3GPP NB-IoT for Smart Environments: Testbed, Experimentation and Use Cases

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***Abstract*—3GPP Narrowband Internet of Things (NB-IoT) is attracting a lot of attention as a technology offering a low power wide area networking (LP WAN) solution for a massive amount of devices communicating at low data rates in the licensed bands. In this paper, we present the NB-IoT from a perspective of developing an operative testbed and experimentation platform that allows for NB-IoT applications in various smart environments. We start by providing an overview of the radio access network communication properties of NB-IoT in terms of the main procedures, link utilization and energy efficiency, that we find relevant from the application end-to-end connectivity perspective. We proceed with description of NB-IoT testbed and experimentation platform developed for our in-house research and development. Finally, we present our first-hand experience of developing NB-IoT smart environment applications ranging accross different application domains, from rural outdoor to urban indoor services.**

***Index Terms*—Smart environment, Internet of Things, 3GPP NB-IoT, LPWAN**

I. INTRODUCTION

Short range wireless communication technologies have set the stage for proliferation of Internet of Things (IoT) over the past decade. However, important application domains remained out of reach of these technologies. Recently, a new low-power wide area networking (LP WAN) solutions emerged with a goal to close this gap by covering wide geographical areas [1]. In the licensed spectrum, 3GPP Narrowband Internet of Things (NB-IoT) technology is currently being deployed by mobile network operators (MNOs) after the 3rd Generation Partnership Project (3GPP) Release 13 version of the standard (also known as LTE-A Pro) has been published in June 2016 [2]. After the initial phase, where the chipsets from different manufacturers have been integrated as part of the NB-IoT modules and offered on the market, the phase of wider commercial usage of NB-IoT technology is currently at its early stages [3].

With a certain experience collected over the past years in the domain of development, testing and deployment of NB-IoT-based devices, our aim is to present a testbed/experimentation and application and service-oriented outlook of NB-IoT technology through several specific use cases. The paper aims to build upon recent survey papers covering technical aspects of NB-IoT technology [4]–[6], and uses both the insights from technology and hands-on experience from testing, development and implementation to present several NB-IoT use cases we deployed across widely different environments.

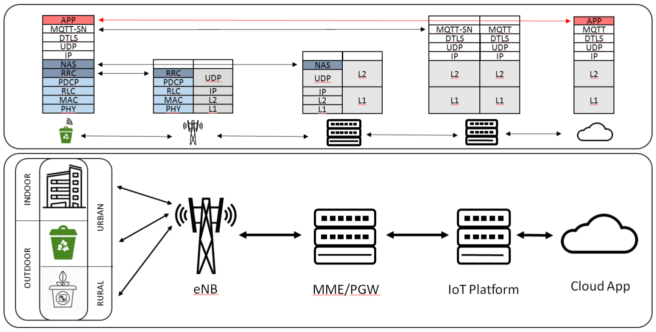

Fig. 1. NB-IoT System and Protocol Structure.

II. 3GPP NB-IOT TECHNOLOGY

3GPP NB-IoT Requirements: Key demand for LP WAN technologies is the network ability to serve a massive number of devices, provide extended coverage, and use energy efficient modes of operation in order to extend the lifetime of a battery-operated device. Although cellular 3GPP technologies have not been designed with such priorities, a sequence of modifications and simplifications of 3GPP Long Term Evolution (LTE) standard succeeded in making NB-IoT a competitive LP WAN technology [2]. The main features of a new standard include: support for massive connectivity (tens of thousands of devices per cell), infrequent data transmissions (several packets per day), low data rates (up to 250 kbps), extended coverage through higher link budget (164 dB) as compared to both LTE (142.7 dB) and Global System for Mobile (GSM) network (144 dB), reduced signaling and enhanced power saving modes in comparison to LTE. From the end user perspective, the technology offers possibility of designing low-cost battery-operated sensor nodes whose lifetime, under normal operating conditions, may exceed 10 years. In addition, from the user perspective, no network infrastructure is needed (installation and maintenance of network devices/gateways) as the device connects directly to a base station of a MNO.

3GPP NB-IoT Deployment: NB-IoT is designed to seamlessly coexist with 3GPP LTE, reusing LTE radio access network (RAN) and evolved packet core (EPC) protocols and infrastructure, as illustrated in Fig. 1 [4]. MNOs initial deployments rely on in-band NB-IoT deployment, where NB-IoT signal is allocated into existing 180 KHz-wide LTE physical resource blocks (PRB). Guard-band and stand-alone deployments are also possible and will gain popularity with the process of GSM spectrum refarming. In Europe, NB-IoT is deployed in LTE bands 8 and 20 (800/900 MHz) providing support for wide area propagation and deep indoor penetration. Coverage extension (CE) is achieved by redesigning LTE physical layer to support data packet repetitions, thus exploiting channel time-variations and combined signal reception to increase the decoding probability. To support extended lifetime for battery-operated devices, NB-IoT defines two low-power operation modes: extended Discontinuous Reception (eDRX) and Power Saving Mode (PSM), each defined with specific timing parameters (cycle periodicity). Optimally balancing between network parameters and repetitions defined for CE classes, and network timers and durations in eDRX/PSM, is fundamental for establishing desirable network performance for different applications and services [7], [8].

3GPP NB-IoT Applications and Services: NB-IoT is designed to meet the needs of applications that require support for massive number of devices, each of which communicates infrequently and with low data rates, where the latency of data delivery is not critical. It addresses standard goals of LP WAN connectivity, providing wide-area coverage in rural areas and deep penetration in urban areas. In this paper, we dissect the application space using two axes: indoor vs. outdoor and urban vs. rural. The commonly considered NB-IoT use case: metering applications (electricity, water, gas) mainly falls into indoor urban category, although it may stretch to outdoor rural scenario, including measurements in power grids or gas pipelines as part of smart infrastructures. Outdoor urban domain will be the most important arena for NB-IoT applications, where use cases such as tracking (children or pet trackers), smart parking, street lighting and traffic signaling, payment processing, smart city-wide bicycles, smart waste control, and other smart city services will be relevant. The outdoor rural case covers important applications in smart agriculture domain, cattle and wildlife tracking and monitoring, but also various asset tracking applications (trucks, goods) and fleet management.

III. 3GPP NB-IOT COMMUNICATIONS

NB-IoT Radio Access Network Communication: NB-IoT radio interface almost entirely reuses the LTE design [4], [6]. Here, we provide high-level review of uplink (UL) and downlink (DL) transmission procedures, emphasizing critical aspects such as packet repetitions and low-power modes that affect RAN throughput, coverage and energy efficiency, relevant to subsequent use cases.

From signaling perspective, in normal network operation, NB-IoT user equipment (UE) is attached to the network using Radio Resource Control (RRC) protocol. By default, UE spends time in RRC Idle state, in which evolved Node B (eNB) cannot allocate resources to UE. If UE needs to send/receive data, it transits to RRC Connected state. When in RRC Idle, UE can be configured to save energy using one or a combination of eDRX and PSM modes. In both modes, UE sleeps and only periodically wakes up to receive eNB-originated signals: the tracking update (TAU) signal in PSM, and additional paging channel in eDRX mode. The duration of eDRX and PSM cycles are governed by specific timers, which can be set by the network or the device itself may request specific timer values [7], [8].

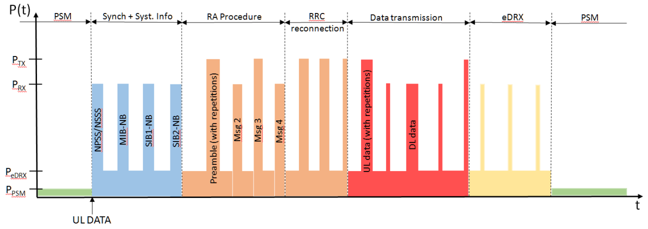

Fig. 2. Uplink data transmission phases for NB-IoT device originated transmission.

Fig. 2 illustrates the main phases in the UE originated UL data transmission. The UE has been in PSM mode, however, the internal packet generation event triggered wake up. UE wakes up from PSM mode to acquire downlink synchronization through NB-IoT synchronization signals (NPSS/NSSS), and system information (MIB, SIB-1 and SIB-2 information blocks). UE then initiates random access (RA) procedure by randomly selecting and transmitting RA preamble in the upcoming random access channel slot. If successful, the RA procedure involves exchange of four messages, after which eNB grants uplink resources to the UE. RRC procedure of re-establishing RRC connection follows, establishing a secure data radio bearer. UL data packet is transmitted with suitable physical layer configuration including the appropriate configuration of packet repetitions. Upon transmission, UE stays transits in RRC Idle and stays in eDRX mode until timer expires, when it transits to PSM mode. For network originated DL transmission, eNB first informs UE about the pending DL data through paging channel or TAU signal [7].

End-to-end NB-IoT connectivity: End-to-end NB-IoT connectivity targets deployment of a reliable and efficient communication mechanism between NB-IoT UE and a cloud application instance. This mechanism can be implemented using either IP-based or Non-IP data delivery. In general, Non-IP solution is more bandwidth efficient as it introduces no overhead in addition to the payload data. The downside of Non-IP data delivery is that it is only possible in case the MNO has deployed an in-network Connected Device Platform (CDP) server supported by NB-IoT chipset manufacturer.

NB-IoT equipment manufacturers support standard transport layer protocols, namely UDP and TCP. Two important classes of application layer protocols in IoT applications are REST-based and publish-subscribe protocols [11]. A good solution favors lightweight protocols with minimum overhead, e.g., MQTT-SN over UDP instead of MQTT over TCP as an

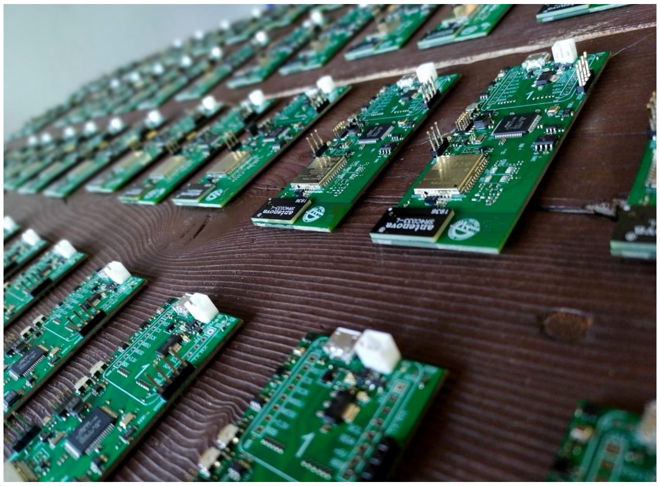

Fig. 3. FTN NB-IoT devices for massive testbed.

example of bandwidth friendly publish-subscribe solution, and CoAP over UDP instead of HTTP over TCP as an example of efficient REST-based solution. Some MNOs deploy in-network IoT platforms that provide seamless connectivity between lightweight protocols utilized by end devices, and bandwidth hungry REST-based cloud APIs (Figure 1). Before adoption of a widely accepted IoT platform solution implemented by majority of MNOs, users will need to make a strategic choice of protocols for end-to-end communication.

IV. NB-IoT TESTBED AND USE CASES

NB-IoT Testbed and Experimentation: For the purpose of creating a testbed and perform in-house experimentation, we developed a testbed containing about 100 NB-IoT devices, shown in Figure 3. The platform provides source of various data: 1) Radio channel conditions (SNR, RSSI, total TX/RX time and power, BLER, etc), 2) NB-IoT module energy consumption data, and 3) Fine-grained protocol message exchange logs. Using machine learning tools, in our future work, we will target optimization of energy efficiency of NB-IoT communications, optimal network selection for random access channel parameters, etc. For example, in our recent work [8], we use this data to provide in-depth analysis of NB-IoT module energy consumption during different stages of data transmission shown in Figure 2. The testbed devices are connected to a MNO network via macro-cellular base station in the neighbourhood of FTN building. However, one can also use 3GPP-compliant open-source LTE/NB-IoT software running base station and core network elements using commodity servers and USRP radio modules [12]. Finally, our testbed is currently in the process of extension with additional 50 mobile NB-IoT devices capable of logging GPS/accelerometer data suitable for outdoor urban/rural logistics use cases.

NB-IoT Example Use Cases: Designing an efficient application based on NB-IoT technology requires know-how in configuring and tailoring different system components: i) NB-IoT device design, ii) radio access network system parameters, iii) end-to-end connectivity between the device and the system backend (including security and maintenance aspects), and iv) cloud-based backend design [9]. Next, we present our experience with three different use cases: i) smart illumination in office buildings, ii) smart waste collection, and iii) plant disease forecasting system.

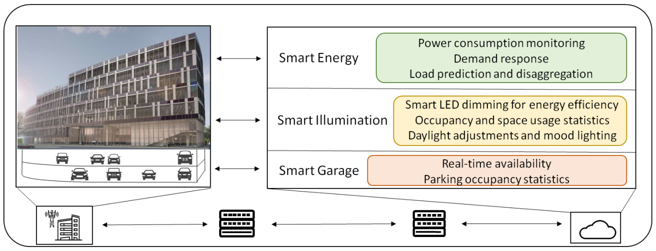

Fig. 4. FTN Smart office building testbed.

Indoor urban use-case: Smart Illumination – The initial target for NB-IoT in urban indoor scenarios are metering applications. However, through our urban indoor use case, we argue on strong NB-IoT case for smart office building services. Due to building shapes, insulation and metallic windows that restrict RF propagation in/out of the modern office and commercial buildings (e.g., shopping malls), more and more businesses are deploying indoor base stations (HeNB) with distributed antenna systems (DAS). With LTE HeNBs and DAS installed, strong coverage of NB-IoT signal can be made available across the building, providing connectivity for thousands of indoor deployed NB-IoT devices via secure licensed spectrum technology.

Figure 4 illustrates a large-scale smart building NB-IoT testbed currently in the process of deployment at FTN building, University of Novi Sad. Herein, we focus on a Smart illumination setup developed in the context of H2020 SENSIBLE project. Using desktop installed NB-IoT sensors, smart illumination system gathers user preferences (favorable illumination levels), user presence and current illumination levels (including periodical daylight illumination measurements) at the desk plane and feed this information to central illumination system that optimizes dimming levels of LEDs across the building for improved energy efficiency and user comfort and satisfaction [13].

Outdoor urban use-case: Smart Waste Collection System – One of the focuses in the smart city context is to optimize cost savings, reduce time and work efforts and reduce negative environmental impact. Waste control management has impact on several aforementioned areas. It can optimize work effort, time, cost and traffic for waste collection from waste containers. It is an outdoor urban use-case where NB-IoT features better results in terms of message delivery and lower number of repetitions according to our comparisons with other LP WAN technologies. This especially holds true for the waste containers located in the building basements. Figure 5 depicts the smart waste containers that create alert if the level of waste exceeds the trigger level, and the receiving software