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Building Upon NB-IoT Networks: A Roadmap Towards 5G New Radio Networks

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ABSTRACT Narrowband Internet of Things (NB-IoT) is a type of low-power wide-area (LPWA) technology standardized by the 3rd-Generation Partnership Project (3GPP) and based on long-term evolution (LTE) functionalities. NB-IoT has attracted significant interest from the research community due to its support for massive machine-type communication (mMTC) and various IoT use cases that have stringent specifications in terms of connectivity, energy efficiency, reachability, reliability, and latency. However, as the capacity requirements for different IoT use cases continue to grow, the various functionalities of the LTE evolved packet core (EPC) system may become overladen and inevitably suboptimal. Several research efforts are ongoing to meet these challenges; consequently, we present an overview of these efforts, mainly focusing on the Open System Interconnection (OSI) layer of the NB-IoT framework. We present an optimized architecture of the LTE EPC functionalities, as well as further discussion about the 3GPP NB-IoT standardization and its releases. Furthermore, the possible 5G architectural design for NB-IoT integration, the enabling technologies required for 5G NB-IoT, the 5G NR coexistence with NB-IoT, and the potential architectural deployment schemes of NB-IoT with cellular networks are introduced. In this article, a description of cloud-assisted relay with backscatter communication, a comprehensive review of the technical performance properties and channel communication characteristics from the perspective of the physical (PHY) and medium-access control (MAC) layer of NB-IoT, with a focus on 5G, are presented. The different limitations associated with simulating these systems are also discussed. The enabling market for NB-IoT, the benefits for a few use cases, and possible critical challenges related to their deployment are also included. Finally, present challenges and open research directions on the PHY and MAC properties, as well as the strengths, weaknesses, opportunities, and threats (SWOT) analysis of NB-IoT, are presented to foster the prospective research activities.

INDEX TERMS Backscatter communication, cloud RAN, enabling market, long-term evolution, machine-type communication, narrowband Internet of Things, 5G new radio coexistence, PHY, MAC, SWOT analysis.

I. INTRODUCTION

The Narrowband Internet of Things (NB-IoT) is a release 13 3GPP technology built on the platform of long-term evolution (LTE) functionalities. NB-IoT will continue to coexist and operate seamlessly with new 5G networks, thus supporting LTE-IoT deployment scenarios. The existing 4G LTE networks employed to test the implementation of different NB-IoT connectivity and applications [1] remain an ongoing effort, particularly as the capabilities of various existing low-power wide-area network (LPWAN) technologies continue to grow [2]. Despite the attempt to optimize current LTE broadband systems, they remain unsuitable for many machine-type communication (MTC) applications. MTC plays an essential role in the core of NB-IoT connectivity between devices and the cloud. 5G networks are expected to create a horizontal transformation approach [3] to drive massive numbers of NB-IoT devices and applications by expanding the operation of the cellular-IoT. 5G data infrastructure plays a vital role in LPWA-based IoT devices

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that need strong security, widespread availability, ultra-low latency, ultra-low power consumption, wide coverage area, low device cost and high reliability [4] for streamlining and improving a variety of services and industries. According to the International Data Corporation (IDC) survey, billions of dollars are spent by companies to drive 5G services requiring ubiquitous connectivity, including mobile, nomadic, and stationary, to the tens of billions of devices, objects, and machines [5]. The connected devices in return, generate immense economic value across the world. To make NB-IoT a core component in achieving this dream, a roadmap for NB-IoT towards 5G networks is the focus of the present article.

Considering the differences between this survey and other articles that have emerged to examine NB-IoT connectivity and limitations, this is the first survey paper detailing practical features of NB-IoT coexistence with 5G new radio (5G NR), and open research challenges that may hinder the conduct of NB-IoT carriers within the NR network. For instance, the author of [6] surveyed a comparative study of media access control (MAC) layer protocols of long-range and short-range LPWA technologies to gain insight, and a reference study of the features, constraints, behavior and open research issues of IoT applications. The author in [7] analyses the design decisions' impact on the design goal requirements for the suitability of given IoT applications. The author outlines seventeen use cases across twelve domains to prioritize each design goal's significance to those applications. The analysis of technical terms based on the physical and MAC layers of LPWA technologies was surveyed in [8]. In [9], a physical layer design for DL scheduling and resource allocation in NB-IoT was presented. The highlight of [10] documents the draft reforms made of NB-IoT standardization, with the comprehensive study process from the perspective of physical and MAC layers. The surveys mentioned above have presented a brief knowledge of the NB-IoT network relationship with 5G NR networks. However, the survey mentioned provides immense guidance for our studies.

In comparison to current studies, the contributions of this paper are as follows:

- A comprehensive flowchart of the 5G-IoT class of connectivity is presented and also, a definite difference between the NB-IoT protocol stack and the OSI reference model concerning optimized LTE NB-IoT architecture is discussed, as well as the popular features of the 3GPP releases from 13 to 17.
- We list specific features between the 5G NR and NB-IoT numerologies to promote the coexistence of 5G NR and NB-IoT, and also, describe the limitations of the technical performance properties of 5G NB-IoT networks, as well as the current solutions proffered for the PHY/MAC channel communications challenges.
- We describe the possibility of architectural design for cloud-assisted relay with ambient backscatter communication for the 5G NB-IoT network.
- We discuss the market analysis of NB-IoT, the benefits for a few use cases, and possible critical challenges related to their deployment.
- The research challenges and discussion of 5G NB-IoT networks for planning future research works, as well as a SWOT analysis of NB-IoT, are presented.

This paper is structured as follows: Section II presents the background to the 5G-IoT class of connectivity. Section III discusses the overview of NB-IoT, highlights the technical differences between NB-IoT and other LPWA technologies, and summarizes the design objectives and benefits of NB-IoT. Section IV presents the OSI layer framework and optimized LTE-NB-IoT architecture design and the 3GPP standardization and releases for NB-IoT. Section V details the 5G architecture design for NB-IoT integration, and the enabling technology needed for the 5G NB-IoT network. Section VI describes the possibility of architectural design of cloud-assisted relay with ambient backscatter communication for 5G NB-IoT. Section VII highlights the 5G NR coexistence with NB-IoT, the similarity between the NR and NB-IoT, and the achievable architecture deployment schemes for asynchronous and synchronous network distribution structures. Section VIII discusses the technical performance properties of NB-IoT, detailing the PHY/MAC challenges concerning various channel parameters and possible solutions. Section IX describes the enabling market analysis for NB-IoT, applications and use cases with some potential problems affecting their deployment. Section X discusses the open research challenges and provides a SWOT analysis of NB-IoT in 5G NR carrier networks and finally, section XI concludes the survey.

II. BACKGROUND TO 5G-IOT CLASS OF CONNECTIVITY

The 5G networks utilize intelligent architectures of radio access technology (RAT), dynamic by nature, coherent, and flexible over multiple advanced technologies that can support NB-IoT and a wide variety of IoT applications. According to the new 3GPP releases 16 and 17, the adaptation of 5G-IoT services can create a link with high performance and low complexity to virtually everything around us [11]. The 5G-IoT can improve the spectral efficiency and data rate of NB-IoT, and thus promote the total addressable market of NB-IoT devices and 3GPP solutions for IoT use cases. In Figure 1, 5G-IoT has three classes of connectivity, namely; wired, wireless, and satellite [12], but wireless technologies will be reviewed. The 5G-IoT wireless technologies can be classified into two groups based on transmission distance as short-range MTC wireless technologies (e.g. WHAN, Wi-Fi, and WPAN, examples such as Bluetooth, Mi-Wi, ANT, 6lowpan, ZigBee, and Z-wave) [13] and long-range MTC wireless technologies (e.g. low-power, wide-area networks (LPWAN)), and finally, the MTC services [14].

Considering the perspective of frequency spectrum licensing, LPWAN can be categorized into two classes, namely; the non-3GPP standards (unlicensed spectrum) and the 3GPP standards (licensed spectrum), [14]. The first category

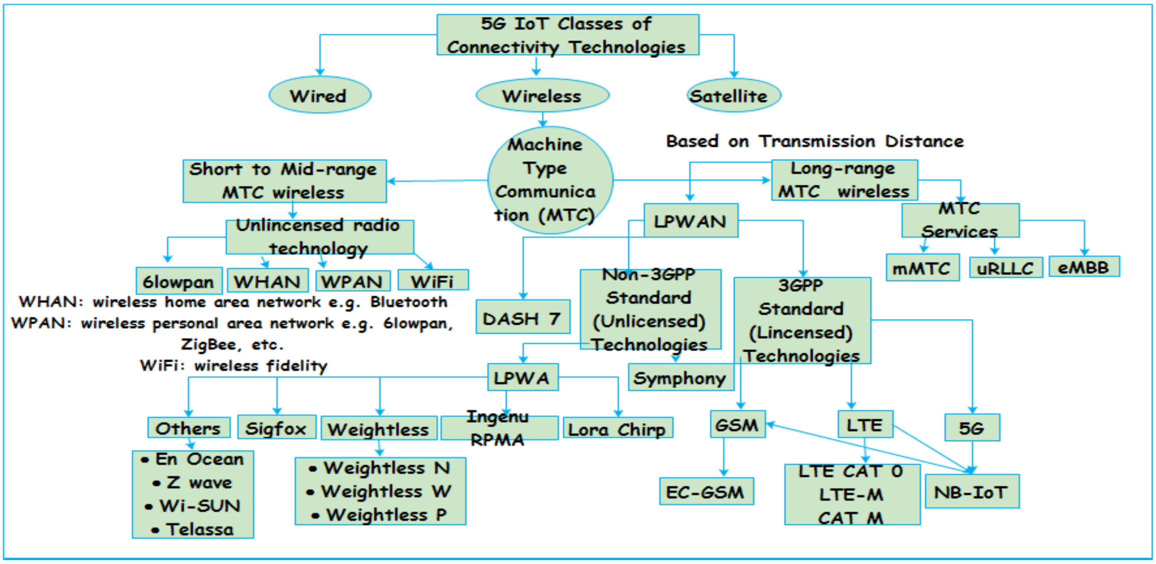

FIGURE 1. Classes of 5G-IoT connectivity Based on Transmission Distance.

consists of LPWA technologies such as Sigfox LoRa, Weightless, Ingenu RPMA, Z-wave [15], etc. that are of custom and non-standard implementation. For instance, LoRa and Sigfox operate in the sub-Gigahertz unlicensed spectrum while RPMA operates in 2.4 GHz industrial, scientific and medical (ISM) bands. More importantly, this category has limited channel access due to the spectrum shared between different technologies. The transmission time has a limited duty cycle and a listen-before-talk or frequency-hopping scheme implemented to avoid interference with other coexisting systems. The second category is based on 2G/3G cellular technologies (such as the GSM, CDMA, WCDMA), LTE, and evolves LTE technology that supports different classes of terminals [16]. The standards for the second category (licensed spectrum) were developed by the 3GPP and 3GPP2 [10]. Unlike the unlicensed spectrum, the licensed spectrum does not suffer from the duty cycle and uncontrollable interference [17]. In general, MTC has limited power at the device side while the network can still benefit from the increased downlink link-budget due to the high base station (BS) transmitting power. Based on the modification, specific demands [18] and features of MTC services related to 3GPP set objectives of release 13, three (3) kinds of narrowband air interfaces were defined, namely, extended-coverage GSM internet of things (EC-GSM-IoT), enhanced machine-type communication (eMTC) known as LTE-M (LTE-Cat M1) or Cat M and the new NB-IoT technology.

The EC-GSM-IoT is a high-potential, long-range, low-energy, and low-complexity technology-based eGPRS system. The eMTC supports applications with higher data rate and mobility requirements designed for LTE enhancement, for the implementation of MTC and IoT. As regards the new NB-IoT technology, on the other hand, the focus of this article is intended for intelligent low-data rate applications for data perception and acquisition.

The MTC service offers an optimized 3GPP network support to connected devices and services to the potential 5G-IoT as specified in Rel. 14 [19]. The 5G-IoT, is expected to connect more than 70 use cases cutting across a range of new services and markets from IoT to vehicular communications, applications, and control, industrial automation, tactile internet, drone control systems, remote maintenance, and monitoring systems [20], theft prevention and recovery, as well as smart cities [21], smart buildings and surveillance [22], intelligent health systems, smart metering [23], smart grid [24], smart parking, smart lighting, shared bicycle, connected cow [15], [25], and lots of other use cases. The use cases have inspired research issues related to the capacity and services of the deployed 5G communication systems.

The 5G-MTC services are: Enhanced mobile broadband (eMBB), Ultra-reliable and low-latency communication (uRLLC), and lastly, massive machine type communication (mMTC). The services offer enhanced localization support, multicast, mobility, high data rate, positioning update, new user equipment output class necessary for system throughput, and link adaptation to 5G NB-IoT and cellular IoT.

To further bolster this point, two-step strategies are adopted by 3GPP to puzzle-out the technological challenges from the MTC services. The transition strategy is the first step taken.

The first strategy optimizes the existing network and technologies to offer MTC services [26]. The second strategy, termed a long-term strategy, provides support to the rising large-scale MTC services based on the introduced new air interface of NB-IoT, and for maintaining core competitiveness to non-3GPP LPWA technology [27].

The diverse NB-IoT software and hardware solutions deployed from different vendors such as the Skyworks [28], Media Tek [29] Qualcomm [30], Sierra wireless [31], Neul (Huawei) [32], Intel [33] and so on, have made it possible for the Telecom operators across the globe to carry out

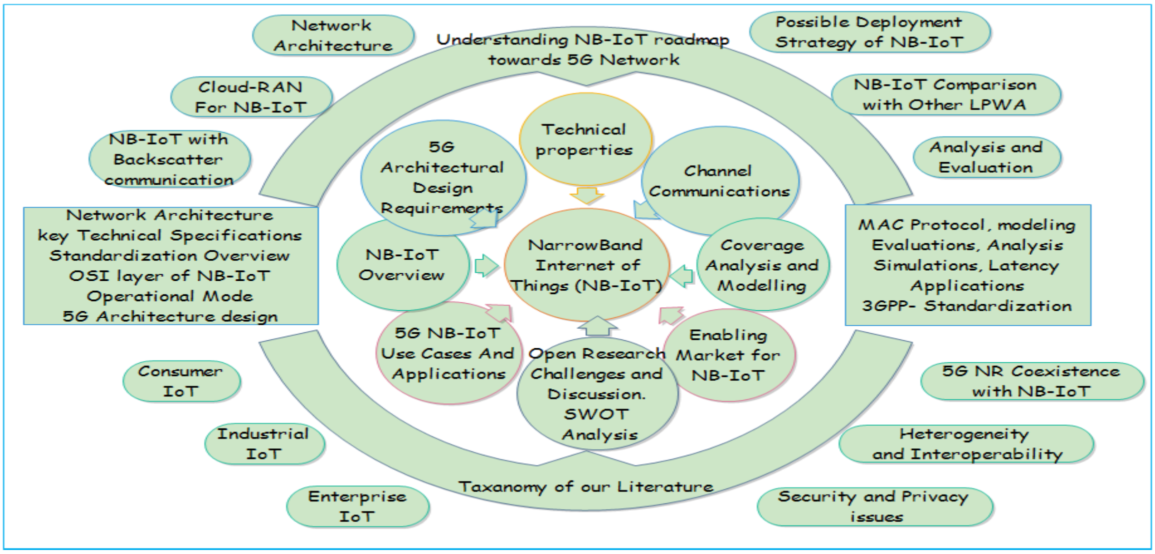

FIGURE 2. Brief Taxonomy of Literature.

practical feasibility studies of different NB-IoT use cases with real-life trials such as the smart city in Las Vegas, USA [34], smart metering and tracking in Brazil [35], NB-IoT at sea in Norway [36], [37] and so on, to mention a few. The products implemented from different vendors speed up the adopted NB-IoT technology. Numerous studies detailing the architecture design and OSI layer, coverage enhancement mechanism, theories, modeling, security challenges, channel estimation and limitations are highlighted in this survey. Figure 2 presents the taxonomy of the literature studies. The study classifies nine main sections, each section with a sub-branch as mentioned above.

III. AN OVERVIEW OF NARROWBAND INTERNET OF THINGS (NB-IoT)

NB-IoT is an open 3GPP standard optimized for MTC traffic to lower the energy consumption of IoT use cases. The narrowband radio technology was designed specifically for LPWA applications to support a low data rate, very low power consumption, scalability, and long-range coverage of cellular data. It promotes the development and implementation of intelligent IoT. NB-IoT can be integrated into the 5G new radio (5G-NR) networks, to bolster the ultralow-end IoT applications, including the intelligent meters, remote sensors and smart health systems [15].

NB-IoT (also known as LTE-Cat-NB1) provides simplification and optimization of enterprise-grade technical specifications that reduce the radio overhead and deliver IP and non-IP data [38], being the practical choice for carriers, device manufacturers and enterprise users [39]. The NB-IoT integrates into the existing network and promotes optimal coexistence by occupying a physical resource block of 180kHz for both uplink (UL) and downlink (DL) operations or by replacing one GSM carrier of 200kHz without compromising the host network's performance. According to [38], NB-IoT supports cell reselection in idle state but does not aid hand-over services in the connected state. Also, due to the features of employing power-saving mode (PSM), NB-IoT lacks provision for QoS. Table 1 tabulates the key technical specifications (KTS) of NB-IoT in comparison with other LPWA technologies.

The summary of the design objectives and benefits of NB-IoT [17], [40]–[42] is as follows;

- The complexity of the transceiver is lower.
- Energy consumption is lower.
- Radio-chirp is lower.
- It has a maximum-coupling loss of 164 dB for coverage improvement.
- It should provide multi Physical Resource Block (PRB)/Carrier support.
- It adopts a HARQ process of adaptive and asynchronous for both UL and DL.
- FDD only and half-duplex User Equipment (UE)
- Employs 180kHz (1PRB) for narrowband physical DL channel.
- Uses 3.75kHz random-access preambles (RAP).
- Can adopt a single tone (15 kHz/3.75 kHz) or multi-tone (n*15 kHz, n = (3,6,12)).
- Uses 680 bits and 1000 bits of the maximum transport block size (TBS) for DL and UL.
- NB-IoT offers support for up to 10s for UEs using eDRX when connected, but uses 3hrs for UEs in idle state.
- Has a power spectral boosting of 6dB relative to the LTE system, and the multiple repetitions method can aid in improving the received signal quality.
- NB-IoT provides 20dB improvement in coverage relative to LTE.
- An NB-IoT carrier can support the transmission of short messages to the network from more than a hundred thousand devices. Additional carriers to the system can scale the network connections to millions of devices.