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***Abstract*—Narrowband Internet of Things (NB-IoT) technology emerged in Release 13 as one of the solutions to provide cellular IoT connectivity. NB-IoT is designed to achieve better indoor coverage, support of a massive number of low-throughput devices, with relaxed delay requirements, and lower energy consumption. Particularly, the extensive coverage of NB-IoT poses a great challenge. The goal is to cover devices in areas previously inaccessible by cellular networks due to penetration losses or remote locations. To solve this, NB-IoT utilizes bandwidth reduction and repetitions. However, for the targeted low range of Signal to Noise Ratio (SNR), the coverage gain due to repetitions can be significantly limited by the performance of the channel estimator. In this paper, we provide an analytical evaluation framework to study the performance of NB-IoT. Our analysis includes the limitations due to realistic channel estimation and delves into the estimation of the SNR. Additionally, the conducted evaluation shows the impact of the coverage extension in the final performance of the NB-IoT User Equipment (UE) in terms of uplink packet transmission latency and battery lifetime. Specifically, regarding UE's battery lifetime, for a Maximum Coupling Loss (MCL) of 164 dB, realistic channel estimation evaluations obtain a battery lifetime reduction of approximately 90% compared to ideal channel estimation.**

***Index Terms*—NB-IoT, channel estimation, SNR, analytical model, energy consumption.**

I. Introduction

Internet of Things (IoT) concept embodies the vision of everything connected. This vision encompasses a vast ecosystem of emerging use cases in different markets such as industrial machinery, health-care, autonomous vehicles, smart meters, among many others. Owing to the diversity of IoT application requirements, a single technology is not capable of addressing all of the IoT use cases. Inside this diversity, Low-Power Wide-Area Networks (LPWAN) remained a central focus for the IoT. LPWANs are able to deliver low-power, low-speed and low-cost connectivity with wide-range coverage to IoT applications. LPWAN is composed of a set of various technologies that can use licensed or unlicensed spectrum, and include proprietary or open standard options.

On one hand, SigFox, LoRaWAN, and Ingenu are examples of LPWANs in unlicensed spectrum [1]. On the other hand, Long Term Evolution category M1 (LTE-M) and Narrowband IoT (NB-IoT) are examples in the licensed LTE spectrum. Previously the standardization of LTE-M and NB-IoT, cellular technologies were not extensively used in IoT, mostly due to cost issues. Thus, in order to quickly respond to the emerging IoT market, the Third Generation Partnership Project (3GPP) started a feasibility study on providing cellular IoT connectivity. As a result, both LTE-M and NB-IoT were included in 3GPP Release 13. Particularly, NB-IoT is based on LTE specification and reuses several technical components. The design of NB-IoT focuses on devices that are low cost, use low data rates, have reduced (or even no) mobility, also require long battery lifetime, and often operate in remote and deep indoor areas.

The coverage gain required in NB-IoT to reach long distances and deep penetration is achieved by means of Power Spectral Density (PSD) boosting and repetitions. In NB-IoT, all channels can use repetitions to extend coverage if it is needed. Furthermore, each repetition is self-decodable, and all repetitions are confirmed just once.

In the literature, [2] evaluates the coverage performance of NB-IoT and provide an insight on this topic. Other work such as [3] shows the performance of the downlink and uplink data channels of NB-IoT. However, these contributive works provide final results for specific configurations that hinder the comparison of the results. The experiments made on the testbed of [4] show that the NB-IoT coverage gain due to repetitions can be significantly limited by the channel estimator performance. Additionally, it derives an analytical bound for the Signal to Noise Ratio (SNR) gain from repetitions considering the channel estimation (CE) quality.

Our work adopts the analytical bound derived in [4] to extend the presented analysis of the performance of NB-IoT considering non-ideal factors. The aim of this work is threefold. Firstly, to provide an analytical evaluation framework to analyze the performance of NB-IoT. Secondly, to study the limitations and trade-offs of the repetitions in NB-IoT when considering realistic CE. Thirdly, to estimate the impact of the coverage extension in the final performance of the NB-IoT User Equipment (UE) in terms of uplink packet transmission latency and battery lifetime. Specifically, the main contributions of this work are:

- Derivation of analytical expressions based on the Shannon

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theorem to describe the transmission in NB-IoT.
- Derivation of analytical expressions to describe realistic CE and the use of cross-subframe.
- Investigation of the relationship between the CE error and the required SNR through simulations.
- Proposal of an analytical evaluation framework to estimate the performance of an NB-IoT UE.

Our analytical evaluation framework is divided into three main issues: i) SNR estimation; ii) Link adaptation; iii) NB-IoT energy consumption and delay estimation. The analysis presented in this work delves into the estimation of the SNR. The second and third issues of our analytical evaluation framework are based on the analysis presented in our two previous works [5], [6]. The results show the limited SNR gain when increasing repetitions if realistic CE is assumed. Specifically, regarding UE's battery lifetime, for a Maximum Coupling Loss (MCL) of 164 dB, realistic CE evaluations obtain a battery lifetime reduction of approximately 90% compared to ideal CE.

The remainder of the paper is organized as follows. Section II gives an introduction to NB-IoT. Section III describes the system model. Section IV details the main issues of our NB-IoT analysis. Section V presents the numerical results. Finally, Section VI sums up the conclusions.

II. Background

Massive Machine Type Communications (mMTC) is one of the three usage scenarios envisaged in the International Mobile Telecommunication (IMT) for 2020 and beyond. Most of IoT applications are part of mMTC. mMTC traffic is characterized by a large number of devices deployed that report sporadically to an application server. In order to fulfill the mMTC set of requirements, NB-IoT has to support four Key Performance Indicators (KPI) [7]:

- Latency of at most 10 seconds.
- Target coverage of 164 dB MCL.
- UE battery lifetime beyond 10 years, assuming a stored energy capacity of 5 Wh.
- Massive connection density of 1,000,000 devices per square km in an urban environment.

From the previous KPIs, enhanced coverage while maintaining energy consumption is an indispensable characteristic of NB-IoT. To achieve this goal, NB-IoT adopts a new radio access design built from existing LTE.

At the physical layer, an NB-IoT carrier uses a bandwidth of 180 kHz. In downlink, Orthogonal Frequency-Division Multiple Access (OFDMA) is used with a 15 kHz subcarrier spacing and 12 subcarriers. In uplink, Single-Carrier Frequency-Division Multiple Access (SC-FDMA) is applied, using either 3.75 kHz or 15 kHz subcarrier spacing. For both uplink and downlink, there are 7 OFDMA symbols within a slot, and a subframe consists of two slots.

NB-IoT supports both single-tone and multi-tone operations in uplink. Particularly for multi-tone uplink transmission (12, 6 or 3 tones) only 15 kHz subcarrier spacing is allowed. In Release 13 and 14, NB-IoT only supports Frequency Division Duplex (FDD) half-duplex mode. For both uplink and downlink, there are five physical channels:

TABLE I: NB-IoT RU configurations.

Subcarrier spacing (kHz)	Number of subcarriers	Number of slots	RU duration (ms)
3.75	1	16	32
15	1	16	8
	3	8	4
	6	4	2
	12	2	1

- Narrowband Physical Broadcast CHannel (NPBCH): master information for system access.
- Narrowband Physical Downlink Control CHannel (NPDCCH): scheduling information.
- Narrowband Physical Downlink Shared CHannel (NPDSCH): downlink dedicated and common data.
- Narrowband Physical Random Access CHannel (NPRACH): random access.
- Narrowband Physical Uplink Shared CHannel (NPUSCH): uplink data.

Furthermore, to lengthen battery lifetime, NB-IoT inherits LTE's power saving techniques, *i.e.*, Power Saving Mode (PSM) and extended/enhanced Discontinuous Reception (eDRX). Both techniques enable a relaxed monitoring of the NPDCCH to save energy.

A. Data transmission in NB-IoT

The smallest unit in uplink to map a transport block in NB-IoT is a Resource Unit (RU). Table I shows the 5 possible RU configurations according to the 3GPP specification. The specification [8] provides the allowed configurations of NPUSCH Transport Block Size (TBS) as a function of the number of RUs and Modulation and Coding Scheme (MCS) level. For multi-tone configurations, only QPSK modulation is used. For single-tone configurations, the phase rotated $\pi/2$-BPSK or $\pi/4$-QPSK modulations can be used.

Due to the possible long duration of the transmissions/receptions, NB-IoT needs to introduce gaps. Depending on the channel, the configuration of the gap is different. Additionally, regarding the transmission power, NB-IoT only supports open loop power control. Therefore, the uplink power control depends on a combination of cell-specific parameters, the selected RU configuration, and UE's measured parameters, without a direct feedback given by the eNB. For more information of both topics, see [8] and [9].

B. Coverage enhancement

NB-IoT targets 20 dB coverage extension compared to General Packet Radio Service (GPRS). To achieve this coverage enhancement, NB-IoT relies on two approaches: bandwidth reduction and repetitions. Note that both approaches enhance the received SNR by means of lengthening the transmission/reception. On the one hand, bandwidth reduction concentrates the limited power on a narrower bandwidth at the UE. Therefore it boosts the uplink PSD. On the other hand,

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the successive repetitions can be incrementally soft combined at the receiver before decoding to raise error correction.

In uplink, the transmission can be repeated {1, 2, 4, 8, 16, 32, 64, 128} times, using the same transmission power on each repetition. In downlink, the number of repetitions are {1, 2, 4, 8, 16, 32, 64, 128, 192, 256, 384, 512, 768, 1024, 1536, 2048}. The arrangement of the repetitions depends on the number of tones, subcarrier spacing, and the radio conditions.

To allow for coherent demodulation of the uplink and downlink channels, NB-IoT has two reference signals: Demodulation Reference Signal (DMRS) in uplink, and Narrowband Reference Signal (NRS) in downlink. Reference symbols, hereafter called in this work as *pilot symbols*, are inserted in the time-frequency resource grid to allow CE. In downlink, NRS is included in all subframes that may be used for broadcast or downlink transmission using specific resource elements of the resource grid. In uplink, DMRS is only multiplexed with the data. Depending on the uplink transmission, DMRS is included in either one or three SC-FDMA symbols per slot. Then, from these known transmitted pilot symbols the receiver can estimate the channel response. Note that the quality of the estimation is limited by the number of pilot symbols and the received SNR.

Under the targeted low range of SNR of NB-IoT, an accurate CE becomes a dominant issue that limits the coverage improvement [10]. In these radio conditions, the performance of the channel estimator is expected to be poor. Since most of the NB-IoT UEs are stationary or have little mobility, the channel can be considered very slowly time-variant. Therefore, the CE could be improved using multiple consecutive subframes for the estimation, also known as *cross-subframe CE*. This improvement would be constrained by the coherence time of the channel. Consequently, the length of the time-domain filter of the cross-subframe CE has to be carefully chosen to avoid performance degradation.

III. System model

Let us consider an NB-IoT in-band deployment on an LTE cell. In this cell, there is an NB-IoT UE and an eNB. While the UE is camping on the cell, it transfers data to the network periodically. To save battery, after the end of the communication with the eNB and a period of NPDCCH monitoring, the UE stays in PSM. Therefore, prior uplink data, the UE needs to reestablish the Radio Resource Control (RRC) connection between the UE and the eNB [5]. To do that, we assume the UE performs an RRC Resume procedure. Please note that the analysis presented in this work focuses on the study of the uplink transmission, although the analysis is reciprocal for downlink considering subframes instead of RUs, and the specific parameters of downlink.

In this paper we adopt the following notations. Bold upper case letters stand for matrices. Superscripts $(.)^H$ and $(.)^{-1}$ respectively denote the Hermitian transpose and matrix inverse, whereas the operator $\mathbb{E}\{.\}$ denotes the expectation.

We assume a very slowly time-variant channel and low Doppler frequency (1Hz). We only consider channel losses because of path loss, denoted as L, then $MCL = L$. To compensate channel losses, the UE adjusts its transmission power

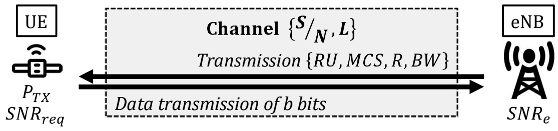

Fig. 1: System model.

TABLE II: Main definitions

Notation	Description
P_{tx}	Transmission power
BW	Bandwidth
SCS	Subcarrier spacing
N_T	Number of tones
R_b	UE's data rate
b	UE's data packet size
RU	Number of RUs
T	Duration of an RU
SNR_{req}	Required SNR at the UE
SNR_e	SNR at the eNB
BW_{eff}	Bandwidth efficiency
SNR_{eff}	SNR required efficiency
R	Number of repetitions
σ	Channel estimation error
σ^2	Mean square error
$\mathbf{H}$	Channel response vector
$\hat{\mathbf{H}}$	Estimated channel response vector
γ	Bandwidth utilization
$\hat{E_b}$	Energy per transmitted bit
W_{cs}	Cross-subframe window
η_p	Cross-subframe correction factor

P_{tx} up to a maximum allowed value P_{max}. Consequently, the SNR, denoted as $\frac{S}{N}$, can be calculated as

$$\frac{S}{N} = \frac{P_{tx}}{L \cdot F \cdot N_o \cdot BW} \quad (1)$$

where N_o is the thermal noise density, F is the receiver noise figure, $BW = SCS \cdot N_T$ is the allocated bandwidth, SCS is the subcarrier spacing, and N_T is the number of tones. Fig. 1 depicts the overall system model. Additionally, Table II provides the adopted notation.

When the eNB configures the UE's data transmission, we consider four parameters: number of RUs, MCS level, the bandwidth allocated, and the number of repetitions. For downlink receptions, we consider three parameters: number of subframes, MCS level, and number of repetitions. For both downlink and uplink, we assume the same information is included in each repetition and combined at the receptor using Chase Combining. In this work, we consider QPSK modulation. The combination of the MCS, number of RUs, and allocated bandwidth determine the data rate of the transmission, derived as

$$R_b = \frac{b + CRC}{RU \cdot T} \quad (2)$$

where R_b is measured in bits/s, b is the size of the data packet in bits, CRC is the size in bits of the Cyclic Redundancy Check code, RU is the number of RUs allocated to the UE, and T is the duration in seconds of an RU. Note that the duration of the RU depends on the bandwidth allocated to the UE. As the number of tones decreases, T increases. Herein, we denote this dependency on the bandwidth as $T^{(BW)}$.

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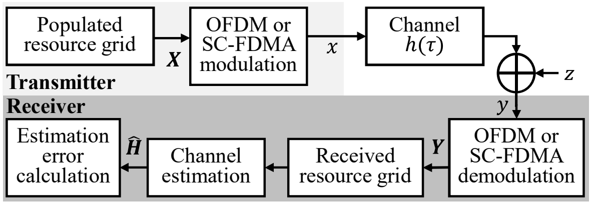

Fig. 2: Realistic CE block diagram.

The selected configuration of the transmission parameters determines the $\frac{S}{N}$ at the UE's receiver. We define SNR_{req} as the minimum $\frac{S}{N}$ to successfully decode the uplink transmission, then $\frac{S}{N} \geq SNR_{req}$. When applying repetitions or bandwidth reduction, the values of SNR_{req} and $\frac{S}{N}$ can be modified. Specifically for uplink repetitions, the same data is repeatedly transmitted R times. The received transmission's copies at the eNB can be combined to raise error correction. The resulting SNR after the coherent combining of the copies is defined as effective SNR, denoted as SNR_e. For ideal CE, the SNR_e can be expressed as

$$SNR_e = \sum^{R} SNR_{req} = R \cdot SNR_{req} \tag{3}$$

For realistic CE, there is an estimation error, denoted as σ. This CE error will impact the system's performance and limit the gain from repetitions. To model realistic CE, both transmit and receive chains and the propagation channel are shown in Fig. 2. Let us consider the received uplink pilot signal in frequency domain as (in matrix notation)

$$\mathbf{Y} = \mathbf{X}\mathbf{H} + \mathbf{Z} \tag{4}$$

where $\mathbf{Y}$ is the received pilot signal vector given as $\mathbf{Y} = [Y[0], Y[1], \cdots, Y[N-1]]^T$. The notation $Y[k]$ indicates the received pilot tone at the kth subcarrier. The diagonal matrix $\mathbf{X}$ is the transmitted pilot signal, with $\mathbb{E}\left\{|X[k]|^2\right\} = 1$, and $\mathbf{Z}$ denotes the Gaussian noise vector given as $\mathbf{Z} = [Z[0], Z[1], \cdots, Z[N-1]]^T$, with $\mathbb{E}\{Z[k]\} = 0$ and $Var\{Z[k]\} = \left(\frac{S}{N}\right)^{-1}$. The variance is obtained from the L assumed in the channel. Furthermore, $\mathbf{H}$ is the frequency response of the channel vector given as $\mathbf{H} = [H[0], H[1], \cdots, H[N-1]]^T$.

We consider a fading multipath channel model of M distinct paths [11]. The channel impulse response during the OFDM symbol in time domain can be expressed as

$$h(\tau) = \sum_{i}^{M} a_i \delta(\tau_i) \tag{5}$$

where a_i and $\delta(\tau_i)$ respectively represent the path gain and the propagation delay of the ith path.

In the channel model, the total power is normalized to one. $\mathbf{H}$ is the Fast Fourier Transform (FFT) transformation of $h(\tau)$, *i.e.*, $\mathbf{H} = FFT_N[h(\tau)]$. For realistic CE, the channel estimate, denoted as $\hat{\mathbf{H}}$, can be modeled as

$$\hat{\mathbf{H}} = \mathbf{H} + \mathbf{H_e} \tag{6}$$

where $\mathbf{H_e}$ is the estimation error which has a variance σ.

We assume a Least Squares (LS) channel estimator. Therefore, from the known reference uplink pilot symbols, we estimate the channel response as $\hat{\mathbf{H}} = \mathbf{X}^{-1}\mathbf{Y}$.

From the channel estimation, the Minimum Square Error (MSE) of the channel estimator σ^2 can be expressed as

$$\sigma^2 = \mathbb{E}\left\{\left(\mathbf{H} - \hat{\mathbf{H}}\right)^H \left(\mathbf{H} - \hat{\mathbf{H}}\right)\right\} \tag{7}$$

Note that for downlink, the channel coefficients of the subcarriers without pilot symbols have to be obtained by means of linear interpolation. Then, from the calculated MSE, we obtain the CE error as $\sigma = \sqrt{\sigma^2}$.

Finally, we adopt the analytical bound for the SNR gain from signal repetition defined in [4]. This analytical bound provides the approximated SNR_e from the $\frac{S}{N}$, the CE error σ, and the number of repetitions R:

$$SNR_e = \frac{R \cdot \left(\sigma + \frac{S}{N}\right)}{\left(\sigma + 1 + \frac{\sigma}{\frac{S}{N}}\right) \cdot \left(1 + \frac{\sigma}{2 \cdot \frac{S}{N}}\right)} \tag{8}$$

If $\frac{S}{N} = SNR_{req}$, from equations (3) and (8) we can observe the relationship between SNR_{req} and SNR_e when considering repetitions for ideal and realistic CE. Unlike the analytical bound for the SNR gain when doubling repetitions of (8), we consider there is a direct improvement on the SNR_{req} when bandwidth reduction technique is applied for both ideal and realistic CE, and the transmission power is maintained. This improvement is due to uplink PSD boosting as the bandwidth reduction technique concentrates a given power on a narrower bandwidth. This PSD boost can be calculated using (1).

IV. NB-IoT ANALYSIS

In the following subsections, we describe the main points of our NB-IoT analysis. The aim is to estimate the SNR_{req} of the UE considering the new concerns of NB-IoT, such as coverage enhancement approaches and channel estimation errors at low SNR range. We study three uplink transmission configuration approaches in NB-IoT: RU number modification, bandwidth reduction, and repetitions. These three approaches are represented in the analysis as $(.)^{(RU,BW,R)}$, respectively.

Note that our study provides the minimum bounds obtained from the Shannon theorem of three parameters: i) the required SNR, denoted as SNR_{req}; ii) the energy per transmitted bit $\hat{E_b}$; and iii) the bandwidth utilization γ. To satisfy this analysis, rearranging (1) and assuming $\frac{S}{N} = SNR_{req}$, the transmission power is calculated as

$$P_{tx} = SNR_{req}^{(RU,BW,R)} \cdot L \cdot F \cdot N_o \cdot BW \tag{9}$$

However, the equation (9) does not include the constraints of the 3GPP's open loop uplink power control mechanism for NB-IoT defined in [8]. Therefore, for higher values of P_{tx}, the resulting values of the parameters analyzed will exceed the values obtained through Shannon theorem.

From now on, our study is divided into two approaches. Firstly, we assume ideal CE and consequently provide a baseline analysis of NB-IoT, based on [6]. Secondly, we present

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a more detailed analysis that considers non-ideal factors, such as realistic CE.

A. Baseline NB-IoT analysis

Based on the Shannon theorem, the SNR at the eNB, denoted as SNR_e, can be derived as

$$SNR_e = 2^{R_b/BW} - 1 = 2^{\frac{b+CRC}{BW \cdot RU \cdot T^{(BW)}}} - 1 \tag{10}$$

By substituting (3) into (10), the required SNR at the UE can be expressed as

$$SNR_{req}^{(RU,BW,R)} = \frac{2^{R_b^{(RU,BW,1)}/BW} - 1}{R} = \frac{2^{\frac{b+CRC}{BW \cdot RU \cdot T^{(BW)}}} - 1}{R} \tag{11}$$

where $(.)^{(RU,BW,1)}$ denotes the number of repetitions is equal to its minimum $R = 1$. From (11), ideally, doubling repetitions can bring about 3 dB gain. From the data rate of the UE, we can obtain the bandwidth utilization γ of the transmission as

$$\gamma^{(RU,BW,R)} = \frac{R_b^{(RU,BW,1)}}{R \cdot BW} = \frac{b + CRC}{R \cdot BW \cdot RU \cdot T^{(BW)}} \tag{12}$$

Furthermore, let $\frac{E_b}{N_o} = \frac{SNR_{req}}{\gamma}$ be the lower bound of the received energy per bit to noise power spectral density ratio, and $\hat{E_b}$ be the energy per transmitted bit, then

$$\hat{E_b}^{(RU,BW,R)} = \frac{E_b}{N_o}^{(RU,BW,R)} \cdot L \cdot F \cdot N_o = \frac{SNR_{req}^{(RU,BW,R)}}{\gamma^{(RU,BW,R)}} \cdot L \cdot F \cdot N_o = \frac{2^{\frac{b+CRC}{BW \cdot RU \cdot T^{(BW)}}} - 1}{\frac{b+CRC}{BW \cdot RU \cdot T^{(BW)}}} \cdot L \cdot F \cdot N_o \tag{13}$$

Note that $\hat{E_b}^{(RU,BW,R)}$ is no longer a function of the number of repetitions. The utilization of repetitions reduces the SNR_{req} at the expense of the reduction of γ. For more details of the influence of the other parameters, see [6].

B. Detailed NB-IoT analysis

In this subsection we introduce step by step the non-ideal factors that impact the performance of NB-IoT.

1) Shannon capacity fitting: The Shannon bound is the theoretical maximum data rate of the channel for a given SNR and bandwidth. Although LTE is near the Shannon bound, NB-IoT performance is to be analyzed and compared to the Shannon bound. In order to capture this factor accurately, we use a modified Shannon capacity formula. This approximation (14) was originally proposed in [12] for LTE. Therefore, the modified Shannon formula is as follows:

$$C = BW \cdot BW_{eff} \cdot log_2\left(1 + \frac{SNR_e}{SNR_{eff}}\right) \tag{14}$$

where C is the capacity of the channel measured in bits/s, BW_{eff} is the bandwidth efficiency of the used technology (*i.e.*, NB-IoT), and SNR_{eff} is the efficiency of the SNR in NB-IoT.

For our analysis, once all the parameters of the modified Shannon bound are estimated, the SNR_e can be calculated knowing the bit rate and the bandwidth of the transmission or reception. Considering the UE's data rate $R_b = C$ and rearranging (14), the SNR_e can be expressed as

$$SNR_e = \left(2^{\frac{R_b}{BW \cdot BW_{eff}}} - 1\right) \cdot SNR_{eff} \tag{15}$$

2) Channel estimation: In order to include the effect of the presence of CE errors in realistic CE, we adopt the analytical bound for the SNR gain from signal repetition defined in [4] and shown in equation (8). Then, by substituting (15) into (8), we obtain the approximation of the SNR_{req} for realistic CE:

$$\left(2^{\frac{R_b}{BW \cdot BW_{eff}}} - 1\right) \cdot SNR_{eff} = \frac{R \cdot \left(\sigma + SNR_{req}\right)}{\left(\sigma + 1 + \frac{\sigma}{SNR_{req}}\right) \cdot \left(1 + \frac{\sigma}{2 \cdot SNR_{req}}\right)} \tag{16}$$

Unlike the baseline analysis of Section IV-A, in this case there is not a simple solution when solving equation (16) for SNR_{req}. Then, we obtain SNR_{req} through an iterative method in the results section. Note that σ depends on the SNR_{req}. This is due to the quality of the CE depends on the amplitude of the received pilot symbols, and therefore, the SNR_{req}. In order to use (16), we need to know the dependency of σ and SNR_{req}. To do that, we develop two simulators, one for OFDMA for the downlink channels and another for SC-FDMA for the uplink channels. The goal of these simulators is to emulate the transmission and reception chains of both systems to estimate the σ of the CE under different conditions. After conducted simulations (see Section V-A),we found the dependency between the σ and the SNR_{req} can be expressed in dB as a linear dependency, given by

$$\sigma_{dB} = c_1 \cdot SNR_{req,dB} + c_2 \tag{17}$$

where $SNR_{req,dB}$ and σ_{dB} are measured in dB, and c_1 and c_2 are constants that depend on the cross-subframe window used in the CE and the modulation technique.

3) Cross-subframe: To minimize the effects of noise on the realistic CE, the channel estimates are averaged. Under the hypothesis of slowly time-variant channel, the utilization of cross-subframe CE can produce a substantial noise reduction.

Fig. 3 depicts a simplified block diagram of the steps performed for uplink cross-subframe CE considering a cross-subframe window $W_{cs} = 2$ in our simulators. The value of W_{cs} denotes the number of resources to be considered in the cross-subframe CE. For uplink, these resources are the number of RUs. For downlink, the number of subframes.As showed in Fig. 3, the steps performed by the simulators are as follows: 1) start a channel realization out of K realizations; 2) extract the pilot symbols from their known location within the received matrix of symbols; 3) obtain the LS estimation of the channel; 4) average the pilots estimates within the cross-subframe window considered; 5) compute the MSE of the estimation; and 6) if the Kth realization finished, all obtained MSEs are averaged. When we consider cross-subframe technique in our evaluation, the configuration of the transmission/reception

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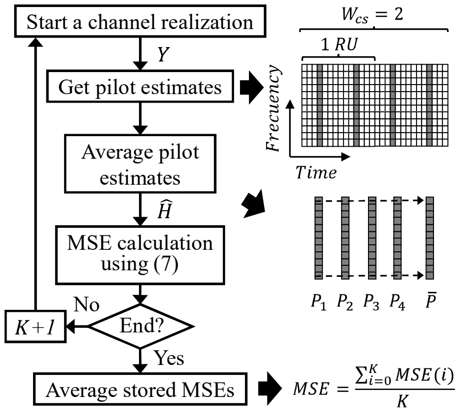

Fig. 3: Block diagram of an uplink CE using cross-subframe with a window of 2, where P_n represents the nth DMRS vector and $\bar{P}$ the time averaged vector.

determines the value of W_{cs}. For example, in uplink, W_{cs} is derived as

$$W_{cs} = min\left(W_{cs}^{max}, 2^{\lfloor log_2(RU\cdot R\cdot \eta_p)\rfloor}\right) \tag{18}$$

where W_{cs}^{max} is the maximum cross-subframe window considered and η_p is a correction factor. This correction factor is used to include single-tone configurations have less DMR symbols than multi-tone configurations.

The simulation of different values of W_{cs} provides a set of c_1 and c_2 values of equation (17), as can be seen later in Section V-A. Finally, the value of W_{cs} used in the transmission/reception determines the equation (17) to be used in (16) when we estimate the SNR_{req}.

V. Numerical results

This section explains the obtained simulation results of our analysis and discusses the performance of NB-IoT considering three different scenarios, labeled to as:

- `ideal`: ideal CE, that is $\hat{\mathbf{H}} = \mathbf{H}$.
- `wcs`: realistic CE with cross-subframe. In this scenario, larger transmissions could benefit from the use of larger cross-subframe windows.
- `nocs`: realistic CE without cross-subframe technique.

The performance of NB-IoT is measured in terms of uplink packet transmission latency and UE's battery lifetime. To do that, we propose an evaluation framework with the following three main steps, namely:

1) SNR_{req} estimation from the analysis presented in Section IV. This estimation includes the issues explained in Section IV, i.e., the proposed NB-IoT's Shannon fits, ideal or realistic CE, and the cross-subframe CE technique when applied.
2) Utilization of the outcome of step 1 as an input to configure the link adaptation of the signaling packet transfers required prior to the uplink data transmission. For uplink, the link adaptation is done using the algorithm of our previous work [6].

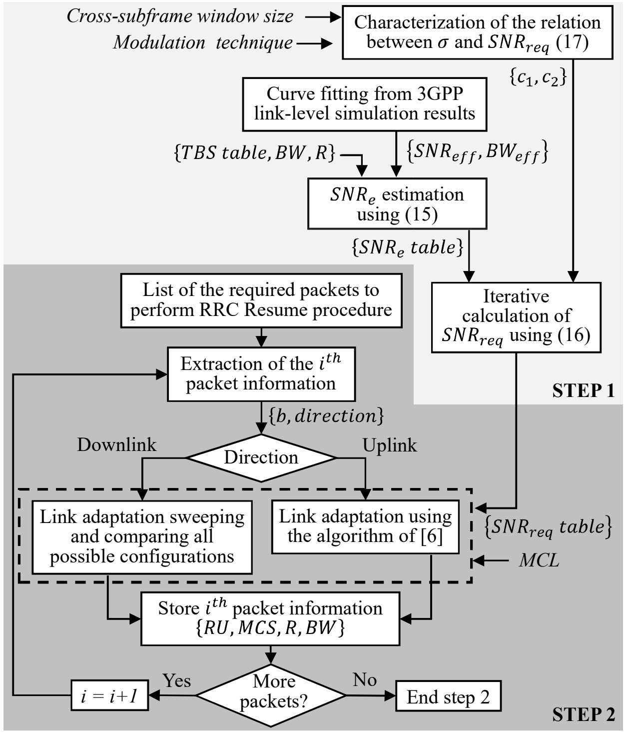

Fig. 4: Block diagram of steps 1 and 2 of our evaluation framework.

3) Estimation of the NB-IoT performance from our previous energy consumption model [5]. The model uses a Markov chain and four power levels (i.e. transmission, reception, inactive, and standby) to describe the UE power consumption while it performs the required steps to communicate with the eNB. In this framework, the model uses the output of the link adaptation of step 2 to configure the energy consumption and delay of each packet transferred during the control procedure assumed. In this evaluation, the NPUSCH transmission power follows the 3GPP power control for NB-IoT [8].

To clarify the evaluation process, Fig. 4 depicts steps 1 and 2. This figure shows the inputs and outputs of each stage of the evaluation. Additionally, in step 3, the two-dimensional Markov chain of [5] is an adaptation for NB-IoT of the LTE model originally proposed in [13].

Please note that although the link adaptation algorithm of [6] was presented for the baseline analysis of Section IV-A, it works well for the non-ideal factors included in this work. This algorithm minimizes the transmission time. However, the energy consumption is more critical in NB-IoT. From the analysis of Section IV-B, we can estimate the analytical energy consumption as $\hat{E_b} \cdot (b + CRC)$, where the values of $\hat{E_b}$ are limited when exceed the maximum obtained from P_{max}. Note that when $MCL \geq 110dB$ both objectives, that is, to minimize the energy consumption or transmission time, get the same energy consumption. This is because both objectives have the same optimal positions in the TBS table.

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TABLE III: Shannon correction parameters values

Parameter	NPUSCH Multi-tone	NPUSCH Single-tone	NPDSCH
BW_{eff}	0.35	0.35	0.58
SNR_{eff}	1	0.60	1.90

TABLE IV: Values of the parameters of (17) for different number of cross-subframe windows for LS channel estimator

W_{cs}	SC-FDMA		OFDMA	
	c_1	c_2	c_1	c_2
1	-0.4896	4.4971	-0.4998	14.5262
2	-0.4844	3.0252	-0.4995	13.0035
4	-0.4780	1.5869	-0.4990	11.5017
8	-0.4725	0.1239	-0.4992	9.9952
16	-0.4475	-1.1335	-0.4969	8.5077

A. Parameter settings

For the first step of our evaluation framework, the correction values for Shannon formula are derived through curve fitting to the 3GPP's link-level simulation results for NPUSCH [14] and NPDSCH [15]. Table III summarizes the correction values obtained. In this case, NPDCCH performance, *i.e.* the required number of repetitions to achieve the needed SNR_{req}, is obtained from the results of [16].

Additionally, in order to estimate the SNR_{req} when applying repetitions, step 1 needs the CE error σ used in (16). To do that, the components c_1 and c_2 of (17) that define the dependency between σ_{dB} and $SNR_{req,dB}$ are obtained through simulation of σ for NPUSCH and NPDSCH pilots. The simulation of the pilots in uplink and downlink follows the 3GPP specification for NB-IoT [9]. The configuration of OFDMA and SC-FDMA is done according to 3GPP LTE 1.25 MHz carrier bandwidth. The components c_1 and c_2 are obtained for five different cross-subframe windows. For each configuration considered, 5000 channel realizations are simulated. Table IV summarizes the resulting parameters.

Finally, to determine W_{cs}, we set $\eta_p = 1$ for multi-tone configurations, and $\eta_p = 0.6667$ for single-tone configurations. Table V includes both steps 2 and 3 parameters.

TABLE V: Parameters for NB-IoT performance estimation [8], [17], [18].

Energy consumption configuration			
Variable	Value		
Standby power consumption	0.015 mW		
Inactive power consumption	3 mW		
Reception power consumption	80 mW		
Maximum transmission power consumption	500 mW (included 60 mW for other analog and baseband circuitry)		
Power amplifier efficiency	45%		
Battery capacity	5 Wh		
UE's transmit power for NPRACH	Subclause 16.2.1.1.1 of [8], where: $InitRXPower = -100dBm$ $\Delta_{preamble} = 0$ $PowerRampingStep = 0dB$		
Connected DRX cycle	256 ms		
On duration DRX timer	1 NPDCCH period		
Idle DRX cycle	5120 ms		
Active timer	20 s		
Preamble detection probability	Preamble: $1 - e^{-i}$, where i indicates the ith preamble transmission. Other packets: 1		
Physiscal layer			
Propagation condition	Typical Urban (TU) 20 paths, 1Hz		
Carrier frequency offset	20 Hz		
UE | eNB noise figure	5 dB | 3 dB		
UE | eNB power class	23 dBm | 35 dBm		
Protocol overhead			
Higher layer procedure	RRC Resume		
PDCP/RLC/MAC overheads	5B / 2B / 2B		
Packet sizes on top of PDCP	Latency estimation: Uplink report: 85B Battery lifetime estimation: Uplink report: 50B Downlink Application ACK: 65B		
NB-IoT design			
NPDCCH design	Format: 0, Aggregation level: 2 Periodicity: $T_{NPDCCH} = R_{MAX} \cdot G$, where $G = 1.5$		
Start of NPUSCH transmission after the end of its associated NPDCCH	8 ms		
Start of NPDSCH transmission after the end of its associated NPDCCH	5 ms		
Coverage level (CL) thresholds	MCL = {144, 154} dB		
CL configuration for Random Access	Level 0	Level 1	Level 2
NPRACH/NPDCCH repetitions	1	8	32
Random Access Opportunity	40 ms	240 ms	640 ms
Synchronization time	327 ms	341 ms	597 ms
Master Information Block (MIB) acquisition time	111 ms	111 ms	483 ms

B. Analysis results

In the first step of our evaluation framework, we estimate the SNR_{req} in different configurations of number of RUs, MCS, BW and R. Figures 5, 6, and 7 are examples of the analysis of this step. Fig. 5 presents the comparison of the spectral efficiency as a function of the MCL for our NB-IoT fits and the baseline Shannon bound. As it can be seen, NB-IoT presents a great gap between its performance and the Shannon bound. This is due to implementation issues and the repetition coding scheme used in NB-IoT. For large MCLs ($MCL > 150$ dB), there is a performance deficit up to 5 dB approximately of the NB-IoT fits compared to Shannon.

Fig. 6 shows the analyzed transmission properties of Section IV-B. In this analytical evaluation the transmission power follows (9) without constrains of the 3GPP, specifically we assume $BW = 180$ kHz, and $L = 100$ dB. The comparison of two different RU allocations highlights the benefit of cross-subframe technique in `wcs` compared to `nocs`. For a given TBS size, a greater number of RU achieves a lower $\hat{E_b}$.

Fig. 7 shows the impact of the CE error when doubling repetitions to extend coverage in uplink for a TBS of 504b with 5 RUs. As the SNR_{req} is lower, the CE error increases. Therefore, in this range of SNR_{req} the gain when doubling repetitions is limited in `wcs` and `nocs` scenarios compared to `ideal` scenario. Furthermore, we can see `wcs` improves the results of `nocs` due to the benefits of cross-subframe CE.

Regarding the last step of our evaluation framework, Figures 8 and 9 represent the performance of a NB-IoT UE for the three scenarios considered in this work. The configuration of the parameters for the estimations of both figures is similar to the parameters of the evaluations done in [17] and [18], such as the size of the uplink reports or the DRX configuration.

Fig. 8 shows the latency estimation when a UE performs an RRC Resume procedure to transfer an uplink report.

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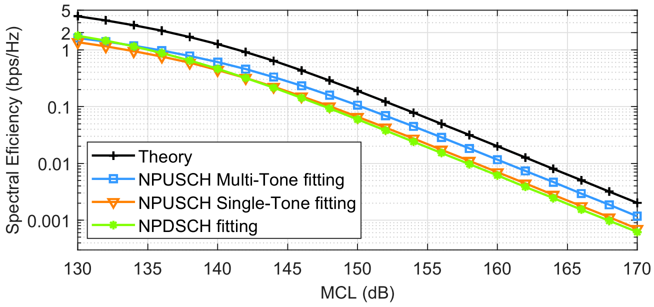

Fig. 5: Spectral efficiency versus MCL considering the Shannon bound curves, and the proposed NB-IoT fits.

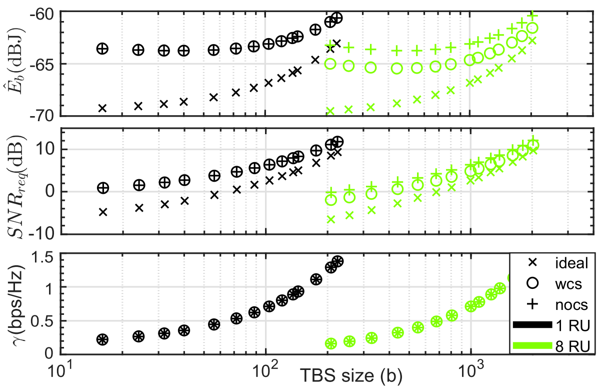

Fig. 6: Transmission properties comparison as a function of the TBS size for different number of RUs and the three scenarios.

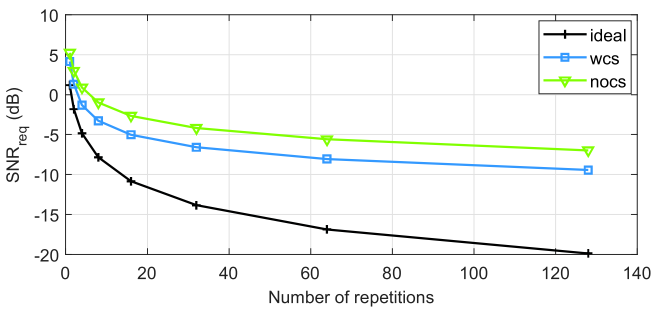

Fig. 7: Example of degradation of the SNR gain in `wcs` and `nocs` scenarios compared with `ideal` scenario when a higher number of repetitions is used in uplink.

The latency is calculated adding the time components for synchronizing, setting up the connection, and transmitting the uplink report of 85B. The latency has two abrupt steps when there is a change of coverage level due to the increase of the time dedicated to synchronization and repetitions in the NPRACH. As expected, `ideal` scenario obtains the best results and can be evaluated for greater MCLs than `wcs` and `nocs` scenarios. Additionally, the included results from [17] and `ideal` scenario are similar. For both, the support of a latency of at least 10 seconds is achieved up to the MCL of 164 dB. Nevertheless, `wcs` and `nocs` attain worse results than `ideal` scenario. This is owing to the degradation of the SNR gain when doubling repetitions in realistic CE. Therefore, for higher MCLs that rely on repetitions to extend coverage, this degradation exacerbates the difference between realistic CE (`wcs` and `nocs` scenarios) and ideal CE (`ideal` scenario).

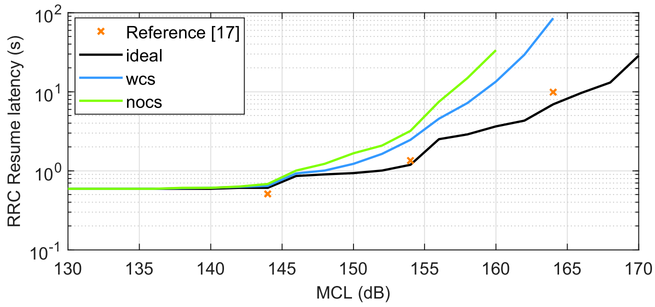

Fig. 8: RRC Resume procedure latency versus MCL.

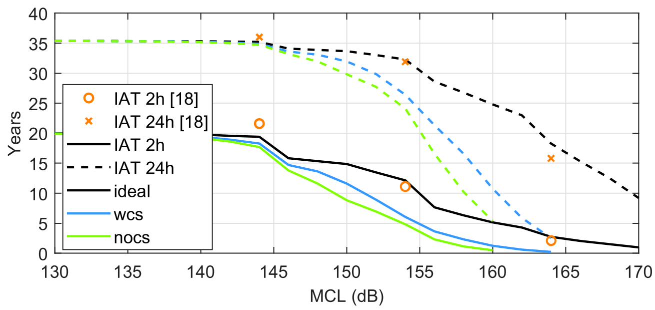

Fig. 9: Battery lifetime estimation versus MCL of a NB-IoT UE considering two different IATs.

Fig. 9 shows the battery lifetime estimation sweeping the MCL and considering two different Inter-Arrival Time (IAT). In this estimation we consider the UE transmits an uplink report of 50B and waits for the reception of a downlink application acknowledgment of 65B. After the acknowledgment and prior the UE enters PSM, this estimation includes the monitoring of the control channels until the expiration of the active timer. The figure includes the results from [18].

Our analytical `ideal` scenario provides similar results to the source [18]. When we consider realistic CE, the results of battery lifetime are more pessimistic. As seen before, this detriment in the battery lifetime is greater as the MCL increases. Particularly for UEs with small IATs, this effect is noted before. For example, when MCL = 154 dB, `wcs` presents a battery lifetime reduction of a 50% and 18% compared to `ideal` for IATs of 2h and 24h, respectively. However, when MCL = 164 dB, both IATs obtain similar values, reaching a battery lifetime reduction of a approximately 90% in `wcs` compared to `ideal` scenario.

VI. Conclusion

In this paper we propose an analytical framework to estimate the performance of NB-IoT for three different scenarios: i) ideal CE; ii) realistic CE with cross-subframe; iii) realistic CE without cross-subframe. The performance of NB-IoT is evaluated in terms of uplink packet transmission latency and UE's battery lifetime. Our analytical framework is divided into

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three issues: i) SNR estimation; ii) Link adaptation; iii) NB-IoT energy and delay estimation. The analysis presented in this work delves into the SNR estimation. To do that, this analysis is based on Shannon capacity fitting for NB-IoT and the estimation of the dependency of the CE error and the SNR.

The conducted evaluations show the performance of the SNR gain when doubling repetitions is significantly affected when assuming realistic CE compared to ideal CE. As the MCL increases, this degradation increases due to larger CE errors. When realistic CE is considered, the use of cross-subframe improves its results. Specifically, regarding UE's battery lifetime, for an MCL = 154 dB, realistic CE with cross-subframe shows a battery lifetime reduction of a 50% and 18% compared to ideal CE for IATs of 2h and 24h, respectively. However, for higher MCL such as 164 dB, both IATs reach a battery lifetime reduction of approximately 90% in realistic CE with cross-subframe compared to ideal CE.

For future work, we intend to deepen in the study of the coverage extension limitation considering other channel models, channel estimators, higher Doppler frequencies, or study the limitations of PSD boost.

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