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# The Narrowband Internet of Things (NB-IoT) Resources Management Performance State of Art, Challenges, and Opportunities

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**ABSTRACT** The Narrowband Internet of Things (NB-IoT) has been introduced in the 3rd Generation Partnership Project (3GPP) Rel-13 with the aim to provide low-cost, low-power, wide-area cellular connectivity for the Internet of Things. With the exponentially increasing number of connected wireless devices in the order of 100 billion, it has become crucial that researchers develop efficient resource management techniques to meet the $5^{th}$ Generation (5G) quality of service (QoS) requirements. Recently, several research challenges including the low modulation data rates, energy-expensive channel coding techniques, and the fast-growing number of connected devices have been identified as some of the main issues encountered in the design and deployment of NB-IoT systems. In addition, several techniques have emerged in the literature to resolve some of these challenges of NB-IoT systems. However, the research activities towards the enhancement of the NB-IoT resource management are yet to continue in the next half-decade before, high data rates, energy-efficient, and scalable NB-IoT specifications can be released for the standardisation and commercialisation. Considering the limited number of existing surveys of such technical enhancement approaches in a broader perspective (i.e. energy efficiency, data rate performance and scalability) and also the non-existence, to the best of our knowledge, of a comparative survey, this paper seeks to elaborate, describe and compare the performances of such resources management approaches. Of the multiple NB-IoT resources, the focus of this paper is on the data rate, energy efficiency, and scalability enhancement schemes that have been proposed for the last three years. The contribution of the paper lies in the analysis, synthesis, comparison and summarised alignments of some of the major existing schemes towards identifying challenges faced by the NB-IoT development. Finally, this work seeks to identify research challenges, open questions, and opportunities that could arise from the existing techniques analysed.

**INDEX TERMS** Data rates, energy efficient, challenges, narrowband IoT (NB-IoT), opportunities, resources, scalability, reliability.

## I. INTRODUCTION

The Internet today has become ubiquitous. It touches almost every corner of the globe and is affecting human life in its different aspects [1]. It is predicted that there will be around 28 billion connected devices by 2021 of which more than 15 billion will be connected Machine to Machine (M2M) and consumer-electronics devices. This is illustrated in Fig. 1 [23].

A new class of wireless network technologies is therefore required to support the fast growth and development of the Internet of Things (IoT). This is also due to the specific requirements and characteristics of IoT objects such as low power consumption, long range, low cost and security. Indeed, the ambitious efficient use of network resources have already triggered considerable research and development

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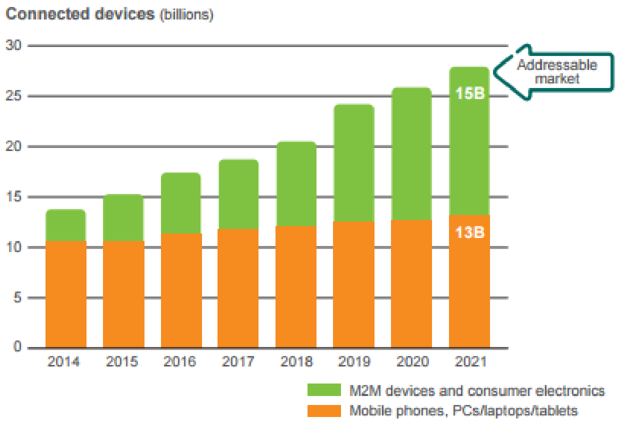


**FIGURE 1.** Expected growth in number of connected devices [23].

**TABLE 1.** Most common LPWAN technologies.

| Unlicensed | Licenced |
|---|---|
| LoRa | NB-IoT |
| SigFox | LTE-M(LTE Cat-M1) |
| Symphony Link | NB-Fi (Narrowband Fidelity) |
| iFrogLab | LTE-MTC |
| ThingPark Wireless | UNB (Ultra Narrow Band) |
| Ingenu [6] | WEIGHTLESS-P [5] |

interest in terms of the development of novel techniques and approaches at all network layers, that are specific to the IoT.

One of the areas that has received attention recently is Low Power Wide Area Networks (LPWAN). Low Power Wide Area (LPWA) describes a category of wireless communication technologies designed to support Internet of things (IoT) deployments. LPWA, therefore, represent the group of technologies aimed at enabling power efficient and cheap wide area communication that Machine to Machine (M2M) communication can rely on for a much more power efficient deployment and operation [4]. LPWA technologies are expected to serve a diverse range of vertical industries and support a range of applications and deployment scenarios which existing mobile technologies may not currently be best placed to connect. The main aim of the LPWA technologies designs consists of delivering strong coverage over large areas, great power efficiency, massive scale, low cost communications and low bandwidth [3].

To date LPWAN has become one of the fastest growing markets in IoT with many LPWAN technologies being developed both in the licensed and unlicensed spectra. Some of the most popular LPWA technologies being developed can be classified as given in Table 1.

From the list of most common LPWAN technologies in Table 1, it has been identified that the Long Range (LoRa) as well as the Narrowband Internet of Things (NB-IoT) are the two most popular and emerging technologies within the unlicensed and the licensed bands respectively [7].

### A. COMPARISON OF THE NB-IoT AND OTHER IoT TECHNOLOGIES

The Narrowband Internet of Things (NB-IoT) is a novel narrowband radio technology specifically designed for IoT, which can be directly deployed in Global System for Mobile Communications (GSM) or Long-Term Evolution (LTE) networks with the objective of reducing deployment costs [8]. However, there exists other wireless communication technologies that enable the deployment of the Internet of Things. Fig. 2 presents a comparison of different technologies for IoT and the evolution towards to 5G.

At a recent plenary meeting in South Korea, the Third Generation Partnership Project (3GPP) completed the standardisation of NB-IoT in which NB-IoT is regarded to be a very important technology and a large step for 5G IoT evolution [57]. Industries, including Ericsson, Nokia, and Huawei, have shown great interest in NB-IoT as part of 5G systems, and spent lots of effort in the standardisation of NB-IoT [58] which has been widely considered as a main technique for next-generation wireless communications. NB-IoT is expected to provide improved coverage and support a massive number of low-throughput devices, low delay sensitivity, ultra-low device costs, and low device power consumption [59]. The question of how to achieve these benefits, particularly improved coverage, data rates and energy efficiency is a great challenge.

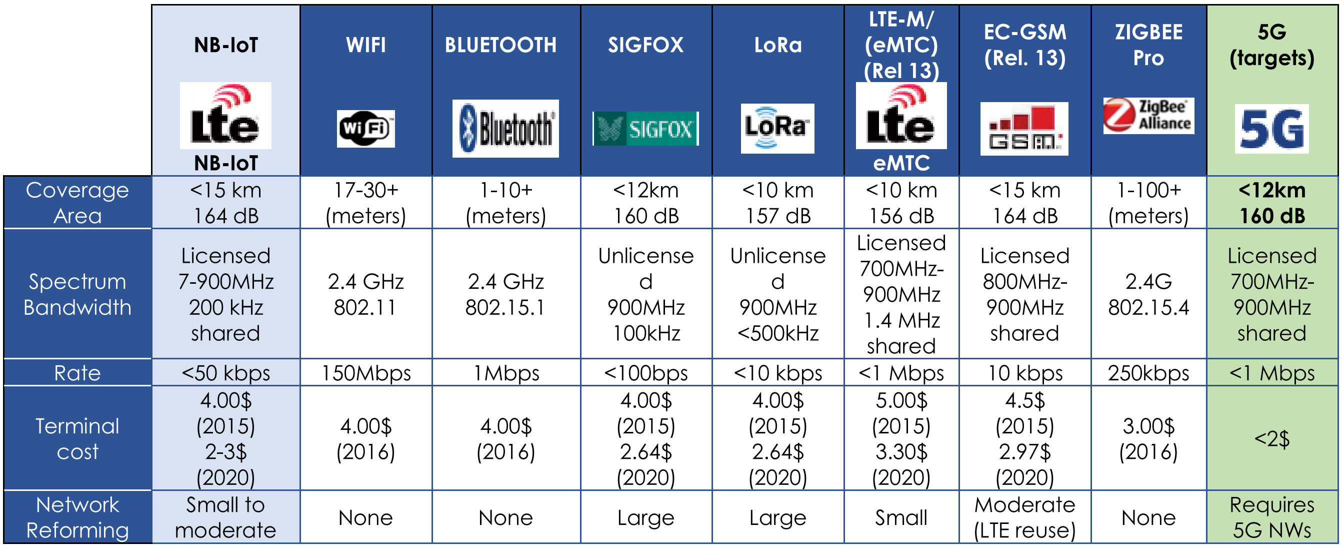
In 3GPP standardisation, repeating transmission data and the associated control signaling several times has been utilised as a base solution to achieve coverage enhancement for NB-IoT [60], [62], [63]. Other existing works on NB-IoT take into account the new feature of repetition [57], [64]. The approach is to consider performing a link adaptation for resource management to enhance energy, data rate, coverage efficiency by considering a two dimensional space, namely the modulation and coding scheme (MCS) level selection as is considered in traditional LTE systems as well as the determination of the repetition number.

### B. NB-IoT AND LoRa PHY LAYER COMPARISON

This section briefly discusses the key technical differences, at PHY layer between the NB-IoT Technology (considered as the leading LPWAN technology in the licensed band) and the Long Range (LoRa) technology (considered as the leading technology in the unlicensed band).

The LoRa LPWAN technology operates in the non-Licensed band below 1 GHz for long range communication. It uses Chirp Spread Spectrum (CSS) modulation at the PHY layer which allows it to trade data rate (low) for sensitivity within a fixed channel bandwidth making it quite robust against interference. The CSS modulation is also known for its long range capabilities mainly due to its robustness against interference. As a result, it finds wide applications in military [65].

By using a spread spectrum modulation technique, LoRa not only provides long range capability, but also a great link budget performance. It is important to note that the spread spectrum provides orthogonal separation between signals. This is done by using a unique spreading factor for individual signals. This approach is advantageous in terms of data rate management. The relationship between the necessary data



| | NB-IoT<br>NB-IoT | WIFI | BLUETOOTH | SIGFOX | LoRa | LTE-M/ (eMTC) (Rel 13)<br>eMTC | EC-GSM (Rel. 13) | ZIGBEE Pro | 5G (targets) |
|---|---|---|---|---|---|---|---|---|---|
| Coverage Area | <15 km<br>164 dB | 17-30+ (meters) | 1-10+ (meters) | <12km<br>160 dB | <10 km<br>157 dB | <10 km<br>156 dB | <15 km<br>164 dB | 1-100+ (meters) | **<12km**<br>**160 dB** |
| Spectrum Bandwidth | Licensed<br>7-900MHz<br>200 kHz<br>shared | 2.4 GHz<br>802.11 | 2.4 GHz<br>802.15.1 | Unlicensed<br>900MHz<br>100kHz | Unlicensed<br>900MHz<br><500kHz | Licensed<br>700MHz-900MHz<br>1.4 MHz<br>shared | Licensed<br>800MHz-900MHz<br>shared | 2.4G<br>802.15.4 | Licensed<br>700MHz-900MHz<br>shared |
| Rate | <50 kbps | 150Mbps | 1Mbps | <100bps | <10 kbps | <1 Mbps | 10 kbps | 250kbps | <1 Mbps |
| Terminal cost | 4.00$<br>(2015)<br>2-3$<br>(2020) | 4.00$<br>(2016) | 4.00$<br>(2016) | 4.00$<br>(2015)<br>2.64$<br>(2020) | 4.00$<br>(2015)<br>2.64$<br>(2020) | 5.00$<br>(2015)<br>3.30$<br>(2020) | 4.5$<br>(2015)<br>2.97$<br>(2020) | 3.00$<br>(2016) | <2$ |
| Network Reforming | Small to moderate | None | None | Large | Large | Small | Moderate (LTE reuse) | None | Requires 5G NWs |

**FIGURE 2. Performance Comparison of some common IoT Technologies [3], [23] and [17].**

rate and the chip rate and symbol rate being used for the LoRa network has been modelled in [103] as:

$$R_b = SF \times \frac{1}{\left[\frac{2^{SF}}{BW}\right]} \; bits/sec \tag{1}$$

where "SF" is the spreading factor and "BW" is the modulation bandwidth (Hz). As is clearly shown in equation 1, the data bit rate is directly proportional to the modulation Bandwidth.

In the modulation of LoRa, the spreading of the spectrum is achieved by generating a chirp signal that continuously varies in frequency. An advantage of this method is that timing and frequency offsets between transmitter and receiver are equivalent which greatly reduces the complexity of the receiver design. LoRa also has other advantages such as adaptive data rate, scalable bandwidth, high-power efficiency, and resistance to multipath.

On the other hand, the NB-IoT can be regarded as a new air interface on its own despite the fact that it is integrated into the LTE. This is because NB-IoT removes many features of LTE, including handover, measurements to monitor the channel quality, carrier aggregation, and dual connectivity in order to satisfy the energy efficiency and low power operation (energy efficiency) NB-IoT design criteria as elaborated in section II.

Unlike LoRa that uses a non-licensed band, NB-IoT uses the same frequency bands as LTE which are licenced frequency bands subdivided into 12 sub-carriers of 15 kHz each in the downlink (DL) using OFDM access method and 3.75 or 15 kHz in the uplink(UL) using the single carrier FDMA (SC-FDMA) access scheme. It is also important to note that NB-IoT uses a PSK which is the same modulation technique as used in LTE.

NB-IoT occupies a frequency band of 180 kHz bandwidth which corresponds to one resource block in LTE transmission. This results in three possible operational modes depending on where the block is located within the LTE spectrum as illustrated in Fig. 3.

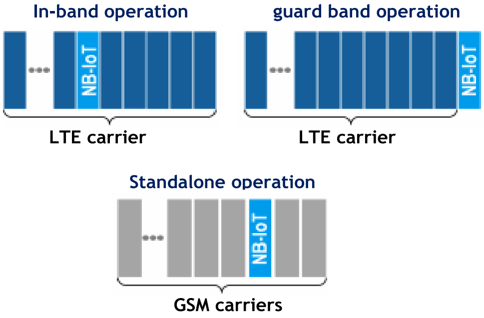


**FIGURE 3. NB-IoT band operational modes.**

The three operational modes include

1) *In-band operation* utilising resource blocks within an LTE carrier.
2) *Guard band operation*, utilising the unused resource blocks within an LTE carrier's guard-band.
3) *Stand alone operation*: A possible scenario is the utilisation of currently used GSM frequencies. With their bandwidth of 200 kHz there is still a guard interval of 10 kHz remaining on both sides of the spectrum.

Table 2 provides a comparative summary of the key differences at the PHY layer between LoRa and NB-IoT.

In summary, the objective of this work is to provide a survey of existing articles that focus on enhancing one or more of the NB-IoT resources and critically assess their respective performances by comparing them based on energy efficiency, data rates and network scalability and identifying potential research opportunities for future work. The focus of the article is on existing channel coding approaches,

**TABLE 2.** Comparative table between PHY features of LoRa and NB-IoT.

| PHY parameters | LoRa | NB-IoT |
|---|---|---|
| Modulation | CSS | QPSK |
| Link Budget | 154dB | 150dB |
| Spectrum | Unlicensed | Licensed LTE bandwidth |
| Bandwidth | 500 KHz - 125 KHz | 180KHz |
| Peak Data Rate | 290bps-50Kbps (DL/UL) | DL:234.7kbps; UL:204.8kbps |
| 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, Inband guard band operation |
| Power efficiency | Very High | Medium High |
| Area Traffic Capacity | Depends on gateway type | 40 devices per household<br>$\approx$ 55k devices per cell |
| Interference immunity | Very High | Low |
| Standardization | De-facto Standard | 3GPP Rel.13 |
| Mobility | Better than NB-IoT | No connected mobility (only idle mode reselection) |

modulation level selection schemes, and network scalability approaches. The rest of the paper is organised as follows. Section II presents and describes the main NB-IoT design objectives. Section III discusses the most common NB-IoT applications and their associated resource challenges while section IV focuses on into the security challenges and associated solutions specifically. Section V discusses related work on the existing energy-efficient NB-IoT Channel coding schemes. Section VI describes and discusses the work related to NB-IoT modulation selection schemes designs for data rate performance enhancement. Section VII discusses link Adaptation Schemes for enhanced NB-IoT scalability. In Section VIII, the NB-IoT performance Challenges and open issues are identified and discussed. Section IX analyses the aspects of NB-IoT as part of 5G cellular IoT while section X discusses the Software Defined Network (SDN) and the Network Function Virtualization (NFV) of NB-IoT within 5G systems, before conclusions are drawn and recommendations for future directions are formulated in section XI.

For convenience, a list of commonly used abbreviations commonly used in this paper are given below:

| | |
|---|---|
| **NB-IoT** | Narrowband Internet of Things |
| **PHY** | Physical Layer |
| **LoRa** | Long Range |
| **BSs** | Base Stations |
| **LPWAN** | Low Power Wide Area Network |

## II. NB-IoT DESIGN OBJECTIVES

NB-IoT mainly aims at offering energy and cost efficient connectivity to a large number of objects distributed over a wide geographical area [96]. Like most IoT technologies, one of the main objectives of the NB-IoT designs is to achieve machine type communication (MTC). Fig. 4 clearly depicts the different MTC applications of the NB-IoT together with the corresponding design objectives by clearly classifying them in massive and critical MTC applications.

From the literature, it can be argued that some of the NB-IoT design objectives are conflicting. This section briefly describes the design goals of NB-IoT systems as well as some of the techniques proposed in literature for achieving them. Some of the main design objectives in the design of the NB-IoT systems are as follows:

### A. LONG RANGE COMMUNICATION

In order to achieve wide area coverage, the NB-IoT design is required to produce a high quality of signal propagation and deeper signal penetration capable of reaching basements and deep areas of buildings. According to [108], the design targets signals that are often quantitatively estimated to ±20 dB gain over average cellular signals. This gain translates into end-to-end device connections over a distance ranging from a few to tens of kilometres and vary with respect to the type of deployment environments (rural, urban, etc.). In order to achieve long range NB-IoT designs, most of research work throughout literature has proposed the following (Physical) PHY layer design techniques,

- *The Use of the Sub-GHz Band:* Most NB-IoT designs have proposed the use the Sub-GHz range in order to improve the robustness and reliability of communication at lower power costs. The sub-GHz band provides better signal quality at a wider coverage area and longer distance mainly for two main reasons. Firstly, unlike the 2.4 GHz band, the sub-GHz band consists of lower frequencies which therefore experiences lower attenuation and multipath fading caused by obstacles and dense surfaces such as concrete walls as modelled by the Friis formula given by

  $$L = 20 \times \log_{10}(\frac{4 \times \Pi \times d \times f}{c}) \tag{2}$$

  where $L$ represents the approximation (ideal case: isotropic antennas and free space) attenuation, $d$ represents the distance between the transmitting and receiving antennas, $f$ and $c$ represent the frequency and the speed of light respectively.
  Secondly, the sub-GHZ band has been proven to be less congested when compared to the 2.4 GHz and 5 GHz bands which are bands used for common wireless technologies such as Wi-Fi, cordless phones, Bluetooth, ZigBee, and other wireless technologies specific to home appliances [108]. By achieving robust and highly reliable communication, the use of the Sub-GHz band results in longer communication range and lower power consumption.
- *Optimal Selection of Modulation Scheme:* In order to achieve long range communication, some work on efficient NB-IoT designs found in literature such as [57], [111] and [9] have proposed efficient techniques for modulation scheme selection. The common idea behind most proposed approaches consists of a trade off between high data rate and higher energy in each transmitted bit (or symbol) at the physical layer (PHY).

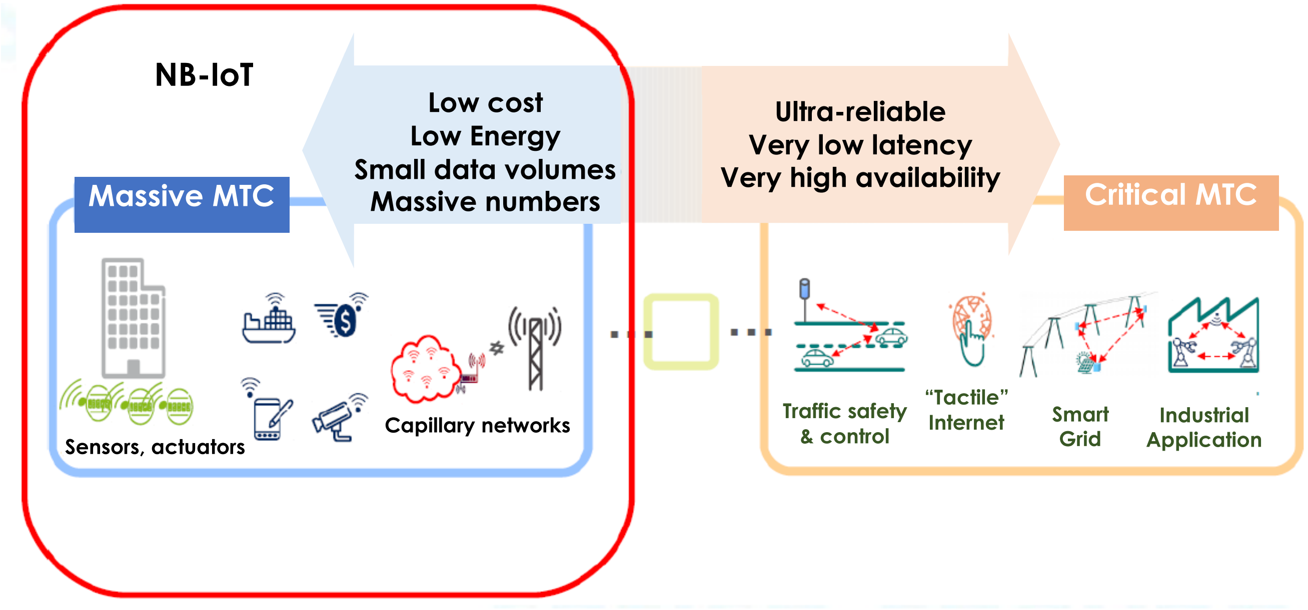


**FIGURE 4.** NB-IoT Machine Type Communication Applications [107].

This design technique allows for a signal that is more immune to noise and interference and that can travel longer transmission distances. Therefore, in general the identified aim of most designs is to achieve a link budget of 150 ± 10 dB which can translate into a few kilometres and tens of kilometres in urban and rural areas respectively [57]. Encoding more energy into the bits of a signal (or symbols) results in very high decoding reliability on the receiver side. Typical receiver sensitivities could therefore be as low as -130 *dBm*.

The modulation techniques used for most LPWAN technologies can be classified into two main categories namely narrowband techniques and spread spectrum techniques. Spread spectrum techniques spread a narrowband signal over a wider frequency band but with the same power density. The actual transmission is a noise-like signal that is harder to detect by an eavesdropper, is more resilient to interference, and is robust to jamming attacks (secure) [108].

Compared to other LPWAN technologies such as the LTE Cat-M1 which mainly uses spread spectrum modulation techniques, most work on NB-IoT designs found in literature such as [57], [108] and [9], propose the utilization of narrowband modulation techniques. In general, narrowband modulation techniques provide a high link budget which is often less than 25 KHz. They are very efficient at frequency spectrum sharing between multiple links, and they experience a very low noise level within each individual narrow band. In order to further reduce the experienced noise, some LPWAN technologies, such as SIGFOX, WEIGHTLESS-N, and TELENSA use ultra narrow band (UNB) with widths as short as 100 Hz [9]. They are therefore able to achieve longer transmission ranges.

One of the major differences between narrowband modulation techniques and spread spectrum techniques is that spread spectrum techniques often require more processing gain on the receiver side to decode the received signal (below the noise floor). However, no processing gain through frequency de-spreading is required to decode the signal at the receiver in the case of narrowband modulation techniques. This results in simpler and less expensive transceiver designs. Different variants of spread spectrum techniques such as Chirp Spread Spectrum (CSS) and Direct Sequence Spread Spectrum (DSSS) are used by existing standards LPWA technologies.

Other authors such as [11] have proposed the use of machine learning techniques as a mechanism to enhance coverage in narrowband-IoT. Instead of employing a random spectrum access procedure, the approach consists of using a dynamic spectrum access technique which results in reducing the number of required repetitions, increasing the network's coverage and reducing the energy consumption. Instead of random access based on slotted ALOHA, which randomly selects the channel in which to transmit in order to establish connection with the cell. It is proposed in this work that dynamic spectrum access be used in order to learn the channel which is more likely to be available and in good coverage conditions. The spectrum learning process can be modelled as a multi-armed bandit (MAB) framework as proposed in [12], [13]. Depending on the location of the UE (outdoor, indoor, basements) and the channel conditions (high or low SNR), the quality of the physical channels changes. Therefore, choosing the channel with the best quality (i.e. coverage level) potentially leads to reliable transmissions, and is less costly in terms of energy consumption.

### *B. LOW POWER OPERATION*

In order to reduce maintenance cost, battery powered IoT objects should have a lifetime of at least 10 years or more. This is a key design requirement for IoT/M2M designs. According to most work in literature, the battery lifetime is often dependent on a number of factors which include the network topology, the duty cycle being used and the task distribution between end-devices and Base Stations (BS) [67]–[69].

a) *Network Topology:*
According to [97], when the NB-IoT system is made up of a high number of connected objects over a wide geographical area, mesh network topology not only suffers from high deployment costs, but it also suffers from the ''bottleneck problem''. This is due to the fact that as the traffic is forwarded over multiple hops towards a gateway, some devices become more congested than others depending on their location or network traffic patterns. This results in shortening of their battery lifetime which limits the overall network lifetime to only a few months or years.
Therefore, most NB-IoT systems use the star network topology by connecting end devices directly to base stations obviating the need for the dense and expensive deployments of relays and gateways altogether. This technique results in huge energy savings. Compared to the mesh topology, the devices need not waste precious energy in busy-listening to other devices that want to relay their traffic through them. In the star topology used by most LPWAN technologies in general and also used by NB-IoT systems in particular, the base station is always kept switched ON in order to provide convenient and quick access when required by end-devices. It is important to point out that although most LPWA technologies use the star topology, some of them do make use of a tree or mesh topology. However, the later often require considerably complex protocol designs in order to achieve a similar energy efficiency performance to that of the star network topology [94].

b) *Duty Cycle Management:*
Another technique that is often used to achieve power efficient operation of NB-IoT systems consists of opportunistically turning off M2M/IoT devices of high power consumption such as the radio transceiver circuit. Applying an improved duty cycle on the radio transceiver circuit's power by turning the radio only when data needs to be transmitted or when data is received has shown a considerable reduction in the overall power consumption of the network [56].

A number of studies in literature on NB-IoT systems have looked at the impact of other PHY layer aspects on the energy consumption of the system. As a result, this work proposes to look at the impact and contribution of the modulation scheme selection as well as the channel coding on the overall energy consumption of the NB-IoT system.

### *C. LOW COST DESIGN*

Low cost design specification remains a key player in the commercial success of NB-IoT designs. This design condition can be better expressed by the following cost optimisation formulation: ''Achieving the connection of a large number of devices (as many devices as possible) while keeping both the hardware cost (e.g. below \$5 [18]) and the subscription cost per unit device as low as possible (e.g. \$1 [19])''. Some of the most common techniques, mechanisms and approaches used by NB-IoT technologies for achieving the objective of low cost design include,

- *The Reduction in Hardware Complexity:* Significant efforts are made in this area at both the NB-IoT device level as well as on the design of the different hardware platforms involved. These effort include for example the relaxation of the base-band processing which considerably reduces the computing requirements at the eNB. This automatically translates to cheaper hardware devices that significantly cut on cost [20]. Such efforts also includes the reduction of the Radio-Frequency (RF) components [21] on the RF path of the NB-IoT nodes. This is for example achieved by the use of an RF switch integrated circuit capable of switching multiple radios present on the NB-IoT node to the same antenna path by means of a basic low power output pin of the processor on board [22]. This RF hardware minimisation technique has been proven to be cost-efficient but also of minimal local interference between radio activities on the NB-IoT node [23].
- *The Simplification of the Network Infrastructure:* A a result of the effort of virtualization of NB-IoT network functions [24], [25], there has been significant reduction in memory storage requirements within the various parts in the network architecture such as the SGW (serving Gateway), the Mobility Management Entity (MME) and the Cellular Internet of Things Radio Access Network (CIoT RAN) [26].

## III. NB-IoT MOST COMMON APPLICATIONS AND ASSOCIATED NETWORK RESOURCES CHALLENGES

### *A. SMART METERING*

One of the most suitable uses for NB-IoT is smart metering. NB-IoT is commonly used for water, gas and electricity metering [43]. The uniqueness of NB-IoT systems as used for water and gas metering as opposed to electricity metering is the limited energy availability for NB-IoT nodes. Most water and gas meters are battery operated. The limited energy availability poses a challenge on their design because the design has to ensure a long network lifetime [44]. Due to the energy limitations, water and gas meters are often constrained to using low energy consuming communication technologies unlike electricity meter designs which can still explore other power hungry communication technologies such as cellular (LTE, GPRS etc) [45]. Battery powered NB-IoT modules do not need power connection, deliver deep indoor penetration, and thereby, establish a reliable connections even in areas where mobile reception is poor [46]. The provider is able to read the meter remotely and the end customer does not have to stay at home in order to wait for the meter reader to take meter readings at the user's premises [28].

Another case scenario is the one of application of the NB-IoT for remote smart energy metering. In the energy sector, the developing of smart metering networks allows operators and companies to improve the production efficiency and to offer an enhanced service to customers [27].

The authors in [28] propose a deployment analysis of the NB-IoT system for several metering systems with the objective of assessing its coverage and capacity performance. A number of case scenarios are set-up [28] to assess the performance. This can be summarised as follows:

- Energy metering (Gas metering for example): User equipment is placed in a deep indoor location sometimes in an underground area. This means that they are affected by extra path-loss compared to units in an outdoor situation such as water meters.These devices are static.
- Air quality metering: These type of smart NB-IoT meters are also static (not mobile) and would normally be placed in a household location. Although these devices are placed indoors, they are not often in an area of deep indoor location like the gas meters for example.
- Smart yard water meters: These water consumption counters and loggers are often deployed in an outdoor location. This makes them experience almost no path-losses.

All these devices in these three case scenarios are assumed to communicate daily to a NB-IoT Base Station on a periodic interval in order to send their daily consumption values. The study demonstrates that the devices in the outdoor location benefit from better signal strength when compared to the devices inside the house which in turn possess an advantage over the NB-IoT gas meters located in the deep indoor locations. This translates into more network reliability for outdoor devices which then affects their energy and channel capacity performance relative to the indoor and deep indoor devices.

### B. SMART CITIES

In Smart Cities, NB-IoT systems can be used in street lighting as discussed in [29]. Lamp posts fitted with appropriate modules can be switched on and off or dimmed remotely and can trigger an alarm if they malfunction [30]. If a city connects its parking spaces using NB-IoT, better utilisation is achieved of available parking. Motorists are directed by a smart parking guidance system to the nearest free parking space by the shortest route [31], [32]. In waste disposal, garbage cans fitted with NB-IoT modules alert a control centre when they are full. As a consequence, waste disposal companies can optimise vehicle routes and reduce costs [33].

A typical case scenario for the use of NB-IoT in smart cities applications is described and analysed in [47]. The scenario consists of NB-IoT devices placed in various parts of a city in heterogeneous environments with different network coverage conditions. These devices are used for parking management, traffic control, waste management and many other day to day city management operations. They primarily serve to log data for predictive and reactive city management planning [48]. The experience has demonstrated a clear energy performance difference between various types of devices depending on whether they are mobile or static, indoors or outdoors, urban or sub-urban. Some key challenges related to the deployment of NB-IoT systems in a smart city application have been identified. These include network planning and optimization to ensure reliable and long coverage, network latency and as well as the localisation of nodes

### C. LOCALISATION

The NB-IoT is suitable for locating pets or valuables both indoor and outdoor scenarios. In order to not lose sight of a pet or an expensive personal item, an NB-IoT module can be a low-cost alternative to a GSM tracker. NB-IoT presents an entire new set of opportunities for low power, low cost localisation of both moveable and fixed assets such as cars, sensor nodes [36]. As use case scenario is the use of triangulation to establish localisation of NB-IoT nodes between three nearest base stations can be low energy approach as compared to each nodes having its own GPS module. Based on the Signal-to-Noise Ratio (SNR) of the packet received from the three nearby BSs with well known GPS locations,the NB-IoT node can reasonably be located [37]. There are many other possible techniques that could be used for localization from NB-IoT device driven communications. These techniques include Observed Time Difference of Arrival (OTDoA) [38] and Received Signal Strength indicator (RSSI) [39] for example.

### D. FARMING AND FORESTRY: MONITORING LIVESTOCK

NB-IoT technology is also suitable for agricultural use where there is no power supply or where network coverage is poor [40]. In irrigation of fields or plantations, tank levels, pump pressure, and flow rates are measured. The location and health of livestock can be monitored as well. In forestry, low-cost sensors can be distributed in large numbers to report information such as temperature, smoke development, or wind direction [41].

### E. INDUSTRY: NB-IoT ON PALLETS AND PIPELINES

In a use case scenario that there is need to monitor oil and gas pipelines, sensors relay important information about pressure, flow rate, or possible leaks. There is often no external power source for pipelines in inaccessible areas [42]. NB-IoT could find appropriate applications since modules have a long service life, require no maintenance, and have a 20 dB wider range than conventional mobile network connections [50].

## IV. NB-IoT SECURITY CHALLENGES: REVIEW, BLOCKCHAIN SOLUTIONS AND OPEN CHALLENGES

It is not appropriate to review and discuss the different challenges faced by an Internet of Things Technology such as the NB-IoT without discussing the security aspects. This section focuses on this specific IoT resource management aspect. Despite the growing number of connected NB-IoT objects, estimated to more than 50 billions by 2020 [70] NB-IoT devices have been proven to be easy to hack, and, therefore could be compromised. Due to their constrained computation, memory and network resources, IoT devices are more vulnerable to attacks than other endpoint devices such as smartphones, tablets, or computers within a cellular network [71].

The key security requirements for IoT as identified by [71] include: data privacy, confidentiality and integrity, authentication, authorization and accounting, availability of services, single point of failure and energy efficiency among others. These key requirements have to be considered during NB-IoT deployment in order to ensure a secure NB-IoT network. However, it is important to note that the consideration of any of the above security requirements during the NB-IoT network design is faced with the challenge of limited network, energy, computation and memory resources which needs to be taken into account in the design of IoT specific emerging technologies for IoT resource management. An important technology that has been proposed is the blockchain approach as discussed by [72]–[74] and [75]. Blockchain consists of a growing list of records, called blocks, that are linked using cryptography. Each block contains a cryptography hash of the previous block, a timestamp, and transaction data (generally represented as a Merkle tree) [77]. The blockchain technology has enabled multiple applications of NB-IoT network designs within the spectrum of crypto-currency, monetization of IoT data using smart contracts and many artificial intelligence (AI) applications such as specialized expert systems [76], [78] and [80].

Despite the multiple advantages presented by solutions such as the blockchain approaches, there exists some security challenges that are yet to be addressed. Some of these challenges which include resources limitations, heterogeneity of devices, interoperability of security protocols, single points of failure, hardware and firmware vulnerabilities, trusted updates and management as well as blockchain vulnerabilities are summarized and discussed as open challenges by [71].

The vulnerability of blockchain is mainly due to the fact that the consensus mechanism depending upon the miner's hashing power can be compromised thereby allowing the attacker to host the blockchain. Similarly, the private keys with limited randomness can be exploited to compromise the blockchain accounts. Effective mechanisms still need to be defined to ensure the privacy of transactions and avoid race attacks which may result in double spending during transactions [71]. These open challenges present research opportunities aimed at further enhancing the security management of NB-IoT networks.

## V. ENERGY EFFICIENT NB-IoT CHANNEL CODING (CC) SCHEMES

Low-Power Wide-Area Network (LPWAN) technologies both in the licensed and unlicensed bands are striving to become energy efficient over very long distances [90].

NB-IoT is designed to extend the lifetime of devices and targets a battery lifetime of more than 10 years. To this end, a careful design of smart channel coding schemes, has been identified as a potential approach towards enhancing NB-IoT energy efficiency [4]. Channel coding is one of the most important aspects in digital communication systems which enables error detection and correction possible [104].

In its current form, the NB-IoT reuses the LTE design extensively including the numerologies, downlink orthogonal frequency-division multiple-access (OFDMA), uplink single-carrier frequency division multiple-access (SC-FDMA), channel coding, rate matching, interleaving, etc. To the best of our knowledge, the only reason for this extensive reuse of the LTE channel coding was to significantly reduce the time required to develop full NB-IoT specifications [50]. However, there are issues very specific to the NB-IoT network designs including the issue of limited energy capacity. Researchers [109], [110] have, therefore, identified a very crucial need to develop novel channel coding techniques very specific to the NB-IoT with different design goals. Our research work as introduced by the present article has identified the energy efficiency issue as a potential research problem. However, other researchers have looked into this problem from different perspectives. The different approaches considered by them are concisely reported in the next paragraphs.

### *A. WHY IS CHANNEL CODING IMPORTANT FOR NB-IoT?*

One of the most important issues in the design of NB-IoT systems is error correction. If well designed, the channel coding technique for NB-IoT can help save considerable amount of energy by significantly reducing the number of required re-transmissions. This justifies the fact that a good number of research have proposed channel coding techniques with the objective of achieving energy efficiency.

### *B. EXISTING NB-IoT ENERGY EFFICIENT CHANNEL CODING (CC) APPROACHES*

From the survey of the literature, the following main approaches have been selected to be the most relevant and recent works,

1) *Automatic Repeat Request (ARQ) Approaches:* In ARQ approaches, the receiver requests re-transmission of data packets. If errors are detected, using some error detection mechanism. The authors in [110] proposes an open loop forward error correction technique for

NB-IoT networks with the objective of optimizing the ARQ signaling. In this approach, signaling only needs to indicate the DL data transfer completion and does not have to be specific on which particular Packet Data Units (PDU) are lost during the transmission. This allows to reduce the simplicity of the channel coding approach, and, therefore, allows saving on computational energy consumption. This approach has proven to be efficient in enhancing the data rate performance in the Downlink (DL) of the NB-IoT network. Due to its low complexity, this approach has further proven to also enhance the energy efficiency of the NB-IoT network as it considerably reduces the computational energy consumption due to data reception on the transceiver of the IoT node. The approach proposed in [109] consists of using an hybrid automatic repeat request (HARQ) process in scenarios where the NB-IoT network can only support half duplex operations. The HARQ approach has demonstrated the ability of reducing the processing time at the IoT node. The obtained results in [109] are able to prove that the use of the HARQ approach can lead to savings up to 20% on the overall energy consumption of the network. This energy efficiency performance has also been proven not to be significantly affected by the increase in the scalability of the NB-IoT network when the HARQ approach is used.

The authors in [113] propose a hybrid channel coding approach. It consists of signaling hybrid automatic repeat request (HARQ) acknowledgements for narrowband physical downlink shared channel (NPDSCH) and uses a repetition code for error correction. In this case, the UE can be allocated with 12, 6 or 3 tones. However, only the 6 and 3 tone formats are introduced for NB-IoT devices due to coverage limitations, cannot benefit from the higher device bandwidth allocation which results in higher energy consumption performance.

2) *Forward Error Correction (FEC) Approaches:* Research ([14], [15], [17]) has investigated the efficiency of different re-transmission and FEC techniques in NB-IoT systems. Several researchers have quantified the effect of a number of network parameters on the efficiency of error correction techniques (and their associated network costs). However, no effort has yet been made to unify these studies into a systematic approach that could help with the selection of the most effective technique given certain network conditions.

The authors in [49] have proposed an improved error correction algorithm for multicast transmission over the LTE network, and by extension, over the Narrowband IoT network. The model used assumes a random distribution of packet losses and a constant loss rate in each scenario. The model can be expanded to include different error distributions and varying loss conditions during a series of NB-IoT downlink transmissions. The obtained results demonstrate that the use of a hybrid approach (HARQ and FEC combined) outperforms both the HARQ method used alone as well as the FEC approach used alone in terms of energy efficiency.

The authors in [95] that has proposed the use of open loop forward error correction technique a mechanism to not only enhance the energy efficiency of the NB-IoT network, but also to concurrently achieve efficient downlink data rate performance. The benefit of this approach lies in the fact that it enables extremely reliable firmware downloads which is an important IoT feature in a number of applications among which sensor network applications.

Another Forward Error Correction channel coding approach for Narrowband IoT proposed in [16] has been specifically designed to reduce the number of re-transmision attempts. This is mainly because it has been identified and demonstrated by [91], [92] and [93] that most energy consumption in Internet of Things and Wireless Sensor Networks (WSNs) is consumed through the transmission and the reception phases.

One of the most prominent NB-IoT uplink baseband processing designs mainly consists of two main parts, namely the channel coding processing design and the modulation part. According to most work found throughout the literature [98], most NB-IoT uplink channel coding approaches includes Cyclic Redundancy Check (CRC) generation and attachment, turbo or convolutional coding, and rate matching in their traditional format as inherited from the LTE network infrastructure.

Unlike most LTE devices, the NB-IoT nodes are mostly battery-powered, and, therefore, energy constrained. The traditional LTE channel coding approaches, therefore have been identified by certain studies such as [111] and [106] as not being as energy-efficient in the context of Internet of Things (IoT). Therefore, the authors in [111] have proposed a prediction-based energy saving mechanism which mainly consists of reducing the uplink transmission time as a key to ensure a long lifespan of an IoT device. The mechanism consists of two parts: first, the network architecture predicts the uplink packet occurrence through a deep packet inspection; second, an algorithm predicts the processing delay and pre-assigns radio resources to enhance the scheduling request procedure. In this way, the proposed approach is expected to significantly reduce the number of random accesses and the energy consumed by radio transmission, and therefore, reduce the overall NB-IoT network energy consumption [111]. The network architecture with the prediction-based energy saving mechanism as proposed by [111] can be further enhanced by adding a network clustering mechanism on the radio interface between the different NB-IoT nodes and the eNB instead of having multiple individual links between each node and the eNB. This can to further enhance the overall energy efficiency of the network. Our proposed energy-enhanced architecture diagram is as shown in Figure 5. The following key abbreviations are used:

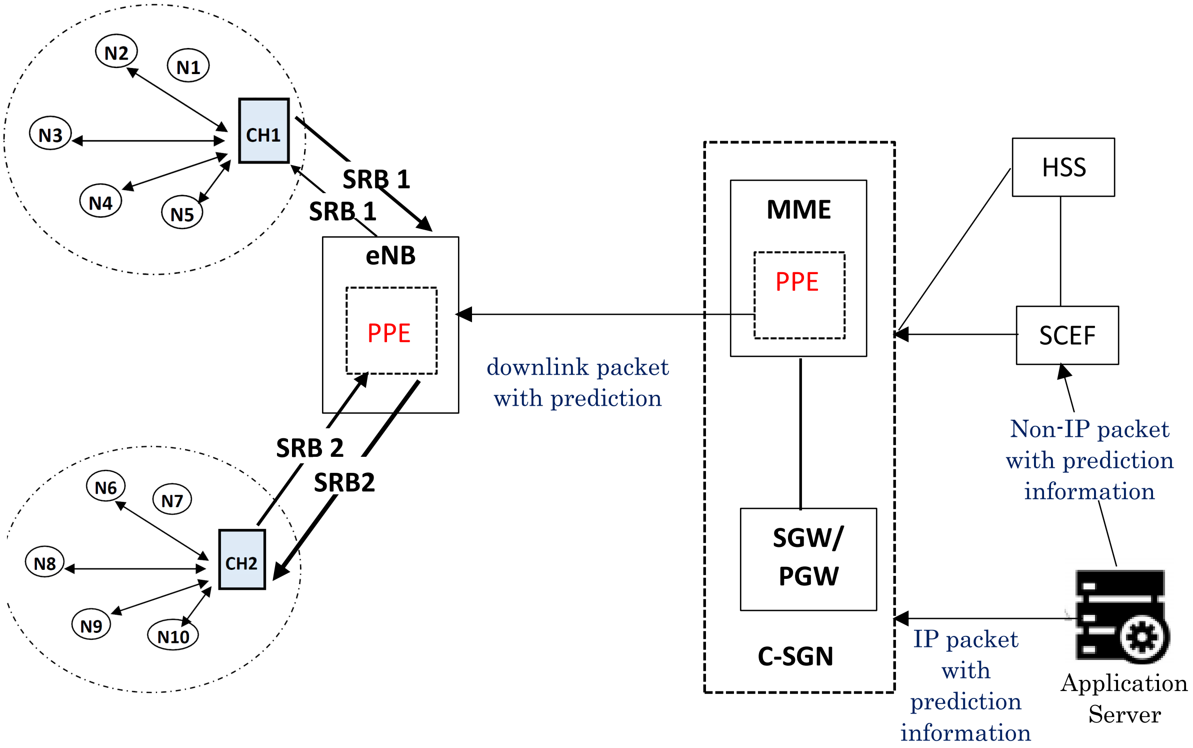


**FIGURE 5.** Energy-enhanced clustering Network architecture with prediction-based energy saving mechanism.

- **SRB: Signaling Radio Bearer**,
- **PPE: Packet Prediction Entity**,
- **PIE: Packet Inspection Entity**,
- **MME: Mobility Management Entity**,
- **SGW: Serving Gateway**,
- **PDN: Packet Data Network**,
- **PGW: Packet Data Network (PDN) Gateway**,
- **C-SGN: Cellular Internet of Things Serving Gateway**,
- **SCEF:Service Capabilities Exposure Function** and
- **HSS: Home Subscriber Server**

Figure 5 shows the NB-IoT network architecture that includes the proposed mechanism. It is basically the same as the conventional network architecture and interface structure but considers two new entities namely the packet inspection entity (PIE) and packet prediction entity (PPE). The PIE, which is logically located on the MME, determines the session type from the packet header inspection, e.g. protocol type, port number, and IP address. The PIE then predicts the occurrence of the up-link response with a designed strategy, aimed at minimising the overall latency.

From an architectural point of view, figure 5 complements the idea of [111] by adding clustering of NB-IoT nodes ($N_1$, $N_2$, $N_3$,…$N_x$) as a technique to further enhance the management of resources within the network. The geographical based clustering of NB-IoT nodes, with one of the nodes playing the role of a Cluster Head (CH, e.g. CH1 and CH2), allows a more decentralized approach in the processing of uplink and downlink packets, and therefore, can be expected to enhance the overall performance of the network in terms of its time (latency), energy and scalability resources.

**TABLE 3.** QPSK signal constellation points for NB-IoT where I is the In-phase component and Q is the Quadrature component.

| b(i), b(i+1) | I | Q |
|---|---|---|
| 00 | $\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ |
| 01 | $\frac{1}{\sqrt{2}}$ | $-\frac{1}{\sqrt{2}}$ |
| 10 | $-\frac{1}{\sqrt{2}}$ | $\frac{1}{\sqrt{2}}$ |
| 11 | $-\frac{1}{\sqrt{2}}$ | $-\frac{1}{\sqrt{2}}$ |

## VI. DATA RATE ENHANCED NB-IoT MODULATION SELECTION SCHEMES

Most NB-IoT modulation approaches consist of a two-stage modulation scheme where data is modulated with quadrature phase-shift keying (QPSK) scheme. The QPSK is often used in conjunction with the orthogonal frequency-division multiplexing for the base-band modulation part. The QPSK, as used for NB-IoT, encodes all the information into the phase of the transmitted signal. The NB-IoT QPSK modulation takes two input bits and maps them into one complex number $I + jQ$ according to the signal constellations as defined in table 3 and visualized in figure 6 [112].

Low-Power Wide-Area Network (LPWAN) technologies both in the licensed and in the unlicensed bands are striving

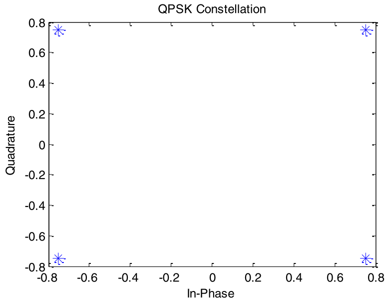


**FIGURE 6.** **The QPSK constellation points used in NB-IoT.**

to become standardised, and therefore, usable in all types of IoT applications including high data rate demanding IoT applications. One major approach that a group of researchers are looking into is modulation scheme selection as a way to achieve that emerging goal [69].

LPWAN in general and NB-IoT in particular, demand reliable data communication at high throughput in severe channel conditions like narrowband interference, frequency selective fading due to multipath and attenuation of high frequencies [61].

Like any LPWAN devices, NB-IoT nodes typically communicate directly to a sink node (Base station in the case of NB-IoT). This removes the need of constructing and maintaining a complex multihop network. However, to ensure efficient and reliable communication, it is suggested that NB-IoT devices will often provide a large number of transmission parameters [90]. For example, a NB-IoT device can be configured to use different spreading factors, bandwidth settings, coding rates and transmission powers which can results in over 6720 possible settings [69]. It is a challenge to determine the setting that minimises transmission energy cost while meeting the required communication performance. This is one of the major issues in current research on LPWAN in general and NB-IoT in particular.

By singling out a particular challenge in this domain, it has been established by [69] that different Modulation Coding schemes (MCS) levels influences the throughput of a system directly. Low MCS and high power are susceptible to improve the transmission reliability, and therefore, enhance the NB-IoT network coverage. However, another study by [61] has also established that if not performed efficiently, the MCS selection process can contribute to reducing the NB-IOT system's throughput and, therefore, result in quite low data rates.

Most competitors in the LPWAN arena have been designed to transmit a few bytes per hour and in some cases even per day. This is the case of Long Range (LoRa) and Sigfox which are mainly designed for applications that only require the transmission of up to 52 bytes of data for LoRa and 12 bytes for Sigfox packets at a time. This poses a problem in real time IoT applications where the application sporadically requires high bandwidth and for which the NB-IoT technology, if well designed, has a great potential and advantages.

In order to enhance the data rate performance of NB-IoT systems, the authors in [50] and [114] propose the use of an adaptive downlink spreading factor channel coding and modulation scheme selection. This approach basically consists of enhancing the Transport Block Size (TBS) to 2536 bits. This allows the data rates to go from the standard 250 kb/s and 226.7 kb/s as per Release 13 of the standard [112], to higher data rates of about 400 kb/s where it was proposed in [50]. These data rates can be reached as a result of the ability to support a second Hybrid Automatic Repeat Request (HARQ) process. This second HARQ process is useful for enhancing the reliability of the link for the UEs that experience favourable channel conditions. The implementation of the optional second HARQ process results in throughput gain as it reduces the overhead as a result of NPDCCH scheduling gaps.

In [114], the authors present an NB-IoT framework that uses non-orthogonal spectral efficient frequency division multiplexing (SEFDM). SEFDM uses less bandwidth when compared to OFDM. The waveform could improve the data rate without the need for more bandwidth. At the base station, the minimum Euclidian norm search detector is used for better error correction. The simulation results reveal that the proposed advanced signal waveform could achieve an improvement of 25% on data rate when compared to OFDM. The work also proposed an overlapped sphere decoding (OSD) detector which reduces the computation complexity when compared to the single sphere decoding detector while guaranteeing the needed performance. However, the model does not explain the impact of CFO due to the non-orthogonality of the subcarriers on the received signal.

## VII. LINK ADAPTATION SCHEMES FOR ENHANCED NB-IoT SCALABILITY

It has been established in [100] and in the 3GPP Release 13 that repeating transmission data or control signals has been considered as a promising approach to enhance the coverage of NB-IoT systems since the repetition number could enhance the transmission reliability but could cause loss in spectral efficiency. Thus, [101] and [102] observed that the link adaptation scheme design needs to provide a reasonable trade-off between transmit reliability and throughput of system by selecting suitable MCS and repetition.

The authors in [104] propose a link adaptation approach that aims at matching the transmission parameters, modulation scheme, and coding rate to the channel conditions in order to make the efficient use of the channel capacity possible. This proposed link adaptation is based on Adaptive Modulation and Coding (AMC). The AMC proposed by [105] is aimed at adapting the modulation scheme and code rate by considering the following:

- **Modulation scheme:** if the Signal-to-Interference plus Noise Ratio is sufficiently high, higher-order modulation schemes with higher spectral efficiency which would imply higher bit rates such as 64 Quadratic Amplitude Modulation (QAM) are used. In the case of

poor SINR a lower-order modulation scheme such as QPSK (Quadratic Phase Shift Keying), which is more robust against transmission errors but has a lower spectral efficiency is used.
- **Code rate:** for a given modulation scheme, an appropriate code rate can be chosen depending on the channel quality. The better the channel quality, the higher code rate is used, and consequently, the higher the data rate.

In NB-IoT systems, a Turbo encoder with a mother code rate of 1/3 can be used for data channels [59]. This will will result in achieving a Rate Matching (RM) module following the Turbo encoder. This configuration has demonstrated that it is possible to obtain other code rates when desired. The authors in [99] as a result suggest that increasing and decreasing the code rate should be done via puncturing and repetition respectively. Both puncturing and repetition are integrated in the Rate Matching module.

## VIII. THE NB-IoT PERFORMANCE CHALLENGES AND OPEN ISSUES

Despite, the recent research and developments work on NB-IoT, the later still faces a number of technical challenges that require proper modelling and adequate solutions. Some of the key challenges faced by NB-IoT design include network scalability, data rate enhancement as well as energy efficiency, network reliability and latency just to name few.

### A. NB-IoT ENERGY EFFICIENCY CHALLENGES AND OPPORTUNITIES

One basic condition which enables the communication between ''things'' in the IoT network is the presence of a properly selected wireless connection. For instance, a Wi-Fi connection is sufficient for a small-range home network that connects two computers and a tablet. However, what if we want to communicate with devices located in hard-to-reach places such as building basements? What if we want to send only small portions of data, but for long distances? Imagine being able to provide a long battery life for water or gas meters, or installing tens of thousands of devices without worrying about interference between them and the bandwidth available to everyone. Well designed NB-IoT could be the answer to these needs and challenges. It is not just another trendy slogan, but a real revolution and completely new possibilities. All these benefits come with associated multiple challenges, primarily amongst which is achieving energy efficient communications happens which is one of the major challenges. This is mainly because NB-IoT nodes are mostly battery operated. Therefore, their network design poses a real research opportunity and challenge which is to enable energy efficiency at all network layers. Some of the key challenges include:

- *Coverage Versus Energy:* It has been established by experimentation [51], that the lifetime of an NB-IoT device depends on the application's reporting rate and the coverage class. This is mainly due to the reliability features (coverage enhancement techniques) in the NB-IoT standard such as high repetitions of sub-frames / resource units and low modulation and coding rates (MCS) used in the physical layer. This constitutes a research opportunity in terms of proposing dynamic and adaptive MCS selection techniques and link adaptation methods more suitable to the NB-IoT Technology. The later should still guarantee acceptable communication coverage.
- *The Spatio-Temporal Variations in Available Energy the Amount That Can be Harvested:* Various research studies including [51], [52], [54], and [53] have proposed energy harvesting as a solution to the energy deficiency problem in NB-IoT. The authors in [54] make use of a mixed strategy that jointly combines efforts of non-orthogonal multiple access (NOMA) and energy harvesting from RF signals energy in order to enhance energy efficiency of the NB-IoT network. In order to maximize the amount of energy harvested from the RF signals, the approach formulates an optimization problem that includes user grouping in most suitable resource blocks, power allocation, and time allocation. The authors in [52] on the other hand propose a technique to harvest energy from thermal difference between two conductive plates on the NB-IoT device. The approach is shown to produce only tens of $\mu$*Watts* for powering the entire sensing/transmitting NB-IoT device.

  However, due to the diverse type of environments in which NB-IoT networks could be deployed, considering their wide range of applications, the availability in time and space of energy harvesting resources being so stochastic makes most of proposed models confined to a well defined deployment environment, and therefore, not dynamic at all [55].
- *Energy Efficiency Versus Communication Latency:* NB-IoT, by design, is not meant to offer millisecond latency such as to simplify chip-set and enhance battery autonomy. The latency in NB-IoT depends upon Transport Block Size (TBS), the number of transmission repetitions and even the network deployment mode. NB-IoT can be deployed in in-band, guard-band, and out-of-band modes each having a different link budget. MNOs will configure different number of repetitions depending upon the deployment mode (link budget).

### B. DATA RATES ENHANCEMENT AND NETWORK RELIABILITY CHALLENGES

As NB-IoT networks designs are proposed, some of the key issues raised include how much data can the network handle as well as what is necessary to transfer this data. It is therefore, necessary for anyone interested in NB-IoT network design to better understand NB-IoT network architecture and deployment/link budget aspects. This opens up a research opportunity for modeling the NB-IoT network at different network layers in order to comprehend and assess the network behaviours specific to the NB-IoT against the cellular network on which it is attached (LTE, 5G). As critical IoT applications become more and more prominent in multiple IoT applications, the question that comes out is who will win the data rate enhancement war among IoT technologies. NB-IoT being a licensed band technology, presents a competitive advantage against non-licensed band technologies such as LoRa and SigFox in this regard. However, achieving data rate enhancement poses couple of research challenges and introduces the following opportunities

- *At the PHY Layer Level:* The current NB-IoT designs mainly propose that the NB-IoT network adopts the modulation schemes inherited from the cellular network to which it is attached. However, due to specific aspects of the NB-IoT PHY layer, it would be more appropriate to propose NB-IoT specific modulation techniques which will enhance the network's data rate performance without deteriorating its reliability in terms of the probability of successful transmissions from NB-IoT nodes to the Base Station Uplink) and vice versa (Down-Link).
- *At the Network Layer Level:* Many NB-IoT design approaches consider single hop data links within NB-IoT cells. This could result in a lower amount of data being sent to the Base Station during up-link sessions. A research opportunity identified with respect to this includes network coding techniques. Technology standards which include network protocols, communication protocols, and data-aggregation standards, are the sum of all activities of handling, processing, and storing the data collected from the NB-IoT nodes. This aggregation increases the value of data by increasing the scale, the scope, and the frequency of data available for analysis.

### C. NETWORK SCALABILITY ISSUES

Connecting so many devices will be one of the biggest challenges of the future of NB-IoT, and it will defy the very structure of current communication models and the underlying technologies. Presently, the NB-IoT being attached to cellular networks such as the LTE mainly relies on the centralised server/client paradigm to authenticate, authorise, and connect different nodes in a network.

This model is sufficient for current NB-IoT ecosystems, where tens, hundreds or even thousands of devices are involved. However, when networks grow to join billions and hundreds of billions of devices, the centralised systems will turn into a bottleneck. Such systems will require huge investments and spending in maintaining cloud servers that can handle such large amounts of information exchange. This could lead to going down if the server becomes unavailable.

The future of NB-IoT will very much have to depend on a decentralising approach where clustering approaches based on network topology as well as artificial intelligence techniques will play a big role in enhancing the network scalability. Part of it can become possible by moving some of the tasks to the edge such as using fog computing models where smart devices such as IoT hubs take charge of mission-critical operations and cloud servers take on data gathering and analytical responsibilities.

Other solutions involve the use of peer-to-peer communications where devices identify and authenticate each other directly and exchange information without the involvement of a broker. Networks could be created in meshes with no single point of failure. This model will have its own set of challenges especially from a security perspective, but these challenges can be met with some of the emerging IoT technologies such as Blockchain.

The blockchain technology can be used as a distributed ledger that can record exchanged communication packets between the NB-IoT nodes and the eNB in an efficient manner and in a verifiable and permanent way. Blockchain technology will allow for secure communications as it provides resistance to data modification due to the fact that each piece of the data being transferred between the two endpoints is linked to its previous block as it contains its cryptographic hash [71].

On the other hand, by storing data across its peer-to-peer network, blockchain as applied in NB-IoT will eliminate a number of risks that come with data being held centrally [74]. The decentralized blockchain may use ad hoc message passing and distributed networking. Every NB-IoT node in a decentralized system will in this way have a copy of the blockchain ensuring that Data quality is maintained as well as computational trust. This decentralization effect could help in reducing network latency as well as enhancing the network's energy efficiency among other resources.

The future of the licensed Internet of Things technologies in general and the one of the NB-IoT in particular, will also count on the virtualization of some of its layers in order to efficiently manage its resources and, therefore, enhance its network performance. This is susceptible to enhance the NB-IoT's network scalability and this way, enable the use of NB-IoT within applications such as Big data analytics required for smart and efficient storage, fog computing as a way to extend the cloud computing platform to the edge of the network. [81]

## IX. THE NB-IoT AS PART OF 5G CELLULAR IoT

Unlike previous generations of mobile networks, the $5^{th}$ generation (5G) technology is expected to fundamentally transform the role that telecommunications technology plays in society [79]. The question many are asking is to know the place of the NB-IoT and other licensed LPWAN technologies such as LTE-M with 5G [33]. The proposed 5G technology has three main pillars.

- enhanced Mobile Broadband (eMBB)
- Ultra Reliability Low Latency Communication(URLLC)
- massive Machine Type Communication (mMTC)

Figure 7 briefly describes these three pillars. The International Telecommunication union (ITU) has defined several

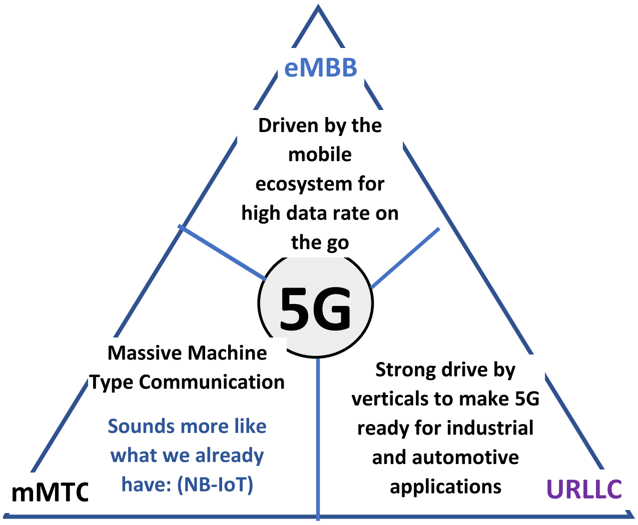


**FIGURE 7.** 5G three pillars and how NB-IoT fits in.

**TABLE 4.** Different NB-IoT releases to cater for ITU requirements [35].

| Release 14 | Release 15 | Release 16 |
|---|---|---|
| Non-anchor carrier | | |
| Release assistance indicator | New PRACH format | |
| Re-connection with RLF | Small cell support | Improve multi-carrier operation |
| Maximum Tx power 14 dBm | TDD support | Inter-RAT cell selection |
| eNB-IoT | FeNB-IoT | NB-IoTenh3 |
| Enhance TBS/HARQ | Enhance cell acquisition | Coexistence with 5G |
| Positioning | Wake up signal | Group wake up signal |
| single-cell multicast | Early data Transmission | Early DL/UL transmission |

requirements of 5G mMTC to address IoT applications [34]. The key requirements include

- Battery life: 10 years at 200 bytes (UL) and 20 bytes (DL) per day
- Coverage: 164 dB with 160 bit/s
- Density: 1 million devices/$km^2$
- Latency: <10 seconds with 20 bytes application package
- Price: Ultra-low cost device
- Additional features such as positioning, multi-cast, mobility etc.

In order to achieve such requirements, the 3GPP has released three more standard versions as summarized in table 4. with:

- eNB-IoT: enhance NB-IoT
- FeNB-IoT: further enhanced NB-IoT
- NB-IoTenh3: NB-IoT enhanced version 3
- RLF: Radio Link Failure
- PRACH:Physical Random Access Channel
- TDD: Time-Division Duplexing
- RAT: Radio Access Technology
- TBS: Transport Block Size
- HARQ: Hybrib Automatic Repeat Request

The key issue here has been how to ensure the coexistence of NB-IoT with 5G network different layers (physical and core). In practice, 5G will see initial deployments in urban areas. This is perhaps beneficial from an IoT perspective since most of key applications of IoT will support Smart Cities, Smart Campuses and Smart Buildings. The NB-IoT being already a licensed band IoT Technology stands a great competitive advantage in terms of integration with cellular 5G over other IoT Technologies in the unlicensed band such LoRa, Sigfox etc. One of the key drivers for 5G IoT is the high bandwidth demand which is naturally posed by a number of applications of the 5G technology. The bandwidth is required to enable enhanced mobile broadband (eMBB)-based 5G services. The integration of the NB-IoT within 5G systems as part of the mMTC is, therefore, a great opportunity towards answering to that huge bandwidth demand as the NB-IoT if well designed, and handle many communication aspects of the network.

However, integrating NB-IoT with 5G systems comes with its own issues and challenges. Some of the issues identified include:

- The lack of agreed-upon end-to-end architecture: Standardization at the lower layers (Data Link Control and Physical) can drive the development of a more inclusive multi-layer multi-application architecture.
- Propagation issues: 5G systems are designed to operate at mmWave frequencies in order to enable high data rates. However, this poses a problem in terms of signal penetration inside buildings [89]. At the same time, indoor solutions are needed for NB-IoT applications. This poses a serious design consideration challenge at the nodal point of view when it comes to NB-IoT networks being used with 5G systems.
- Multiple Access issues: Although in principle it is possible to support multiple access technologies in an IoT sensor (chipset), end-point IoT devices tend to have low complexity in order to achieve an established target price point and on-board power (battery) budget. Therefore, a number of applications will have devices that have a single implemented wireless uplink.
- Energy issues: Due to the fact that most of NB-IoT devices are constrained in terms of processing, memory and energy resources, integrating the NB-IoT network with the cellular 5G network poses a considerable energy stress on NB-IoT nodes when compared to the non-licensed band IoT networks such as LoRa, Sigfox etc. However, the licensed band comes with the advantage of energy harvesting that can be used to compensate for high energy demand. One of the energy harvesting approaches as modelled in [82] considers the ambient backscatter approach. The later consists of taking advantage of the fact that far-field radio frequency (RF) signals in the air carry both information but also energy. If designed properly, the NB-IoT nodes can harvest the energy carried by Electromagnetic Waves (EMs) to sustain their energy levels and, therefore, enhance their lifetime. The work in [82] considers the transmission of one symbol per Orthogonal frequency-division multiplexing (OFDM) symbol over short distances, and

demonstrates that this could result in achieving satisfactory data rates while saving and harvesting a good deal of energy.

Despite the different challenges presented by the integration of NB-IoT as part of 5G cellular IoT, NB-IoT remains very competitive over unlicensed technologies, in terms of the selection of the IoT technology that is best suited for 5G systems. This is because, unlike the unlicensed technologies, the NB-IoT does not pose the issue of heterogeneity of the network which would make it more difficult to manage. Some of the efforts in mitigating the challenges as posed by the integration of the NB-IoT within the 5G systems include the use of SDN and NFV as discussed in section X.

## X. SDN AND NFV FOR NB-IoT WITHIN 5G SYSTEMS

Achieving low power consumption and low cost IoT is among of the key design objectives of NB-IoT systems as integrated with the 5G systems [33]. However, the NB-IoT design forming part of a cellular network could become energy and cost expensive to implement. Therefore, the authors in [83] investigate the use of NB-IoT system implementations to exploit the benefits of another disruptive and emerging technology called the Cloud Radio Network Access (C-RAN). The C-RAN is a concept of centralization and virtualization of the baseband operations of the BS. If properly implemented, the C-RAN can help enhance network performance in various aspects including energy, scalability and reliability. On the other hand, the use of a C-RAN for NB-IoT system design can significantly reduce the high capital expenditures involved in network deployment due to the virtualization of the maximum possible number of network functions by applying NFV and the implementation by means of robust SDN algorithms [88].

The proposed centralization and virtualization of the NB-IoT network design poses a number of challenges. For example, in LTE systems, there are challenges for the implementation of C-RAN because of problems related to the fronthaul capacity as well as the difficulty to comply with very stringent latency requirements. This is where 5G systems with their enhanced performance potential become of great value to the implementation of the NB-IoT functions using a C-RAN approach. Another benefit that can be obtained from the application of the C-RAN to NB-IoT systems is the simplification of the Radio Access Network protocols by removing the functionalities that are not necessary for IoT application. This would not have been possible by using actual hardware based RAN [83].

As a result of the virtualization of the C-RAN, a centralized pool of Baseband Units (BBUs) from various BSs are able to provide statistical multiplexing benefits to the network implementation resulting in higher network performance in terms of lower network latency and lower energy consumption while shifting the transmission burden to the high-speed network infrastructure provided by 5G systems. [84]. This centralization of the Base Stations functions allows for a high level of cooperation among them and enables more network scalability [88]. This concept has been experimented by [85] in form of a flexible SDR-based C-RAN testbed capable to run most RAN technologies on a commodity server.

Finally, as previously discussed, cognitive ambient backscatter approach as discussed by [82], is another technique for enhancing the energy efficiency of NB-IoT systems by superimposing information from a secondary device (NB-IoT node in this case) on a primary signal (a 5G User Equipment for example) with no extra power consuming active component. However, this approach is fully dependant on very accurate channel estimations and sometimes suffers from co-channel direct link interference (DLI) [86]. Therefore, [87] proposes the use of a C-RAN architecture in a 5G network whereby the primary and secondary edge nodes (NB-IoT node and cellular UE for example) would be connected by means of high-speed links to a cloud SDR. This will avoid the channel estimation errors and the DLI resulting in a more energy efficient NB-IoT design.

## XI. CONCLUSION AND FUTURE WORK

This article has explored, analysed, and discussed comprehensively the different aspects related to network resources efficiency in NB-IoT designs and deployment. The article has paid a close attention to issues of energy efficiency, data rate, network reliability, and scalability performance. The article has also identified key challenges in terms of the current state of the NB-IoT designs and has proposed research opportunities. Future work will consider modelling of PHY layer of the NB-IoT network, proposal of an energy efficient technique for MCS selection, data rate enhancement and the management of network scalability. This article is an important tool for any researcher who intends to embark on the study of the NB-IoT network performance enhancement as it provides a clear and concise overview of the different network resources considerations.

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