Performance Evaluation of NB-IoT Coverage

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***Abstract*—Narrowband Internet of Things (NB-IoT) is a new radio access technology, recently standardized in 3GPP to enable support for IoT devices. NB-IoT offers a range of flexible deployment options and provides improved coverage and support for a massive number of devices within a cell. In this paper, we provide a detailed evaluation of the coverage performance of NB-IoT and show that it achieves a coverage enhancement of up to 20 dB when compared with existing LTE technology.**

I. Introduction

IoT refers to the interconnection between various objects that can communicate among each other with minimal need for human supervision. Due to the rapid advances in the field of underlying technologies, IoT has tremendous opportunities in several different areas such as security, asset tracking, remote monitoring, metering (gas, water and electric) and smart grid to name a few. In order to meet the requirements set forth by such applications, the 3GPP (Third Generation Partnership Project) has introduced a new radio access technology called NB-IoT (Narrowband Internet of Things) which provides extended coverage, high capacity, reduced device processing complexity and long battery lifetime.

NB-IoT operation requires a minimum bandwidth of 180 kHz, which is equal to the size of the smallest LTE Physical Resource Block (PRB). Depending on the availability of spectrum, NB-IoT can be either deployed on its own ("standalone operation"), in the guard carriers of existing LTE/UMTS spectrum ("guardband operation") or within an existing LTE carrier by replacing one or more PRBs ("inband operation"). In order to support such flexible deployment scenarios, NB-IoT reuses the LTE design extensively, such as the OFDM (Orthogonal Frequency Division Multiplexing) type of modulation in downlink, SC-FDMA (Single Carrier Frequency Division Multiple Access) in uplink, channel coding, rate matching and interleaving. In addition, a host of new features are added to ensure the demands of IoT based applications. Key design changes from LTE include the synchronization sequences, the random access preamble, the broadcast channel and the control channel. These changes are primarily motivated by the fact that NB-IoT is required to operate on a minimum bandwidth of 180 kHz (1 PRB), whereas many channels in LTE were designed to span multiple PRBs occupying greater bandwidth compared to 180 kHz. These design changes achieve the IoT requirements while ensuring best co-existence performance with the existing LTE system. A detailed description of the NB-IoT system can be found in [1]. In this work, we focus mainly on the coverage performance of NB-IoT, both in the uplink and downlink. It is observed that NB-IoT provides excellent coverage (an improvement by a factor of 20 dB) when compared with legacy LTE system.

The remainder of the paper is organized as follows. In Section II, we provide a general description of the structure of the downlink and uplink channels in NB-IoT. In Section III, we provide detailed evaluations depicting the coverage performance of NB-IoT system followed by a conclusion in Section IV.

II. Downlink and Uplink Physical Channels

In line with LTE design, there are four downlink physical layer channels, namely, the synchronization channel, the broadcast channel, the control channel and the data channel.

a) Synchronization Channel: The synchronization channel in NB-IoT consists of two new signals, namely, the Narrowband Primary Synchronization Sequence (NPSS) and the Narrowband Secondary Synchronization Sequence (NSSS), both of which occupy a bandwidth of 180 kHz. Note that a simple reuse of the synchronization sequences used in LTE would not work since they occupy a bandwidth of 1.08 MHz. The NPSS is used to obtain a coarse estimate of the symbol timing and carrier frequency, while the NSSS is used to obtain the cell identity, the frame boundary and further refine the coarse estimates. The specific sequence design enables handling of large carrier frequency offsets as well as supporting the same number of physical cell IDs as in a standard LTE system.

b) Broadcast Channel: The Narrowband Broadcast Channel (NPBCH) has a periodicity of 10 ms and occupies the first subframe of every 10 ms frame. It carries the Master Information Block (MIB), which consists of 34 bits. A 16 bit CRC is appended giving 50 bits in total, which are then encoded and QPSK modulated over 8 code sub-blocks, with each code sub-block spanning one subframe (1 ms) and consisting of 200 bits. Each code sub-block is repeated 8 times within an 80 ms period, and is independently decodable.

c) Control Channel: The Narrowband Downlink Control Channel (NPDCCH) carries downlink control information. The size of the control information is fixed at 23 bits, and is encoded over 1 subframe. Only two aggregation (or accumulation) levels are supported. Coverage extension is achieved through the use of repetition coding, with support for a maximum of 2048 repetitions.

d) Downlink Shared Channel: The Narrowband Downlink Shared Channel (NPDSCH) carries the data intended for the specific user, in addition to paging, system information and the random access response. A variety of information block sizes ranging from 256 bits to 680 bits are supported, which can be found by looking at the TBS tables in [5]. Repetition coding is used for coverage enhancement, and up to 2048 repetitions can be used.

Tail biting convolutional code (TBCC) is used for encoding all downlink channels (except the synchronization channel which uses cell identity specific sequence).

In the uplink, there are two channels, the Narrowband Random Access Channel (NPRACH) and the Narrowband Uplink Shared Channel (NPUSCH).

a) Random Access Channel: The random access channel enables the user to connect to a base station. The base station uses the random access preamble sent by a user terminal to estimate the uplink timing, which is necessary to issue a timing advance command in order to maintain uplink orthogonality among different users. A detailed description of random access design for NB-IoT can be found in [4]. The preamble consists of 4 symbol groups, with each symbol group comprising of one cyclic prefix and 5 symbols. Two formats are supported with different cyclic prefix lengths for accomodating different cell sizes. Each symbol is modulated on a 3.75 kHz tone, with a 3.75 kHz frequency separation between the first two and last two symbol groups to obtain good timing estimation. In order to improve the timing estimation accuracy, the second and third symbol groups are separated by 22.5 kHz. To support coverage extension, the preamble of 4 symbol groups can be repeated up to 128 times, with a pseudo random frequency separation across repetitions.

b) Uplink Shared Channel: : Contrary to LTE, both the data as well as control information are carried over the uplink shared channel. The distinction is made by using two formats. Format 1 is used for carrying uplink data and uses turbo code for error correction. Format 2 is used for signaling HARQ acknowledgement for downlink data and uses repetition code with user specific scrambling for error correction. Multi-tone transmission is supported using 15 kHz subcarrier spacing, and the user can be allocated with 12, 6, or 3 tones. Two numerologies, 15 kHz and 3.75 kHz, are supported for single-tone transmission. PAPR reduction is achieved by using $\pi/2$-BPSK or $\pi/4$-QPSK with phase continuity between symbols. The same slot structure as legacy LTE PUSCH is used for Format 1, with one DMRS in the middle of a slot. For Format 2, the legacy LTE PUCCH slot structure is reused, with 3 DMRS per slot.

III. Performance Evaluations

In this section, we provide a detailed evaluation of the coverage performance of different NB-IoT channels in various deployment scenarios. The evaluation is based on the assumption of a single cell, and inter-cell interference arising from multiple transmitting cells in the network is not considered. The common assumptions are listed in Table I. The channel model used is a Typical Urban (TU) channel consisting of 12 taps [3] with a Doppler spread of 1 Hz. The Doppler spread denotes the speed of the user terminal relative to the base station, and a value of 1 Hz corresponds to almost stationary devices. The frequency and timing errors in the evaluations of the data and control channels are based on the performance of

TABLE I: Common Simulation Parameters

Parameter	Value
Carrier Frequency f_c	900 MHz
NB-IoT Bandwidth	180 kHz
Channel Model	Typical Urban (TU)
Doppler Spread	1 Hz
DL Antenna Configuration	1 Tx, 1 Rx (Standalone) 2 Tx, 1 Rx (Inband/Guardband)
UL Antenna Configuration	1 Tx, 2 Rx
Transmit Power	43 dBm (DL, Standalone) 46 dBm (DL, Inband/Guardband) 23 dBm (UL)
Noise Figure	5 dB (DL) 3 dB (UL)

TABLE II: Relation between Target SNR (in dB) and MCL for different scenarios

	Downlink, Standalone	Downlink, Inband	Uplink, 15 kHz 1-tone	Uplink, 15 kHz 6-tone
Tx Power	43 dBm	46 dBm	23 dBm	23 dBm
Power Boost	0 dB	6 dB	0 dB	0 dB
Bandwidth	180 kHz	9 MHz	15 kHz	90 kHz
Target SNR	159.4 - MCL	151.4 - MCL	152.2 - MCL	144.4 - MCL

synchronization channel (see Section III-A) in the downlink and the random access channel in the uplink (see Section III-E).

In evaluations considering an inband deployment, the total transmit power of 46 dBm is spread over a 10 MHz LTE channel, giving 29 dBm per PRB (180 kHz). This may be too low to achieve good performance, hence, a power boosting of 6 dB is assumed for the NB-IoT PRB to improve performance, giving a total transmit power of 35 dBm for the NB-IoT PRB. The target SNR (signal to noise ratio) in dBs is computed based on a maximum coupling loss (MCL). The relation between SNR and target MCL is given by (1), and is tabulated in Table II for different scenarios of interest.

$$\begin{aligned}\text{Target SNR} &= \text{Tx Power} + 174 - \text{Noise figure} \\ &\quad -10\log_{10}(\text{Bandwidth})) - \text{MCL} \quad (1)\end{aligned}$$

Using the noise figures from Table I and the methodology in [6], we observe that with a noise figure of 3 dB at the base station, LTE operates at an MCL of 142.7 dB. In the following subsections, we show that NB-IoT can operate at 164 dB MCL, which translates to a coverage enhancement of 20 dB. Due to space constraints, we focus on presenting results for a subset of scenarios, namely, the standalone and inband operation modes at 144 dB and 164 dB MCL.

For the evaluations, a practical channel estimator is used that performs interpolation over multiple subframes with perfect knowledge of the Doppler spread. In order to keep the estimation complexity low, the interpolation procedure is limited to 20 subframes for the downlink and 8 subframes for the uplink.

A. Synchronization Channel

Since IoT devices are typically low cost devices with a poor crystal oscillator, the inaccuracy between the transmitter and receiver clocks can be as large as 20 ppm, which corresponds to a carrier frequency offset of ± 18 kHz. We also account for

TABLE III: Synchronization Performance of NB IoT in different deployment scenarios

	Standalone		Inband	
MCL	144 dB	164 dB	144 dB	164 dB
Target SNR	15.4 dB	−4.6 dB	7.4 dB	−12.6 dB
Detection Prob.	100%	99.8%	100%	99.5%
Time (50% users)	24 ms	64 ms	24 ms	434 ms
Time (90% users)	84 ms	264 ms	84 ms	1284 ms
Time (99% users)	144 ms	754 ms	154 ms	2604 ms
Average time	36.22 ms	117.89 ms	38.2 ms	581.78 ms

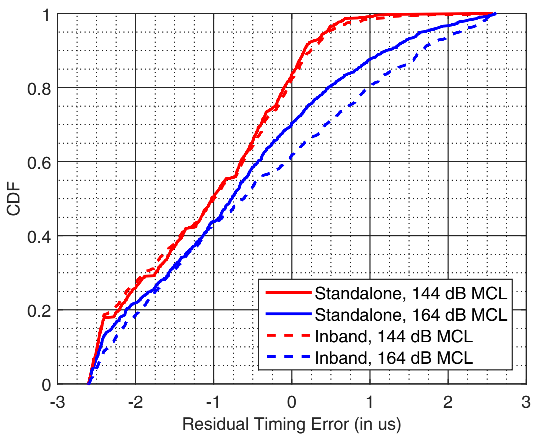

Fig. 1: Residual Timing error (in μs) after synchronization

an additional frequency offset due to the channel raster [1], which can be as large as ± 7.5 kHz in an inband/guardband deployment.The synchronization signal design enables the user terminal to employ a low complexity receiver processing algorithm. Details of the synchronization design and corresponding receiver algorithms can be found in [2].

The performance of the synchronization channel is measured by the total time required to successfully complete the initial synchronization procedure for a given fraction of devices in the cell. In our synchronization evaluations, we assume the presence of a single transmitting cell. The synchronization time at different target SNRs is given in Table III. In the worst case, the synchronization time for 90% of the users is within 1.3 seconds.

The residual timing error is shown in Figure 1, and the residual frequency error is shown in Figure 2. It can be seen that for all the different deployment scenarios, the residual timing error is within ± 2.5 μs, while the residual frequency error is within ± 50 Hz for a majority of the users. Therefore, in all the subsequent evaluations of downlink channels, a timing error uniformly drawn from the range $[-2.5, 2.5]$ μs and a frequency error of ± 50 Hz is assumed. Note that the estimated frequency offset is composed of both the frequency offset due to oscillator inaccuracy and the raster offset. Since the raster offset is not resolved during the synchronization phase, it can lead to a degradation in the performance of NPBCH if not properly accounted for (see Section III-B).

B. Broadcast Channel

The performance of broadcast channel (NPBCH) is provided in Table IV. The criterion for evaluating performance is the target SNR required for achieving a block error rate of 1%.

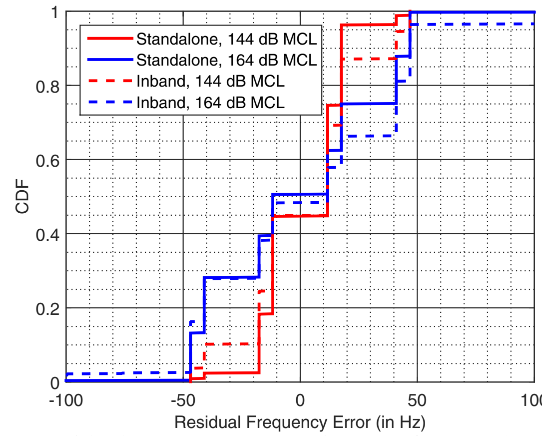

Fig. 2: Residual Frequency error (in Hz) after synchronization

TABLE IV: Performance of NPBCH in different deployment scenarios

	Standalone		Inband	
MCL	144 dB	164 dB	144 dB	164 dB
Target SNR	15.4 dB	−4.6 dB	7.4 dB	−12.6 dB
BLER (Block Error Rate)	0.74%	1%	0.6%	0.4%
Detection Period	10 ms	320 ms	20 ms	1920 ms

PBCH occurs every 10 ms, and each self decodable code subblock is repeated 8 times within 80 ms. The contents of the message transmitted during PBCH changes after every 640 ms. Since the user only knows the 80 ms boundary after the synchronization phase, a total of 8 different positions need to be tried for NPBCH decoding when the SNR is very low. If the user is not able to decode the NPBCH in 640 ms, it keeps trying over subsequent 640 ms windows until the decoding is successful.

An important issue for concern is that the value of the raster offset is not resolved during the synchronization phase. As a result of this, the user clock is either overcompensated or undercompensated leading to a mismatch between the sampling times of the user receiver and the actual sampling time. In the worst case, the raster offset is 7.5 kHz, leading to a drift of ± 5.33 μs over the entire 640 ms NPBCH duration. If the user is able to decode the NPBCH successfully within this time period, the drift may not be significant. However, if the user is unsuccessful, a timing error of ± 5.33 μs is added to the existing timing error in the next decoding attempt, leading to a degradation in performance. This problem is solved by performing multiple decoding tests over different sampling positions with some increase in computational complexity.

From Table IV, we observe that 1920 ms (3 decoding attempts) is required for NPBCH decoding to achieve a coverage target of 164 dB MCL in inband operation.

C. Downlink Control Channel

The performance of downlink control channel is provided in Table V. The target block error rate is 1%. The control information consists of 23 bits. A 16 bit CRC is added to it, resulting in a block size of 39 bits. Using TBCC, this block of 39 bits is encoded and QPSK modulated to occupy 1 subframe. Depending on the deployment option, the coding rate may be different. For example, the standalone

TABLE V: Performance of NPDCCH in different deployment scenarios

	Standalone		Inband	
MCL	144 dB	164 dB	144 dB	164 dB
Target SNR	15.4 dB	-4.6 dB	7.4 dB	-12.6 dB
BLER	1%	0.5%	0.52%	0.6%
Transmission Duration	1 ms	128 ms	4 ms	256 ms

TABLE VI: Performance of NPDSCH in different deployment scenarios

	Standalone		Inband	
MCL	144 dB	164 dB	144 dB	164 dB
Target SNR	15.4 dB	-4.6 dB	7.4 dB	-12.6 dB
Coding Rate	0.58	0.39	0.34	0.42
Modulation	QPSK	QPSK	QPSK	QPSK
RB	4 ms	6 ms	10 ms	8 ms
Repetitions	1	32	1	128
BLER	8.07%	9.58%	9.54%	7.43%
TTI	4 ms	254 ms	12 ms	1364 ms
Data Rate	156.28 kbps	2.42 kbps	51.26 kbps	461.5 bps

and guardband deployments can have 152 resource elements within a subframe, resulting in a coding rate of $\frac{39}{304} = 0.13$. For inband deployments, the available number of resource elements is 104, resulting in a coding rate of 0.19. To improve coverage, the same PDCCH block is repeated over several subframes. The maximum number of allowable repetitions is 2048, which results in a coverage of 172.7 dB MCL for a block error rate of 1%. Due to the channel estimator, a repetition by a factor of 2 results in less than 3 dB improvement in coverage performance.

D. Downlink Shared Channel

The performance of downlink shared channel is provided in Table VI. The results presented here consider an information block size of 680 bits, which is the maximum supported size. A 24 bit CRC is appended resulting in a block size of 704 bits. Different configurations can be chosen based on the TBS table [5] to achieve a desired coverage level. The configuration used in the evaluations is also provided in Table VI. For example, in order to achieve a coverage of 164 dB MCL in an inband deployment, the 704 bits are encoded and QPSK modulated over 10 subframes constituting one resource block (RB), resulting in a coding rate of 0.42. These 10 subframes are then repeated 128 times during transmission resulting in a total of 1280 subframes. Due to the presence of periodic synchronization and broadcast signals, only 15 subframes are available for transmission during a 20 ms period. Therefore, the total transmission time (TTI) is given by 1364 ms. The maximum number of repetitions supported is 2048, achieving a coverage of 173.8 dB MCL and a corresponding data rate of 22.41 bits/second (bps).

a) Sensitivity to Interference: When NB-IoT is deployed in the guard carriers of an LTE system or by replacing a PRB within an existing LTE carrier, the NB-IoT system may be susceptible to interference from the existing LTE system. This is primarily due to the presence of residual frequency offset, which can lead to inter carrier interference. However, since the NB-IoT PRB is already power boosted by 6 dB, the interference observed from adjacent LTE subcarriers is very small. This is illustrated in Figure 3, where the block error rate curves are shown both in the presence and absence of interfering LTE PRBs for an inband scenario. We observe that the performance degradation is almost negligible. In the evaluations, we assume that the LTE signal is present in 10 adjacent PRBs of the NB-IoT PRB on both sides.

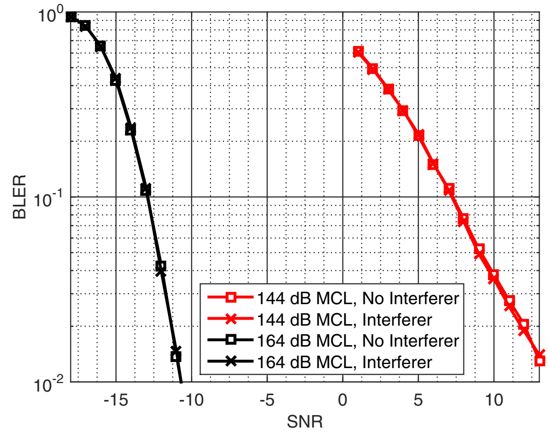

Fig. 3: Block error rate vs SNR for NB-IoT user in the presence of LTE interferer in an inband deployment

E. Random Access Channel

The performance of random access channel can be found in [4]. From [4], it can be seen that the ToA errors are within ± 3 μs with very high probability. Therefore, in all the subsequent evaluations of the uplink channels, a timing error uniformly distributed within $[-3, 3]$ μs is assumed, in addition to a residual frequency error uniformly distributed in the set $\{-50, 50\}$ Hz.

F. Uplink Shared Channel

The performance of uplink shared channel format 2 is provided in Table VII. NPUSCH format 2 carries a 1 bit message signaling either a positive or negative acknowledgement (ACK/NACK), and is encoded using a binary sequence of length 16. Single-tone transmission is used. To achieve coverage extension, the sequence is repeated a certain number of times, the maximum being 128. The target block error rate is 1%. We observe that in order to achieve a coverage of 164 dB MCL, 64 ms is required for transmission when 15 kHz subcarrier spacing is used, and 128 ms is needed for 3.75 kHz subcarrier spacing. For the maximum number of repetitions, a coverage of 170.2 dB for 15 kHz subcarrier spacing, and 174.2 dB for 3.75 kHz subcarrier spacing can be achieved.

The performance of uplink shared channel format 1 along with the configuration used is provided in Table VIII. The results presented here consider an information block size of 1000 bits, which is the maximum supported size. A 24 bit CRC is appended resulting in a block size of 1024 bits. As an example, in order to achieve a coverage of 164 dB MCL with 15 kHz subcarrier spacing, the 1000 bits are encoded, QPSK modulated and mapped over a single tone in frequency and 80

TABLE VII: Performance of NPUSCH Format 2 for different subcarrier spacings

	15 kHz		3.75 kHz	
MCL	144 dB	164 dB	144 dB	164 dB
Target SNR	8.2 dB	-11.8 dB	14.2 dB	-5.6 dB
Repetitions	1	32	1	16
BLER	$< 1\%$	$< 1\%$	$< 1\%$	$< 1\%$
Transmission Duration	2 ms	64 ms	8 ms	128 ms

TABLE VIII: Performance of NPUSCH Format 1 for different subcarrier spacings

	15 kHz		3.75 kHz	
MCL	144 dB	164 dB	144 dB	164 dB
# Tones	3	1	1	1
Target SNR	3.5 dB	-11.8 dB	14.3 dB	-5.7 dB
Coding Rate	0.43	0.52	0.87	0.52
Modulation	QPSK	QPSK	QPSK	QPSK
RB	32	80	48	80
Repetitions	1	64	1	16
BLER	9%	1.5%	1%	0.7%
TTI	32 ms	5120 ms	192 ms	5120 ms
Data Rate	28.43 kbps	192.4 bps	5.2 kbps	193.9 bps

subframes in time constituting one resource block, resulting in a coding rate of 0.52. These 80 subframes are then repeated 64 times during transmission resulting in a transmission time of 5120 ms. The maximum number of repetitions supported is 128, giving a data rate of 73.24 bps and achieving a coverage of 167.6 dB MCL for 15 kHz subcarrier spacing and 170 dB MCL for 3.75 kHz subcarrier spacing.

a) Sensitivity to Interference: As in the downlink, the NB-IoT user is susceptible to interference from LTE users in an inband/guardband deployment. Figure 4 shows the degradation due to interference for the 164 dB MCL configuration for 3.75 kHz subcarrier spacing, and we observe a degradation of approximately 1 dB with 10 dB INR. This degradation is attributed to the different subcarrier spacing of LTE users resulting in loss of uplink orthogonality. For users with 15 kHz subcarrier spacing, we do not observe any degradation. The assumption for interferers are the same as in Section III-D.

b) Sensitivity to Channel Estimation: Channel estimation plays an important role in the performance of the NB-IoT system. In LTE, the transmission duration is usually 1 ms, therefore, the effects of small frequency errors and channel variations do not result in a large performance impact when

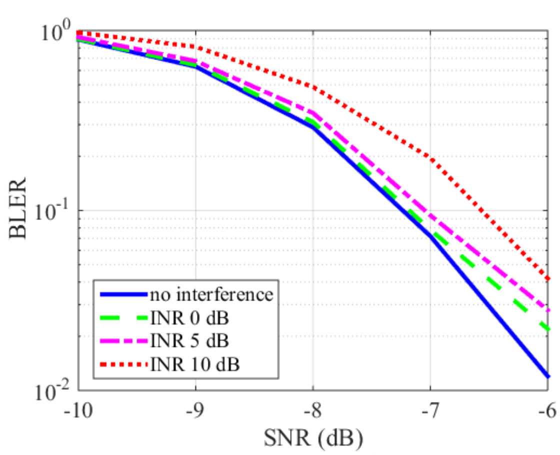

Fig. 4: Block error rate vs SNR for NB-IoT user in the presence of LTE interferer

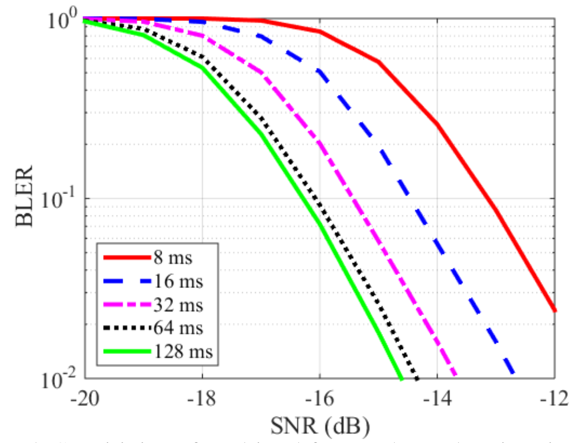

Fig. 5: Sensitivity of multi-subframe channel estimation algorithm

using a sub optimal estimator. However, in NB-IoT system, the duration of single-tone transmissions can range from a few ms to a few seconds. As a result, a joint estimation of the frequency offset and channel is required to achieve good performance. As an example, in Figure 5, we show the block error rates versus SNR for a user operating at 164 dB MCL with 15 kHz subcarrier spacing for different channel estimation block lengths. In order to keep the complexity of the estimator low, we decouple the frequency offset estimation and the channel estimation process over each block. It can be seen that restricting the channel estimation window to 8 ms results in a degradation of 3.5 dB compared to using a 128 ms channel estimation window with increased computational complexity.

IV. Conclusions

In this paper, we provided a comprehensive evaluation of the coverage performance of NB-IoT system, a new radio access technology in 3GPP that provides support for IoT devices. Our evaluations show that compared with existing LTE technology, NB-IoT can provide upto 20 dB coverage enhancement in various deployment scenarios. In addition, NB-IoT also provides good co-existence performance with existing LTE system.

References

[1] Y.-P. E. Wang et al, "A Primer on the Narrowband Internet of Things," *submitted to IEEE Comm Magazine*, 2016. Available at: http://arxiv.org/abs/1606.04171

[2] R1-161936, "NB-PSS and NB-SSS Design," *3GPP TSG RAN WG1 NB-IoT AdHoc Meeting*, Qualcomm Incorporated, Sophia Antipolis, France, March 2016.

[3] ETSI, TS 145005 v10.0.0 (3GPP TS 45.005 version 10.0.0 Release 10),"Digital cellular telecommunications system (Phase2+); Radio transmission and reception", April 2011.

[4] X. Lin, A. Adhikary and Y.-P. E. Wang, "Random Access Preamble Design and Detection for 3GPP Narrowband IoT Systems," *submitted to IEEE Wireless Communication Letters*, 2016. Available at: https://arxiv.org/abs/1605.05384

[5] ETSI TS 136 211 V13.1.0 (3GPP TS 36.211 version 13.1.0 Release 13), "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation," 2016.

[6] 3GPP TR 36.888 V2.1.1, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on provision of low-cost MTC UEs based on LTE; (Release 12)," June 2013.