of the PRBs that are best aligned with the 100 kHz grid and can be used as an NB-IoT anchor carrier are 4, 9, 14, 19, 30, 35, 40, 45. The PRB indexing starts from index 0 for the PRB occupying the lowest frequency within the LTE system bandwidth.

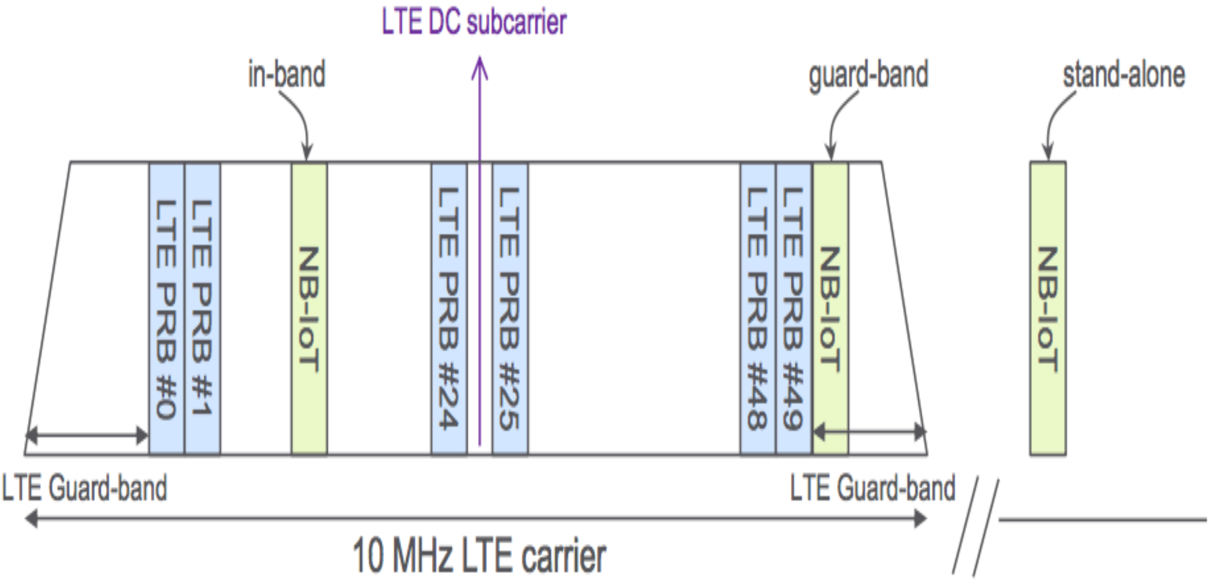


Figure 8. Examples of NB-IoT stand-alone deployment and LTE in-band and guard-band deployments in the downlink.

Figure. 8 illustrates the deployment options of NB-IoT with a 10 MHz LTE carrier. The PRB right above the DC subcarrier, i.e., PRB #25, is centered at 97.5 kHz (i.e. a spacing of 6.5 subcarriers) above the DC subcarrier. Since the LTE DC subcarrier is placed on the 100 kHz raster, the center of PRB#25 is 2.5 kHz from the nearest 100 kHz grid. The spacing between the centers of two neighboring PRBs above the DC subcarrier is 180 kHz. Thus, PRB #30, #35,

#40, and #45 are all centered at 2.5 kHz from the nearest 100 kHz grid. It can be shown that for LTE carriers of 10 MHz and 20 MHz, there exists a set of PRB indexes that are all centered at 2.5 kHz from the nearest 100 kHz grid, whereas for LTE carriers of 3 MHz, 5 MHz, and 15 MHz bandwidth, the PRB indexes are centered at least 7.5 kHz away from the 100 kHz raster. Further, an NB-IoT anchor carrier should not be any of the middle 6 PRBs of the LTE carrier (e.g. PRB#25 of 10 MHz LTE, although its center is 2.5 kHz from the nearest 100 kHz raster). This is due to that LTE synchronization and broadcast channels occupy many resource elements in the middle 6 PRBs, making it difficult to use these PRBs for NB-IoT.

Similar to the in-band deployment, an NB-IoT anchor carrier in the guard-band deployment needs to have center frequency no more than 7.5 kHz from the 100 kHz raster. NB- IoT cell search and initial acquisition are designed for a UE to be able to synchronize to the network in the presence of a raster offset up to 7.5 kHz.Multi-carrier operation of NB-IoT is supported. Since it suffices to have one NB-IoT anchor carrier for facilitating UE initial synchronization, the additional carriers do not need to be near the 100 kHz raster grid. These additional carriers are referred to as secondary carriers.

3.5 Physical Channels

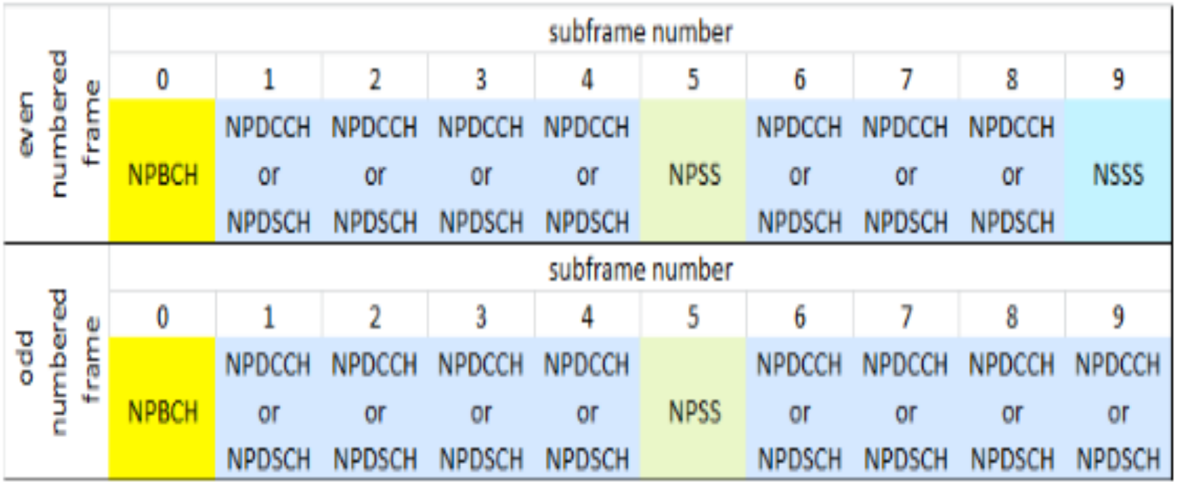
NB-IoT physical channels are designed based on legacy LTE to a large extent. In this section, we provide an overview of them with a focus on aspects that are different from legacy LTE.

3.5.1 Downlink

NB-IoT provides the following physical signals and channels in the downlink.

- Narrowband Primary Synchronization Signal (NPSS)
- Narrowband Secondary Syncronization Signal(NSSS)
- Narrowband Physical Broadcast Channel(NPBCH)
- Narrowband Physical Downlink Control Channel(NPDCCH)
- Narrowband Physical Downlink Shared Channel(NPDSCH)

Unlike LTE, these NB-IoT physical channels and signals are primarily multiplexed in time. Figure 9 illustrates how the NB-IoT subframes are allocated to different physical channels and signals. Each NB-IoT subframe spans over one PRB (i.e. 12 subcarriers) in the frequency domain and 1 ms in the time domain.



	subframe number									
	0	1	2	3	4	5	6	7	8	9
even numbered frame	NPBCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPSS	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NSSS

	subframe number									
	0	1	2	3	4	5	6	7	8	9
odd numbered frame	NPBCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPSS	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH	NPDCCH or NPDSCH

Figure 9. Time multiplexing between NB-IoT downlink physical channels and signals.

NPSS and NSSS are used by an NB-IoT UE to perform cell search, which includes time and frequency synchronization, and cell identity detection. Since the legacy LTE synchronization sequences occupy 6 PRBs, they cannot be reused for NB-IoT. A new design is thus introduced.

NPSS is transmitted in subframe #5 in every 10 ms frame, using the last 11 OFDM symbols in the subframe. NPSS detection is one of the most computationally demanding operations from a UE perspective. To allow efficient implementation of NPSS detection, NB-IoT uses a hierarchical sequence. For each of the 11 NPSS OFDM symbols in a subframe, either $\boldsymbol{p}$ or $-\boldsymbol{p}$ is transmitted, where $\boldsymbol{p}$ is the base sequence generated based on a length-11 Zadoff- Chu (ZC) sequence [17] with root index 5. Each of the length- 11 ZC sequence is mapped to the lowest 11 subcarriers within the NB-IoT PRB.

NSSS has 20 ms periodicity and is transmitted in subframe #9, also using the last 11 OFDM symbols that consist of 132 resource elements overall. NSSS is a length-132 frequency-domain sequence, with each element mapped to a resource element. NSSS is generated by element-wise multiplication between a ZC sequence and a binary scrambling sequence. The root of the ZC sequence and binary scrambling sequence are determined by narrowband physical cell identity (NB- PCID). The cyclic shift of the ZC sequence is further determined by the frame number.

NPBCH carries the master information block (MIB) and is transmitted in subframe #0 in every frame. A MIB remains unchanged over the 640 ms transmission time interval (TTI).

NPDCCH carries scheduling information for both downlink and uplink data channels. It further carries the HARQ acknowledgement information for the uplink data channel as well as paging indication and random-access response (RAR) scheduling information. NPDSCH carries data from the higher layers as well as paging message, system information, and the RAR message. As shown in Figure 9, there are a number of subframes that can be allocated to carry NPDCCH or NPDSCH. To reduce UE complexity, all the downlink channels use the LTE tail-biting convolutional code (TBCC). Furthermore, the maximum transport block size of NPDSCH is 680 bits. In comparison, LTE without spatial multiplexing supports maximum TBS greater than 70,000 bits.

NRS is used to provide phase reference for the demodulation of the downlink channels. NRSs are time-and- frequency multiplexed with information bearing symbols in subframes carrying NPBCH, NPDCCH and NPDSCH, using 8 resource elements per subframe per antenna port.

3.5.2 Uplink

NB-IoT includes the following channels in the uplink.

- Narrowband Physical Random Access Channel(NPRACH)
- Narrowband Physical Uplink Shared Channel(NPUSCH)

NPRACH is a newly designed channel since the legacy
LTE Physical Random Access Channel (PRACH) uses a bandwidth of 1.08 MHz, more than NB-IoT uplink bandwidth. One NPRACH preamble consists of 4 symbol groups, with each symbol group comprising of one CP and 5 symbols. The CP length is 66.67 µs (Format 0) for cell radius up to 10 km and 266.7 µs (Format 1) for cell radius up to 40 km. Each symbol, with fixed symbol value 1, is modulated on a 3.75 kHz tone with symbol duration of 266.67 µs. However, the tone frequency index changes from one symbol group to another. The waveform of NPRACH preamble is referred to as single-tone frequency hopping. An example of NPRACH frequency hopping is illustrated in Figure 10. To support coverage extension, a NPRACH preamble can be repeated up to 128 times.

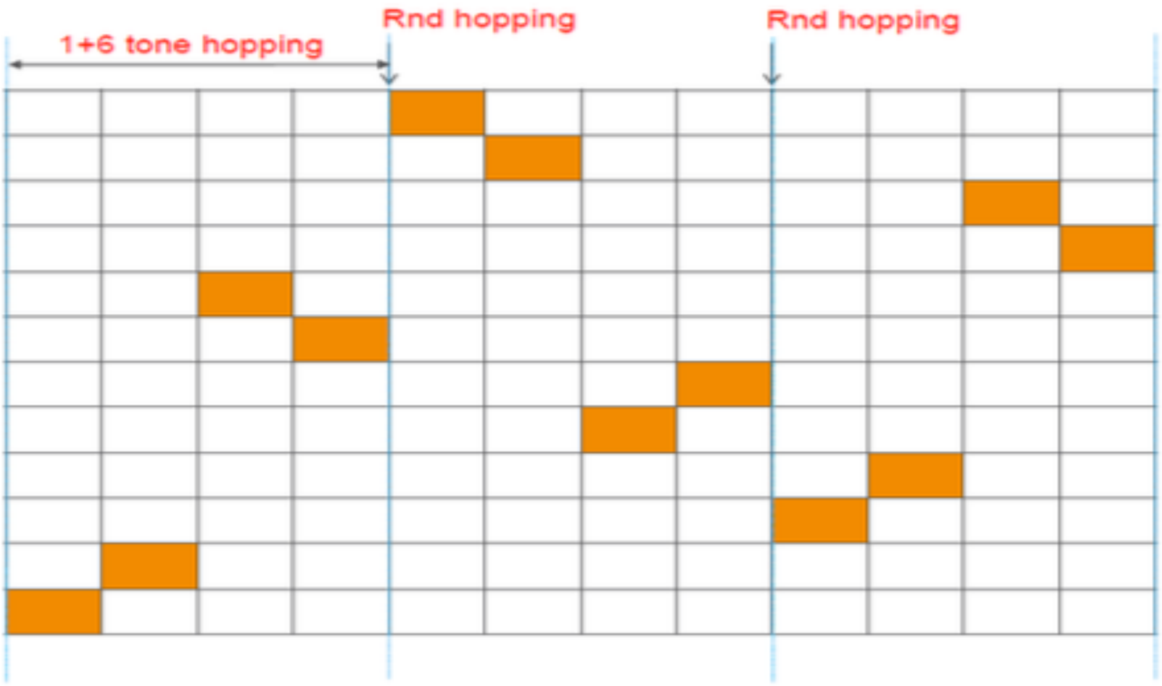
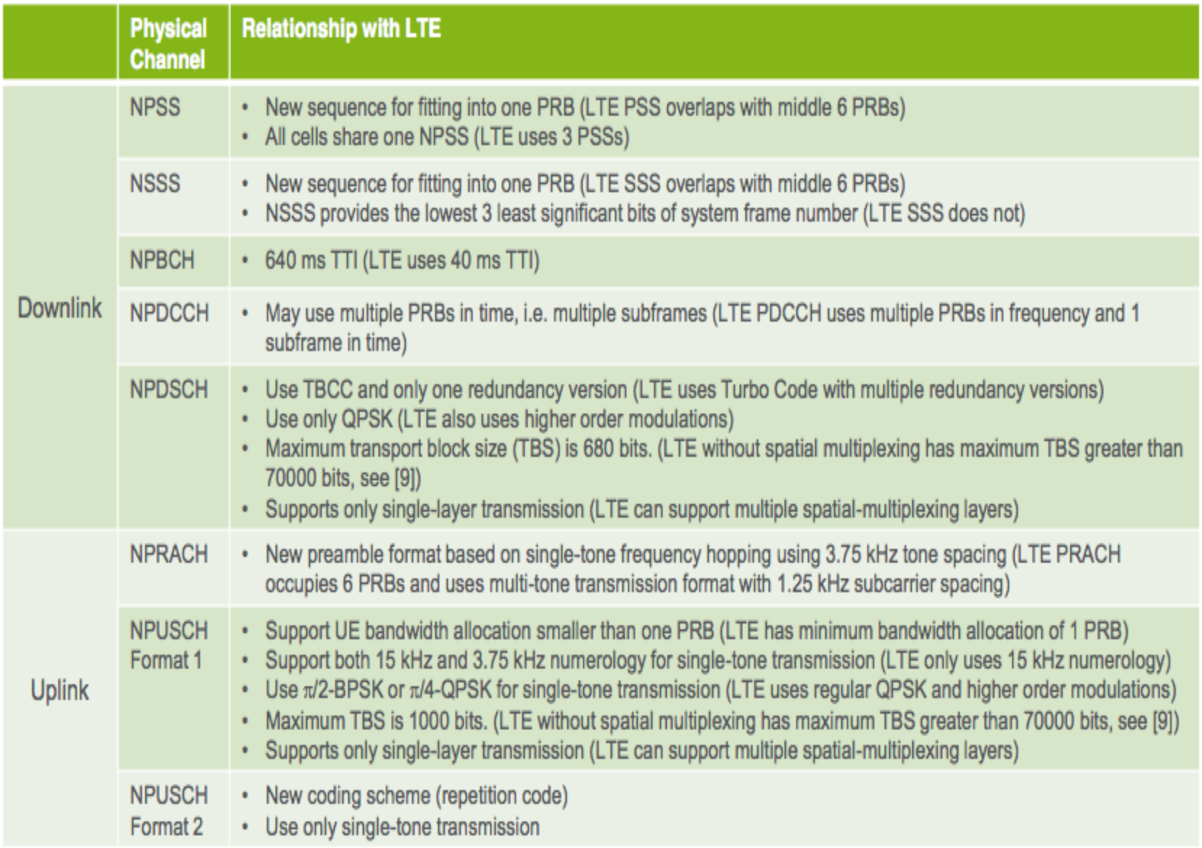


Figure 10. An illustration of NPRACH frequency hopping.

NPUSCH has two formats. Format 1 is used for carrying uplink data and uses the same LTE turbo code for error correction. The maximum transport block size of NPUSCH Format 1 is 1000 bits, which is much lower than that in LTE. Format 2 is used for signaling HARQ acknowledgement for NPDSCH, and uses a repetition code for error correction.NPUSCH Format 1 supports multi-tone transmission based on the same legacy LTE numerology. In this case, the UE can be allocated with 12, 6, or 3 tones. While only the 12-tone format is supported by legacy LTE UEs, the 6-tone and 3-tone formats are introduced for NB-IoT UEs who due to coverage limitation cannot benefit from higher UE bandwidth allocation. Moreover, NPUSCH supports single-tone transmission based on either 15 kHz or 3.75 kHz numerology. To reduce peak-to-average power ratio (PAPR), single-tone transmission uses π/2-BPSK or π/4-QPSK with phase continuity between symbols. NPUSCH Format 1 uses the same slot structure as legacy LTE PUSCH with 7 OFDM symbols per slot and the middle symbol as the demodulation reference symbol (DMRS). NPUSCH Format 2 also has 7 OFDM symbols per slot, but uses the middle three symbols as DMRS. DMRS are used for channel estimation.



	Physical Channel	Relationship with LTE
Downlink	NPSS	• New sequence for fitting into one PRB (LTE PSS overlaps with middle 6 PRBs) • All cells share one NPSS (LTE uses 3 PSSs)
	NSSS	• New sequence for fitting into one PRB (LTE SSS overlaps with middle 6 PRBs) • NSSS provides the lowest 3 least significant bits of system frame number (LTE SSS does not)
	NPBCH	• 640 ms TTI (LTE uses 40 ms TTI)
	NPDCCH	• May use multiple PRBs in time, i.e. multiple subframes (LTE PDCCH uses multiple PRBs in frequency and 1 subframe in time)
	NPDSCH	• Use TBCC and only one redundancy version (LTE uses Turbo Code with multiple redundancy versions) • Use only QPSK (LTE also uses higher order modulations) • Maximum transport block size (TBS) is 680 bits. (LTE without spatial multiplexing has maximum TBS greater than 70000 bits, see [9]) • Supports only single-layer transmission (LTE can support multiple spatial-multiplexing layers)
Uplink	NPRACH	• New preamble format based on single-tone frequency hopping using 3.75 kHz tone spacing (LTE PRACH occupies 6 PRBs and uses multi-tone transmission format with 1.25 kHz subcarrier spacing)
	NPUSCH Format 1	• Support UE bandwidth allocation smaller than one PRB (LTE has minimum bandwidth allocation of 1 PRB) • Support both 15 kHz and 3.75 kHz numerology for single-tone transmission (LTE only uses 15 kHz numerology) • Use π/2-BPSK or π/4-QPSK for single-tone transmission (LTE uses regular QPSK and higher order modulations) • Maximum TBS is 1000 bits. (LTE without spatial multiplexing has maximum TBS greater than 70000 bits, see [9]) • Supports only single-layer transmission (LTE can support multiple spatial-multiplexing layers)
	NPUSCH Format 2	• New coding scheme (repetition code) • Use only single-tone transmission

Figure 11. Summary of NB-IoT physical signals and channels and their relationship with the LTE counterparts.

3.6 Resource Mapping

In this paragraph, we describe how NB-IoT resource mapping is designed to ensure the best coexistence performance with LTE if deployed inside an LTE carrier. In essence, the orthogonality to LTE signals is preserved by avoiding mapping NB-IoT signals to the resource elements already used by the legacy LTE signals. An example is illustrated in Figure 12, in which each column indicates resource elements in one OFDM symbol.

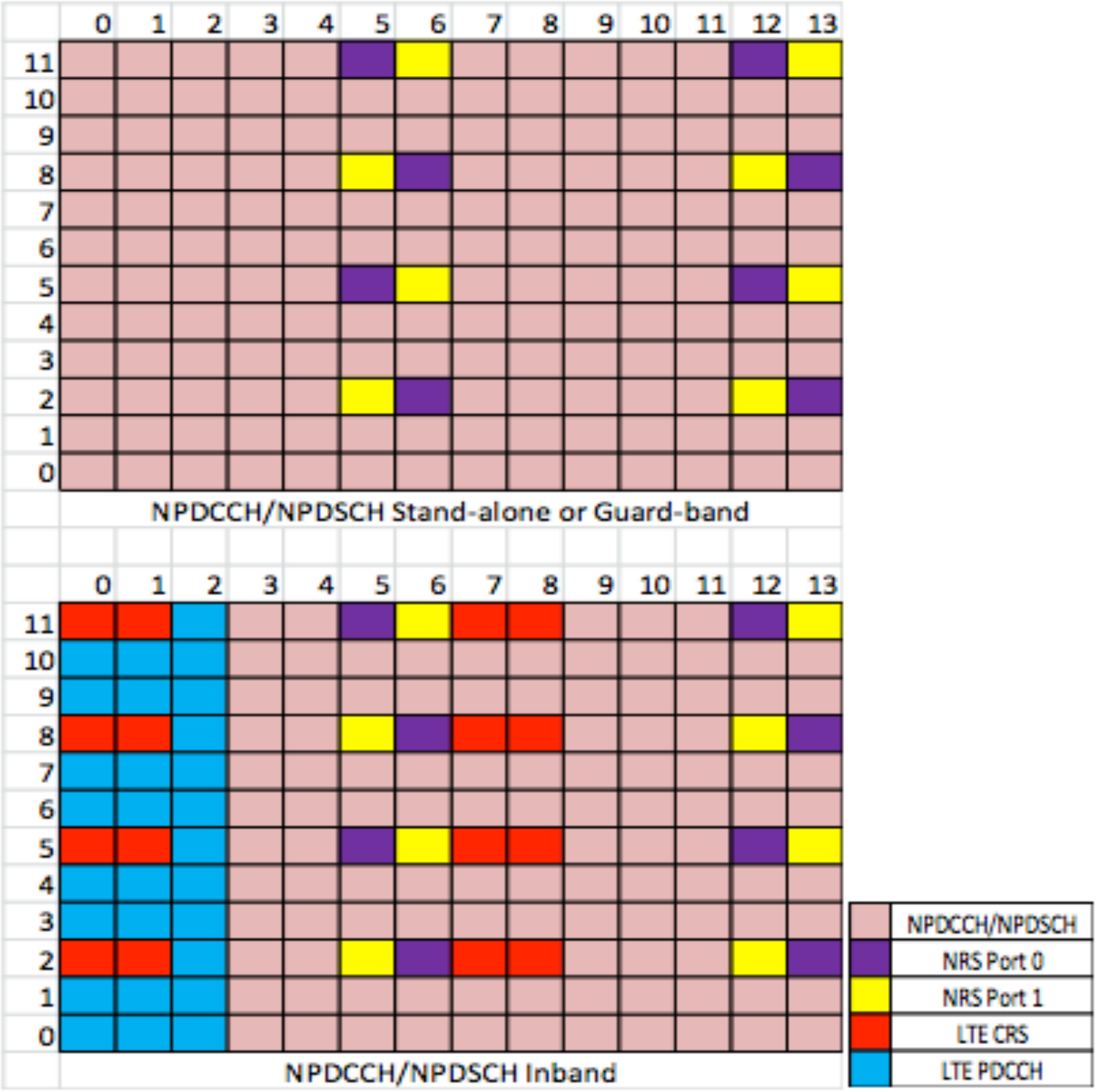


Figure 12. NPDCCH/NPDSCH resource mapping example.

There are 12 resource elements per OFDM symbol corresponding to 12 subcarriers. As shown, for the stand-alone and guard-band deployments, no LTE resource needs to be protected, thus NPDCCH, NPDSCH or NRS can utilize all the resource elements in one PRB pair (defined as 12 subcarriers over one subframe). However, for in-band deployment, NPDCCH, NPDSCH or NRS cannot be mapped to the resource elements taken by LTE Cell-Specific Reference Symbols (CRS) and LTE Physical Downlink Control Channel (PDCCH).

NB-IoT is designed to allow a UE to learn the deployment mode (stand-alone, in-band, or guard- band) as well as the cell identity (both NB-IoT and LTE) through initial acquisition. Then the UE can figure out which resource elements are used by LTE. With this information, the UE can map NPDCCH and NPDSCH symbols to available resource elements. On the other hand, NPSS, NSSS, and NPBCH are used for initial synchronization and master system information acquisition. These signals need to be detected without knowing the deployment mode.

To facilitate this, NPSS, NSSS, and NPBCH avoid the first three OFDM symbols in every subframe as these resource elements may be used by LTE PDCCH. Furthermore, NPSS and NSSS signals overlapping with resource elements taken by LTE CRS are punctured at the base station. Although the UE is not aware of which resource elements are punctured, NPSS and NSSS can still be detected by correlating the received punctured NPSS and NSSS signal with the non-punctured signal since the percentage of punctured resource elements is relatively small.

NPBCH is rate-matched around LTE CRS. This however requires the UE to figure out the location of CRS resource elements, which is dependent of LTE physical cell identity (PCID). Recall that the UE learns cell identity (NB-PCID) from NSSS. The relationship of the values of PCID and NB- PCID used by the same cell is such that the UE can use NB- PCID to determine the LTE CRS locations.

3.7 Cell Search And Initial Acquisition Procedure

Synchronization is an important aspect in cellular communications. When a UE is powered on for the first time, it needs to detect a suitable cell to camp on, and for that cell, obtain the symbol, subframe, and frame timing as well as synchronize to the carrier frequency. In order to synchronize to the carrier frequency, the UE needs to correct any erroneous frequency offsets that are present due to local oscillator inaccuracy, and perform symbol timing alignment with the frame structure from the base station. In addition, due to the presence of multiple cells, the UE needs to distinguish a particular cell on the basis of an NB-PCID. As a result, a typical synchronization procedure consists of determining the timing alignment, correcting the frequency offset, obtaining the correct cell identity, and the absolute subframe and frame number reference.

NB-IoT is intended to be used for very low cost UEs and at the same time, provide extended coverage for UEs deployed in environments with high penetration losses, e.g., basement of a building. Such low cost UEs are equipped with low-cost crystal oscillators that can have an initial carrier frequency offset (CFO) as large as 20 ppm. Deployment in-band and in guard-bands of LTE introduces an additional raster offset (2.5 or 7.5 kHz) as explained in Section II, giving rise to an even higher CFO. Despite of this large CFO, a UE should also be able to perform accurate synchronization at very low SNR.

Synchronization in NB-IoT follows similar principles as the synchronization process in LTE, but with changes to the design of the synchronization sequences in order to resolve the problem of estimating large frequency offset and symbol timing at very low SNR. Synchronization is achieved through the use of NPSS and NSSS. As mentioned the NPSS occurs in subframe #5 of every frame, and the NSSS occurs in subframe #9 of every even numbered frame. The NPSS is used to obtain the symbol timing and the CFO, and the NSSS is used to obtain the NB-PCID, and the timing within an 80 ms block.

For UEs operating at very low SNR, an auto correlation based on a single 10 ms received segment would not be sufficient for detection. As a result, an accumulation procedure over multiple 10 ms segments is necessary. Because of the inherent NPSS design, the accumulation can be performed coherently, providing sufficient signal energy for detection. Because of the large initial CFO, the sampling time at the UE is different from the actual sampling time, the difference being proportional to the CFO. For UEs in deep coverage, the number of accumulations necessary to achieve a successful detection may be high. As a result, the peak of every accumulation process does not add up coherently because of the difference in the true and UE sampling time causing a drift. The drift can be handled by using a weighted accumulation procedure, so that the most recent accumulated value is given higher priority than the previous ones.

After the synchronization procedure is complete, the UE has knowledge of the symbol timing, the CFO, the position within an 80 ms block and the NB-PCID. The UE then proceeds to the acquisition of the MIB, which is broadcast in subframe #0 of every frame carried by NPBCH. The NPBCH consists of 8 self-decodable sub-blocks, and each sub-block is repeated 8 times so that each sub-block occupies subframe #0 of 8 consecutive frames. The design is intended to provide successful acquisition for UEs in deep coverage.

After the symbol timing is known and the CFO is compensated for, in the in-band and guard-band deployment there is still an additional raster offset which can be as high as 7.5 kHz. The presence of raster offset results in either overcompensation or under compensation of the carrier frequency. As a result, the symbol timing drifts in either the forward or backward direction depending on whether the carrier frequency was overcompensated or undercompensated. This may cause a severe degradation in the performance of NPBCH detection if the NPBCH is not detected on the first trial. For example, an unsuccessful detection of NPBCH in the first trial introduces a latency of 640 ms before the next NPBCH detection trial. A 7.5 kHz raster offset leads to a symbol timing drift of 5.33 μs (assuming a carrier frequency of 900 MHz) which is greater than the duration of cyclic prefix. As a result, the downlink orthogonality of OFDM is lost. A solution to this problem comes at the expense of a small increase in computational complexity, where the UE can perform a “hypothesis testing” over the set of possible raster offsets to improve the detection performance. Since the number of possible raster offsets is small and there is only one NPBCH subframes in every 10 subframes, this is feasible from an implementation point of view.

3.8 Random Access

In NB-IoT, random access serves multiple purposes such as initial access when establishing a radio link and scheduling request. Among others, one main objective of random access is to achieve uplink synchronization, which is important for maintaining uplink orthogonality in NB-IoT. Similar to LTE, the contention-based random access procedure in NB-IoT consists of four steps:

- UE transmits a random access preamble
- The network transmits a random access response that contains timing advance command and scheduling of uplink resources for the UE to use in the third step
- The UE transmits its identity to the network using the scheduled resources
- The network transmits a contention- resolution message to resolve any contention due to multiple UEs transmitting the same random access preamble in the first step.

To serve UEs in different coverage classes that have different ranges of path loss, the network can configure up to three NPRACH resource configurations in a cell. In each configuration, a repetition value is specified for repeating a basic random access preamble. UE measures its downlink received signal power to estimate its coverage level, and transmits random access preamble in the NPRACH resources configured for its estimated coverage level. To facilitate NB- IoT deployment in different scenarios, NB-IoT allows flexible configuration of NPRACH resources in time-frequency resource grid with the following parameters.

- Time domain: periodicity of NPRACH resource, and starting time of NPRACH resource in a period.
- Frequency domain: frequency location (in terms of subcarrier offset), and number of subcarriers.

It is possible that in the early NB-IoT field trial and deployment, some UE implementations may not support multi-tone transmission. The network should be aware of UE multi-tone transmission capability before scheduling uplink transmission. Therefore, the UE should indicate its support of multi-tone transmission in the first step of random access to facilitate the network's scheduling of uplink transmission in the third step of random access. To this end, the network can partition the NPRACH subcarriers in the frequency domain into two non-overlapping sets. A UE can select one of the two sets to transmit its random-access preamble to signal whether or not it supports multi-tone transmission in the third step of random access.In summary, UE determines its coverage level by measuring downlink received signal power. After reading system information on NPRACH resource configuration, the UE can determine the NPRACH resource configured and the numbers of repetitions needed for its estimated coverage level as well as random access preamble transmit power. Then the UE can transmit the repetitions of the basic single tone random access preamble back-to-back within one period of the NPRACH resources. The remaining steps in random access procedure are similar to LTE, and we omit the details here.

3.9 Scheduling and HARQ Operation

To enable low-complexity UE implementation, NB-IoT allows only one HARQ process in both downlink and uplink, and allows longer UE decoding time for both NPDCCH and NPDSCH. Asynchronous, adaptive HARQ procedure is adopted to support scheduling flexibility. An example is illustrated in Figure 13.

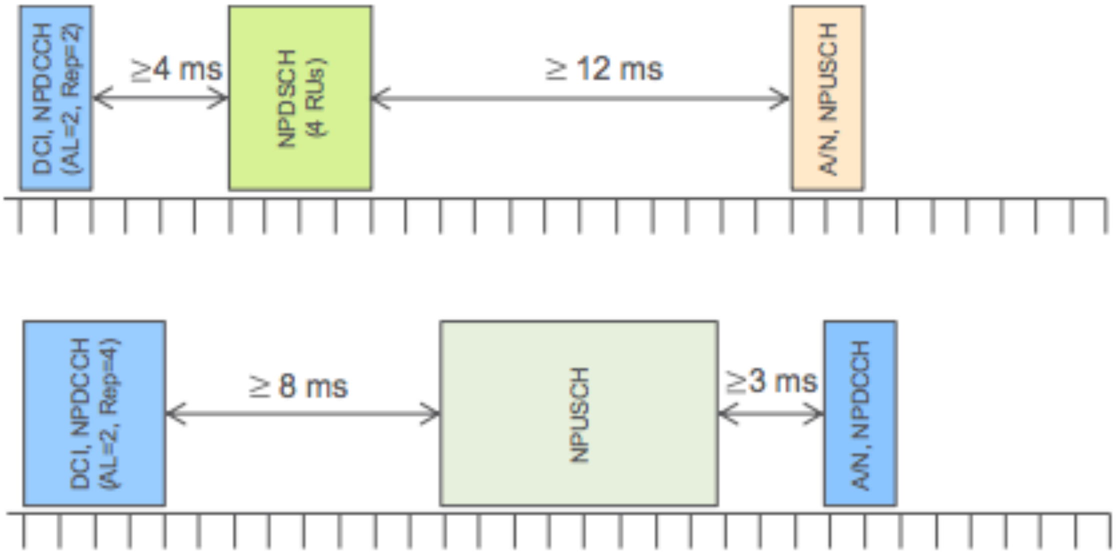


Figure 13. Timing relationship operation (each unit corresponds to one subframe)

Scheduling command is conveyed through Downlink Control Indicator (DCI), which is carried by NPDCCH. NPDCCH may use aggregation levels (AL) 1 or 2 for transmitting a DCI. With AL-1, two DCIs are multiplexed in one subframe, otherwise one subframe only carries one DCI (i.e. AL-2), giving rise to a lower coding rate and improved coverage. Further coverage enhancement can be achieved through repetition. Each repetition occupies one subframe. DCI can be used for scheduling downlink data or uplink data. In the case of downlink data, the exact time offset between NPDCCH and the associated NPDSCH is indicated in the DCI. Since IoT devices are expected to have reduced computing capability, the time offset between the end of NPDCCH and the beginning of the associated NPDSCH is at least 4 ms.

In comparison, LTE PDCCH schedules PDSCH in the same TTI. After receiving NPDSCH, the UE needs to send back HARQ acknowledgement using NPUSCH Format 2. The resources of NPUSCH carrying HARQ acknowledgement are also indicated in DCI. Considering the limited computing resources in an IoT device, the time offset between the end of NPDSCH and the start of the associated HARQ acknowledgement is at least 12 ms. This offset is longer than that between NPDCCH and NPDSCH because the transport block carried in NPDSCH might be up to 680 bits, a lot longer than the DCI, which is only 23 bits long.

Similarly, uplink scheduling and HARQ operation are also illustrated in Fig. 5. The DCI for uplink scheduling grant needs to specify which subcarriers that a UE is allocated. The time offset between the end of NPDCCH and the beginning of the associated NPUSCH is at least 8 ms. After completing the NPUSCH transmission, the UE monitors NPDCCH to learn whether NPUSCH is received correctly by the base station, or a retransmission is needed.

3.10 Performance

IoT use cases are characterized by requirements such as data rate, coverage, device complexity, latency, and battery lifetime. These are thus important performance metrics. Furthermore, according to [18], IoT traffic is forecasted to have compounded annual growth rate of 23% between 2015 and 2023. It is therefore important to ensure that NB-IoT has good capacity to support such a growth in the years to come.

3.10.1 Peak Data Rates

NDSCH peak data rate can be achieved by using the largest TBS of 680 bits and transmitting it over 3 ms. This gives 226.7 kbps peak layer-1 data rate. NPUSCH peak data rate can be achieved by using the largest TBS of 1000 bits and transmitting it over 4 ms. This gives 250 kbps peak layer-1 data rate. However, the peak throughputs of both downlink and uplink are lower than the above figures, when the time offsets between DCI, NPDSCH/NPUSCH, and HARQ acknowledgement are taken into account.

3.10.2 Coverage

NB-IoT achieves a maximum coupling loss 20 dB higher than LTE Rel-12 [19, 20]. Coverage extension is achieved by trading off data rate through increasing the number of repetitions. Coverage enhancement is ensured also by introducing single subcarrier NPUSCH transmission and π/2- BPSK modulation to maintain close to 0 dB PAPR, thereby reducing the unrealized coverage potential due to power amplifier (PA) backoff. NPUSCH with 15 kHz single-tone gives a layer-1 data rate of approximately 20 bps when configured with the highest repetition factor, i.e., 128, and the lowest modulation and coding scheme. NPDSCH gives a layer-1 data rate of 35 bps when configured with repetition factor 512 and the lowest modulation and coding scheme. These configurations support close to 170 dB coupling loss. In comparison, the Rel-12 LTE network is designed for up to approximately 142 dB coupling loss [21].

3.10.3 Device Complexity

NB-IoT enables low-complexity UE implementation by the designs highlighted below.

- Significantly reduced transport block sizes for both downlink and uplink
- Support only one redundancy version in the downlink
- Support only single-stream transmissions in both downlink and uplink
- A UE only requires single antenna
- Support only single HARQ process in both downlink and uplink
- No need for a turbo decoder at the UE since only TBCC is used for downlink channels
- No Connected mode mobility measurement is required. A UE only needs to perform mobility measurement during the Idle mode
- Low sampling rate due to lower UE bandwidth
- Allow only half-duplex frequency-division duplexing (FDD) operation
- No parallel processing is required. All the physical layer procedures and transmission and reception of physical channels occur in sequential manner

The coverage objective is achieved with 20 or 23 dBm PA, making it possible to use an integrated PA in the UE.

3.10.4 Latency And Battery Lifetime

NB-IoT targets latency insensitive applications. However, for applications like sending alarm signals, NB-IoT is designed to allow less than 10 s latency [22]. NB-IoT aims to support long battery life. For a device with 164 dB coupling loss, a 10-year battery life can be reached if the UE transmits 200-byte data a day on average [22].

3.10.5 Capacity

NB-IoT supports massive IoT capacity by using only one PRB in both uplink and downlink. Sub-PRB UE scheduled bandwidth is introduced in the uplink, including single subcarrier NPUSCH. Note that for coverage limited UE, allocating higher bandwidth is not spectrally efficient as the UE cannot benefit from it to be able to transmit at a higher data rate. Based on the traffic model in [22], NB-IoT with one PRB supports more than 52500 UEs per cell [22]. Furthermore, NB-IoT supports multiple carrier operation. Thus, more IoT capacity can be added by adding more NB-IoT carriers.

4

LoraWan VS Nb-IoT

4.1 Indroduction

In this paragraph, we are going to compare these two protocols.We will try to find out which is the pros and cons between these two technologies.

4.2 Technical Physical Differences

LoRa is an emerging technology in the current market, which operates in a non-licensed band below 1 GHz for long-range communication link operation. LoRa is a proprietary spread spectrum modulation scheme that is derivative of chirp spread spectrum modulation (CSS) and which trades data rate for sensitivity within channel bandwidth. CSS, which was developed in the 1940s, was traditionally used in military applications because of its long communication distances and interference robustness. LoRa is its first low-cost implementation for commercial usage. The name LoRa comes from its advantage of long-range capability, which benefits from the long great link budget provided by spread spectrum modulation scheme.

To achieve this, the LoRaWAN network applies an adap- tive modulation technique with multichannel multi-modem transceiver in the base station to receive a multiple number of messages from the channels. The spread spectrum pro- vides orthogonal separation between signals by using a unique spreading factor to the individual signal. This method provides advantages in managing the data rate. The relationship between the required data bit rate with the chirp rate and symbol rate in the LoRa modulation technique [23] is defined as follows:

The LoRa modulation bit rate $R_b = SF * \frac{1}{\left\lceil \frac{2^{SF}}{BW} \right\rceil}\ bits/s$ (4.1)

where SF = spreading factor and BW = modulation band- width (Hz). As shown in Eq. (4.1), the data rate Rb is directly proportional to the spreading factor SF.

NB-IoT is a new IoT technology set up by 3GPP as a part of Release 13. Although it is integrated into the LTE standard, it can be regarded as a new air interface [24]. It is kept as simple as possible in order to reduce device costs and minimize battery consumption, and thus it removes many features of LTE, including handover, measurements to monitor the chan- nel quality, carrier aggregation, and dual connectivity. It uses the licensed frequency bands, which are the same frequency numbers used in LTE, and employs QPSK modulation. There are different frequency band deployments, which are stand- alone, guard-band, and in-band deployment as shown in Fig. 14.

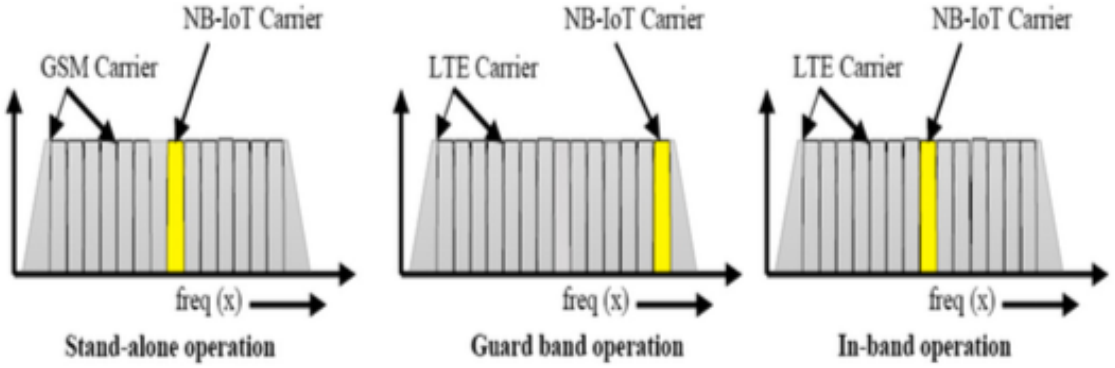


Figure 14. NB-IoT operation mode [24,25].

There are 12 subcarriers of 15 kHz in downlink using OFDM and 3.75/ 15 kHz in uplink using SC-FDMA. The uplink and downlink frequency of NB-IoT FDL, FUL resp. is defined as follows [24]:

$FDL = FDLlow + 0.1(NDL - NofF) + 0.0025\ DL * (2MDL + 1)$ (4.2)
$FUL = FULlow + 0.1(NUL - NofF) + 0.0025\ UL * (2MUL)$ (4.3)

where MDL/UL = offset of NB-IoT channel number to down- link/uplink, FDL/UL low = downlink/uplink operating band, NDL/UL = downlink/uplink E-UTRA absolute radio frequency channel number (EARFCN), NoffDL/UL = Minimum range of NDL/UL for downlink/uplink. NB-IoT utilizes GSM frequency with bandwidth of 200 kHz between guard bands of 10 kHz for stand-alone operation, while unused guard band and resource block of LTE carrier for guard band operation and in-band operations, respectively [24,25]. (See Figure 17.)

4.3 Network architecture Differences

LoRaWAN defines the communication protocol and the system architecture, while LoRa defines the physical layer [26]. LoRaWAN uses long range star architecture (as shown in Fig. 15) in which gateways are used to relay the messages between end- devices and a central core network. In a LoRaWAN network, nodes are not associated with a specific gateway. Instead, data transmitted by a node is typically received by multiple gateways. Each gateway will forward the received packet from the end-node to the cloud-based network server via some backhaul (either cellular, ethernet, satellite, or Wi-Fi). End-devices (i.e. sensors and applications) communicate with one or many gateways through single-hop LoRa communication while all gateways are connected to the core network server via standard IP connections.

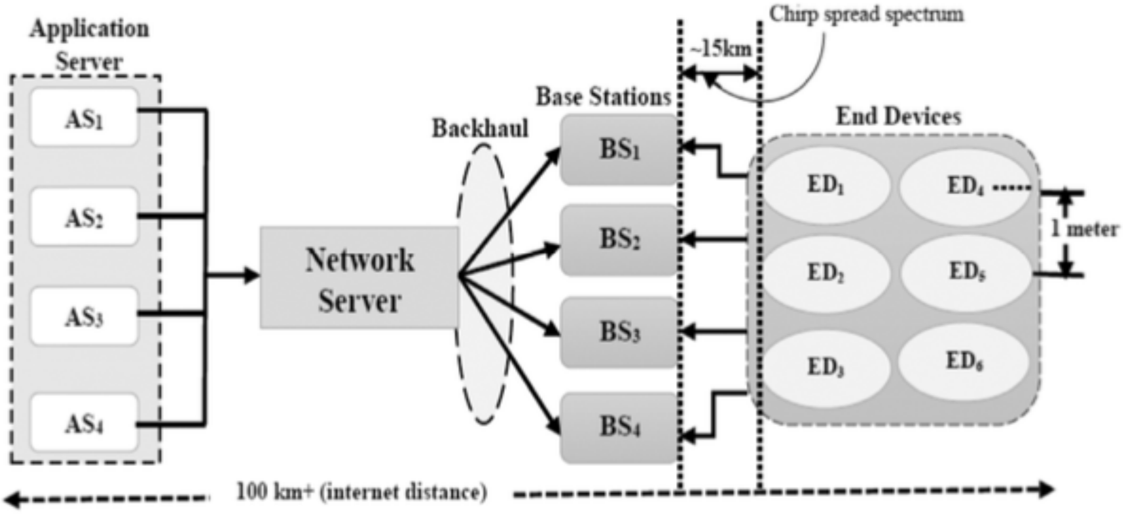


Figure 15. LoRa WAN Network architecture with application server and network server, connected with base station and EDs

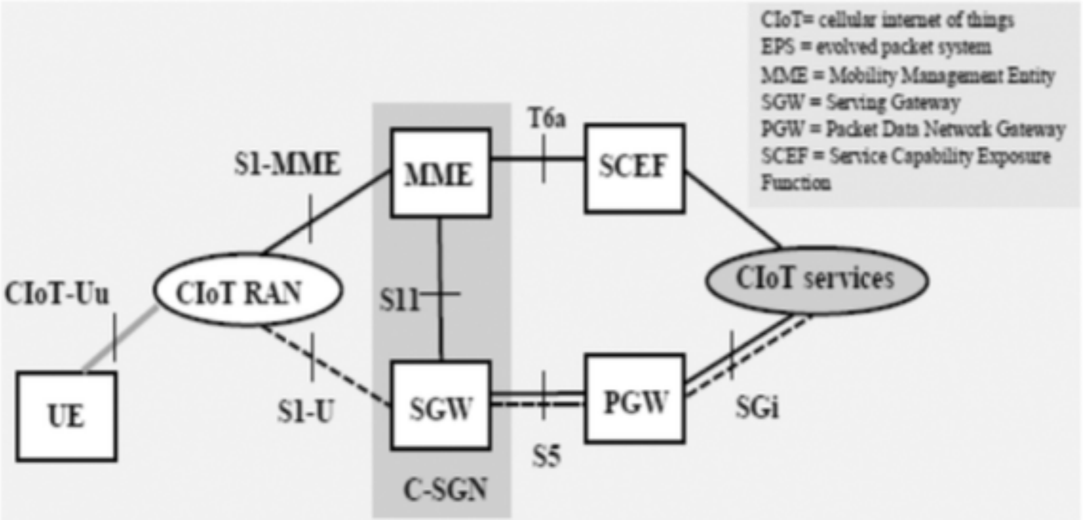
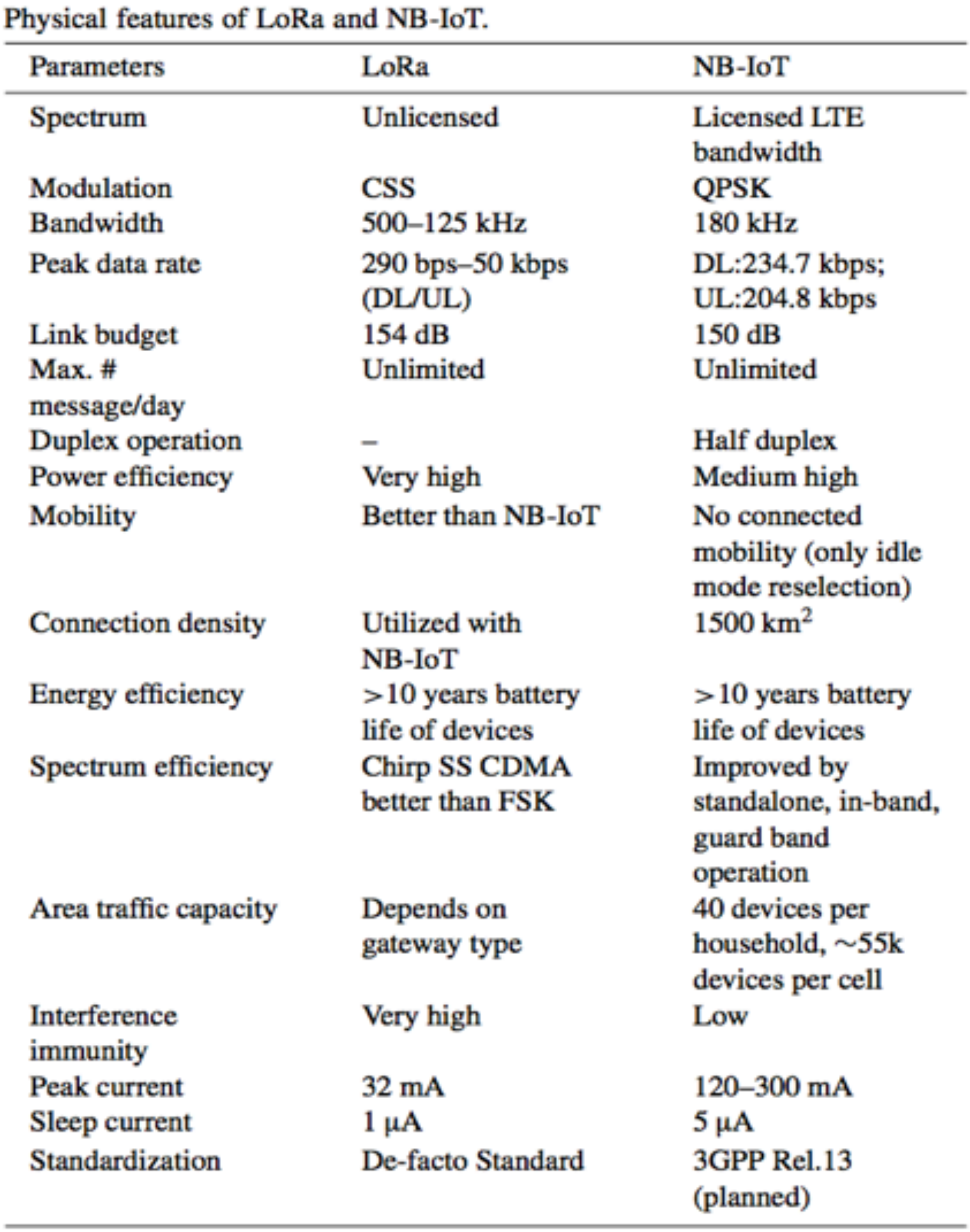


Figure 16. NB-IoT Network architecture [23].

The network server has the required intelligence for filtering the duplicate packets from different gateways, checking security, sending ACKs to the gateways, and sending the packet to the specific application server. Be- cause the network can choose the best quality information among the information transmitted by different gateways, the need of hand-off or handover is removed. If a node is mobile or moving there is no handover needed from gateway to gateway, which is a critical feature to enable asset-tracking applications, a major target application for vertical IoT. By using mesh network, the system can increase the communication range and cell size of the network at the expense of the device battery life.

NB-IoT core network is based on the evolved packet system (EPS) and two optimizations for the cellular internet of things (CIoT) were defined, the user plane CIoT EPS optimization and the control plane CIoT EPS optimization, as seen in Fig. 16. Both planes choose the best path for control and user data packets, for uplink and downlink data. The optimization path for the selected plane is flexible for the data packet generated by the mobile set. The cell access procedure of an NB-IoT user is similar o that of LTE. On the control plane CIoT EPS optimization, the evolved UMTS terrestrial radio access network (E-UTRAN) handles the radio communications between the UE and the MME, and consists of the evolved base stations called eNodeB or eNB. Then, data was transmitted to the packet data network gateway (PGW) via serving gateway (SGW). For non-IP data, it will be transferred to the newly defined node, service capability exposure function (SCEF), which can deliver machine type data over the control plane and provide an abstract interface for the services. With the user plane CIoT EPS optimization, both IP and non-IP data can be transmitted over radio bearers via the SGW and PGW to the application server. In summary, for NB-IoT, the existing E-UTRAN network architecture and the backbone can be reused. The LoRaWAN network architecture is simpler, but the network server is more complex.



Physical features of LoRa and NB-IoT.

Parameters	LoRa	NB-IoT
Spectrum	Unlicensed	Licensed LTE bandwidth
Modulation	CSS	QPSK
Bandwidth	500–125 kHz	180 kHz
Peak data rate	290 bps–50 kbps (DL/UL)	DL:234.7 kbps; UL:204.8 kbps
Link budget	154 dB	150 dB
Max. # message/day	Unlimited	Unlimited
Duplex operation	–	Half duplex
Power efficiency	Very high	Medium high
Mobility	Better than NB-IoT	No connected mobility (only idle mode reselection)
Connection density	Utilized with NB-IoT	1500 km^2
Energy efficiency	>10 years battery life of devices	>10 years battery life of devices
Spectrum efficiency	Chirp SS CDMA better than FSK	Improved by standalone, in-band, guard band operation
Area traffic capacity	Depends on gateway type	40 devices per household, ~55k devices per cell
Interference immunity	Very high	Low
Peak current	32 mA	120–300 mA
Sleep current	1 µA	5 µA
Standardization	De-facto Standard	3GPP Rel.13 (planned)

Figure 17. Physical features of LoRa and NB-IoT.

4.4 Mac Protocol Differences

End nodes in the LoRaWAN network can be divided into three different device classes according to the trade-off between network downlink communication latency versus battery life, as shown in Fig. 18. In addition, three different following MAC protocols were designed for these three device classes, as shown in Fig. 19. Class-A end-devices are battery powered sensors. It has maximum battery life-time and must be supported by all other devices. The functionality of Class-A is shown in Fig. 19, first receive window R × 1 comes exactly Receive Delay 1 s after the end of the uplink modulation. The second slot R × 2 comes exactly Receive Delay 2 s after the end of the uplink modulation.

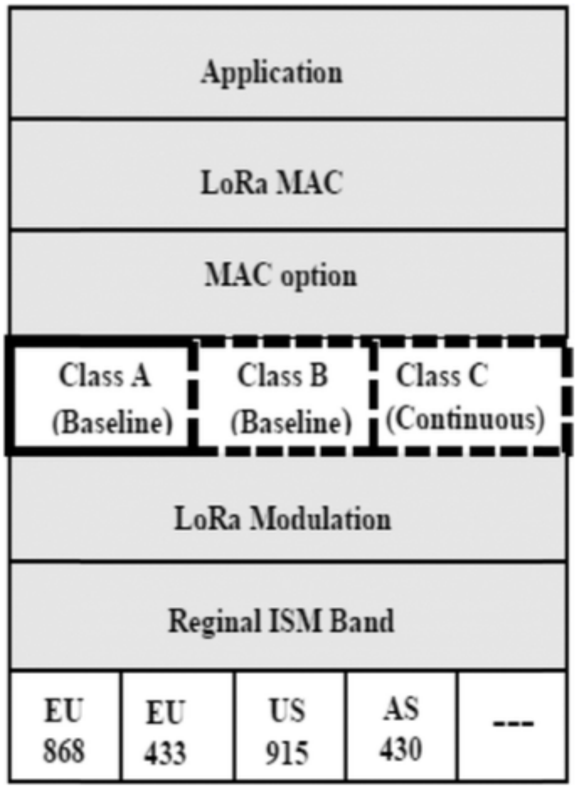


Figure 18. Architecture of a LoRaWAN end-device

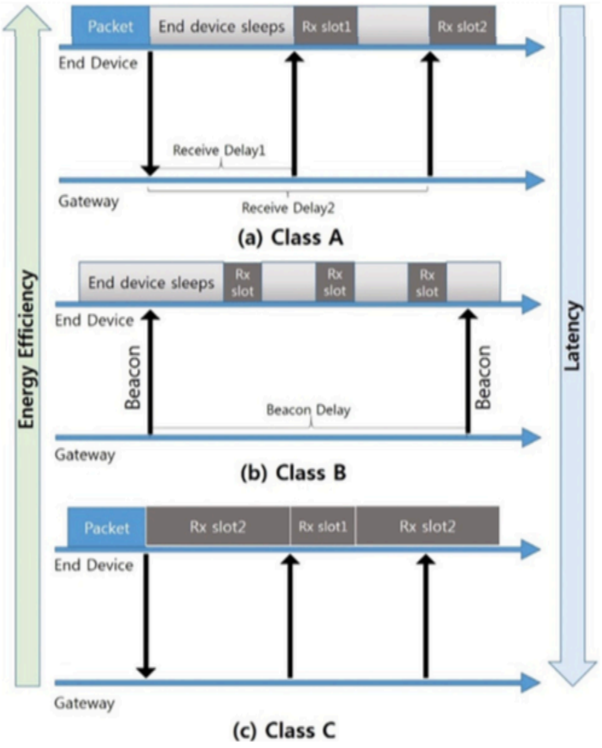


Figure 19. Three device classes receive slot timing.

The receiver stays active until the downlink frame is demodulated. Class-B end-devices are battery powered actuators. All end-devices start and join the network as end- devices of Class A and can then decide to switch to Class B [27]. As shown in Fig. 19, the gateway sends a beacon on a regular beacon delay to synchronize all the end devices in the network. When an end device receives the beacon, it can open a short reception window called "ping slot" predictably during a periodic time slot. Class C end-devices are the main powered actuators. It has the minimum latency in downlink communication compared to the other two classes. For Class C devices in Fig. 19, end-devices not only open two receive windows as Class A but also open a continuous receive window until the end of transmission. These class devices are used for applications that have sufficient power available and thus do not need to minimize reception time windows [28].

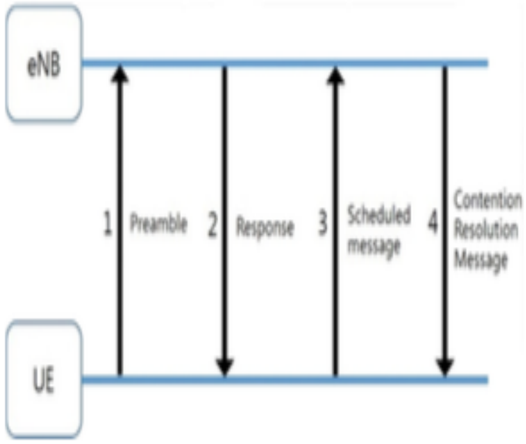


Figure 20. Message for RACH procedure[24]

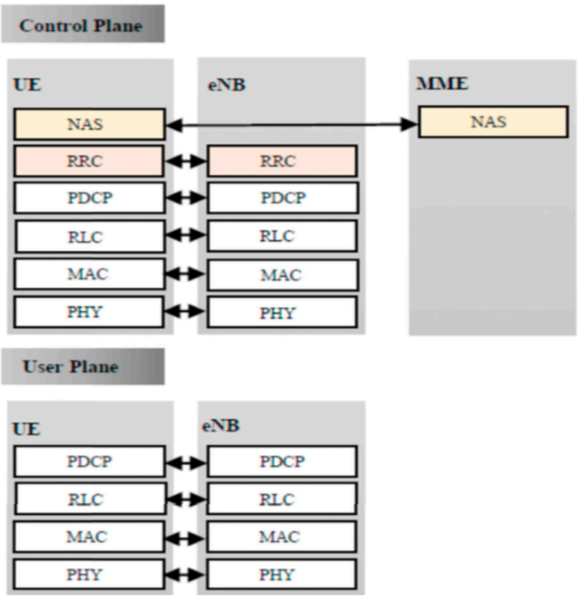


Figure 21. Protocol stack of NB-IoT for Control plane

The protocol stack for NB-IoT is the general fundamental protocol stack of LTE, which is reduced to the minimum and enhanced for re-using and preventing NB-IoT from overhead of unused LTE [24]. The NB-IoT protocol stack is considered as a new air interface for LTE. As shown in Fig. 21, the NB- IoT protocol structure has been divided into control plane and user plane. The packet data convergence protocol (PDCP) is from layer-2 (L2) with a size of 1600 bytes. Non-access stratum (NAS) of the protocol stack conveys non-radio signals between UE and core network. The NAS performs authentication, security control, mobility management, and bearer management. Access stratum (AS) is a layer below NAS and functional between UE and radio network. It is used to manage radio resources in NB-IoT. The radio resource control (RRC) layer minimize signalling by suspend/resume operation of user plane. L2 security provides encryption of NAS signalling and authentication between UE and core network. The mobility management of the user in connectivity mode comes under this protocol. For NB-IoT, the random access channel (RACH) procedure is always contention based and starts with the transmission of a preamble [29]. If the preamble transmission fails, the UE will retransmit until the number of retransmissions reaches the maximum number, which depends on the CE level still without success. Then UE will proceed to the next CE level. If the eNB successfully receives the preamble, the eNB will send the associated random access response to the UE. After that, a scheduled message, msg3, is transmitted in order to start the contention resolution process. The RACH procedure is completed when the associated contention resolution message is transmitted to the UE. Fig. 20 shows the message for this procedure.

4.5 Comparison in terms of IoT Metrics

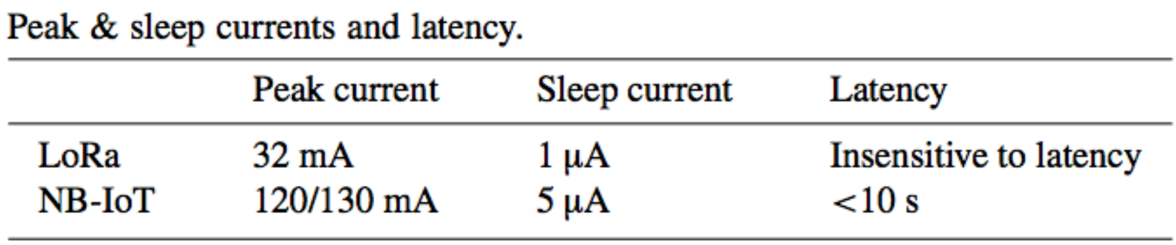
There are many metrics that should be considered when we choose the suitable technology for an IoT application, including quality of service, latency, battery life, coverage, range, deployment model, and cost. The rest of this paper will compare the LoRa and NB-IoT in terms of these metrics based on their technical differences.

4.5.1 Quality of Service (QoS)

LoRa uses unlicensed spectrum and is an asynchronous protocol. LoRa based on CSS modulation can handle inter- ference, multipath, and fading but it cannot offer the same QoS as NB-IoT can provide. This is because NB-IoT uses a licensed spectrum and its time slotted synchronous protocol is optimal for QoS. However, this advantage of QoS is at the expense of cost. Licensed band spectrum auctions of the sub-GHz spectrum are typically over 500 million dollars per MHz [26]. Because of the trade-off between QoS and high spectrum cost, applications that need QoS prefer the NB-IoT, while the applications that do not need high QoS should choose LoRa.

4.5.2 Battery life & latency

In LoRaWAN, devices can sleep for as little or as long as the application desires, because it is an asynchronous, ALOHA- based protocol. In NB-IoT, because of infrequent but regular synchronization, the device consumes additional battery energy, and OFDM or FDMA require more peak current for the linear transmitter. The value of the currents is shown in Figure 22. These extra energy demands determine that device battery life of NB-IoT is shorter than devices based on LoRa. On the other hand, these demands offer NB-IoT the advantage of low latency and high data rate. Therefore, for those applications that are insensitive to the latency and do not have large amounts data to send, LoRa is the best choice. For applications that require low latency and high data rate, NB-IoT is the better choice.



Peak & sleep currents and latency.

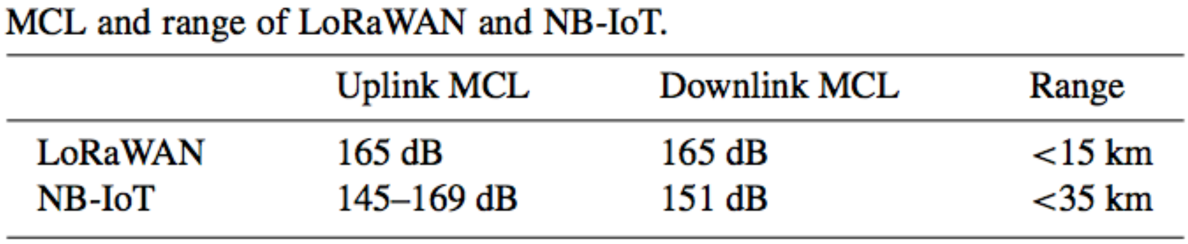
	Peak current	Sleep current	Latency
LoRa	32 mA	1 μA	Insensitive to latency
NB-IoT	120/130 mA	5 μA	<10 s

Figure 22. Peak & sleep currents and latency

4.5.3 Network coverage & range

The major utilization advantage of LoRa is that a whole city could be covered by one gateway or base station. For example, in Belgium, a country with a total area of approximately 30500 km2 [26], the LoRa network deployment covers the entire country with typically seven base stations.

NB-IoT focuses mainly upon MTC class of devices that are installed at places far from usual reach. Therefore, coverage should not be less than 23 dB [24]. The deployment of NB- IoT is limited to 4G/LTE base stations. Thus, it is not suitable for rural or suburban regions that do not have 4G coverage. One significant advantage of the LoRaWAN ecosystem is its flexibility. LoRaWAN may have a wider network coverage than NB-IoT network. The maximum coupling loss (MCL) is the limit value of the coupling loss at which the service can be delivered, and therefore it defines the range of the service [30]. MCL and the range of NB-IoT and LoRaWAN are shown in Figure 23.



MCL and range of LoRaWAN and NB-IoT.

	Uplink MCL	Downlink MCL	Range
LoRaWAN	165 dB	165 dB	<15 km
NB-IoT	145–169 dB	151 dB	<35 km

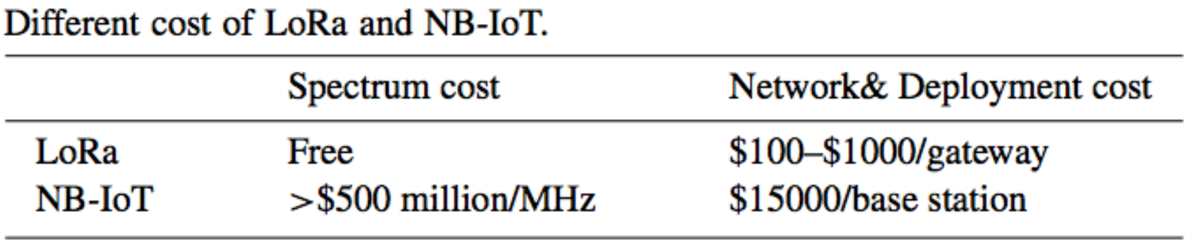
Figure 23. MCL and range of LoRaWAN and NB-IoT.

4.5.4 Deployment model

NB-IoT can be deployed by reusing and upgrading the existing cellular network but its deployments are restricted to the area supported by cellular network. The NB-IoT specification was released in June 2016, and thus it will take additional time to establish the NB-IoT network. On the other hand, the LoRa components and the LoRaWAN ecosystem are mature and production-ready now, although nationwide deployments are still in the rollout phase [31].

4.5.5 Cost

There are different cost aspects that need to be taken into consideration, such as spectrum cost, network cost, device cost, and deployment cost. Table 4 shows the cost of NB-IoT and LoRa. It can be seen that LoRa has a huge advantage in relation to cost.
In Summary, LoRa and NB-IoT have their respective advantages in terms of different factors of IoT, as shown in Figure 24.



Different cost of LoRa and NB-IoT.

	Spectrum cost	Network& Deployment cost
LoRa	Free	\$100–\$1000/gateway
NB-IoT	>\$500 million/MHz	\$15000/base station

Figure 24. Different cost of LoRa and NB-IoT.

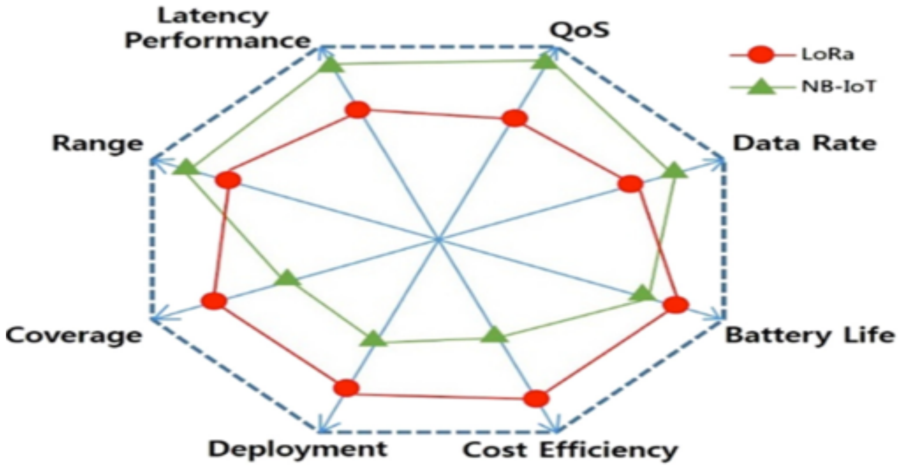
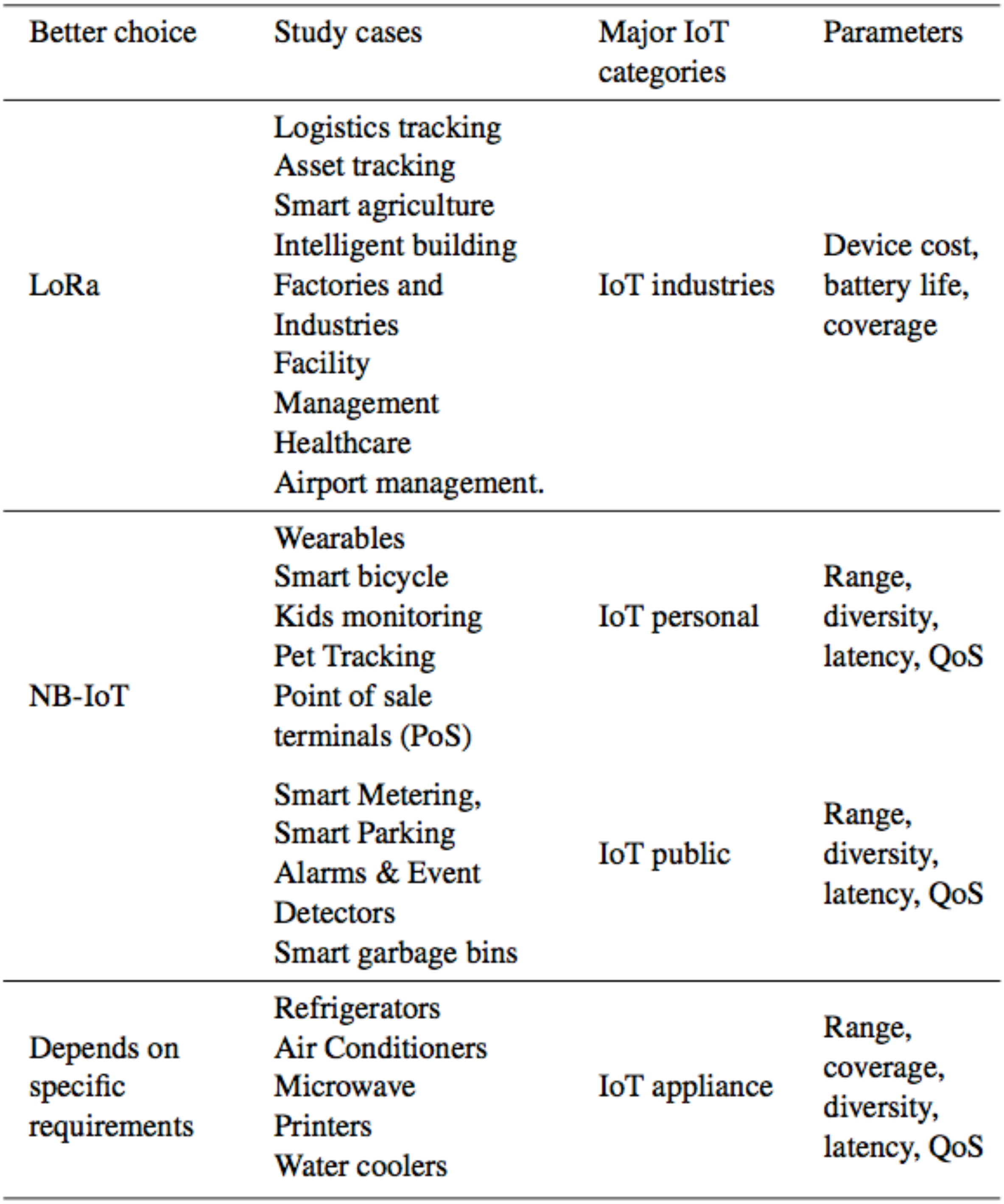


Figure 25. Comparison in terms of various IoT factors.

4.6 Application scenarios

IoT study cases are widely categorized into four types i.e., IoT personal, IoT public, IoT industries, and IoT appli- ance. Each category is better identified as NB-IoT or LoRa and is shown below in Figure 26. LoRa, along with NB-IoT, contributes with 45% of the commercial market in LPWA. The application scenario of these different technologies is the same, but different business markets are involved for develop- ing strategies with different developing parties. For example, The LoRa alliance, established in 2015, mainly focuses on the standardized technical development and in advancing with technical solutions [26].

The application area of LoRa includes communication from vehicular to infrastructure technologies. The LPWA LoRa field is vast, with communication ranging from a few meters to more than 100 km. The cost effectiveness of the NB-IoT network helps to frame a large number of devices with battery life longer than 10 years. It is considered that the network deployment of NB-IoT will provide in the future low cost services in elusive areas. For example, health-care assistance, smart alarms for security and safety at solicited as well as in public places, control of power consumption with energy management, implementation of low cost automatic devices for smart home, and the covering of areas with smart devices to create smart cities.



Better choice	Study cases	Major IoT categories	Parameters
LoRa	Logistics tracking Asset tracking Smart agriculture Intelligent building Factories and Industries Facility Management Healthcare Airport management.	IoT industries	Device cost, battery life, coverage
NB-IoT	Wearables Smart bicycle Kids monitoring Pet Tracking Point of sale terminals (PoS)	IoT personal	Range, diversity, latency, QoS
	Smart Metering, Smart Parking Alarms & Event Detectors Smart garbage bins	IoT public	Range, diversity, latency, QoS
Depends on specific requirements	Refrigerators Air Conditioners Microwave Printers Water coolers	IoT appliance	Range, coverage, diversity, latency, QoS

Figure 26. The IoT use cases along with parameters [32].

5 Performance Evaluation Of LoraWan & NB-IoT

5.1 Indroduction

In this paragraph, we are going to simulate Lorawan protocol with the Matlab platform.For the simulation code we use the code from sakshama ghoslya[33] with some modification to the input parameters.The final result it will be the BER/SNR with different value of spreading factor.The code will be explained in the next paragraph.

5.2 System Model Of LoraWan

The code compares the performance of LoRa spreading factors for bandwidth 125kHz.It generates BER vs SNR curves. LoRa uses CSS (chirp spread spectrum) as modulation with a scalable bandwidth of 125kHz, 250kHz or 500kHz.

In the system model we used AWGN channel model, BW of 125kHz and spreading factor 7-12. To encode data in CSS symbol, bits are transmitted to a specific starting frequency of the chirp signal. To decode the CSS symbol, correlation with copy of a base CSS symbol is used to extract the bits based on the phase shift of the signal.

The code for the simulation is from Sakshama Ghoslya and can be found here http://www.sghoslya.com/ . We will use the next parameters for the simulation:

Parameters	Value
Spreading Factor	7 to 12
Bandwith	125Khz
Sampling Frequensy	125000
Preamble Length	8
Synch Length	2
Total bits to be transmitted in LoRa message	27720
SNR inDb	-40 to 00 with 1 step(-40:1:00)
Total Iterations	100

5.3 Simulation Results LoraWan

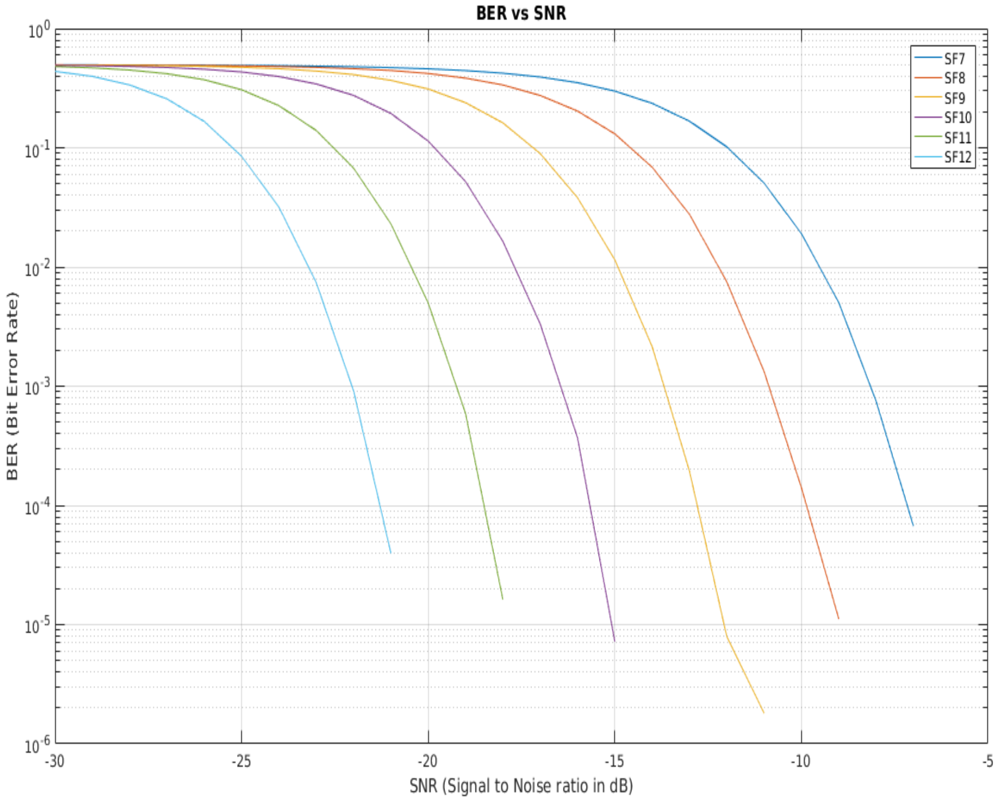


Figure 27. BER/SNR (SF 7-12)

From the results of simulation we can see that when the SNR is bigger when we have lower Bit error rate.Also if we increase the Spreading factor the highest value that the SNR can reach is lower.

5.4 Simulation Of NarrowBand IoT

For the simulation of Nb-Iot we will use a research model from Upsala University and more specific the research with title “Wireless system design NB-IoT downlink simulator”[34]. The aim of the thesis was to develop a toolkit and simulator for the LTE NB-IoT downlink according to the 3GPP release 13 specifications documents. A simulation environment has been created where simulation environment ties the virtual basestation, channel models and virtual user equipment into two linked scripts.On basestation side basic implementations of the available channels have been made. The channel implementations require an input data block to be transmitted and then attaches the correct CRC, codes using the specified encoder, rate matches the coded block as appropriate, scrambles the block and then generates time-frequency grids according to the specifications. Implementations of LTE NB-IoT signals NRS, NPSS, NSSS have been made and included. A basic channel scheduling unit handling the scheduling of NPBCH, NPSS, NSSS, NPDSCH and the downlink relevant type of NPDCCH..On the terminal side channel estimation and equalization have been implemented, and the signals are decoded by reversing the encoding steps: descrambling, de-rate matching, decoding using the Viterbi algorithm and removal of the CRC bits. A simple CRC check is used to measure block error rates.

First to check the transfer through an additive white Gaussian noise (AWGN) channel a comparison between the simulated BER and the theoretical BER is made.The theoretical BER is calculated using equation:

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) = Q(\sqrt{2\gamma_b})$$

Where γb is the SNR per bit ($\frac{E_b}{N_0}$) and Q is the statistical Q function as defined in equation:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{\chi}^{\infty} e^{-\frac{u^2}{2}} du$$

The simulated data is generated using a 16 bit block with 24bit CRC and no repetition for an inband deployment.The step-length is set to 1 and for each step 200bits is transmitted 100 times.The simulation implements no equalization in order to align with the theoretical BER calculation. The graphical comparison can be seen in the next figure:

Parameters	Value
Block	16 bit
CRC code	24 bit
Frequency	1,92 Mhz
Bandwith	180 Khz
Repetitions	1, 4, 64, 512, 2048

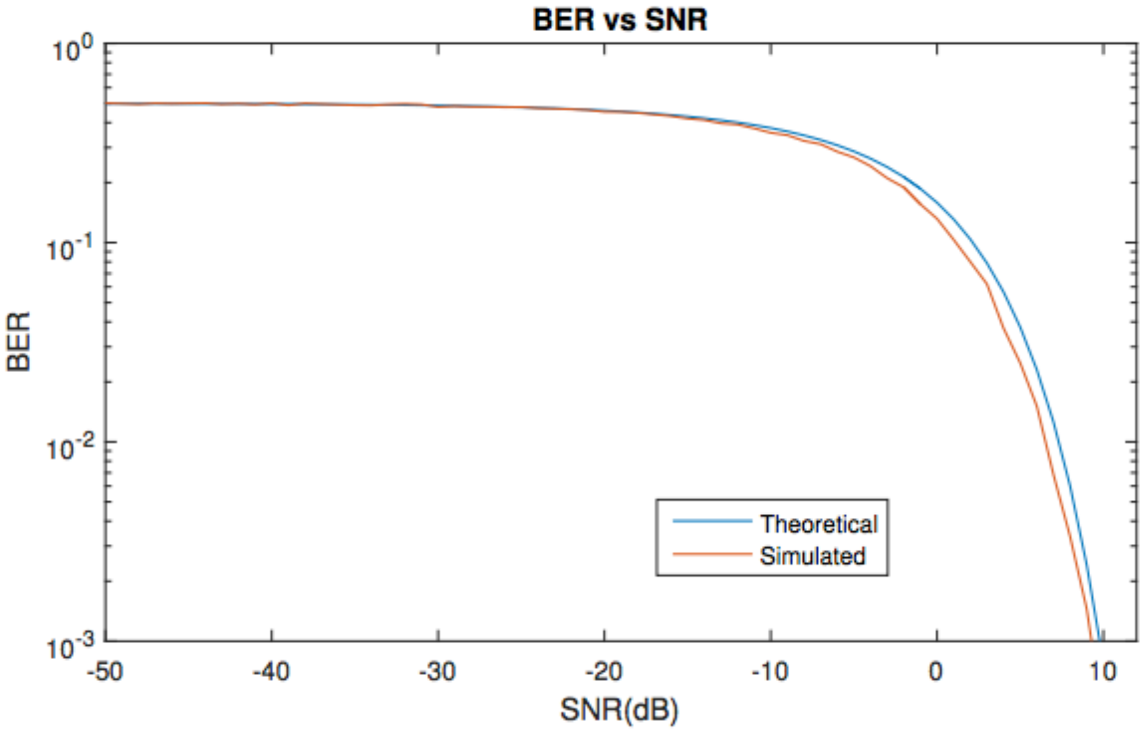


Figure 28. Comparing the developed NB-IoT downlink simulator bit error rates to atheoretically calculated bit error rate.[34]

We will take the results from the research that is for our comparison with Lorawan.So we will take the BLER/SNR results of the NPDSCH for several repetitions.

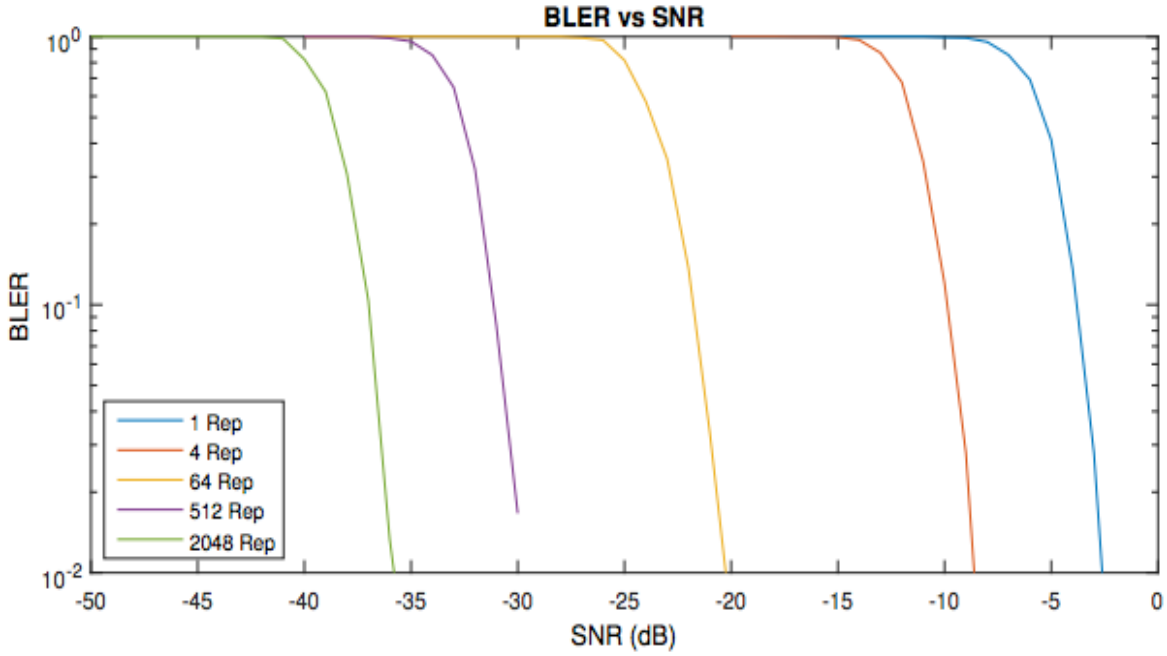


Figure 29. Graphing the simulated block error rates for various repetitions[34]

In order to verify the behavior of the NPBCH and NPDCCH a longer simulation is running the normal-mode to verify the block error rates on these channels. The results are presented in the next figure:

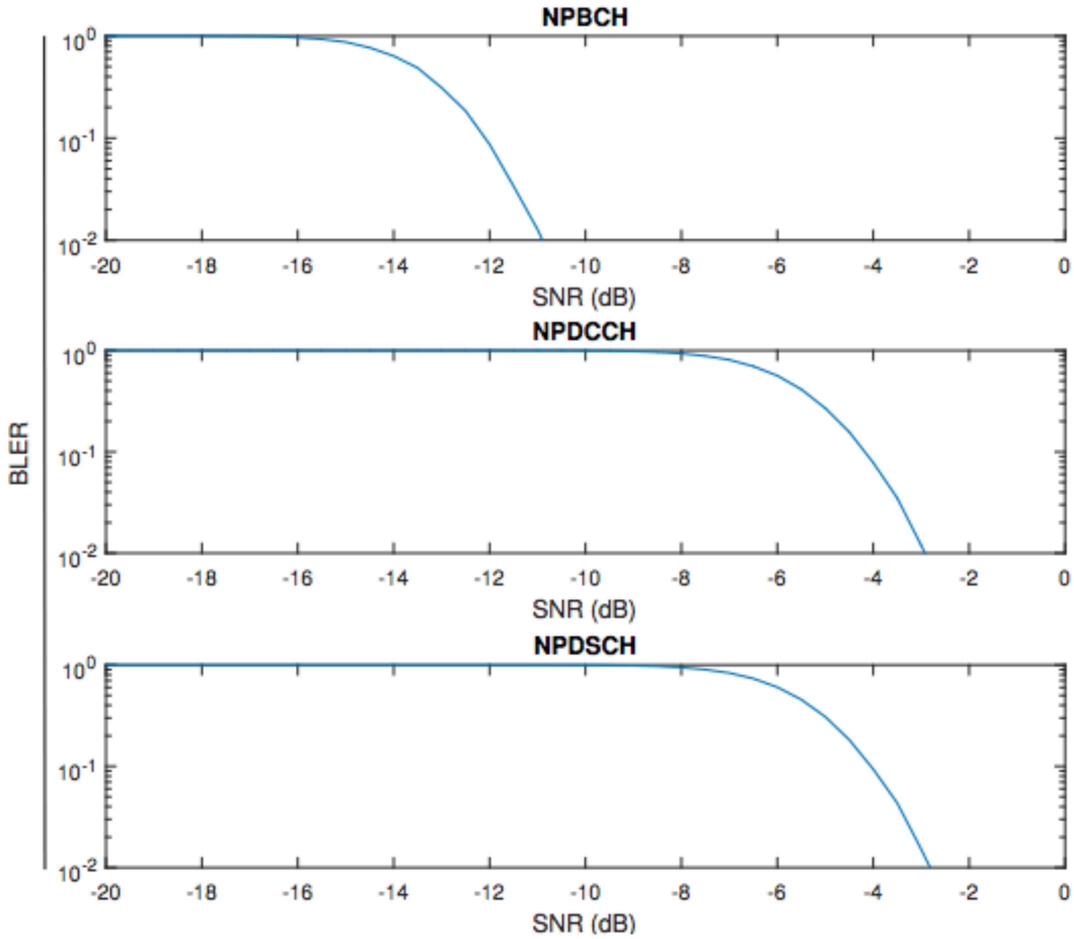


Figure 30. The results from an SNR sweep run in normal-mode with in-band settings.Starting point -20 dB with 0.5dB step-size to 0 dB.NPBCH is accumulated 8 times before being decoded.NPDCCH and NPDSCH are not repeated.[34]

As expected the NPDCCH closely follows the unrepeated NPDSCH when the blocksizes are similiar and the NPBCH curve is as expected left-shifted in relation to the other channels due to the accumulation of repetitions.

5.5 Differences From Simulation

As we can see from the simulation results the Narrowband Iot can reach higher values of the SNR for the same amount of the BER that LoraWan has if the number of repetitions is 1 or 4.When the number of repetitions is more than 4 the LoraWan model reach the same SNR with NB-Iot with lower BER.Also at very high number of repetitions the SNR of Nb-Iot simulation drops to too low values.Of course these results can be a standard comparison for these technologies because it hasn’t the same parameters as an input or the same conditions for the simulation

5.6 Conclusion

As we can see both LoRaWan and NB-IoT have their own advantages and disadvantages according to its different technological principles. In general, there is not a unique LPWA technology, but the most appropriate technology for the specific application. Each application has its specific requirements, which lead to a specific technology choice. Both LoRaWan and NB-IoT have their place in the IoT market. LoRa focuses on the low cost applications. Meanwhile, NB-IoT is directed to applications that require high QoS and low latency.

6 Matlab Code For LoraWan

- **Main Program.m**

```
SF = 7:1:12;                    % Spreading Factor from 7 to 12
BW = 125000;                    % 125kHz
Fs = 125000;                    % Sampling Frequency
preamble_len = 8;               % Preamble length
sync_len = 2;                   % Sync length
total_bits = 27720;              % total bits to be transmitted in
LoRa message
SNR_dB = -40:1:00;              % SNR in DB
SNR = 10.^(SNR_dB/10);          % SNR
Total_iterations = 100;
BER = zeros(Total_iterations,length(SNR_dB));

for sf = 1:1:length(SF)

    num_samples = Fs*(2^SF(sf))/BW;  % Number of samples

    %% Random Number Generation
    [Input_sample_Bi, input_len] =
LoRa_random_number_generation(total_bits,SF(sf));

    rand_num_matrix = reshape(Input_sample_Bi, SF(sf),
input_len);

    % Binary to Gray Conversion
    Input_sample_gray = binary2gray(rand_num_matrix);

    % Binary to Decimal conversion
    Input_sample = bi2de(Input_sample_gray','left-msb')';

    lora_total_sym = preamble_len + sync_len + input_len;  %
Total transmitted symbols


    %% Preamble Generation
    inverse = 0;
    for i = 1:preamble_len
        [out_preamble] =
LoRa_Modulation(SF(sf),BW,Fs,num_samples,0,inverse);
        outp((i-1)*num_samples+1 : i*num_samples) =
out_preamble;
    end
```

```
    %% Sync Symble Generation
    inverse = 1;
    for i = 1:sync_len
        [out_sync] =
LoRa_Modulation(SF(sf),BW,Fs,num_samples,32,inverse);
        outp = [outp out_sync];
    end

    %% Symble Generation
    inverse = 0;
    for i = 1:input_len
        [out_sym] =
LoRa_Modulation(SF(sf),BW,Fs,num_samples,Input_sample(i),inver
se);
        outp = [outp out_sym];
    end


    for ite = 1:1:Total_iterations
        for snr = 1:1:length(SNR_dB)
            %% AWGN Channel
            out_channel = awgn(outp,SNR_dB(snr),'measured');

            %% Reverse chirp generation for receiver
            inverse = 1;
            [out_reverse] =
LoRa_Modulation(SF(sf),BW,Fs,num_samples,0,inverse);
            % Multiplying with the reverse chirp
            for n = 1:1:lora_total_sym
                decoded_out((n-1)*num_samples + 1 :
n*num_samples) = (out_channel((n-1)*num_samples + 1 :
n*num_samples).*out_reverse);
            end

            %% Calculating FFT
            for m = 1:1:lora_total_sym
                FFT_out(m,:) = abs((fft(decoded_out((m-
1)*num_samples + 1 : m*num_samples))));
            end

            %% Decoding the received data
            k=1;
            for m =
(preamble_len+sync_len+1):1:(lora_total_sym)
                [r,c] = max(FFT_out(m,:));
                data_received_De(k) = c-1;
                k = k+1;
            end

            % Decimal to Binary Conversion
```

```
            data_received_bin = 
de2bi(data_received_De,SF(sf),'left-msb')';
            % Gray to Binary Conversion
            data_received_gray = 
gray2binary(data_received_bin);
            % Matrix to array conversion
            data_received = 
reshape(data_received_gray,total_bits,1);



            %% BER Calculation
            BER(ite,snr) = sum(abs(data_received - 
Input_sample_Bi))/total_bits;
        end
    end
    Avg_BER(sf,:) = mean(BER);    % Average BER over all the 
iterations
    clear FFT_out;
    clear outp;
    clear decoded_out;
    clear data_received_De;
    clear data_received_gray;
end



%% Plotting
% Plotting the BER vs SNR curve
semilogy(SNR_dB,Avg_BER);
title('BER vs SNR');
xlabel('SNR (Signal to Noise ratio in dB)');
ylabel('BER (Bit Error Rate)');
legend('SF7','SF8','SF9','SF10','SF11','SF12');
grid on;
```

We use 3 different matlab functions inside the main program.

- LoRa_random_number_generation.m

```
%% Random sequence generation block
% Inputs:
% total_sym: Total no. of random bits to be generated
% SF: Spreading Factor
% Output:
% Input_sample: Random number in decimals
```

```
%%

function [random_number_input, columns] =
LoRa_random_number_generation(total_sym, SF)

rows = SF;
columns = ceil(total_sym/SF);
random_number_input = round(0.75*rand(1,rows*columns))';
```

- binary2gray.m

```
%% Binary to Gray Conversion

function [Input_sample_gray] =  binary2gray(Input_sample_Bi)

[r,c] = size(Input_sample_Bi);
Input_sample_gray = zeros(r,c);

Input_sample_gray(1,:) = Input_sample_Bi(1,:);    % Copying
First bit

for m = 1:1:c
    for g = 2:1:r       % Xor of input bit with last input bit
        Input_sample_gray(g,m) = xor(Input_sample_Bi(g,m),
Input_sample_Bi(g-1,m));
    end
end
```

- gray2binary.m

```
%% Gray to Binary Conversion

function [data_received_bin] = gray2binary(data_received_gray)

[r,c] = size(data_received_gray);
data_received_bin = zeros(r,c);

data_received_bin(1,:) = data_received_gray(1,:);    % Copying
First bit

for m = 1:1:c
    for g = 2:1:r      % Xor of input bit with last output bit
        data_received_bin(g,m) = xor(data_received_bin(g-1,m),
data_received_gray(g,m));
    end
end
```

7 References

[1] “Cellular networks for massive iot: Enabling low power wide area applications,” Ericsson, Tech. Rep., January 2016, ericsson White Paper. [Online].
Available: https://www.ericsson.com/res/docs/ whitepapers/wp iot.pdf
[2] E. Berthelsen and J. Morrish, “Forecasting the internet of things revenue opportunity,” Machina Research, Tech. Rep., April 2015. [Online].
Available: https://machinaresearch.com/report pdf/313
[3] “Lte evolution for iot connectivity,” Nokia, Tech. Rep., 2016, nokia White Paper. [Online]. Available: http://resources.alcatel- lucent.com/ asset/200178
[4] X.Xiong,K.Zheng,R.Xu,W.Xiang,andP.Chatzimisios,“Lowpower wide area machine-to-machine networks: key techniques and prototype,” IEEE Communications Magazine, vol. 53, no. 9, pp. 64–71, September 2015.
[5] S. Wilson. The future of 3g: the case for decommissioning. [Online]. Available: http://www.analysysmason.com/3G- decommission- Oct2015
[6] J. Petajajarvi, K. Mikhaylov, A. Roivainen, T. Hanninen, and M. Pet- tissalo, “On the coverage of lpwans: range evaluation and channel attenuation model for lora technology,” in ITS Telecommunications (ITST), 2015 14th International Conference on, Dec 2015, pp. 55–59.
[7] “5g radio access,” Ericsson, Tech. Rep., April 2016, ericsson White Paper. [Online]. Available: https://www.ericsson.com/res/docs/ whitepapers/wp- 5g.pdf
[8] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, and J. Melia, “Understanding the limits of lorawan,” arXiv preprint arXiv:1607.08011, 2016.
[9] Sigfox. [Online]. Available: http://www.sigfox.com/
[10] N. Sornin, M. Luis, T. Eirich, and T. Kramp, “Lorawan
specification,” LoRa Alliance, Tech. Rep., 2015. [Online]. Available: https://www.lora-alliance.org/portals/0/specs/LoRaWAN% 20Specification%201R0.pdf
[11] https://en.wikipedia.org/wiki/LPWAN
[12] www.lora-alliance.org
[13] "3GPP Low Power Wide Area Technologies - GSMA White Paper"
[14] Ratasuk, R.; Mangalvedhe, N.; Ghosh, A., "Overview of LTE enhancements for cellular IoT," PIMRC, Sept. 2015.
[15] Ratasuk, R.; Prasad, A.; Zexian Li; Ghosh, A.; Uusitalo, M., "Recent advancements in M2M communications in 4G networks and evolution towards 5G," ICIN, Feb. 2015.
[16] 3GPP TR 36.888, Study on provision of low-cost Machine-Type Communications (MTC) User Equipments (UEs) based on LTE, v.12.0.0, June 2013.
[17] D. C. Chu, "Polyphase codes with good periodic correlation properties," IEEE Trans. Inform. Theory, vol. 18, no. 4, pp 531–2, July 1972.
[18] “Ericssonmobilityreport,onthepulseofthenetworkedsociety,” Ericsson White Paper, Jun. 2016. [Online]. Available: https://www.ericsson.com/res/docs/2016/ericsson-mobility-report- 2016.pdf
[19] X.Lin,A.AdhikaryandY.-P.E.Wang,“Randomaccesspreamble design and detection for 3GPP narrowband IoT systems,” Submitted to IEEE Wireless Communication Letters, May 2016.

[20]A.Adhikary,X.LinandY.-P.E.Wang,“Performanceevaluationof NB-IoT coverage,” Submitted to IEEE Veh. Technol. Conf. (VTC), September 2016, Montréal, Canada.

[21]TR36.888v12.0.0,“Studyonprovisionoflow-costmachine-type communications (MTC) user equipments (UEs) based on LTE,” Jun. 2013. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/36_series/36.888/36888-c00.zip

[22] TR 45.820 v13.1.0, “Cellular system support for ultra low complexity and low throughput internet of things,” Nov. 2015. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/45_series/45.820/45820-d10.zip

[23] Semtech, AN 120022, LoRa Modulation Basics, May, 2015. Available: http://www.semtech.com/images/datasheet/an1200.22pdf.

[24] D. Rohde, J. Schwarz, Narrowband Internet of Things, Aug., 2016. Available: https://www.rohde-schwarz.com/us/applications/narrowband-internet-of-things-application-note 56280-314242.html.

[25] 3GPP TR 36.802, Narrowband Internet of Things (NB-IoT), Technical Report TR 36.802 V1.0.0, Technical Specification Group Radio Access Networks, June, 2016.

[26] LoRa Alliance, LoRaWAN What is it. Technical Marketing Work- group 1.0, Nov.,2015.Available:https://www.lora-alliance.org/portals/0/ documents/whitepapers/LoRaWAN101.pdf.

[27] LoRa Alliance, LoRaWAN Specification, July, 2016.

[28] Orange Connected Objects & Partnerships, LoRa Device Developer Guide, April, 2016. Available: https://partner.orange.com/wp-content/ uploads/2016/04/LoRa- Device- Developer- Guide- Orange.pdf.

[29] 3GPP TS 36.321 V13.2.0 Medium Access Control (MAC) protocol specification, June, 2016.

[30] 3GPP TR 36.824 V11.0.0 3rd Generation Partnership Project, Technical Specification Group Radio Access Network, Evolved Universal Terrestrial Radio Access (E-UTRA), LTE coverage enhancements (Release 11), June, 2016.

[31] LoRa Alliance, NB-IoT vs LoRa Technology Which could take gold? White Paper,September,2016.Available:https://www.loraαlliance.org/portals/0/documents/whitepapers/LoRa-Alliance-Whitepaper NBIoT vs LoRa.pdf.

[32]Ericsson,Uen28423-3278,CellularnetworksformassiveIoT,Jan.,2016. Available: https://www.ericsson.com/res/docs/whitepapers/wp iot.pdf.

[33] www.sghoslya.com/p/before-going-through-this-post-please.html

[34] https://uu.diva-portal.org/smash/get/diva2:1083434/FULLTEXT01.pdf