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NB-IoT System

The radio interface, the core network, and its evolution

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SOMMARIO

ABSTRACT

NB-IoT system represents a new solution in the field of telecommunications and IoT applications. In this paper we will introduce this new solution, explaining the context in which it originated and describing the technologies from which it then evolved. We will then analyse the most important aspects that characterize this technology compared to the other similar solutions on the market. Subsequently we will deepen all the stages that led to the evolution of the NB-IoT, mentioning the most important releases published by 3GPP which over the years has been involved in standardizing this technology by defining its properties and characteristics. In the next chapter we will describe in detail the NB-IoT architecture and the LTE communication infrastructure on which it is based and then we will show the optimizations that have been introduced. Finally, the physical layer will be analysed together with its main characteristics, describing the four most important uplink and downlink channels.

INTRODUCTION

The Internet of Things (IoT) has become nowadays a fundamental part of the global digital ecosystem. It allows us to create an interaction between objects and put them in communication with each other to monitor, control and transfer information through internet protocols or well-defined interfaces. In recent years, the decision to connect physical objects (e.g., sensors, machines, cars, products) or virtual objects (e.g., software applications, support systems) to Internet has had a widespread in many fields of application: smart homes, intelligent buildings, automotive industry, healthcare, smart cities, industrial monitoring. Furthermore, it is expected that by 2022, the whole number of IoT-connected devices will reach 18 billion [1]. Due to the growing interest in the IoT market, great strides have been made in the technological field to meet industry needs. In this regard, tens of communication protocols and standards have been defined or adapted to meet the technical characteristics of IoT devices and the requests for the services they offer. Initially, most of these standards and protocols (Wi-Fi, Bluetooth, Z-Wave, ZigBee) were devoted to short-range applications, afterwards new LPWAN technologies were introduced to allow machine-to-machine (M2M) wide-range communications, like SIG, Sigfox, LoRa, LoraWAN and RPMA. These protocols, in addition to guaranteeing long-range transmission (a few kilometres) as shown in Figure 1, also ensure very low energy consumption for transmission/reception of data and represent a low-cost deployment solution. However, they also have a reduced data transfer rate (Kbit/s). LPWAN technology is suitable especially for delay-tolerant IoT services and applications which do not require the transmission/reception of large amount of data (few small messages per day), but require an energetic autonomy to allow them a long battery lifetime (years). Most LPWAN protocols operate in the band frequency Sub-GHz (<1GHz) where the effect of attenuation and multipath fading caused by the presence of obstacles is reduced. Two kinds of modulations can be applied keeping the transmission speed low in order to allocate a greater amount of energy for each single bit transmitted:

- Narrowband (NB): bandwidth below 25 kHz to maximize the use of the frequency spectrum between several devices and minimize the effect of noise on communications.
- Spread Spectrum: expands the signal to be transmitted in a wider frequency band while maintaining the power density, making the signal more robust to interference.

To ensure a low power consumption, star topology is typically used in LPWAN to limit the number of transmissions per device (every node is connected to a central hub), as opposed to mesh networks in which the communication also takes place between a node and the adjacent ones. In addition, random access methods such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or Aloha are used because they do not need any synchronization between the transmitters. This kind of technology operate in the licensed or unlicensed spectrum: many LPWAN protocols exploit license-free spectral bands such as Industrial, Scientific and Medical (ISM) or TV white-spaces. Others share already purchased bands for other types of communication, such as cellular network bands, avoiding additional license acquisition costs [2].

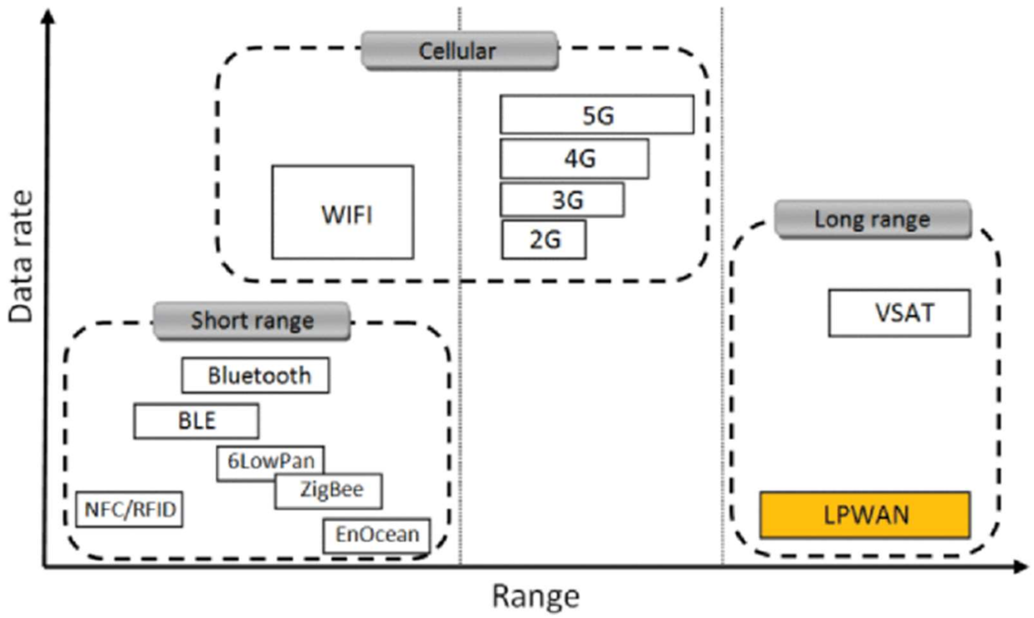

Figure 1: Data rate vs. range: LPWAN positioning

Among the various existing protocols, LoRaWAN, Sigfox and NB-IoT represent the most interesting emergent technologies. Sigfox was founded in 2010 in Toulouse, France, with the idea to connect every object in our physical world. Today it operates in 70 countries with the propose to build the largest IoT ecosystem in the world [3]. LoRaWAN is a technology developed by Semtech and standardized by LoRa-Alliance. It is entirely designed to optimize LPWANs for battery lifetime, capacity, range, and cost [4]. NB-IoT, a new narrowband radio technology, have been introduced for the first time in June 2016 by 3rd Generation Partnership Project (3GPP) through the study item titled" Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT)". Features provided by this technology are addressed to deal with the low-end Machine Type communication (MTC) scenario that is extended coverage, ultra-low device cost, high allowed latency, low power consumption and low Network architecture complexity [5]. In this paper we focus on the latter technology mentioned, analysing the NB-IoT system, its architecture, the radio interface, and its evolutions. However, before going into the details, it is good to know the background necessary to understand the important role that NB-IoT has in this IoT era.

NB-IoT Background

The scope of 3GPP is to guarantee the maintenance and development of the Global System for Mobile communication (GSM) Technical reports and Technical Specifications, as well as evolved radio access technologies [6]. In recent years, the 3rd Generation Partnership Project has had to go through a lot of pressure from cellular stakeholders who need extra effort to provide a truly standard and cellular solution for LPWANs. Before 2005 the large number of IoT use cases was just partially covered by the previous 3GPP standards introduced until release 8. For this reason, during the last 15 years huge progresses has been made to provide a technology that could make all IoT use cases accessible. The Long-Term Evolution mobile technology, simply known as LTE, was introduced in 2005 and its firsts specifications presented by 3GPP in Release 8. In order to better understand the correct evolution that led to the NB-IoT standardization, it is important to introduce the UE concept, traditionally used by 3GPP. The term "User Equipment" (UE) refers to the cellular equipment used by customers to access the network services, such as smartphone or any embedded device used in a M2M equipment. Many different categories have been defined by 3GPP to provide for multiple UE hardware capabilities. Each category support different maximum data rates in the downlink and in the uplink. Category 1 UEs was assigned to the early version of the LTE Machine type communication standards in the Release 8, it supported a maximum bit rates of 10 Mbps in the downlink and 5 Mbps in the uplink. Together with Category 1, which represented the lowest capability, Category 5 was also introduced as the highest capability, with a data rates of 300 Mbps in downlink and 75 Mbps in uplink. However, Category 1 does not still support MIMO system transmission and does not offer the cost, range, and battery requirements that IoT need. With the introduction UE Category 0, in Release 12, it has been possible to reduce costs by 50% compared to Category 1. Moreover, an energy saving functionality has been introduced while the device is not transmitting or receiving in order to reduce power consumption. Subsequently, to meet the growing

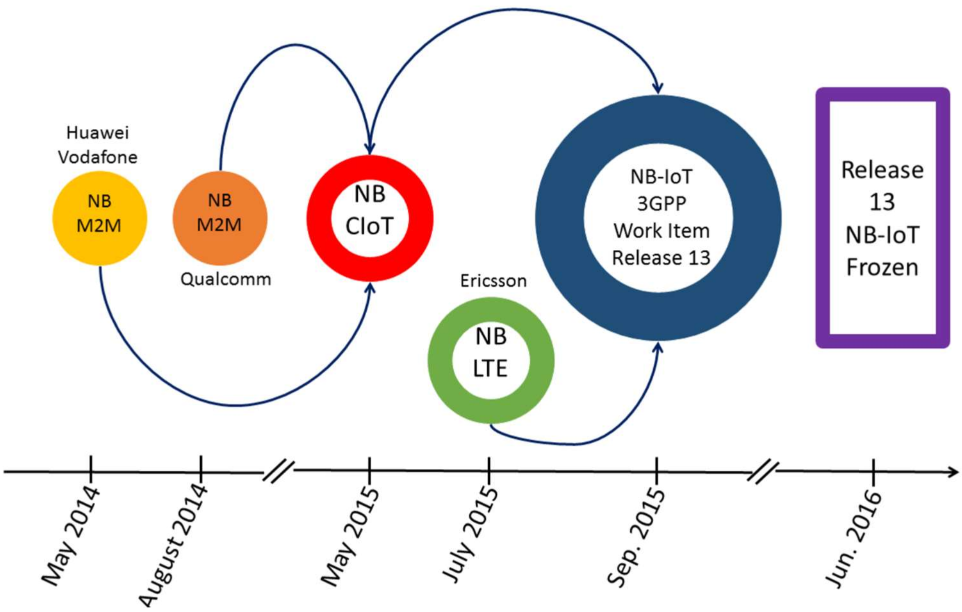

Figure 2: NB-IoT standardization process

needs of the IoT market, in Release 13 a new low-complexity category was introduced allowing to further lower costs by 50%, reducing the system bandwidth to 1.4 MHz.

In addition, technical improvements have been introduced allowing users to reach MTC devices even in areas where coverage is weak. These improvements have had an huge impact on the design of the logical and the physical channels that have to support low bandwidth modalities and enhanced coverage. The key event occurred in May 2014 when Vodafone together with Huawei proposed the NB-M2M study to 3GPP. This topic immediately aroused great interest from other major telecom operators, so at the end of the same year, Qualcomm decided to put forward its proposal for a new NB-IoT version. In May 2015, the two technologies were merged to form NB-CIoT (Narrowband Cellular Internet of Things). Another proposal also came from Ericsson with the NB-LTE. The two technologies differed mainly because the one proposed by Vodafone and Huawei needed a new chipset and was not backward compatible with existing LTE networks, instead the one proposed by Ericcson, NB-LTE, seemed to be compatible and did not need an overlay network. 3GPP accepted both initiative and for that reason decided to concentrate its efforts on the standardization of a single version, that was presented in the Release 13 in November 2015 under the name of “NB-IoT”. The innovations introduced concern a better indoor coverage, the support for huge number of low throughput devices and very low cost and low power consumption devices accessibility. A new Category was assigned to the UE NB-IoT, Cat-NB1, which guarantees a 90% reduction in their architectural complexity. The standardization of NB-IoT technology was a very important issue for 3GPP which took only 9 months to complete the whole process, in June 2016. In subsequent releases, interest in NB-IoT has grown more and more and for this reason new features have been introduced to support further use cases. Release 14 brought innovations regarding an improvement in the downlink and uplink data rate and introduced support for additional LTE features in order to increase the possible applications of NB-IoT such as OTDOA positioning method based on Narrowband Positioning Reference Signal (NPRS). In Release 15 was introduced a new category Cat NB2 and LTE Device to Device, added the support for the Time Division Duplexing (TDD) and improved the spectral efficiency. In Release 16 no new features have been introduced but previous ones have been improved: transmission efficiency enhancement, lower power consumption, improvement on network management and multi-carrier operation. In release 17 the features that planned to be presented include an improvement in the downlink and uplink data rate and the support for NB-IoT carrier selection, which depends on the level of coverage and carrier specifications [7].

THE PROTOCOL STACK OF NB-IOT SYSTEM AND ARCHITECTURE

The NB-IoT protocol stack is based on OSI model, developed by International Standard Organization (ISO), with some new changes introduced to meet the massive machine-type communication (mMTC) requirements. NB-IoT architecture, at first did not have an inheritance to follow so it had to rely on the well-defined structure of the LTE cellular network, which was there for several years. It is possible to identify two main blocks in the NB-IoT protocol stack which are called: Control plane and Data plane. The former takes care of managing the data flow between one node and the next one, while the latter contains all protocols that regulate the connection to the network and the UE. As shown in Figure 3, the 3GPP defined a six layers protocol stack consisting of the physical layer (PHY), medium access control (MAC), radio link control (RDL), packet data convergence protocol (PDCP), radio resource control (RRC) and non-access stratum (NAS).

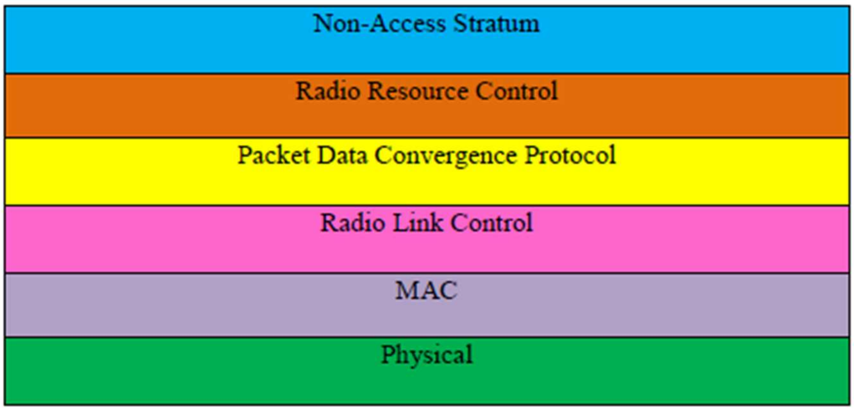

Figure 3: Protocol stack of NB-IoT

The two lower layers represent the Access Stratum (AS), they handle the physical processing and transmission/reception of data through the wireless connection and the Radio Resource Control protocols (RRC). The only difference with the OSI model concerns the five upper layers which are now replaced by the NAS, Non-Access Stratum. The NAS, which may not contain some of the OSI layers such as the application, the presentation, and the transport layer, is responsible for the radio transmission between the UE and the Evolved Packet Core (EPC) and for the authentication, mobility management and security control [5]. In the protocol stack, the data packets can be exchanged within each layer through the Protocol Data Units (PDU) or between the different layers through the Service Data Units (SDU), realizing what is called the encapsulation principle. The information contained in the layer N-1, the PDU, is forwarded to the upper layer N becoming the new SDU. Layer N in turn adds its own Protocol Control Information (PCI) to the header so the PCI plus the SDU becomes the new PDU of the layer N. In this way the User plane data (which includes the PHY, MAC, RLC, and PDCP layers) are encapsulated in the Control plane messages and then transmitted.

As already mentioned, the NB-IoT architecture is based on the existing one of the LTE systems simplifying its core network, the Evolved Packet Core (EPC), to meet the traffic models requirements and reduce device complexity. To simply provide a brief description, the EPC represent the latest version of the core network architecture adopted over UTRAN and introduced by 3GPP in Release 8. The previously solutions were based on circuit-switching and packet switching networks. In GSM for example a circuit-switched network was adopted. This means that, before the communication, a physical connection between the two nodes is established in order to have a reserved circuit line for the communicating partners. Having a dedicated line leads, obviously, to a series of limitations as regards the performance and distribution of network resources. On the other hand, in GPRS, where packet-switching network was adopted, the communication line is shared among the users and the information is split in smaller units, called packets. This guarantees better performance, lower complexity switching devices and, therefore, lower costs. UMTS (3G) then maintained this idea of a core network consisting mainly of two domains: the packet and the circuit. With the evolution of the 3G system, the 3GPP decided to adopt the Internet Protocol (IP) and that the EPC would no longer support circuit-switching but it would be an evolution of the packet-switching system already adopted in UMTS and GPRS. This new idea of EPC includes four main components which are: the Mobility Management Entity (MME), the Serving Gateway (SGW), the Packet Data Network Gateway (PGW) and the Home Subscriber Server (HSS). The MME is the node that interfaces with the LTE access network. It works with the control plane and oversees choosing the SGW and the PGW for a UE also providing authentication and authorization processes for the user. The HSS is essentially a database containing user-related and subscriber-related information. The gateways in general work on the data plane, implement the IP protocol and interconnect the different networks to the UE. The SGW allows to exchange incoming and outgoing data packets directly with the UE. It represents the element of the EPC that first interfaces with the radio side of the communication system, the last stage before reaching the user. Finally, the PGW, also known as Packet Data Network Gateway (PDN Gateway), represents the exit point for a local network providing connection with the Internet, this means that it put in communication the UE with the external networks. In addition, each UE can have multiple connections with several PDN Gateway

Figure 4: EPC architecture with E-UTRAN access

at the same time for accessing different packet data networks.

In Figure 4 we can observe a diagram concerning the UE-EPC-Internet system just described, which uses the LTE access network, UTRAN, composed of the evolved NodeB (eNodeB), which represent the LTE base station, the evolved packet core and the connection with external networks. However, E-UTRAN is not the only kind of access technology supported from the EPC. 3GPP made sure that all existing access technologies could interface with the new version of the core network. In fact, it defined the specifications for radio access Networks such as E-UTRAN, UTRAN and GERAN (radio access network of GSM / GPRS). The EPC was designed to support also Non-3GPP access technologies including WLAN, WiMAX, CDMA and NB-IoT [8].

The simplified version which the NB-IoT architecture is based on takes care of forwarding small data packets through the NAS. The core network in this case includes a new entity called C-SGN (Cellular IoT Serving Gateway Node) which combines some of the functions of the Data-plane and Control-plane, gathering functionalities that are usually found in MME, in the SGW and in some cases in the PGW. The S1-CP (S1 control plane) function, implemented by MME, which supports the S1-MME interface with eNodeB, is replaced by S1-lite, an optimized version also based on S1AP protocol (S1 application part), which implements only the necessary S1AP messages. These S1AP messages are able to efficiently transport small User plane data packets. Two main optimizations concerning a signalling optimization are introduced. The first one is called DONAS (data over NAS) and involves the control plane. It allows us to send data directly from the MME in the EPS to the UE without having to interact with the base station thus without involving the User plane. This gives the possibility to eliminate part of the necessary EU requirements regarding the User plane. The other solution includes the introduction of a new mode, the RRC Suspend / Resume. It is optional and introduces improvements in the User plane such as the optimization of the signalling overhead and the battery life of the UE. The RRC protocol resides in the Access Stratum as we have already seen, it takes care of managing the state of the network working in two main states, RRC_Connected and RRC_idle. In RRC_ connected the connection between UE and eNodeB is established, in this way the UE can receive or transmit data and furthermore it is possible to locate the UE through the cell. In RRC_idle the connection is inactive but the UE can be reached at any time by an incoming request. Whenever there is no traffic, the network switches to the RRC_idle state to save battery and radio resources. The RRC Suspend/Resume mode ensures to reduce the signalling overhead needed to switch from the idle state to Connected one, therefore brings a reduction of the signalling massages required with respect to the non-optimized version. Furthermore, the RRC Suspend/Resume procedures have to be supported by different components of the communicating system like eNodeB, MME and UE. MME for instance must store the information about UE connection when the RRC is in the Suspended state. it is also necessary to adapt to the new procedures the S1AP that provides the signalling service between the eNodeB and the evolved packet core. The base station, like the MME, must also be able to save the EU context when the connection is suspended, as well as being able to support new RRC procedures. The user, on the other hand, has to save the AS-related information when in the RRC_idle. The DONAS solution instead provide a support for the efficient transmission of small data for IP and non-IP protocol. It is based on the lightweight core network architecture which allow to transfer uplink small data within the initial NAS uplink message to which it is added a new massage to contain downlink response data. There is no need to set the user plane for what concerns the RRC messages and security settings of the AS, so these efforts can be avoided. IP and non-IP data can be sent over Control plane also through the Service Capability Exposure Function (SCEF) which is part of the Architecture Enhancements for Service Capability Exposure (AESE). This new solution was introduced in release 13 and provides Network services to 3rd parties.

PHYSICAL LAYER DESIGN

The technical features of the NB-IoT reside mainly in the PHY layer which is considered the layer that hosts most of the innovations introduced in the NB-IoT. Qualities such as scalability, data rate and coverage area are all part of the PHY. The radio resources are shared among different downlink (DL) and uplink (UL) NB-IoT channels, as we can see in the Figure 5. These channels are based on the existing ones of the LTE system with the necessary modifications to support narrow bandwidth. Before describing each channel, it is necessary to know that NB-IoT supports three operation modes: in-band, guard-band, and stand-alone. In in-band mode some LTE Resource Blocks (RBs) are assigned to the NB-IoT. So, all the base stations are shared between LTE and NB-IoT allowing a more efficient management of the frequency spectrum. This solution allows both systems to integrate perfectly with each other, thus being able to exploit the same infrastructure made up of eNodeBs. In guard-band operation mode, the NB-IoT utilizes the guard band of the LTE carriers, without causing interference. In stand-alone operation, NB-IoT con replace one or more GSM carrier.

	Channel	Usage
DL	Narrowband Physical Downlink Control Channel (NPDCCH)	Uplink and downlink scheduling information
	Narrowband Physical Downlink Shared Channel (NPDSCH)	Downlink dedicated and common data
	Narrowband Physical Broadcast Channel (NPBCH)	Master information for system access
	Narrowband Synchronization Signal (NPSS/NSSS)	Time and frequency synchronization
UL	Narrowband Physical Uplink Shared Channel (NPUSCH)	Uplink dedicated data
	Narrowband Physical Random Access Channel (NPRACH)	Random access

Figure 5: NB-IoT channels and signals

- *NPDCCH*: is almost the same of the physical downlink control channel in LTE. Represent the physical channel that carries the Downlink Control Indicator (DCI). The DCI specifies the scheduling information for downlink and uplink for each eNodeB and allocates Physical Resource Blocks (PRBs) that transport data for NPDSCH or NPUSCH data. The NPDCCH is based on control channel elements (CCE) that are assigned two by two to each pair of PRBs where one CCE corresponds to the upper six subcarriers and the second one to the lower six subcarriers. It is possible to associate only two CCEs for each DCI, this means that this channel has Aggregation Level (AL) of two. In NB-IoT, a repetition of transmission is performed to achieve extra coverage; it consists of repeating the same transmission different time. For each UE, in NPDCCH transmission the maximum number of repetitions, indicate by the parameter Rmax, is chosen from the levels (1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048) and it is function of its coverage level. Once Rmax has been chosen, the UE knows which search space to decode, i.e., it knows which subframes it should look to find an NPDCCH transmission. The DCI also contain the number of repetitions performed in the transmission so that the UE knows when the NPDCCH transmission is complete. the following relation permit to obtain the first subframe of the search space:
  $(10nf + floor(ns/2)) \bmod T = floor\ (DoffsetT)$
  where ns is the slot index, nf represent the system frame number, Doffset is a parameter which can assume the values 0, 1/8, 1/4, 3/8. T is the period obtained by T=Rmax × G, where G is a parameter that relates Rmax with the research space, it represents the distance between two successive NPDCCH and it is always T≥4 ms. There exist three types of DCI,

namely the DCI format N0 consist of 23 bits and is used for carrying NPUSCH scheduling, N1 consist of 23 bits and transport NPDSCH scheduling control, while the N2 format with a payload of 15 bits transports paging and direct messages for NPDSCH.

- *NPDSCH*: is controlled by NPDCCH and is transmitted after a minimum time interval of 4ms to ensure the UE to decode the NPDCCH. NPDSCH occupies the full downlink bandwidth and can forward a transport block with the maximum size of 680 bits. It supports two modalities of transmission: transmission on port 0 (single antenna port) and transmission on port 0 and port 1 (dual antenna port). NPDSCH can transmit different allocated subframes chosen form (1, 2, 4, 8, 16, 32, 64, 128, 192, 256, 384, 512, 768, 1024, 1536, 2048). On downlink the instantaneous data rate can reach the peak of 170 kbps in in-band mode while the sustained one can have a maximum peak of 26.2 kbps.
- *NPRACH:* employ single-tone transmission where the subcarriers occupy a 3.75 Hz frequency slot. It supports two cyclic prefixes to specify different cell sizes: 66.7μs (10km) and 266.7 μs (35 km). We can configure up to three different NPRACH resources for every single cell, each of which allows us to specify a different level of coverage. A resource needs five parameters to be configured: frequency location, number of repetitions, number of subcarriers and periodicity.
- *NPUSCH*: is intended to ensure wide coverage area, massive traffic capacity and long battery lifetime. It supports both multi-tone and single-tone transmission: the single-tone configuration with frequency of 3.75 kHz or 15 kHz while the multi-tone configuration with the support of 15 kHz. In NPUSCH can be mapped up to ten resource units in a single transport block, where a resource unit is intended as the smallest amount of time frequency resource [9].

CONCLUSIONS

In this paper a general view of the NB-IoT is first provided, then we went into detail describing its structure and the entire stack of layers by comparing the NB-IoT with the LTE, the communication system from which it originated and on which it is based for its distribution and operation. Subsequently we focused on the functioning of the physical layer responsible for the physical distribution of information through the communication system composed of UE, eNodeB and Evolved Packet Core. We have introduced this new technology by describing its history and going through all the stages that have allowed its consolidation as a

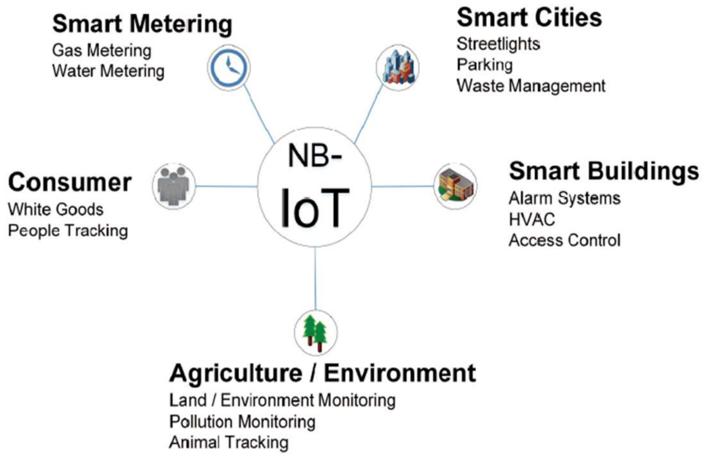

Figure 6: Smart applications of NB-IoT

preponderant part of everyday life in which it finds space in many applications. Due to its main features, NB-IoT can be employ where there is the need of real-time data transmissions, low latency, long battery life, wide coverage, and massive capacity. For instance, NB-IoT can be applied in autonomous reporting services like smoke detectors or autonomous periodical reporting services which requires a small data transmission per day or per hour like intelligent monitoring systems (water quality monitoring, gas monitoring pollution monitoring, etc). Among the most relevant application scenarios, like we can see in Figure 6, we have smart cities, smart buildings, wearable devices, smart homes. Smart city aims to interconnect buildings, vehicles, streetlamps, and any other object that is part of a city in order to obtain an intelligent management of the main infrastructures, improving services and the quality of life. These discussions want to provide a big-picture of NB-IoT that is field of study rich in topics and implications for future applications.

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