# NB-IoT Technology Overview and Experience from Cloud-RAN Implementation

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## Abstract

The 3GPP has introduced a new narrowband radio technology called narrowband Internet of Things (NB-IoT) in Release 13. NB-IoT was designed to support very low power consumption and low-cost devices in extreme coverage conditions. NB-IoT operates in very small bandwidth and will provide connectivity to a large number of low-data-rate devices. This article highlights some of the key features introduced in NB-IoT and presents performance results from real-life experiments. The experiments were carried out using an early-standard-compliant prototype based on a software defined radio partial implementation of NB-IoT that runs on a desktop computer connected to the network. It is found that a cloud radio access network is a good candidate for NB-IoT implementation.


## Introduction

The Internet of Things (IoT) is revolutionizing the way we live and is expected to create steady growth in the economy. According to the IoT paradigm, everything and everyone can be connected. This vision redefines the way people interact with each other and with things they are surrounded by. Currently, there are more than 16 billion connected devices worldwide, and Ericsson forecasts that by 2021 the number will grow to nearly 28 billion connections [1]. Cisco predicts that the number of networked devices per capita will grow from 2.2 in 2015 to 3.4 in 2020 [2]. Machine-to-machine (M2M) communications or machine-type communications (MTC) plays an essential role at the core of IoT for the connectivity between devices and the cloud.

Massive MTC refers to a set of use cases in which a large number of mostly battery-powered devices that seldom transmit or receive small amounts of data are deployed in the field. In those use cases, the main requirements for the underlying radio technologies are low power consumption, low data rate, scalability, and long range. In recent years, low power wide area (LPWA) radio technologies have emerged to address this market. In the unlicensed spectrum, technologies such as LoRa, Sigfox, and radio phase multiple access (RPMA) are popular choices for massive MTC. LoRa and Sigfox operate in sub-gigahertz unlicensed spectrum, while RPMA operates on the 2.4 GHz industrial, scientific, and medical (ISM) band. All these LPWA technologies support tens of thousands of connections with up to 10 years of battery life and coverage distance reaching 10 km. Unlicensed spectrum, however, has limitations in channel access as the spectrum is often shared between different technologies. Typically, transmission time is limited with a duty cycle, and either *listen-before-talk* or *frequency hopping* schemes are required to avoid interference with coexisting systems. To provide larger capacity for massive MTC use cases, it is of interest to look into solutions in the licensed spectrum. Licensed bands do not suffer from duty cycle limitations and uncontrollable interference. The licensed conditions typically allow higher transmit powers to be used. In the MTC case, power is limited at the device side, but the network can still benefit from the increased downlink link budget due to higher base station (BS) transmission power.

The Third Generation Partnership Project (3GPP) introduced the first IoT-specific user equipment (UE) in Long Term Evolution (LTE) Release 12, known as LTE Cat-0 or LTE-M. LTE CAT-0 features include peak data rate of 1 Mb/s over 1.08 MHz bandwidth and support for UEs with half duplex operation and power saving mode. Recently, in its LTE Release 13, 3GPP has standardized a new radio access network (RAN) technology called narrowband IoT (NB-IoT) [3] which can operate in 200 kHz carrier. Essentially, NB-IoT has been designed for low cost, long battery life, high coverage, and deployment of a large number of devices. It inherits basic functionalities from the LTE system, while it operates in a narrow band. With a software upgrade, core network elements of an operator's existing LTE network can be enabled to support NB-IoT. This is essential for reducing deployment cost and time.

Some of the main benefits of NB-IoT are: less complexity in transceiver design, low power consumption, lower cost for the radio chip, and coverage enhancement. Discontinuous reception (DRX) allows devices to save power by going to sleep, and occasionally waking up and listening


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for incoming data and paging messages from the network. The periodicity by which devices should wake up is configured by DRX cycles. NB-IoT supports extended DRX (eDRX) cycles, which can reach up to 10 s for UEs in connected state and about 3 h for UEs in idle state [4]. Due to its small bandwidth, the power spectral density of NB-IoT carrier can be boosted by 6 dB compared to legacy LTE. Moreover, the received signal quality can be improved by combining multiple repetitions. As a result, NB-IoT offers 20 dB coverage enhancement compared to LTE [5]. A single NB-IoT carrier can support more than 100,000 UEs [1] that occasionally send small updates to the network. This can be scaled to millions of connections by adding more carriers to the network.

Another disruptive and emerging technology which facilitates IoT deployment is cloud-RAN (C-RAN). C-RAN is based on the concepts of centralization and virtualization for the baseband operation of a BS. By centralization, C-RAN tries to improve performance, and by virtualization, it aims to reduce capital expenditures (CAPEX) by applying network functions virtualization (NFV) to the RAN. In other words, by using commercial cloud servers, service providers can scale up their deployments more rapidly. This kind of approach also allows different radio access technologies to share the same physical network infrastructure. In LTE, crucial C-RAN problems are related to fronthaul capacity and latency requirements. Low protocol stack processing requirements and relaxed latency targets make NB-IoT a suitable candidate for C-RAN implementation. NB-IoT is a narrowband technology, and its design leads to rather loose latency requirements for the fronthaul link. It can potentially be implemented using C-RAN, where all the baseband processing and higher-layer protocol stacks are implemented by software. In this way, NB-IoT can be virtualized and deployed in general-purpose cloud-based infrastructure. Moreover, C-RAN opens the opportunity for distributed antenna system (DAS) or femtocell type deployments in large buildings or industrial premises.

This article highlights NB-IoT features that have been introduced in Release 13 and have actually been implemented (layer 1, L1, and part of the L2 and L3 protocol stack) on a flexible software defined radio (SDR)-based C-RAN testbed. Our implemented SDR can run any RAN technology on a commercially available personal computer.

The article is organized as follows. We highlight targets and applications of NB-IoT. The required physical layer features are presented. We discuss C-RAN implementation aspects of NB-IoT. Performance results from testbed measurements are reported. Finally, conclusions are drawn.

## Motivation, Aims, and Applications

The massive MTC use case includes (but is not limited to) smart metering, smart agriculture, and connected street lighting. In city environments, connected devices may need to be placed into locations not reachable by today's networks, for example, basements, or inside buildings in remote areas in the countryside. Standardization of NB-IoT was completed during 3GPP's RAN#72 plenary meeting, and all features that are part of Release 13 have been frozen [6].

The most important goals for a cellular IoT technology and massive MTC type of use cases include low device complexity and cost; extended coverage so that devices in hard to reach locations can be reached; and long battery life, exceeding 10 years of lifetime with typical battery capacity of 5 Wh. Additionally, massive MTC scenarios target support of very large amounts of devices per cell with a traffic pattern consisting of small and infrequent messages. NB-IoT fulfills all of these requirements.

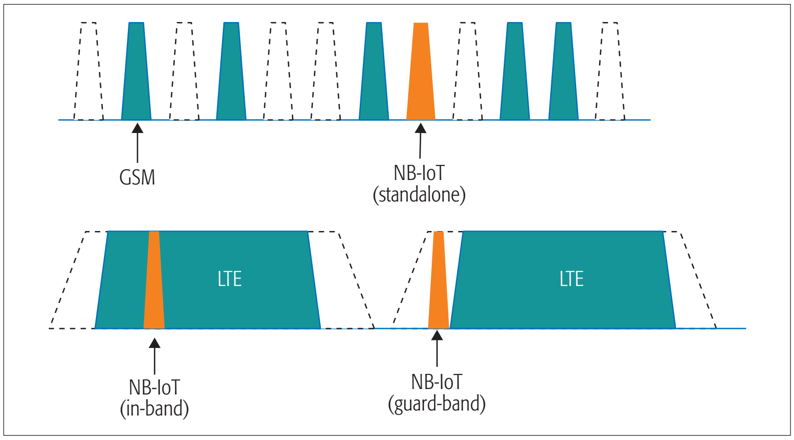

Figure 1. NB-IoT operation modes.

One additional important requirement for the new 3GPP radio interface technology was the ability to deploy in 200 kHz bandwidth used in Global System for Mobile Communications (GSM) networks, thus allowing for more deployment options in licensed spectrum. As a result, a single NB-IoT carrier spans a bandwidth of 180 kHz in uplink and 180 kHz in downlink with frequency-division duplexing (FDD). This is equivalent to the bandwidth of one physical resource block (PRB) in LTE. Thus, NB-IoT can be deployed in three different operation modes, as illustrated in Fig. 1.

**Standalone operation:** In standalone operation, NB-IoT would be (typically) deployed within one or more existing and re-farmed GSM carriers. In standalone operation, all available BS transmission power can be used for NB-IoT.

**In-band operation:** An in-band deployment within normal LTE carrier uses the same PRBs as LTE. There are some scheduling restrictions in this deployment mode as some resources are restricted for LTE operation (e.g., for the physical downlink control channel and reference signals). The transmit power is shared between legacy LTE and NB-IoT operation.

**Guard band operation:** Unused resource blocks within LTE carrier's guard band are utilized, and the NB-IoT cell is served by the same BS, also sharing the maximum BS transmission power. In general, less interference is expected compared to in-band operation as the LTE interferer is only located on one side of the NB-IoT carrier.

As the NB-IoT channel bandwidth is reduced compared to LTE, the physical signals and channels are redesigned to fit into 180 kHz for all necessary procedures. For added capacity, it is possible to operate NB-IoT in multi-PRB mode, where one anchor carrier is used to transmit at least common signals and channels, such as synchronization signals and broadcast system information, and secondary carriers where UEs can be

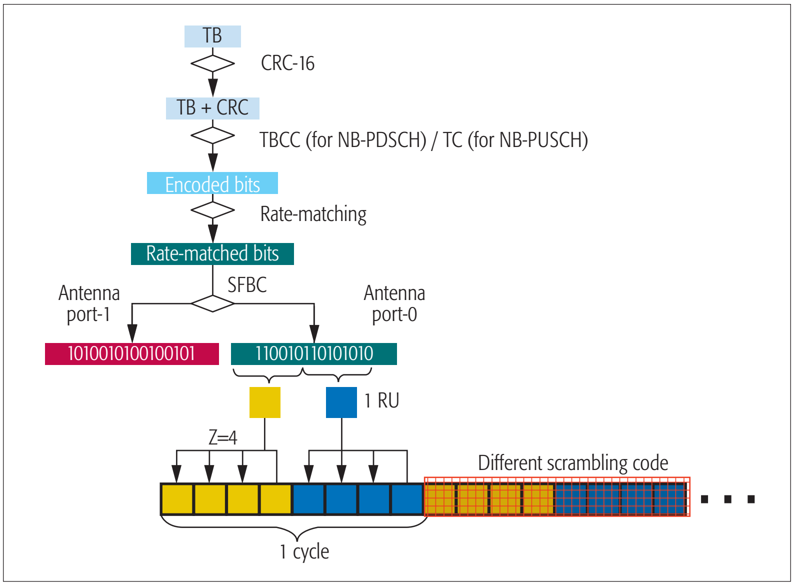


**Figure 2.** Physical layer processing of TB, which is transmitted on NBPDSCH/NB-PUSCH.

moved by higher-layer signaling to receive and transmit over the data channels.

## Physical Layer

Most novel NB-IoT features come from the new physical layer design. Since NB-IoT requires narrow bandwidth, it can effectively use small chunks of re-farmed spectrum, for example, from a GSM band or within an existing LTE carrier. As in LTE, orthogonal frequency-division multiplexing (OFDM) with 15 kHz sub-carrier spacing is used in downlink. On the other hand, uplink allows both single-tone and multi-tone operations. For single-tone operation, 3.75 kHz and 15 kHz sub-carrier spacing are supported. Multi-tone uplink transmission is according to single-carrier frequency-division multiple access (SC-FDMA) with 15 kHz sub-carrier spacing. In downlink and the 15 kHz version of uplink transmissions, one NB-IoT carrier has 12 sub-carriers. The subframe duration is 1 ms, which is similar to LTE. Hence, there is not enough room for frequency-domain multiplexing of physical channels. All downlink channels are multiplexed in time. Some channels span multiple subframes. For example, up to 10 resource units can be scheduled for data transmissions on both uplink and downlink shared channels. A UE is not required to monitor more than one channel at a time. Moreover, half-duplex operation was selected to save on implementation complexity (or cost). As a consequence, UE cannot transmit in uplink and monitor downlink simultaneously.

### Physical Channels and Signals

The physical layer downlink channels of NB-IoT are the physical broadcast channel (NB-PBCH), physical downlink control channel (NB-PDCCH), and physical downlink shared channel (NB-PDSCH) [7]. Supported transmission modes are *single antenna port* and *two antenna ports with transmit diversity* using space frequency block coding (SFBC). Synchronization signals and reference signal (NB-RS) are also transmitted in downlink. There are only two uplink channels: physical uplink shared channel (NB-PUSCH) and physical random access channel (NB-PRACH). Demodulation reference symbols (DMRSs) are transmitted in subframes that contain NB-PUSCH. No more than one type of physical channel can be transmitted simultaneously on a given carrier.

**Synchronization Signals:** Similar to LTE, NB-IoT has two synchronization signals: primary synchronization signal (NB-PSS) and secondary synchronization signal (NB-SSS).

**NB-PBCH:** The NB-PBCH carries a master information block (MIB) and is transmitted in the first subframe of each radio frame. The information contained in the MIB includes system information block (SIB) scheduling information, number of antenna ports, and deployment mode.

**NB-PDCCH:** NB-PDCCH is used to transmit downlink control information (DCI), which carries scheduling information for both uplink and downlink data transmissions. Resources for NB-PDCCH are grouped into control channel elements (CCEs). A CCE occupies six sub-carriers in a subframe. Hence, there are two CCEs per subframe. One key difference with respect to LTE is that forward scheduling is used; that is, NB-PDCCH is sent before the NB-PDSCH with a gap in between. This is similar to Cat-M1/eMTC UEs [7]. Likewise, the search space design is slightly different and takes repetitions into account.

**NB-PDSCH:** Downlink payload transport blocks (TBs) are transmitted on NB-PDSCH. Scheduling information about NB-PDSCH is transmitted over NB-PDCCH. The smallest scheduled resource unit (RU) is one carrier spanning one subframe. The BS can allocate up to 10 downlink subframes. The maximum TB size (TBS) is limited to 680 bits. Unlike LTE, only quadrature phase shift keying (QPSK) modulation is supported. Moreover, the TB bits are encoded using tail-biting convolutional coding (TBCC). Repetitions are done in cycles where in each cycle, each subframe is repeated consecutively $Z$ times where $Z = \min(4, \text{Repetition})$ (Fig. 2). Different scrambling codes are applied to each cycle.

**NB-PUSCH:** The NB-PUSCH carries UE's TBs (NB-PUSCH Format-1) and uplink control information (UCI) (NB-PUSCH Format-2). The NB-PUSCH RU size varies from 2 to 16 slots depending on the number of tones, which can be 1, 3, 6, or 12. The slot lengths are 0.5 ms and 2 ms for sub-carrier spacing of 15 kHz and 3.75 kHz, respectively. This is one key difference from LTE uplink, which has fixed RU length of 1 ms. NB-PUSCH Format-2 supports single-tone transmission only and carries 1-bit UCI that corresponds to hybrid automatic repeat request (HARQ) feedback for NB-PDSCH TBs. Physical layer processing of NB-PUSCH Format-1 is similar to NB-PDSCH with the exception that turbo coding (TC) is used instead of TBCC. The maximum TBS for NB-PUSCH is 1000 bits where up to 10 RUs can be scheduled. Both NB-PDSCH and NB-PUSCH Format-1 use single-process adaptive HARQ. Uplink HARQ retransmissions are asynchronous. This is another visible difference from LTE.

**NB-PRACH:** NB-PRACH uses a single-tone transmission scheme and 3.75 sub-carrier spacing. NB-PRACH preamble transmission can be repeated up to 128 times over contiguous subframes. The BS can configure up to three NB-PRACH resources with different coverage levels. Each NB-PRACH resource is defined by periodicity, number of repetitions, and a set of sub-carriers.

### Signal Repetition

In NB-IoT, repetitions of transmissions on different physical channels are used to provide enhanced coverage. The number of repetitions depends on the coverage enhancement level required by a UE. A UE determines its coverage enhancement level based on the reference signal received power (RSRP) threshold set by the network [4]. Even though each repetition is separately decodable, multiple repetitions help boost the signal strength for UEs that have weak coverage. For transmissions on NB-PDCCH and NB-PDSCH, up to 2048 repetitions are possible, while NB-PUSCH and NB-PRACH support maximum of 128 repetitions.

Ideally, 2048 and 128 repetitions of NB-IoT channels would improve the received signal-to-noise ratio (SNR) at least by a factor of 33 dB and 21 dB in downlink and uplink, respectively. This suggests that UE should be able to decode downlink channels even when the received signal is more than 25 dB below the noise floor. However, operations under such extreme condition suffer from even small hardware impairments and estimation errors. One significant factor that should be considered is channel estimation error. In general, pilot-based channel estimation quality in narrowband signals is heavily impacted by the channel coherence time. We present the system performance that was observed from practical measurements using SDR-based C-RAN implementation of the NB-IoT protocol.

## NB-IoT in the Cloud

One of the NB-IoT development targets is to simplify the RAN protocols by removing functionality not needed for IoT applications. The simplified system is easier to implement and more cost-efficient to deploy. Among other benefits, the simplified system can be implemented on a general-purpose computing platform. These aspects make NB-IoT attractive for implementation in cloud computing platforms.

Global cloud computing infrastructure offers scalability, efficiency, and the possibility to reduce costs. A RAN implemented in a cloud platform is called C-RAN [8]. A typical C-RAN comprises a set of remote radio units (RRUs) connected to a centralized pool of baseband units (BBUs). There are various C-RAN configurations realized by different functional splits among network elements in the RAN protocol stack. In a typical scenario, one or more RRUs are controlled by a RAN protocol stack instance, which can be hosted in a virtual machine (VM).

Centralized processing of baseband signals from multiple RRUs has many advantages such as interference management, seamless handover, and better energy and spectral efficiency. Despite its benefits, C-RAN has many challenges that need to be addressed. One of the challenges is the capacity requirement for fronthaul links between RRUs and BBUs to transport the baseband signals. Continuously increasing capacity in cellular networks also means that the data rates between RRUs and BBUs increase. In the baseband, each data bit is represented by multiple quantization level bits. Thus, wideband signals and multiple antenna configurations need huge fronthaul link capacity. For example, a single LTE BBU instance with 20 MHz carrier, 4× 4 antenna configuration, and 32-bit I/Q sample precision requires 7.9 Gb/s fronthaul capacity. Another challenge in C-RAN is the latency between the RRUs and BBUs. The fronthaul link in C-RAN introduces additional delay for baseband signal processing. For example, in LTE uplink, synchronous HARQ is used, and the acknowledgments are sent exactly on the fourth subframe (4 ms) after the uplink transmission [9]. With fronthaul delay in C-RAN, the baseband processing has less time for analyzing and acknowledging the packets.

Since NB-IoT was designed with asynchronous HARQ, it led to relaxed timing requirements. In NB-IoT, for uplink HARQ, the UE expects feedback any time later than four subframes after the transmission has ended. In this case there is no explicit acknowledgment (ACK) or negative ACK (NACK), as there is no separate feedback channel (physical HARQ indicator channel) in downlink like for legacy LTE. The UE instead waits for the next uplink grant, and assumes the previous data were not received if the new data indicator (NDI) in the DCI is not set. For downlink HARQ, the minimum response time is 13 ms. This response time depends on the configuration of the network, and can be extended to 18 ms and 21 ms for 15 kHz and 3.75 kHz sub-carrier spacing, respectively. The feedback in this case is carried on NB-PUSCH using Format-2.

Relaxed latency requirements together with reduced baseband processing complexity make the NB-IoT radio stack suitable for C-RAN platforms. The system can be implemented in software that can be compiled for various cloud platforms or VMs. Low bandwidth of NB-IoT means that fronthaul data transmission requirements are modest and can be served by off-the-shelf network routers as illustrated in Fig. 3. Looser latency requirements allow RRUs to be located further away, and as such one C-RAN BBU server can span a larger area. We have developed a flexible SDR-based C-RAN testbed [10] that can run any RAN technology on a commodity server. This is made possible by creating Virtual Hardware Enhancement Layer (VHEL) [11] middleware between the RAN protocol stack and the BBU. VHEL hides real-time constraints of radio transceivers from multi-threaded protocol implementations, which run as state machines. Data can be lost due to either the fronthaul link or failure to meet the processing deadline. VHEL presents to the physical layer such events as channel fading impairments. The designed platform facilitates radio protocol execution on top of an Ethernet network. SDR implementation also opens an opportunity to add new features such as network-controlled device-to-device (D2D) communication [12], dynamic spectrum sharing [13], MTC on LTE random access channel (RACH) [14], and DAS [10].

We have implemented the NB-IoT protocol stack in C++. The test network illustrates C-RAN suitability for NB-IoT. It also enables us to measure the performance of an NB-IoT system. The implementation concentrates on NB-IoT lower layers, and a limited set of features are imple-

One of the NB-IoT development targets is to simplify the RAN protocols by removing functionality not needed for IoT applications. The simplified system is easier to implement and more cost efficient to deploy. Among other benefits, the simplified system can be implemented on to a general purpose computing platform.

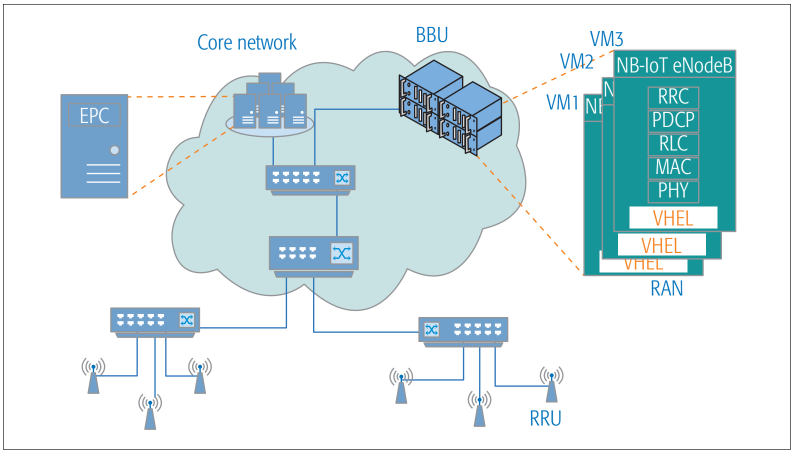


**FIGURE 3.** SDR-based implementation of NB-IoT in a C-RAN environment.

mented. It is left for further study how an NB-IoT C-RAN system scales with a larger number of IoT nodes and the full set of features.

## System Performance

Performance measurements were carried out using the SDR implementation of NB-IoT. The testbed comprises a standard host computer and SDR hardware as the radio front-end. The protocol runs on an Ubuntu Linux-based desktop computer. All baseband processing and a subset of medium access control (MAC) and radio resource control (RRC) protocol implementations run as software. The baseband I/Q samples are transported over the network between the general-purpose processor and the universal software radio peripheral (USRP) [15], which performs conversion between baseband and RF signals. USRP x310 with UBX-160 RF-daughterboard was used during the measurement. The USRPs are fed with a 10 MHz reference clock. Even though the testbed can operate on any frequency band from 10 MHz to 6 GHz, carrier frequencies of 640 MHz and 635 MHz were used for downlink and uplink transmissions, respectively. All the parameters are summarized in Table 1.

| | | |
|---|---|---|
| Environment | Host operating system | Ubuntu 14.04 LTS |
| | Remote radio head | USRP-X310 |
| | RF daughterboard | UBX-160 |
| | USRP master clock rate | 184.32 MHz |
| | Downlink carrier frequency | 640 MHz |
| | Uplink carrier frequency | 635 MHz |
| | BS antennas | 1 Tx, 1 Rx |
| | NB-UE antennas | 1 Tx, 1 Rx |
| | Transmitter gain | 15 dB |
| | Receiver gain | 15 dB |
| | Doppler frequency | 0 Hz, 80 Hz |
| NB-IoT parameters | Channel | NB-PUSCH |
| | Number of resource units | 2 |
| | MCS index | 0,3,6 |
| | TBS (bits) | 32,104,176 |
| | $R_{max}$ | 128 |
| | Decoding attempts | Every cycle (every four repetitions: $R$ = 4, 8, …,128) |

**TABLE 1.** Measurement parameters.

For the sake of measurement, the BS schedules one NB-UE in each uplink transmission opportunity. Although there are two antenna ports at the BS, only the first port was used. The maximum number of repetitions is $R$ = 128. In each window, the BS allocates two resource units for NB-PUSCH. Since 15 kHz sub-carrier spacing is used, one uplink TB transmission lasts 2$R$ ms. The repetition pattern of NB-PUSCH follows a cyclic subframe level repetition where in each cycle, each of the scheduled subframes is repeated $Z$ = min(4, $R$) = 4 times. Therefore, the whole NB-PUSCH codeword is repeated every 8 ms. In order to save power, the BS's receiver attempts to decode NB-PUSCH data after every fourth repetition. In the case of early successful decoding, the remaining uplink repetitions are discarded. The number of repetitions that are required to successfully decode the uplink data depends on the received SNR and the channel coherence time.

### Fast Fading Channel

A first set of measurements were performed over a single-tap channel with Doppler shift of 80 Hz, which would correspond to a speed of 136 km/h of the machines for the carrier frequency used. Since the channel's coherence time is short, the performance of the BS's receiver presents the worst case scenario that a UE could face.

### Static Channel

In this setup, the Doppler frequency was set to 0 such that all repetitions of an NB-PUSCH codeword fall within the coherence time of the channel. This is the best case scenario for the channel estimator.

Figure 4 shows the number of repetitions that were needed by the BS's receiver in order to successfully decode NB-PUSCH data. The statistics include only messages that were successfully decoded. Modulation and coding scheme (MCS) indices 0, 3, and 6 indicate TBS of 32, 104, and 176 bits, respectively. The results show that performance gain from signal repetitions is limited by the channel coherence time. In static condition (or very slow fading channel), NB-IoT can benefit from averaging of channel estimates over successive subframes, especially for operations under very low SNR values. The throughput plot in Fig. 5 confirms this claim.

## Conclusion and Future Perspectives

NB-IoT is an attractive new technology, enabling cost-efficient and flexible massive MTC deployments within cellular systems. The technology helps broaden the applicability of cellular technologies as the connectivity of choice from high-performance and high-end devices toward simpler and lower-cost devices typical for the IoT. The NB-IoT design has many similarities to LTE, and can, in many cases, be deployed as a software upgrade to an operator's existing LTE network. Simplified baseband processing and signaling protocols are attractive features of NB-IoT for C-RAN implementation. NB-IoT can operate in narrow bandwidth, and hence requires moderate fronthaul link capacity, which is an important factor in RAN virtualization. Moreover, the latency requirements of NB-IoT are loose compared to LTE such that processing delay caused by multiple hops in cloud infrastructure can be tolerated. With cloud-based implementation, NB-IoT can benefit from deployment flexibility.

NB-IoT has improved coverage compared to LTE. This comes from signal repetitions and increased power spectral density due to relatively smaller bandwidth. The performance gain from repetitions is constrained by channel estimation accuracy. Our measurements indicate that the coverage is limited by the coherence time of a fading channel. In an ideally static channel, up to 20 dB uplink coverage gain can be achieved from 128 repetitions. This pushes the operating SNR below −22 dB for the lowest MCS index. In a fast fading channel, however, the SNR should be at least −12 dB. This implies that the coverage gain from repetitions is reduced by more than 10 dB as a result of short channel coherence time.

As shown by Fig. 5 the repetition coding scheme used in the NB-IoT is quite far from the Shannon bound. In downlink, repetition coding is justified due to the simple decoding at the receiver. In the uplink case, there is no specific need to require simple decoding at the receiver. Hence, it would be possible to improve the uplink link budget by using a more complex coding scheme with only a minor increase of complexity at the UE side. Further standardization of NB-IoT is continuing for 3GPP Release 14. Currently discussed topics include improved positioning support, enabling multicast downlink transmissions using single-cell point-to-multipoint, new power classes to support lower maximum transmission power, improvements on multi-PRB operation and mobility, and service continuity enhancements.

This article highlights some of NB-IoT's features, C-RAN implementation aspects, and challenges. Due to its low computational complexity, cloud/SDR-based implementation of NB-IoT BSs with cheap remote radio heads opens up the possibility of NB-IoT femtocell deployments for large buildings and industrial sites. Despite its potential, however, there some issues regarding C-RAN that need further studies. Among these are fronthaul link requirements, scalability, and network resource slicing between IoT applications and other broadband services.


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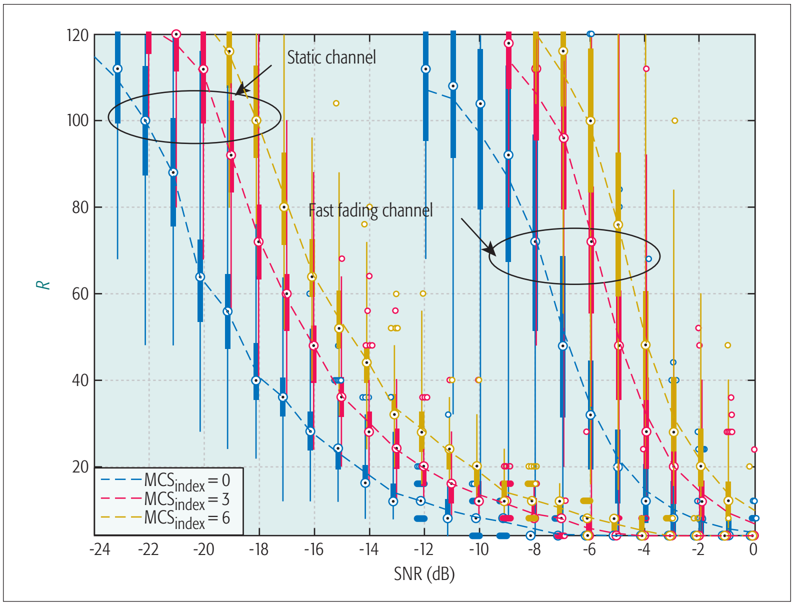


**Figure 4.** Minimum number of repetitions needed for decoding NB-PUSCH TB.

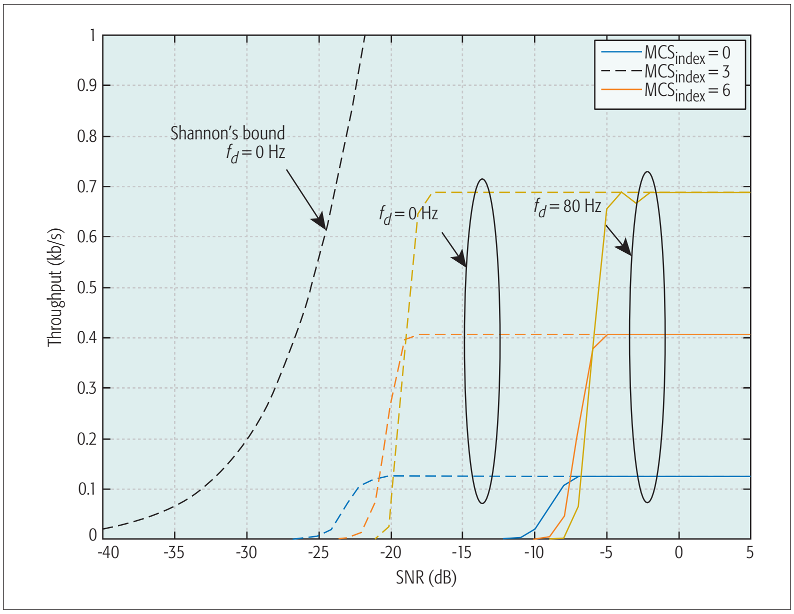


**Figure 5.** Physical layer throughput.

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## Biographies

YIHENEW DAGNE BEYENE is a doctoral researcher at Aalto University, Finland. He received his B.Sc. degree in electrical engineering from Bahir Dar University, Ethiopia, in 2007, and his M.Sc. degree in communications engineering from Aalto University in 2012. Since May 2011, he has been with the Department of Communications and Networking, Aalto University, where he is currently pursuing a Ph.D. degree. He has been working on SDR-based cloud-RAN implementation of wireless systems such as LTE, NB-IoT, and broadband 5G. He has also implemented pre-standard features and schemes for cellular systems. Some of the implementations are interference cancellation for overlay secondary spectrum sharing in TV white space, a cloud-RAN testbed, D2D communications, and MTC for LTE. His current research interests include Cloud-RAN, MTC, IoT, and interference management in wireless systems. He is a recipient of an Aalto University ELEC doctoral school grant, an Elisa HPY Research Foundation grant, and a Nokia Scholarship.

RIKU JÄNTTI [M'02, SM'07] is an associate professor (tenured) in communications engineering and the head of the Department of Communications and Networking at the Aalto University School of Electrical Engineering. He received his M.Sc (with distinction) in electrical engineering in 1997 and D.Sc (with distinction) in automation and systems technology in 2001, both from Helsinki University of Technology (TKK). Prior to joining Aalto (formerly TKK) in August 2006, he was professor pro tem in the Department of Computer Science, University of Vaasa. He is an Associate Editor of *IEEE Transactions on Vehicular Technology*. He is also an IEEE Vehicular Technology Society Distinguished Lecturer (Class of 2016). His research interests include radio resource control and optimization for MTC, cloud-RANs, spectrum and coexistence management, and RF Inference.

OLAV TIRKKONEN (olav.tirkkonen@aalto.fi) received his M.Sc. and Ph.D. in theoretical physics from TKK. Currently he is an associate professor in communication theory in the Department of Communications and Networking, Aalto University. His current research interests are in coding theory, multiantenna techniques, and cognitive management of 5G cellular systems.

KALLE RUTTIK is currently a teaching researcher in the Department of Communications and Networking at the School of Electrical Engineering, Aalto University. He acquired a Dipl.Eng. degree from Tallinn Technical University in 1993, and a Lic. Tech. degree from TKK in 1999. His research interests include radio physical layer algorithms, software radio, base station implementation, NB-IoT, and cloud -RAN.

SASSAN IRAJI [M'00, SM'05] (sassan.iraji@aalto.fi) received his Ph.D. degree from Tampere University of Technology, Finland, his M.Sc. (with distinction) from Aalto University, and his B.Sc. from Tehran University, Iran, all in electrical engineering, in 2005, 1999, and 1992, respectively. He served at Nokia from 1997 to 2012, holding various positions from senior research engineer to senior technology manager, principal researcher, and research leader. He was the founder of the Internet-of-Things team at the Nokia Research Center, 2006–2008. He is currently with Aalto University as a research fellow, where he teaches, manages research projects, and guides graduate students. He has numerous patents and papers published in the field of wireless communications. His current research interests fall within the field of wireless communication systems toward 5G, IoT, and ultra-reliable low-latency communications. He is also one of the co-founders of Klick Technologies Ltd. (http://www.klicktek.com), a spin-off company from Aalto University that provides IoT solutions and adaptive gateways.

ANNA LARMO received her M.Sc. degree in communication technology from TKK in 2005. Since 2004, she has been with Ericsson Research, Finland, focusing on radio protocols on different wireless systems. She is currently a master researcher with Ericsson Research, and her current research interests include IoT technologies, radio protocols, performance evaluation, radio resource management, and simulator development. She has also been active in the areas of innovation and patenting.

TUOMAS TIRRONEN is a senior researcher at Ericsson Research, which he joined in 2012. He received his M.Sc. in teletraffic theory in 2006 from TKK and his D.Sc. in communications engineering in 2010 from Aalto University. He is currently working on developing concepts and standards for 4G and 5G wireless technologies with focus on 3GPP MTC and IoT, performance evaluation, and energy efficiency. He has (co-) authored several conference and journal papers, and is involved in innovation work and patenting.

JOHAN TORSNER (johan.torsner@ericsson.com) is a research manager in Ericsson Research and is currently leading Ericsson's research activities in Finland. He joined Ericsson in 1998, and has held several positions within research and R&D. He has been deeply involved in the development and standardization of 3G and 4G systems, and has filed over 100 patent applications. His current research interests include 4G evolution, 5G, and MTC.