NB-IoT System for M2M Communication

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***Abstract* — In 3GPP, a narrowband system based on Long Term Evolution (LTE) is being introduced to support the Internet of Things. This system, named Narrowband Internet of Things (NB-IoT), can be deployed in three different operation modes – (1) stand-alone as a dedicated carrier, (2) in-band within the occupied bandwidth of a wideband LTE carrier, and (3) within the guard-band of an existing LTE carrier. In stand-alone operation mode, NB-IoT can occupy one GSM channel (200 kHz) while for in-band and guard-band operation modes, it will use one physical resource block of LTE (180 kHz). The design targets of NB-IoT include low-cost devices, high coverage (20-dB improvement over GPRS), long device battery life (more than 10 years), and massive capacity. Latency is relaxed although a delay budget of 10 seconds is the target for exception reports. The specifications for NB-IoT are expected to be finalized in 2016. In this paper, we describe the targets for NB-IoT and present a preliminary system design. In addition, coverage, capacity, latency, and battery life analysis are also presented.**

Keywords—NB-IoT, M2M communication, narrowband IoT system, latency, and capacity analysis.

I. INTRODUCTION

The Internet of Things (IoT) refers to interconnection and exchange of data among devices. To support IoT, Machine-to-machine (M2M) communication is needed. M2M is defined as data communication among devices without the need for human interaction. Examples of IoT services include security, tracking, payment, smart grid, and remote maintenance/monitoring. An estimated 50 billion connected devices will be deployed by 2020 [1].

With the widespread introduction of LTE, low-power wide area IoT connectivity has been introduced for LTE [1][2]. In LTE Rel-12, low-cost devices with material cost comparable to EGPRS devices was introduced [3]. In LTE Rel-13, two new features supporting narrowband machine type communications (MTC) are being introduced. The features are called eMTC (enhanced MTC) and Narrowband IoT (NB-IoT) [5][6]. In eMTC, a new UE with reduced radio frequency (RF) bandwidth of 1.4 MHz in downlink and uplink is introduced. In addition, eMTC also introduces coverage enhancement to provide better indoor support. However, eMTC operates in-band as part of the wideband LTE carrier.

NB-IoT, however, is a new narrowband IoT system built from existing LTE functionalities. It can be deployed in three different operation modes – (1) stand-alone as a dedicated carrier, (2) in-band within the occupied bandwidth of a wideband LTE carrier, and (3) within the guard-band of an existing LTE carrier. In stand-alone deployment, NB-IoT can occupy one GSM channel (200 kHz) while for in-band and guard-band deployment, it will use one physical resource block (PRB) of LTE (180 kHz). The design targets of NB-IoT include low-cost devices, high coverage (20-dB improvement over GPRS), long device battery life (more than 10 years), and massive capacity (greater than 52K devices per channel per cell). Latency is relaxed although a delay budget of 10 seconds is the target for exception reports.

Since NB-IoT is expected to adopt a design based on existing LTE functionalities, it is possible to reuse the same hardware and also to share spectrum without coexistence issues. In addition, NB-IoT can simply plug into the LTE core network. This allows all network services such as authentication, security, policy, tracking, and charging to be fully supported.

The paper is organized as follows. In Section II, NB-IoT system design is presented. In Section III, performance evaluations for coverage, capacity, latency, and battery life are provided. Finally, conclusions are drawn in Section IV.

II. NB-IOT SYSTEM DESIGN

In Rel-13, NB-IoT will be introduced for cellular IoT with the following design targets for all deployment operations [4] -

- Improved indoor coverage: The target is to achieve an extended coverage of 20 dB compared to legacy GPRS devices. This corresponds to achieving target maximum coupling loss (MCL) of 164 dB. At this MCL, data rate of at least 160 bps should be supported at the application layer for both the uplink and downlink.
- Support of massive number of low-throughput devices: The target is to support at least 52547 devices within a cell-site sector. This target was determined using 40 devices per household with the household density based on the assumption for London provided in [3] (1517 household density per sq. km and cell inter site distance of 1732 m).
- Reduced complexity: The goal is to provide ultra-low complexity devices to support IoT applications.
- Improved power efficiency: The target is to provide battery life of ten years with battery capacity of 5 Wh at 164 dB MCL.
- Latency: Exception report latency of 10 seconds or less is the target for 99% of the devices.

In addition, NB-IoT will support three deployment operation modes as previously described to provide flexibility based on available spectrum and use cases as described below. In stand-alone operation, NB-IoT can be used as a replacement of one or more GSM carriers. This allows efficient re-farming of GSM carriers for IoT.

For in-band operation, one or more PRBs are reserved for NB-IoT. This is shown in Fig. 1 where 1 PRB is reserved. Within this reserved region, NB-IoT signals must not be transmitted in time-frequency resources reserved for LTE (consisting of legacy control region and reference signals). The total eNB power is shared between LTE and NB-IoT with the possibility to use power spectral density (PSD) boosting on the

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NB-IoT PRB. Sharing of PRBs between NB-IoT and LTE allows for more efficient use of the spectrum and seamless increase in NB-IoT capacity as more devices are added to the network. In addition, although they are two separate systems, they can be supported using the same eNB hardware.

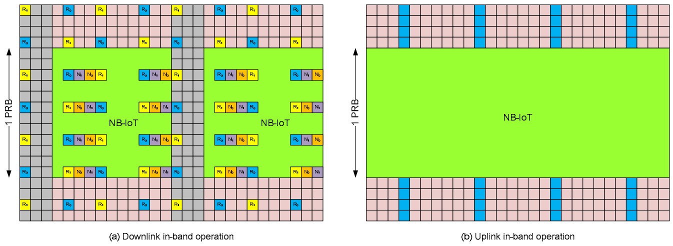

Fig. 1. In-band operation for NB-IoT.

In guard-band mode of operation, NB-IoT will utilize new resource blocks within the guard-band of an LTE carrier. An illustration of this is shown in Fig. 2. Note that it may be possible to allocate the NB-IoT PRB right next to the outer LTE PRB. This, however, will depend on the channel raster for NB-IoT. In addition, since the NB-IoT carrier has been placed in the LTE guard band, additional guard band for the adjacent carrier or a filter with a faster roll off may be required. For instance, in Fig. 2, since the left-hand edge of the transmit spectrum is shifted left due to the NB-IoT carrier with higher PSD, the left-hand edge of the required guard band shifts left too. Presently, this issue is being studied.

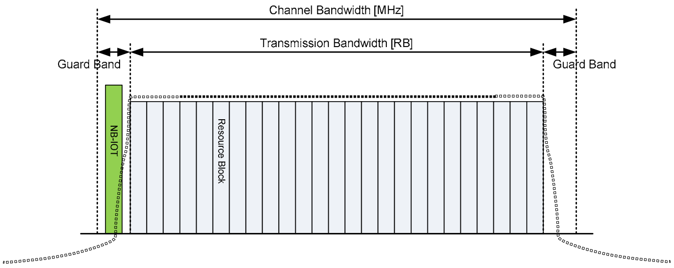

Fig. 2. Guard-band operation for NB-IOT.

Based on performance evaluations, NB-IoT will support the following numerologies.

- Downlink: OFDMA with 15-kHz subcarrier spacing.
- Uplink: single-tone and multi-tone transmissions. For single-tone transmission, 3.75-kHz and 15-kHz channels will be supported. For multi-tone transmission, transmissions are based on SC-FDMA with 15-kHz subcarrier spacing.

For in-band deployment, if 3.75-kHz subcarrier spacing is used, for single-tone transmission in the uplink, there will be interference between NB-IoT and LTE. However, this interference can be minimized by scheduling users with similar SNR requirements in NB-IoT and nearby LTE PRBs. For 15-kHz subcarrier spacing, on the other hand, orthogonality between LTE and NB-IoT subcarriers is maintained.

In addition, NB-IoT UE will support only 180 kHz RF bandwidth for both downlink and uplink. Furthermore, NB-IoT need to support only half duplex operations, 1 hybrid automatic repeat request (HARQ) process, and reduced peak data rate of less than 100 kbps. This will provide significant cost saving on the UE.

Fig. 3 illustrates one example system design for NB-IoT based on existing channels. While there is an obvious difference in the bandwidth of the physical broadcast channel and the synchronization signals between LTE (1.08 MHz) and NB-IoT (180 kHz), the figure illustrates that there are also differences in the time durations between the corresponding channels in each subframe. Another important feature that can be noted from the figure is that the narrowband physical uplink shared channel (NB-PUSCH) can occupy less than 1 PRB of the LTE system via the support of single-tone or multi-tone transmission.

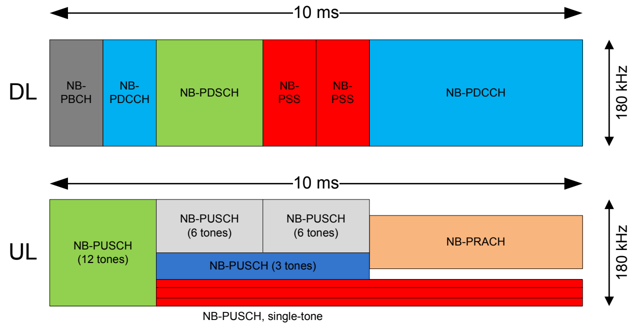

Fig. 3. Example NB-IoT design (stand-alone).

Table I lists the potential channels and signals to be supported in NB-IoT.

TABLE I. NB-IOT CHANNELS AND SIGNALS

	Channel
DL	Narrowband Physical Downlink Control Channel (NB-PDCCH)
	Narrowband Physical Downlink Shared Channel (NB-PDSCH)
	Narrowband Physical Broadcast Channel (NB-PBCH)
	Narrowband Synchronization Signal (NB-PSS/NB-SSS)
UL	Narrowband Physical Uplink Shared Channel (NB-PUSCH)
	Narrowband Physical Random Access Channel (NB-PRACH)

Note that there is no uplink control channel in NB-IoT. As a result, uplink acknowledgement will be transmitted on the NB-PUSCH, while scheduling request will have to be indicated using random access procedure.

III. PERFORMANCE ANALYSIS

Performance analysis is shown in this section including coverage, capacity, latency, and battery life. Since for in-band and guard-band operation modes, total power is shared between LTE and NB-IoT, performance will be similar. The only difference is that guard-band operation will not require OFDM symbols to be reserved for legacy control region. Therefore, only in-band results will be shown. Table II shows relevant simulation assumptions used in this study.

TABLE II. SIMULATION ASSUMPTIONS

Parameter	Stand-alone	In-band
System bandwidth	200 kHz	10 MHz
Frequency band	900 MHz	
eNB transmit power for NB-IoT	43 dBm	35 dBm
MS transmit power	23 dBm	
Propagation channel	TU	
Doppler spread	1 Hz	
Antenna configuration	DL: eNB: 1Tx, MS: 1Rx	DL: eNB: 2Tx, MS: 1Rx
	UL: eNB: 2Rx, MS: 1Tx	
Frequency error	Random from [-50, +50] Hz	
Thermal noise density	-174 dBm/Hz	
eNB receiver noise figure	3 dB	
UE receiver noise figure	5 dB	
Interference margin	0 dB	
Receiver processing gain	0 dB	

The stand-alone case is intended for GSM refarming using existing infrastructure. Hence, only 1 transmit antenna is used at the eNB which is the typical deployment scenario for GSM. For the in-band case, although the system bandwidth is 10 MHz, only 1 PRB is used for NB-IoT with the rest reserved for wideband LTE. Also, only 35 dBm of power is available for NB-IoT in the in-band case as the total power is shared between LTE and NB-IoT. This is based on 46 dBm total eNB power distributed among 50 PRBs with 6 dB power boosting for the NB-IoT PRB.

A. Coverage Analysis

The target is to achieve an extended coverage of 20 dB compared to legacy GPRS devices. This corresponds to achieving target MCL of 164 dB [4]. At this MCL, data rate of at least 160 bps should be supported at the application layer for both the uplink and downlink.

For coverage analysis, link level performance has been investigated for the channels listed in Table I. Simulation assumptions specific to each physical layer channel are given below –

- NB-PBCH – The payload consists of 34 bits and 16-bit CRC. The NB-PBCH is transmitted every 10 ms in subframe #0 using five OFDM symbols in the subframe. The NB-PBCH content changes every 640 ms (i.e. 64 transmissions, once every 10 ms).
- NB-PDSCH – The payload consists of 776 bits and 24-bit CRC transmitted over 12 subframes (12 ms). Convolution coding and QPSK modulation are used.
- NB-PDCCH – The payload consists of 48 bits and 16-bit CRC transmitted over 12 subframes (12 ms).
- NB-PUSCH – The payload consists of 776 bits and 24-bit CRC transmitted over 2160 subframes (2160 ms) using SC-FDMA single-tone transmission. Turbo coding and QPSK modulation are used.

Link results for the NB-PBCH is shown in Fig. 4 for in-band operation mode. In this case, the target SNR is −12.6 dB (corresponding to 164-dB MCL). Because the NB-PBCH is transmitted periodically, UE can combine multiple copies of the transmission and performance is given by the acquisition time. From the figure, it is seen that the acquisition time at −12.6 dB SNR is approximately 1920 ms when transmitting NB-PBCH every 10 ms. If reference signal boosting is used, the acquisition can be reduced to 1280 ms for approximately 90% of the users. In this case, the reference signal is boosted by puncturing an equivalent number of data symbols.

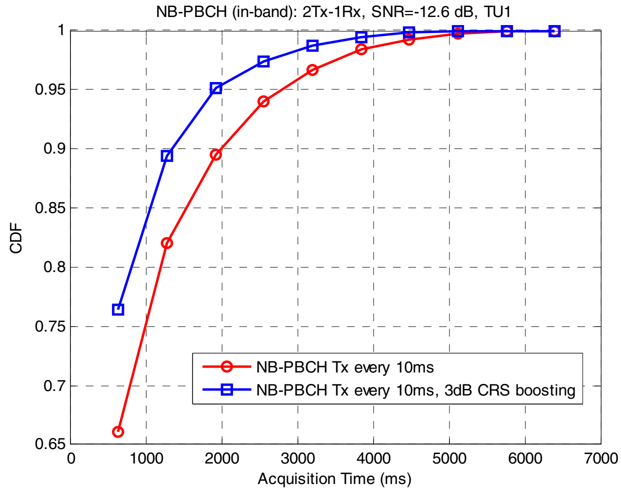

Fig. 4. NB-PBCH performance.

Link results for the NB-PUSCH is shown in Fig. 5. Using single-tone transmission and total transmission time of 2160 ms, the 10% BLER operating point was achieved at SNR of −5.8 dB. This corresponds to a data rate of 0.37 kbps at the physical layer and 0.31 kbps at the application layer.

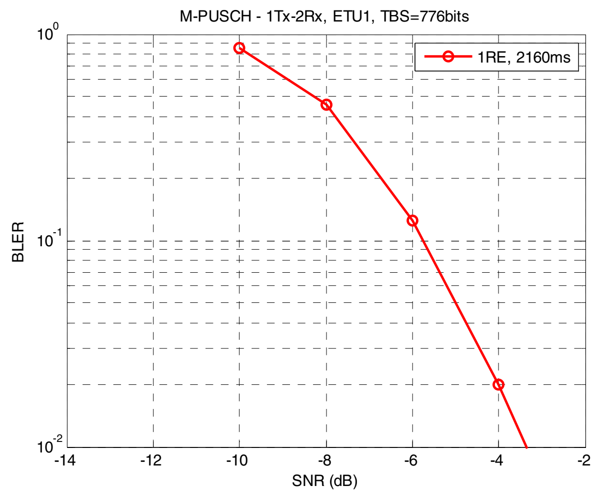

Fig. 5. NB-PUSCH performance.

Due to space limitation, link results for the NB-PDCCH and NB-PDSCH are not shown. Performance of these channels can be seen in [8]-[10]. In general, coverage requirements of these channels can be extended by using repetitions.

Table III shows the link budget for stand-alone scenario. Due to limited space, only results for the data channels are shown. It is shown that the target MCL of 164 dB can be achieved for the channels considered. At this MCL, application layer data rate of 2.73 kbps in the downlink and 0.31 kbps in the uplink can be supported.

TABLE III. LINK BUDGET FOR STAND-ALONE DEPLOYMENT

Channel	NB-PDSCH	NB-PUSCH
Data rate (kbps) above SNDCP	2.73	0.31
Transmitter		
Max Tx power (dBm)	43	23
(1) Actual Tx power (dBm)	43	23
Receiver		
(2) Thermal noise density (dBm/Hz)	-174	-174
(3) Receiver noise figure (dB)	5	3
(4) Interference margin (dB)	0	0
(5) Occupied channel bandwidth (Hz)	180,000	2,500
(6) Effective noise power = (2) + (3) + (4) + 10 log ((5)) (dBm)	-116.4	-137.0
(7) Required SINR (dB)	-5.0	-5.8
(8) Receiver sensitivity = (6) + (7) (dBm)	-121.4	-142.8
(9) Rx processing gain	0	0
(10) **MCL** = (1) –(8) + (9) (dB)	**164.4**	**165.8**

Table IV shows the link budget for in-band scenario. In this case, a total of 46 dBm of power is available at the eNB. Out of this total power, 35 dBm is used for NB-IoT (with 6-dB power boosting relative to LTE PRBs). It is shown that the target MCL of 164 dB can be achieved for the channels considered. At this MCL, application layer data rate of 0.44 kbps in the downlink and 0.31 kbps in the uplink can be supported. The data rate in the downlink is significantly lower than in the stand-alone due to smaller transmit power and the need to reserve some time-frequency resource for LTE.

TABLE IV. LINK BUDGET FOR IN-BAND DEPLOYMENT

Channel	NB-PDSCH	NB-PUSCH
Data rate (kbps) above SNDCP	0.44	0.31
Transmitter		
Max Tx power (dBm)	46	23
(1) Actual Tx power (dBm)	35	23
Receiver		
(2) Thermal noise density (dBm/Hz)	-174	-174
(3) Receiver noise figure (dB)	5	3
(4) Interference margin (dB)	0	0
(5) Occupied channel bandwidth (Hz)	180,000	2,500
(6) Effective noise power = (2) + (3) + (4) + 10 log ((5)) (dBm)	-116.4	-137.0
(7) Required SINR (dB)	-13.7	-5.8
(8) Receiver sensitivity = (6) + (7) (dBm)	-130.1	-142.8
(9) Rx processing gain	0	0
(10) **MCL** = (1) –(8) + (9) (dB)	**165.1**	**165.8**

B. *Capacity Analysis*

In this section, system-level results are provided. The macro-cell system simulation scenario is of a traditional 57-cell system setup with wrap-around. Detailed system simulation parameters are described in [4]. The traffic model is based on Mobile Autonomous Reporting (MAR) on the uplink and is described in Table V.

TABLE V. MAR TRAFFIC MODEL [4]

Parameter	Value
Application payload size distribution	Pareto distribution with shape parameter alpha = 2.5 and minimum application payload size = 20 bytes with a cut off of 200 bytes i.e. payloads higher than 200 bytes are assumed to be 200 bytes.
Periodic inter-arrival time	Split of inter-arrival time periodicity for MAR periodic is: 1 day (40%), 2 hours (40%), 1 hour (15%), and 30 minutes (5%)

For capacity, the target is to support at least 52547 devices within a cell site sector. System-level simulation results show that at least 72K devices can be supported within a cell site sector per NB-IoT channel [7].

C. *Latency Analysis*

Exception report latency of 10 seconds or less is the target for 99% of the devices. In this case, latency evaluation at performed for 164 dB MCL for exception reporting consisting of 20 bytes application report, 65 bytes upper layer protocol header, and 15 bytes SNDCP/LLC/RLC/MAC/CRC overhead is assumed. The following steps are used in calculating the exception report latency –

- Synchronization
- Master Information Block (MIB) acquisition
- Random access including Msg 1-4. This also includes a waiting time between reception of random access preamble and Random Access Response (RAR) transmission in case the eNB is in the middle of a downlink transmission.
- Uplink grant + data transfer (for 99% confidence level)

Table VI shows the latency results. It can be seen that latency is below 10 seconds in both scenarios.

TABLE VI. LATENCY EVALUATION

Activity	Stand-alone	In-band
Synchronization	520	1110
MIB acquisition	640	1920
PRACH	1440	1440
Wait	572	1440
DCI + RAR	72	288
Msg3	349	349
DCI + Msg4	83	299
DCI (UL grant)	45	153
UL Data Tx (99% confidence)	2883	2883
Total Latency	6604	9882

D. *Battery Life Analysis*

For power consumption, the target is to minimize consumption to provide battery life of ten years with battery capacity of 5 Wh at 164-dB MCL. The analysis assumes periodic uplink reporting with the transactions during an uplink reporting event are shown in Fig. 6.

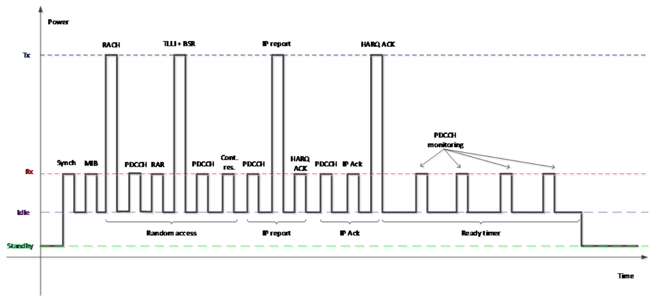

Fig. 6. Message exchange during an uplink reporting event.

The power consumption per state used the assumption in Table VII.

TABLE VII. CURRENT CONSUMPTION ASSUMPTIONS

	Power [mW]
Battery power during Tx (assuming 44% PA efficiency)	543
Battery power for Rx	90
Battery power when Idle but not in PSS	2.4
Battery power in Power Save State (PSS)	0.015

In Table VIII the estimated lifetime in years are presented for two different packet sizes, two reporting intervals and at 164-dB MCL coverage level.

TABLE VIII. BATTERY LIFE (YEARS)

Packet size, reporting interval	Stand-alone	In-band
50 bytes, 2 hours	2.6	2.4
200 bytes, 2 hours	1.2	1.2
50 bytes, 1 day	18.0	16.8
200 bytes, 1 day	11.0	10.5

The energy consumption evaluation shows that the 10 year battery life target can be met or exceeded for "once per day" traffic scenarios.

IV. CONCLUSION

This paper provides an overview of NB-IoT and discusses the design targets of NB-IoT include low-cost devices, high coverage (20dB improvement over GPRS), long device battery life (more than 10 years), and massive capacity. Our results show that the targets can be achieved in all deployment scenarios.

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