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Narrowband Internet of Things

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Abstract—**Narrowband Internet of Things (NB-IoT) is a new cellular technology introduced in 3GPP Release 13 for providing wide-area coverage for the Internet of Things (IoT). This article provides an overview of the air interface of NB-IoT. It describes how NB-IoT addresses key IoT requirements such as deployment flexibility, low device complexity, long battery life time, support of massive number of devices in a cell, and significant coverage extension beyond existing cellular technologies.**

Keywords; NB-IoT, LPWA, LTE

I. INTRODUCTION

The Internet of Things (IoT) is the next revolution in the mobile system. IoT services are likely to be a key driver for further growth in cellular network. The global market for IoT devices is expected to grow from about 6 billion connected IoT devices in 2016 to approximately 18 billion by 2022 [1]. At the same time, IoT unit sales will increase from almost 2.3 billion devices in 2017 to roughly 5.7 billion devices in 2022 assuming an average life of a IoT device of close to 7 years, even though the IoT device life time will vary widely by application area.

Cellular IoT is expected to provide numerous services, including utility meters, vending machines, automotive (fleet management, smart traffic, real time information to the vehicle, security monitoring and reporting), medical metering and alerting. Already, devices such e-book readers, GPS navigation aids and digital cameras are connected to the internet.

The key requirements for cellular IoT to enable these services and be competitive are: long battery life, low device cost, low deployment cost, extended coverage and support for massive number of devices.

Cellular IoT solution based on LTE meets these requirements and enhances the radio and core networks. The radio network needs to work with simple, low cost devices. The transmission and higher layer protocols need to help devices consume less power, with the aim of achieving a battery life of over ten years. Finally, extended coverage is required for deep indoor and rural areas.

This paperwork provides a state-of-the-art overview of the air interface of NB-IoT with a focus on the key aspects where NB-IoT deviates from LTE. In particular, it's highlighted the NB-IoT features that help achieving the previously mentioned design objectives.

II. IOT BACKGROUND

A. *IoT technology landscape*

Today, 2G modules are the dominant solution for IoT, but the fastest growth will be in LTE modules. Low power, wide area and low cost modules are key enablers for the rapid changes expected. A low module cost is needed for LPWA (Low Power Wide Area) IoT devices to gain market share from short-range connectivity standards and wireless sensor networks like ZigBee and Wi-Fi.

LPWA IoT solutions can be divided into proprietary (i.e. non-3GPP) LPWA technologies and (3GPP) cellular IoT. SigFox and LoRa are both proprietary technologies deployed in unlicensed bands. For all these technologies, deployment in spectrum lower than 1GHz spectrum helps achieve maximum coverage, but higher bands in the spectrum may still be used.

Three separate tracks for licensed cellular IoT technologies are being standardized in 3GPP:

- LTE-M, an evolution of LTE optimized for IoT in 3GPP RAN. First released in Rel.12 in Q4 2014, further optimization is being included in Rel.13 with specifications completed in Q1 2016.
- NB-IoT, the narrowband evolution of LTE for IoT in 3GPP RAN, included in Rel.13 with specifications completed in Q2 2016.
- EC-GSM-IoT, an evolution of GSM optimized for IoT in 3GPP GERAN, included in Rel.13 with specifications completed in Q2 2016.

Finally, a 5G solution for cellular IoT is expected to be part of the new 5G framework by 2020. The link budget is similar in all solutions, with a slight improvement for narrowband solutions such as NB-IoT and EC (Extended Coverage)-GSM-IoT. LoRa and SigFox are planned to share spectrum with other solutions in the unlicensed bands.

Some alternative proposals for NB-IoT operate in a dedicated 200 kHz carrier refarmed from GSM, but do not support spectrum sharing with LTE networks. Based on an LTE narrowband evolution, this is designed to operate in a 200kHz carrier refarmed from GSM but has the further advantage of being able to operate in shared spectrum with an existing LTE network, thus requiring no additional deployment of antennas, radio or other hardware. The solutions for LTE-M, NB-IoT and EC-GSM-IoT will equally operate in spectrum shared with existing LTE or GSM networks - LTE-M and NB-IoT would be supplementary solutions addressing different use cases, with higher capacity on LTE-M and slightly lower cost and better coverage on NB-IoT.

B. IoT transmission schemes

Narrowband IoT (NB-IoT) is a new low power wide area (LPWA) technology specifically developed for the Internet of Things (IoT), for devices that require small amounts of data, over long periods and indoor coverage. NB-IoT is a new 3GPP radio-access technology in the sense that it is not fully backward compatible with existing 3GPP devices. It is however designed to achieve excellent co-existence performance with legacy GSM, General Packet Radio Service (GPRS) and LTE technologies. NB-IoT requires 180 kHz minimum system bandwidth for both downlink and uplink, respectively. The choice of minimum system bandwidth enables a number of deployment options. A GSM operator can replace one GSM carrier (200 kHz) with NB-IoT. An LTE operator can deploy NB-IoT inside an LTE carrier by allocating one of the Physical Resource Blocks (PRB) of 180 kHz to NB-IoT. With this selection, the following operation modes are possible:

- Standalone operation. A possible scenario is the utilization of currently used GSM frequencies. With their bandwidth of 200 kHz there is still a guard interval of 10 kHz remaining on both sides of the spectrum
- Guard band operation, utilizing the unused resource blocks within an LTE carrier's guard-band
- In-band operation utilizing resource blocks within an LTE carrier

These modes are visualized in the Figure 1.

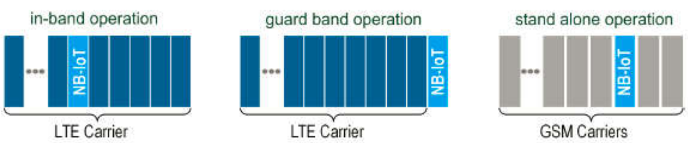

Figure 1. Operation modes for NB-IoT

In the in-band operation, the assignment of resources between LTE and NB-IoT is not fixed. However, not all frequencies, i.e. resource blocks within the LTE carrier, are allowed to be used for cell connection. They are restricted to the values given in Table I.

As indicated in Table I, there is no support for in-band operation of an LTE band with 1.4 MHz bandwidth. A conflict between resources used by the LTE system like the cell specific reference signals (CRS) or the downlink control channel at the start of each sub-frame must be taken into account when resources are allocated for NB-IoT. Further, an NB-IoT anchor carrier should not be any of the middle 6 PRBs of the LTE carrier (e.g. PRB#25 of 10 MHz LTE, although its center is 2.5 kHz from the nearest 100 kHz raster). This is due to that LTE synchronization and broadcast channels occupy many resource elements in the middle 6 PRBs, making it difficult to use these PRBs for NB-IoT.

TABLE I. ALLOWED LTE PRB INDICES FOR CELL CONNECTION IN NB-IOT IN-BAND OPERATION

LTE system bandwidth	**3MHz**	**5MHz**	**10MHz**	**15MHz**	**20MHz**
LTE PRB indices for NB – IoT synchronization	2, 12	2, 7, 17, 22	4, 9, 14, 19, 30, 35, 40, 45	2, 7, 12, 17, 22, 27, 32, 42, 47, 52, 57, 62, 67, 72	4, 9, 14, 19, 24, 29, 34, 39, 44, 55, 60, 65, 70, 75, 80, 85, 90, 95

NB-IoT reuses the LTE design extensively, including the numerologies, downlink orthogonal frequency-division multiple-access (OFDMA), uplink single-carrier frequency-division multiple-access (SC-FDMA), channel coding, rate matching, interleaving, etc. This significantly reduces the time required to develop full specifications. Also, it is expected that the time required for developing NB-IoT products will be significantly reduced for existing LTE equipment and software vendors. The normative phase of NB-IoT work item in 3GPP started in September 2015 [3] and the core specifications complete in June 2016. Commercial launch of NB-IoT products and services is expected to be around the end of 2016 and the beginning of 2017.

III. PHYSICAL CHANNELS

NB-IoT physical channels are designed based on legacy LTE to a large extent. In this section, it is shown an overview of them with a focus on aspects that are different from legacy LTE.

A. Downlink channels

NB-IoT provides the following physical signals and channels in the downlink.

- NPBCH, the narrowband physical broadcast channel
- NPDCCH, the narrowband physical downlink control channel
- NPDSCH, the narrowband physical downlink shared channel
- NRS, Narrowband Reference Signal
- NPSS and NSSS, Primary and Secondary Synchronization Signals are defined.

The figure 2 illustrates the connection between the transport channels and the physical channels.

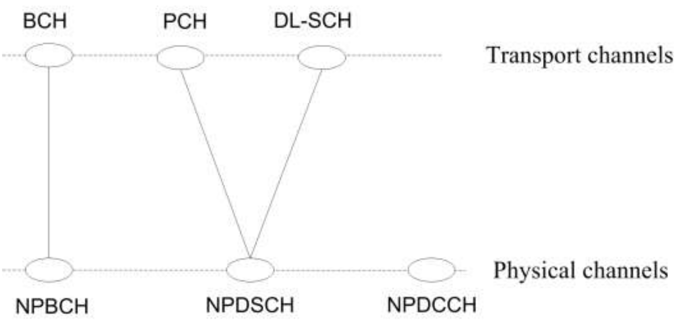

Figure 2. Mapping of the transport channels to the physical channels

Unlike LTE, these NB-IoT physical channels and signals are primarily multiplexed in time (Figure 3). Each NB-IoT subframe spans over one PRB (i.e. 12 subcarriers) in the frequency domain and 1 ms in the time domain. No PUCCH, PHICH or PCFICH defined for NB-IOT carriers and an explicit HARQ ACK/NACK feedback is applied.

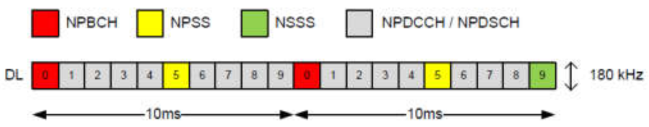

Figure 3. NB-IoT multiplexing in time

1) Narrowband Synchronization Signals

NPSS and NSSS are used by an NB-IoT UE to perform cell search, which includes time and frequency synchronization, and cell identity detection. Since the legacy LTE synchronization sequences occupy 6 PRBs, they cannot be reused for NB-IoT. A new design is thus introduced.

NPSS is transmitted in sub-frame #5 in every 10 ms frame, using the last 11 OFDM symbols in the sub-frame. NPSS detection is one of the most computationally demanding operations from a UE perspective. To allow efficient implementation of NPSS detection, NB-IoT uses a hierarchical sequence. A length 11 Zadoff-Chu sequence in frequency domain [5] is taken for the sequence generation of the NPSS. This sequence is fixed and therefore carries no information about the cell. It is transmitted in SF5 of each radio frame, so that its reception allows the UE to determine the frame boundary.

NSSS has 20 ms periodicity and is transmitted in sub-frame #9, also using the last 11 OFDM symbols that consist of 132 resource elements overall. NSSS is a length-132 frequency-domain sequence, with each element mapped to a resource element. NSSS is generated by element-wise multiplication between a ZC sequence and a binary scrambling sequence. The root of the ZC sequence and binary scrambling sequence are determined by narrowband physical cell identity (NB-PCID). The cyclic shift of the ZC sequence is further determined by the frame number.

2) Narrowband Reference Signal

NRS is used to provide phase reference for the demodulation of the downlink channels. NRSs are time-and-frequency multiplexed with information bearing symbols in sub-frames carrying NPBCH, NPDCCH and NPDSCH, using 8 resource elements per sub-frame per antenna port.

3) NPBCH

NPBCH carries the master information block (MIB) and is transmitted in sub-frame #0 in every frame. A MIB remains unchanged over the 640 ms transmission time interval (TTI).

4) NPDCCH

The NPDCCH indicates for which UE there is data in the NPDSCH, where to find them and how often they are repeated. Also, the UL grants are provided therein, showing the resources the UE shall use for data transmission in the UL. Finally, additional information like paging or system information update is contained in the NPDCCH as well.

5) NPDSCH

NPDSCH carries data from the higher layers as well as paging message, system information, and the RAR message. As shown in Fig. 3, there are a number of sub-frames that can be allocated to carry NPDCCH or NPDSCH. To reduce UE complexity, all the downlink channels use the LTE tail-biting convolutional code (TBCC). Furthermore, the maximum transport block size of NPDSCH is 680 bits. In comparison, LTE without spatial multiplexing supports maximum TBS greater than 70,000 bits.

B. Uplink channels

NB-IoT includes the following channels in the uplink:

- NPRACH, the narrowband physical random access channel
- NPUSCH, the narrowband physical uplink shared channel.

The figure 4 illustrates the connection between the transport channels and the physical channels.

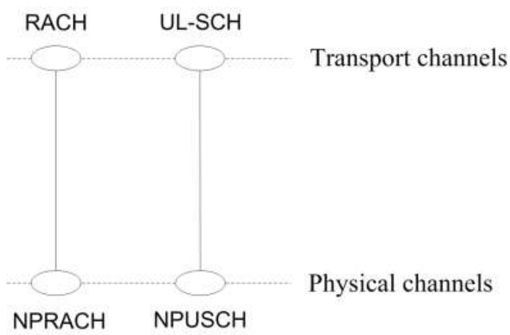

Figure 4. Mapping between the transport channels and the physical channels in UL

1) NPRACH

NPRACH is a newly designed channel since the legacy LTE Physical Random Access Channel (PRACH) uses a bandwidth of 1.08 MHz, more than NB-IoT uplink bandwidth. One NPRACH preamble consists of 4 symbol groups, with each symbol group comprising of one CP and 5 symbols. Frequency hopping is applied on symbol group granularity, i.e. each symbol group is transmitted on a different subcarrier. By construction, this hopping is restricted to a contiguous set of 12 subcarrier. Depending on the coverage level, the cell may indicate that the UE shall repeat the preamble 1, 2, 4, 8, 16, 32, 64, or 128 times, using the same transmission power on each repetition.

2) NPUSCH

NPUSCH has two formats. Format 1 is used for carrying uplink data and uses the same LTE turbo code for error correction. The maximum transport block size of NPUSCH Format 1 is 1000 bits, which is much lower than that in LTE. Format 2 is used for signaling HARQ acknowledgement for NPDSCH, and uses a repetition code for error correction. NPUSCH Format 1 supports multi-tone transmission based on the same legacy LTE numerology. In this case, the UE can be allocated with 12, 6, or 3 tones. While only the 12-tone format is supported by legacy LTE UEs, the 6-tone and 3-tone formats are introduced for NB-IoT UEs who due to coverage limitation cannot benefit from higher UE bandwidth allocation. To reduce peak-to-average power ratio (PAPR), single-tone transmission uses p/2-BPSK or p /4-QPSK with phase continuity between symbols.

IV. PROTOCOL STACK AND SIGNALING BEARER

The general principle for the protocol layers is to start with the LTE protocols, reduce them to a minimum and enhance them as needed for NB-IoT. This way, the proven structures and procedures are re-used while overhead from unused LTE features is prevented. Consequently, the NB-IoT technology can be regarded as a new air interface also from the protocol stack point of view, while being built on a well established fundament.

One example thereof is the bearer structure. Signaling radio bearer are partly re-used from LTE. There is the SRB0 for RRC messages transmitted over the CCCH logical channel, and the SRB1 for RRC messages and NAS messages using the DCCH logical channel. However, there is no SRB2 defined [6].

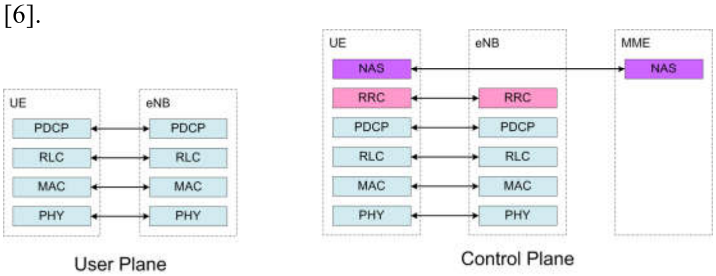

Figure 5. Protocol stacks for NB-IoT

In addition, a new signaling radio bearer, the SRB1bis is defined. It is implicitely configured with SRB1 using the same configuration, however without the PDCP. This channel takes the role of the SRB1 until security is activated, then SRB1bis is not used anymore. This also implies that for the Control Plane CIoT EPS optimisation, only SRB1bis is used at all, because there is no security activation in this mode. The protocol stacks are the same as for LTE with functionalities optimized for NB-IoT (Figure 5).

V. NB-IOT OBJECTIVES

IoT use cases are characterized by requirements such as data rate, coverage, latency, and battery lifetime. These are thus important performance metrics. In figure 6 are presented the main NB-IoT characteristics.

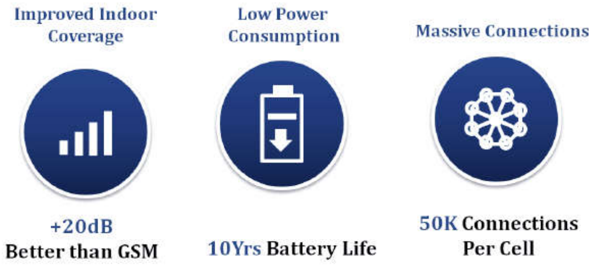

Figure 6. Inherent capabilities of NB-IOT

A. Long battery life

Providing M2M support for locations with no direct power source such as water meters and sensors requires battery operated devices. A device power saving mode (PSM) was introduced in Rel.12 to improve device battery life significantly. A device that supports PSM will request a network for a certain active timer value during the attach or tracking area update (TAU) procedure. The active timer determines how long the device remains reachable (by checking for paging according to the regular DRX cycle) for mobile terminated transaction upon transition from connected to idle mode. The device starts the active timer when it moves from connected to idle mode. When the active timer expires, the device moves to power saving mode. In power saving mode, the device cannot be reached as it does not check for paging, but is still registered with the network. The device remains in PSM until a mobile originated transaction (e.g. periodic TAU, uplink data transmission) requires it to initiate any procedure towards the network. The whole procedure is shown in figure 7.

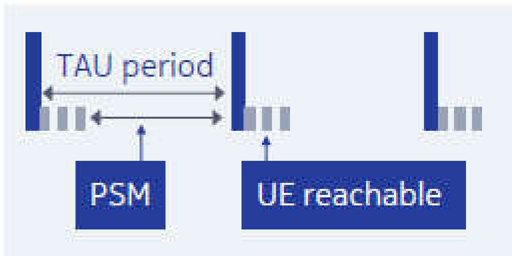

Figure 7. NB-IoT enhanced battery options

NB-IoT aims to support long battery life. For a device with 164 dB coupling loss, a 10-year battery life can be reached if the UE transmits 200-byte data a day on average [7].

On the Figure 8 is shown Nokia case study for different deployment options of battery life in dependency of MCS (Maximum Coupling Loss) for one report per hour.

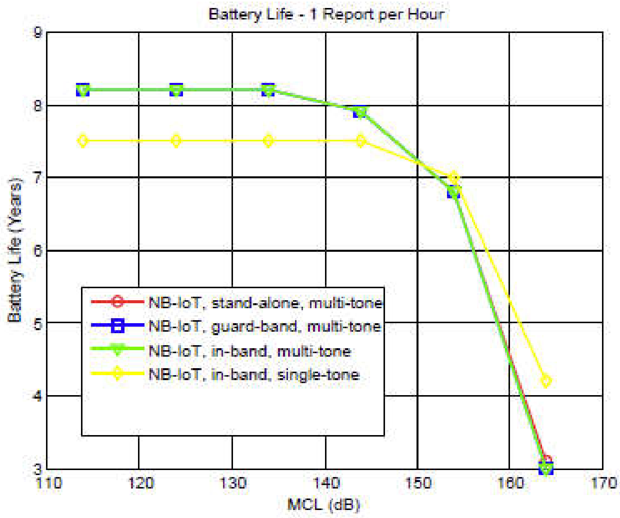

Figure 8. Battery life in dependency of MSC (dB)

B. Low device and deployment costs

LTE was designed in 3GPP Rel.8 to provide affordable mobile broadband and has been developed by subsequent 3GPP releases. Yet the focus has always been on optimizing performance, a factor that has created increasing complexity. Rel.12 looks at how to reduce the complexity of LTE with lower performance Key Performance Indicators (KPIs) while still complying with the LTE system. This reduced complexity helps cut costs significantly. Estimated device costs in 2016: 4$ and in 2020: 2$ -3$.

Reusing LTE for narrowband IoT systems takes advantage of existing technology as well as the installed system base. It is possible to reuse the same hardware and share spectrum by making LTE-M and NB-IoT compatible with LTE, without running into coexistence.

C. Capacity

NB-IoT supports massive IoT capacity by using only one PRB in both uplink and downlink. Sub-PRB UE scheduled bandwidth is introduced in the uplink, including single subcarrier NPUSCH. Note that for coverage limited UE, allocating higher bandwidth is not spectrally efficient as the UE cannot benefit from it to be able to transmit at a higher data rate. Based on the traffic model in [7], NB-IoT with one PRB supports more than 52500 UEs per cell [7]. Furthermore, NB-IoT supports multiple carrier operation. Thus, more IoT capacity can be added by adding more NB-IoT carriers.

D. Throughputs

NDSCH peak data rate can be achieved by using the largest TBS of 680 bits and transmitting it over 3 ms. This gives 226.7 kbps peak layer-1 data rate. NPUSCH peak data rate can be achieved by using the largest TBS of 1000 bits and transmitting it over 4 ms. This gives 250 kbps peak layer-1 data rate. However, the peak throughputs of both downlink and uplink are lower when the time offsets between DCI, NPDSCH/NPUSCH, and HARQ acknowledgement are taken into account. In Figure 9 it can be seen the throughputs for different deployments and their dependence of coverage.

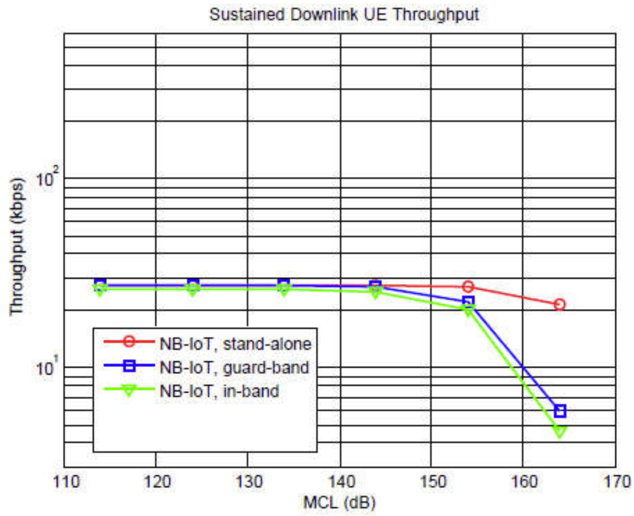

Figure 9. Throughputs in bad coverage

E. Coverage

NB-IoT achieves a maximum coupling loss 20 dB higher than LTE Rel-12 [8]. Coverage extension is achieved by trading off data rate through increasing the number of repetitions. Coverage enhancement is ensured also by introducing single subcarrier NPUSCH transmission and π/2-BPSK modulation to maintain close to 0 dB PAPR, thereby reducing the unrealized coverage potential due to power amplifier (PA) back-off. NPUSCH with 15 kHz single-tone gives a layer-1 data rate of approximately 20 bps when configured with the highest repetition factor, i.e., 128, and the lowest modulation and coding scheme. NPDSCH gives a layer-1 data rate of 35 bps when configured with repetition factor 512 and the lowest modulation and coding scheme. These configurations support close to 170 dB coupling loss. In comparison, the Rel-12 LTE network is designed for up to approximately 142 dB coupling loss [9].

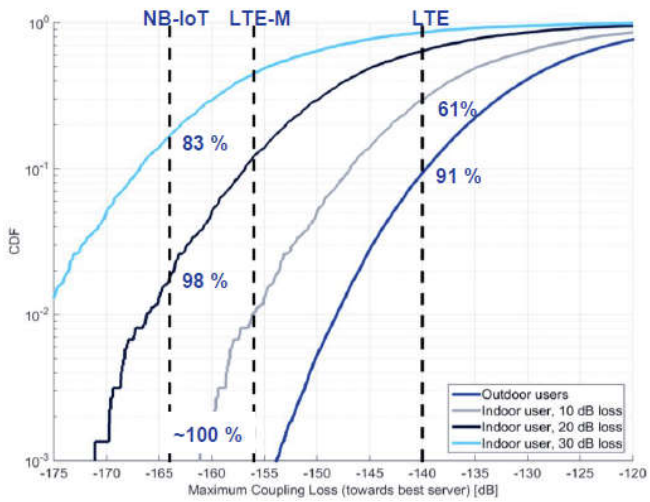

Figure 10. Rural coverage probability

Nokia case studies showed that NB-IoT provides ~100% indoor coverage in both urban and rural area. Urban area case studies from NY shows ~100% coverage for NB-IoT, even at level -1 and rural area cases studies from Denmark shows ~100% coverage for light outdoor to indoor penetration loss , reducing to 83% for level -1 (Figure 10) for coupling loss of -165dB.

VI. IoT APPLICATIONS

A. Smart metering

One of the most suitable uses for NB-IoT is smart metering [11]: gas and water meters, unlike smart electricity meters, are not connected to the electricity supply and are also often located in cellars where conventional mobile network connections are usually either weak or non-existent. Battery-powered NB-IoT modules need no power connection, deliver deep indoor penetration, and thereby establish a reliable connection even in areas where mobile reception is poor. The provider is able to read the meter remotely and the end customer does not have to stay at home in order to wait for the meter reader to come by.

B. Smart Cities

In Smart Cities [11], NB-IoT technology can be used in street lighting, for example. Lamp posts fitted with appropriate modules can be switched on and off or dimmed remotely and can trigger an alarm if they malfunction. If a city connects its parking spaces by NB-IoT, better use is made of free capacities. Motorists are directed by a smart parking guidance system to the nearest free parking space by the shortest route. In waste disposal, garbage cans fitted with NB-IoT modules alert a control center when they are full. As a consequence, waste disposal companies can optimize vehicle routes and reduce costs.

C. Localization

NB-IoT is suitable for locating pets or valuables. In order to not lose sight of a pet or an expensive bike, an NB-IoT module can be a low-cost alternative to a GSM tracker.

D. Farming and forestry: Monitoring livestock

NB-IoT technology is also suitable for agricultural use where there is no power supply or where network coverage is poor. In irrigation of fields or plantations, tank levels, pump pressure and flow rates are measured. The location and health of livestock can be monitored too [11]. In forestry, low-cost sensors can be distributed in large numbers in the woods to report information such as temperature, smoke development or wind direction.

E. Industry: NB-IoT on pallets and pipelines

In order to monitor oil and gas pipelines, sensors relay important information about pressure, flow rate or possible leaks. There is often no external power source for pipelines in inaccessible areas. Here too, NB-IoT is a contender because modules have a long service life, require no maintenance and have a 20 decibel wider range than conventional mobile network connections [11].

F. Transport & logistics

In transportation and logistics very little information is often needed in very small data packets. So NB-IoT is a suitable low-cost solution. In container tracking, for instance, hourly notification of the container's location is all that is required. For refillable tanks or bottles, industrial liquid or gas providers monitor levels, pressure and temperature as required.

VII. CONCLUSION

With the NB-IoT technology specified in Release 13, 3GPP has created a new cellular air interface which is fully adapted to the requirements of typical machine type communications. It is optimized to small and infrequent data packets and abstains from cellular features not required for that purpose. This way, the UE can be kept in a cost efficient way and needs only a small amount of battery power.

Data transmission is kept to a small frequency band of 180 kHz. The signaling part may be reduced to one or only a few NB-IoT carrier, whereas the remaining ones may be fully utilized for data transfer. This way, a considerable amount of bandwidth is used for data transfer.

With Release 14, the development of NB-IoT will continue [10]. According to the current plans, NB-IoT will be extended to include positioning methods, multicast services required e.g. for software update, mobility and service continuity, as well as further technical details to enhance the field of applications for the NB-IoT technology.

REFERENCES

[1] Entner: IoT at a crossroads in 2017, http://www.fiercewireless.com/tech/entner-iot-at-a-crossroads-2017

[2] What is NB IoT, https://5g.co.uk/guides/what-is-narrowband-iot/

[3] Qualcomm, Incorporated, "Narrowband IoT (NB-IoT)," RP-151621, 3GPP TSG RAN Meeting #69, Sept. 2015. [Online]. Available: http://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_69/Docs/RP-151621.zip

[4] 3GPP TR 36.802 V0.3.0 (2016-05); Technical Specification Group Radio Access Networks; Narrowband Internet of Things (NB-IoT); Technical Report for BS and UE radio transmission and reception (Release 13)

[5] D. C. Chu, "Polyphase codes with good periodic correlation properties," IEEE Trans. Inform. Theory, vol. 18, no. 4, pp 531–2, July 1972.

[6] 3GPP RP-151621 New Work Item: NarrowBand IOT (NB-IOT)

[7] TR 45.820 v13.1.0, "Cellular system support for ultra low complexity and low throughput internet of things," Nov. 2015. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/45_series/45.820/45820-d10.zip

[8] A. Adhikary, X. Lin and Y.-P. E. Wang, "Performance evaluation of NB-IoT coverage," Submitted to IEEE Veh. Technol. Conf. (VTC), September 2016, Montréal, Canada.

[9] TR 36.888 v12.0.0, "Study on provision of low-cost machine-type communications (MTC) user equipments (UEs) based on LTE," Jun. 2013. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/36_series/36.888/36888-c00.zip

[10] 3GPP RP-161324 3GPP Work Item Description Enhancements of NB-Io

[11] M. Ruggieri, H.Nikookar, "Internet of Things – From Research and Inovation to Market Deployment".