Narrowband Internet of Things (NB-IoT) and LTE Systems Co-existence Analysis

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***Abstract*—In this paper, we establish a comprehensive uplink system model for in-band and guard-band Narrowband Internet of Things (NB-IoT) with arbitrary sample duration in the NB-IoT device. The mathematical expressions of received LTE and NB-IoT signals are derived. Moreover, the close-form interference power on the LTE signal from the adjacent NB-IoT signal is given analytically. The result shows that the sample duration of NB-IoT device has significant impact on its desired signal and on the interference to the LTE user equipment (UE). Numerical results show that the analytical expressions match the simulated ones perfectly, which verifies the effectiveness of proposed system model and derivations. The work in this paper provides a valid guidance for NB-IoT system deployment and co-existence analysis.**

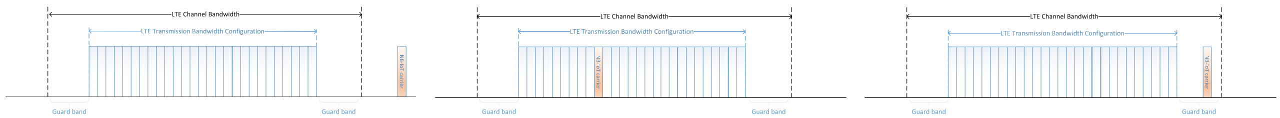
***Index Terms*—Narrowband Internet of Things (NB-IoT), mixed numerology, multi-service co-existence, network slicing.**

I. Introduction

It has been predicted that there will be more than 10 billions Internet of Things (IoT) devices in the world in 2021, where around 10% of them will be based on cellular networks [1]. In order to get access to the new market, mobile network operators together with communication equipment manufacturers promoted the standardization progress for cellular IoT techniques. A series of radio technology standards named NB-IoT (Narrowband Internet of Things) were standardized by the 3rd Generation Partnership Project (3GPP) recently [2]. NB-IoT is designed to operate on the existing cellular networks, e.g., Evolved Universal Mobile Telecommunications System Terrestrial Radio Access (E-UTRA) and Global System for Mobile Communication (GSM). There are several key performance indicators (KPIs) for NB-IoT, e.g., improved coverage (up to 35km), support for massive number of devices (50K/cell), ultra low cost (5 US dollars per device) and energy efficient modules (10 years battery life) [3][4].

To utilize the spectrum resource efficiently and flexibly, NB-IoT devices could be assigned to three different operation modes as shown in Fig. 1. Stand-alone operation mode in Fig. 1(a) utilizes the spectrum currently allocated to GSM systems as well as some scattered spectrum for potential IoT deployment. In-band operation mode shown in Fig. 1(b) utilizes the resource blocks (RBs) within LTE carriers. Guard-band operation mode in Fig. 1(c) utilizes the RBs in the LTE carriers' guard band [3]. The last two operation mode enables the reuse of LTE base stations (BSs) by only updating their software. However, since NB-IoT devices have much lower sampling rate than LTE BS for the sake of low cost, the reuse of the LTE BS radio frequency (RF) (e.g., analog to digital converter and RF filter) and baseband (e.g., discrete Fourier Transform) processing chain may destroy the carrier orthogonality of the Orthogonal Frequency Division Multiplexing (OFDM) system, and hence may invalidate the extensively used algorithms (e.g., channel equalization and estimation) and performance analysis method.

Due to the physical layer configuration difference between the NB-IoT and LTE resource blocks, in the in-band and guard-band modes, the orthogonal system is destroyed and thus cause interference among sub-carriers. Co-existence performance between LTE and NB-IoT have been investigated in 3GPP by extensive system level simulations [3], and the study shows the feasibility of in-band and guard-band NB-IoT mechanism. In the literature, researches about NB-IoT are focused on, e.g., scheduling [5] and frame structure design [6]. Some studies about co-existence between different slices (i.e., services with different network configurations) have been finished, e.g., [7][8] have proposed the concept of multi-service which can accommodate services with different RF and base band configurations. Performance analysis on inter-slice-interference and cancellation have been proposed in [9][10]. In addition, preliminary work about channel equalization and interference analysis for uplink in-band/guard-band NB-IoT has been proposed in [11], where different sampling rates but same symbol length are considered for LTE and NB-IoT. With such an assumption, the square wave duty cycle of the NB-IoT signal is 100%. This may lead to three-fold problems: 1) the unnecessarily long sample duration may result in energy inefficiency, which is against the original intention to design low power consumption NB-IoT devices; 2) the sample duration of NB-IoT needs to be very accurate to maintain the consistency with LTE system, which is a challenge for low cost IoT devices; 3) according to the analysis in [11], such an assumption will bring the frequency selectivity among NB-IoT sub-carriers, which may



(a) Standalone operation (b) In-band operation (c) Guard-band operation

Fig. 1. Operation modes of NB-IoT

significantly degrade the NB-IoT signal performance.

To address the aforementioned problems, in this paper, we consider arbitrary sample duration (also referred as sample length in the rest of this paper) for NB-IoT user equipment (UE). Thus, the study is a general case of [11], and such a flexible model constructs the foundation of sample duration optimization and significant gain can be expected. Based on this general model, mathematical expression of the NB-IoT equivalent channel frequency response (CFR) is derived, and the interference between NB-IoT and LTE is analyzed. It reveals that with different NB-IoT sample durations, one-tap equalization could still be implemented to keep the low complexity of receiver algorithms. In addition, our derivation shows that the NB-IoT UE is free of interference from LTE UE, while the interference from NB-IoT UE to LTE UE depends on the guard band between them as well as the NB-IoT sample duration. These two factors may significantly affect the interference level and distribution in LTE devices. The work in this paper provides an analytical guidance for the practical NB-IoT and LTE coexisting system deployment.

The rest of this paper is organized as follows. In Section II, LTE and NB-IoT coexisting system model is presented. Section III gives the mathematical derivations of equivalent NB-IoT CFR and interference from NB-IoT to LTE. Simulation results are illustrated and discussed in Section IV. Finally, the conclusion is given in Section V. The meanings of notations used in this paper are listed in Table. I.

TABLE I
LIST OF NOTATIONS

Notation	*Meaning*
$\{\cdot\}^H$	Hermitian conjugate
$\{\cdot\}^T$	Transpose operation
$\mathbb{E}\{\mathbf{A}\}$	Expectation of matrix $\mathbf{A}$
diag$\{\mathbf{A}\}$	Form a diagonal matrix by taking the diagonal elements of matrix $\mathbf{A}$
diag$\{\mathbf{a}\}$	Form a diagonal matrix taking each elements of vector $\mathbf{a}$
$\mathbf{I}_M$	M length identity matrix
$\mathbf{0}_{M\times N}$	$M\times N$ zero matrix

II. System Model

An uplink LTE and NB-IoT coexisting system model is shown in Fig. 2, where two different subscripts are applied to distinguish the parameters for LTE ($\{\cdot\}_L$) and IoT ($\{\cdot\}_I$).

The LTE UE and BS in the constructed system follow the normal LTE configurations with S_L to be the sampling rate, while the sampling rate S_I for NB-IoT is much smaller than S_L for the purpose to maintain low complexity and energy consumption. Without losing generality, we consider two RBs are allocated (i.e., one for LTE and another one for NB-IoT) and each RB contains M sub-carriers. The sub-carrier index for LTE and NB-IoT can be expressed as two non-overlapping sets, i.e., $\{M_L, M_L+1, \cdots, M_L+M-1\}$ and $\{M_I, M_I+1, \cdots, M_I+M-1\}$, respectively. The guard band between them is $B_G = |M_I - M_L| - M$. Assuming the DFT size for LTE system is N_L, and the DFT size for NB-IoT UE is N_I. Then we can define the upsampling rate for NB-IoT as $G = N_L/N_I$ with $G \in \mathbb{N}^+$ for simplicity. According to the Nyquist sampling theorem, the DFT size of NB-IoT N_I should be no less than M. To avoid introducing trivial sub-carrier mapping and selection during the derivation, here we assume $N_I = M$. But it should be noticed that the derivations in this paper could be extended to $N_I > M$ easily.

Assuming that the transmitting LTE and NB-IoT signals are $\mathbf{x}_L$ and $\mathbf{x}_I$, respectively. The mathematical expressions of the signals after passing through the multi-path channel can be written as:

$$\mathbf{x}_{I,tx} = \mathbf{A}_I\mathbf{C}_I\mathbf{F}_{\mathbf{N_I}}\mathbf{x}_I + \tilde{\mathbf{n}}_I, \quad (1)$$
$$\mathbf{x}_{L,tx} = \mathbf{A}_L\mathbf{C}_L\hat{\mathbf{F}}_{\mathbf{N_L}}\mathbf{x}_L + \tilde{\mathbf{n}}_L, \quad (2)$$

where $\mathbf{F}_{\mathbf{N_I}}$ is a N_I-points normalized IDFT matrix, and $\hat{\mathbf{F}}_{\mathbf{N_L}}$ takes the $M \in \{M_L, M_L+1, \cdots, M_L+M-1\}$ rows of $\mathbf{F}_{\mathbf{N_L}}$, who is a N_L-points normalized IDFT matrix. $\mathbf{A}_I$ and $\mathbf{A}_L$ are two Toeplitz matrices comprising of $\mathbf{h}_I$ and $\mathbf{h}_L$, respectively, in which $\mathbf{h}_I \in \mathbb{C}^{1\times L_{CH,I}}$ is the power normalized channel impulse response (CIR) of NB-IoT, and $\mathbf{h}_L \in \mathbb{C}^{1\times L_{CH,L}}$ is the power normalized CIR of LTE (with there corresponding channel length to be $L_{CH,I}$ and $L_{CH,L}$, respectively). $\mathbf{C}_I$ and $\mathbf{C}_L$ are the Cyclic Prefix (CP) insertion matrices which can be formed as follows:

$$\mathbf{C}_I = [\mathbf{0}_{L_{CP,I}\times(N_I-L_{CP,I})}, \mathbf{I}_{L_{CP,I}}; \mathbf{I}_{N_I}], \quad (3)$$
$$\mathbf{C}_L = [\mathbf{0}_{L_{CP,L}\times(N_L-L_{CP,L})}, \mathbf{I}_{L_{CP,L}}; \mathbf{I}_{N_L}], \quad (4)$$

where $L_{CP,L}$ and $L_{CP,I}$ are the CP length of LTE and NB-IoT in a unit of their corresponding sample duration. We assume that the CP length is larger than the length of the channel in both systems to avoid inter symbol interference (ISI). The last terms in equation (1) and (2) (i.e., $\tilde{\mathbf{n}}_I$ and $\tilde{\mathbf{n}}_L$) are white noises.

Then, after receiver processing (e.g., analog to digital conversion, CP removal and DFT), the received NB-IoT and LTE signals before channel equalization can be written as:

$$\mathbf{y}_I = \tilde{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}\mathbf{R}_L\mathbf{\Psi}_I\mathbf{U}\mathbf{A}_I\mathbf{C}_I\mathbf{F}_{\mathbf{N_I}}\mathbf{x}_I + \mathbf{v}_I + \mathbf{n}_I, \quad (5)$$
$$\mathbf{y}_L = \hat{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}\mathbf{R}_L\mathbf{A}_L\mathbf{C}_L\hat{\mathbf{F}}_{\mathbf{N_L}}\mathbf{x}_L + \mathbf{v}_L + \mathbf{n}_L, \quad (6)$$

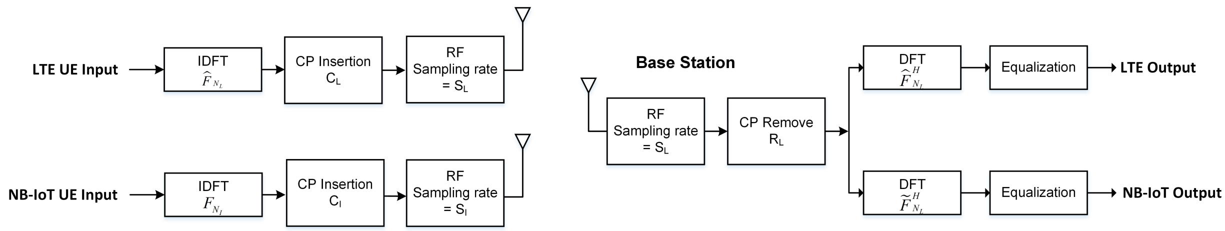


Fig. 2. Uplink LTE/NB-IoT co-existence system

where the first terms in equation (5) and (6) represent the desired signals for NB-IoT and LTE, respectively. The second term $\mathbf{v}_I$ represents the interference from LTE to NB-IoT while $\mathbf{v}_L$ is the interference from NB-IoT to LTE. The last terms $\mathbf{n}_I$ and $\mathbf{n}_L$ are the added random Gaussian noises. Specifically, in the desired part of equation (5) and (6), $\hat{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}$ and $\tilde{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}$ are two sub-matrices of $\mathbf{F}^{\mathbf{H}}_{\mathbf{N_L}}$, the former one takes the $M \in \{M_L, M_L+1, \cdots, M_L+M-1\}$ columns of $\mathbf{F}^{\mathbf{H}}_{\mathbf{N_L}}$ and the latter one takes the $M \in \{M_I, M_I+1, \cdots, M_I+M-1\}$ columns of $\mathbf{F}^{\mathbf{H}}_{\mathbf{N_L}}$. $\mathbf{R}_I$ and $\mathbf{R}_L$ are CP removal matrices which can be formed as follows:

$$\mathbf{R}_I = [\mathbf{0}_{N_I \times L_{CP,I}}, \mathbf{I}_{N_I}], \tag{7}$$
$$\mathbf{R}_L = [\mathbf{0}_{N_L \times L_{CP,L}}, \mathbf{I}_{N_L}]. \tag{8}$$

$\mathbf{\Psi}_I \in \mathbb{C}^{(N_L+L_{CP,L})\times(N_L+L_{CP,L})}$ is a diagonal matrix which is used to move the NB-IoT signal to its assigned sub-carriers, and the i-th diagonal element of $\mathbf{\Psi}_I$ is:

$$\mathbf{\Psi}_I(i) = e^{j2\pi(i-L_{CP,L}-1)(M_I-1)/N_L}. \tag{9}$$

At last, the most important variable in this paper, $\mathbf{U}$, is a $(N_L+L_{CP,L}) \times (N_I+L_{CP,I})$ upsampling matrix with its upsampling rate to be G. By setting an appropriate matrix $\mathbf{U}$, we can achieve arbitrary NB-IoT sample duration easily. If we define the NB-IoT sample duration as b times the length of LTE sample[1], the upsampling matrix can be formulated as:

$$\mathbf{U} = \begin{pmatrix} B & 0 & \cdots & 0 \\ 0 & B & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & B \end{pmatrix}, \tag{10}$$

where $B = [1, 1, \cdots, 1]^T_{1\times b}$. Bearing the aforementioned information in mind, the interference terms $\mathbf{v}_I$ and $\mathbf{v}_L$ can be written as:

$$\mathbf{v}_I = \tilde{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}} \mathbf{R}_L \mathbf{A}_L \mathbf{C}_L \hat{\mathbf{F}}_{\mathbf{N_L}} \mathbf{x}_L, \tag{11}$$
$$\mathbf{v}_L = \hat{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}} \mathbf{R}_L \mathbf{\Psi}_I \mathbf{U} \mathbf{A}_I \mathbf{C}_I \mathbf{F}_{\mathbf{N_I}} \mathbf{x}_I. \tag{12}$$

III. Desired Signal and Interference Analysis

In this section, we will first derive the equivalent CFR and interference terms for both NB-IoT and LTE signals with a generalized model by setting an arbitrary $b \in [1, G]$. By defining T_c as the symbol duration for both LTE and NB-IoT[2], the LTE sample duration can be calculated as $T_{s,L} = T_c/N_L$ and NB-IoT sample duration $T_{s,I} = bT_{s,L} = bT_c/N_L$. An example with $b = 2$ and $G = 5$ is shown in Fig. 3. It can be found that the special case in [11] is equivalent to $b = G$ in this model. Another special case $b = 1$ is investigated later in this section, which will show that the desired signal of NB-IoT has no frequency selectivity comparing with [11].

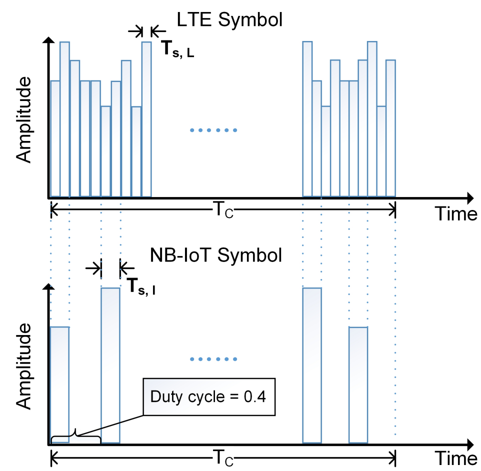


Fig. 3. LTE v.s NB-IoT symbol structure with $b = 2$ and $G = 5$.

1) General case: According to the above assumptions, we can have $L_{CP,L} = GL_{CP,I}$ and thus $\mathbf{R}_L \mathbf{\Psi}_I \mathbf{U} = \bar{\mathbf{\Psi}}_I \bar{\mathbf{U}} \mathbf{R}_I$, where $\bar{\mathbf{\Psi}}_{\mathbf{I}}$ takes the last N_L rows and columns of $\mathbf{\Psi}_{\mathbf{I}}$, and $\bar{\mathbf{U}}$ comprising of the first N_L rows and N_I columns of $\mathbf{U}$. If we define the first term of $\mathbf{y}_I$ in equation (5) as $\mathbf{y}_{I,des}$, then it can be reformed as:

$$\begin{aligned} \mathbf{y}_{I,des} &= \tilde{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}} \bar{\mathbf{\Psi}}_I \bar{\mathbf{U}} \mathbf{R}_I \mathbf{A}_I \mathbf{C}_I \mathbf{F}_{\mathbf{N_I}} \mathbf{x}_I \\ &= \bar{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}} \bar{\mathbf{U}} \mathbf{R}_I \mathbf{A}_I \mathbf{C}_I \mathbf{F}_{\mathbf{N_I}} \mathbf{x}_I, \end{aligned} \tag{13}$$

where $\bar{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}$ takes the first M-th columns of $\mathbf{F}^{\mathbf{H}}_{\mathbf{N_L}}$. As we all know, under the condition that CP length is larger than the length of channel, the insertion and removal of CP could convert the multi-path channel to a circular one, i.e.,

$$\begin{aligned} \mathbf{y}_{I,des} &= \bar{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}} \bar{\mathbf{U}} \mathbf{A}_{cir,I} \mathbf{F}_{\mathbf{N_I}} \mathbf{x}_I \\ &= \frac{1}{\sqrt{G}} \sum_{i=1}^{b} \bar{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L},\mathbf{i}} \mathbf{A}_{cir,I} \mathbf{F}_{\mathbf{N_I}} \mathbf{x}_I, \end{aligned} \tag{14}$$

[1]Hence, the square wave duty cycle of NB-IoT signals is $\frac{b}{G}$. Here we assume b is an integer for simplicity.

[2]Strictly speaking, the overall symbol duration of NB-IoT symbol is $\frac{b}{G}T_c$.

where $\bar{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L,i}}$ comprising of every G-th columns of $\bar{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}$ (i.e., the i-th, $(i+G)$-th, $\cdots$, $[i+(N_I-1)G]$-th column). It can be proved that $\bar{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L,i}} = \mathbf{\Phi}_i \mathbf{F}^{\mathbf{H}}_{\mathbf{N_I}}$, with the k-th ($k \in [1,2,\cdots,M]$) diagonal element of $\mathbf{\Phi}_i$ to be $e^{-j2\pi(i-1)(k-1)/N_L}$. If we define $\mathbf{H}_I = \sqrt{N_I}\text{diag}(\mathbf{F}^{\mathbf{H}}_{\mathbf{N_I}}\tilde{\mathbf{h}}_I)$, where $\tilde{\mathbf{h}}_I = [\mathbf{h}_I, \mathbf{0}_{1\times(N_I-L_{CH,I})}]^T$, $\mathbf{y}_{I,des}$ can be further simplified as:

$$\begin{aligned}\mathbf{y}_{I,des} &= \frac{1}{\sqrt{G}}\sum_{i=1}^{b}\mathbf{\Phi}_i\mathbf{F}^{\mathbf{H}}_{\mathbf{N_I}}\mathbf{A}_{cir,I}\mathbf{F}_{\mathbf{N_I}}\mathbf{x}_I \\ &= \frac{1}{\sqrt{G}}\sum_{i=1}^{b}\mathbf{\Phi}_i\mathbf{H}_I\mathbf{F}^{\mathbf{H}}_{\mathbf{N_I}}\mathbf{F}_{\mathbf{N_I}}\mathbf{x}_I \\ &= \frac{1}{\sqrt{G}}\sum_{i=1}^{b}\mathbf{\Phi}_i\mathbf{H}_I\mathbf{x}_I.\end{aligned} \tag{15}$$

As for the interference from LTE to NB-IoT (i.e., $\mathbf{v}_I$ in equation (11)), it is easy to obtain $\mathbf{v}_I = 0$ since $\tilde{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}$ and $\hat{\mathbf{F}}_{\mathbf{N_L}}$ corresponding to two sets of orthogonal sub-carriers. By defining $\mathbf{\Gamma} = \frac{1}{\sqrt{G}}\sum_{i=1}^{b}\mathbf{\Phi}_i$, the received NB-IoT signal can be represented as:

$$\mathbf{y}_I = \mathbf{\Gamma}\mathbf{H}_I\mathbf{x}_I + \mathbf{n}_I. \tag{16}$$

For the desired LTE signal, i.e., the first term of equation (6), it can be derived as equation (17) by defining $\mathbf{H}_L = \sqrt{N_L}\text{diag}(\hat{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}\tilde{\mathbf{h}}_L)$, where $\tilde{\mathbf{h}}_L = [\mathbf{h}_L, \mathbf{0}_{1\times(N_L-L_{CH,L})}]^T$.

$$\mathbf{y}_{L,des} = \mathbf{H}_L\mathbf{x}_L. \tag{17}$$

While the interference term $\mathbf{v}_L$ in equation (6) can be derived following the same procedures as for $\mathbf{y}_{I,des}$, i.e.,

$$\begin{aligned}\mathbf{v}_L &= \check{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}\bar{\mathbf{U}}\mathbf{A}_{cir,I}\mathbf{F}_{\mathbf{N_I}}\mathbf{x}_L \\ &= \frac{1}{\sqrt{G}}\sum_{i=1}^{b}\mathbf{\Theta}_i\mathbf{H}_I\mathbf{x}_I,\end{aligned} \tag{18}$$

where $\check{\mathbf{F}}^{\mathbf{H}}_{\mathbf{N_L}}$ comprising of the M columns $\in [mod(M_L+N_L-M_I+1,N_L), mod(M_L+N_L-M_I+2,N_L),\cdots,mod(M_L+N_L-M_I+M,N_L)]$ of $\mathbf{F}^{\mathbf{H}}_{\mathbf{N_L}}$, and $\mathbf{\Theta}_i$ is the circularly shifted version of a diagonal matrix, whose m-th ($m \in [1,2,\cdots,M]$) diagonal element is $e^{j2\pi(i-1)(M-m+B_G+1)/N_L}$. The shift length of $\mathbf{\Theta}_i$ is $L_S = M_I - M_L$. It should be noticed that the shift direction depends on the sign of L_S, i.e., shift to the left if $L_S > 0$ while shift to the right if $L_S < 0$. By defining $\mathbf{\Lambda} = \frac{1}{\sqrt{G}}\sum_{i=1}^{b}\mathbf{\Theta}_i$, the received LTE signal can be represented as:

$$\mathbf{y}_L = \mathbf{H}_L\mathbf{x}_L + \mathbf{\Lambda}\mathbf{H}_I\mathbf{x}_I + \mathbf{n}_L. \tag{19}$$

Based on equation (19) and the assumption that channel is power normalized, i.e. $\mathbb{E}(\mathbf{H}_I\mathbf{H}_I^H) = \mathbf{I}_{N_I}$, we can calculate the interference power from NB-IoT to LTE as:

$$\begin{aligned}\mathbf{p} &= \mathbb{E}[\text{diag}(\mathbf{v}_L\mathbf{v}_L^H)] \\ &= \text{diag}(\mathbf{\Lambda}\mathbf{\Lambda}^H).\end{aligned} \tag{20}$$

From equation (16), it can be seen that the equivalent CFR for NB-IoT is no longer the Fourier Transform of its CIR, but the phase shifted version of it. Here we can find that one-tap equalization is applicable as long as the equalization coefficients are updated accordingly. Conversely, the distortion caused by the sampling rate misalignment can be compensated in NB-IoT transmitter by precoding the transmitted signal with a matrix $1/\mathbf{\Gamma}$, and thus the receivers who can only perform traditional one-tap equalization could be used as well. However, the mismatched sampling rate results in an interference from NB-IoT to LTE, as shown in (19), which would degrade the LTE performance. From equation (20), it can be found that the power level of the interference depends on the NB-IoT sample duration as well as the guard band B_G.

2) Special case with $b=1$: Assuming NB-IoT sample duration is as short as that of LTE, we can have the NB-IoT sample length as $T_{s,I} = T_c/N_L$. By implementing $b=1$ into equation (16) and (19), the received NB-IoT and LTE signals can be written as:

$$\mathbf{y}_I = \frac{1}{\sqrt{G}}\mathbf{H}_I\mathbf{x}_I + \mathbf{n}_I, \tag{21}$$

$$\mathbf{y}_L = \mathbf{H}_L\mathbf{x}_L + \frac{1}{\sqrt{G}}\mathbf{\Theta}_1\mathbf{H}_I\mathbf{x}_I + \mathbf{n}_L, \tag{22}$$

where the $\mathbf{\Theta}_1$ in equation (22) is a circularly shifted version of $\mathbf{I}_M$. Similarly, the interference power can be calculated as:

$$\begin{aligned}\mathbf{p} &= \mathbb{E}[\text{diag}(\mathbf{v}_L\mathbf{v}_L^H)] \\ &= \frac{1}{G}\mathbf{I}_{N_I}.\end{aligned} \tag{23}$$

From (21), it can be found that although the sampling rate of NB-IoT UE is different from LTE system, by setting its sample duration as short as LTE UE, the only influence to NB-IoT signal detection is presented as a constant attenuation factor $1/\sqrt{G}$. In addition, according to (23), the power of interference $\mathbf{p}$ is $1/G$ for each assigned LTE sub-carrier regardless of other factors (e.g., guard band between LTE and NB-IoT UE).

In the next section, we will investigate how the parameters $\mathbf{\Gamma}$ and $\mathbf{\Lambda}$ affect the NB-IoT and LTE system performance by means of simulations.

IV. Simulation results

In this section, numerical results are illustrated to investigate the uplink system performance. Specifically, in Section IV-1, the impact of sampling method (i.e., parameter b) and guard band (i.e., B_G) on LTE system in terms of interference power and BER performance will be investigated; while in Section IV-2, the impact of sampling method on NB-IoT system in terms of signal power selectivity and BER performance will be studied. We consider the extended typical urban (ETU) channel defined by 3GPP in all simulations. The DFT sizes are $N_L = 300$ and $N_I = 12$, while the CP lengths (in terms of number of samples) are $L_{CP,L} = 25$ and $L_{CP,I} = 1$, respectively. In addition, it is assumed that NB-IoT UE modulates the signals with Quadrature Phase Shift

Keying (QPSK) scheme and LTE UE with 16-Quadrature Amplitude Modulation (QAM) scheme.

1) LTE performance in the co-existence system: To show the interference from NB-IoT, Fig. 4 illustrates the average mean square error (MSE) over 12 sub-carriers in the assigned LTE RB with $b = [1, 2, 10, 25]$, respectively. Note that when $b = 25$, the system is consistent with the state-of-the-art NB-IoT system in [11]. It can be observed that the

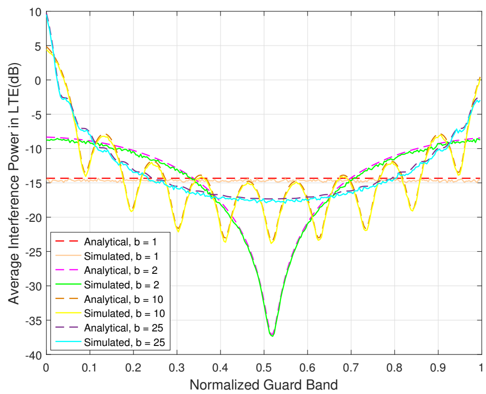


Fig. 4. Average interference power in LTE v.s $N_{B,G}$ with different b.

analytical and simulation results matched perfectly. Generally, the interference level firstly goes down with the increasing of the guard band, and then, start to rise after the guard band is larger than half of the total bandwidth. This is because of the circular property of baseband processing. However, as discussed in the previous section, the interference power is flat over different guard bands when $b = 1$. It is interesting to notice that with different NB-IoT sample durations, the interference falling into LTE sub-carriers varies differently. For example, when LTE and NB-IoT are close to each other (i.e., the normalized guard band $B_{G,N}$ is less than 0.2), the shortest NB-IoT sample duration results in the smallest interference among the four cases; while it generates the largest interference when $B_{G,N} \in [0.4, 0.6]$. A 3D graph to specify the relationship among guard band, NB-IoT sample length and the interference power is plotted in Fig.5. The properties presented in these figures can be served as a reference in the resource selection/scheduling process of in-band/guard-band NB-IoT.

In Fig. 6, the BER v.s E_b/N_0 performance for LTE is illustrated with different $B_{G,N}$ and b. It can be seen that in general, the BER performance of LTE is much better with large guard band, i.e., $B_{G,N} = 0.5$. However, when $b = 1$, the performance does not change with the guard band increasing. This can be explained according to Fig. 4, where the interference power in LTE is flat over different guard bands. Furthermore, with flexible selection of b, we can achieve significant performance gain than the state-of-the-art scenario (i.e., $b = 25$).

2) NB-IoT performance in the co-existence system: Next, let us look at NB-IoT performance. Based on equation (16) we can see that the NB-IoT signal is free of interference no matter

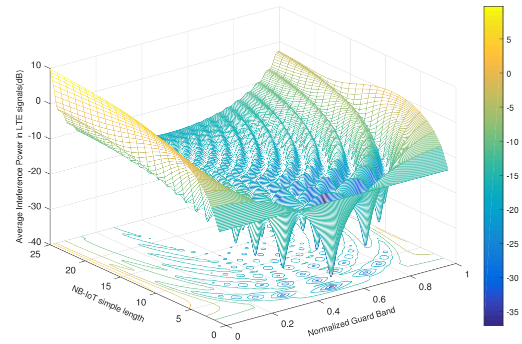


Fig. 5. 3D graph to specify the relationship among guard band, NB-IoT sample length and the generated interference power.

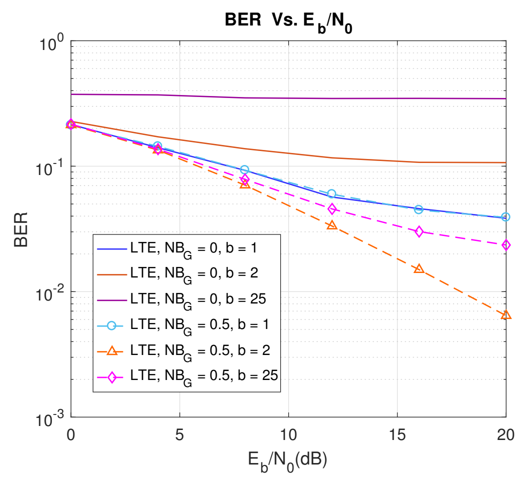


Fig. 6. BER v.s E_b/N_0 of LTE with different $N_{B,G}$ and b.

how b changes, however, the value of b does affect the NB-IoT performance in terms of desired signal power level and distribution. Fig. 7 demonstrates the relationship between the mean of the desired signal power $|\mathbf{\Gamma}|^2$ and b in each NB-IoT sub-carrier. It can be seen that with different sample length, $\mathbf{\Gamma}$

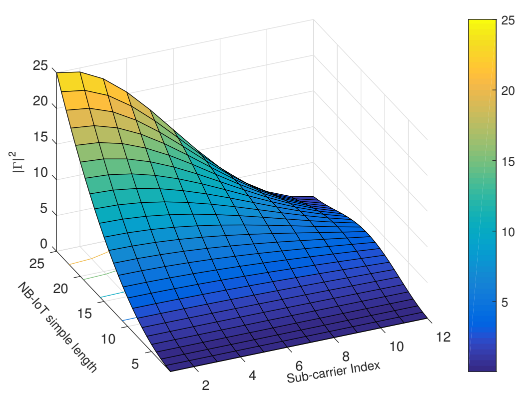


Fig. 7. $|\mathbf{\Gamma}|^2$ v.s b in different NB-IoT sub-carriers.

has vastly different influence on the NB-IoT signals' power. When the sample length b is small, the elements' values in $\mathbf{\Gamma}$

are almost evenly distributed, however, the distortion caused by $\mathbf{\Gamma}$ on the NB-IoT signal is increasing as b becoming larger. We call this as frequency selectivity/signal power selectivity property of $\mathbf{\Gamma}$. In principle, the distortion caused by $\mathbf{\Gamma}$ can be perfectly compensated by setting the one-tap equalization coefficients accordingly. Nevertheless, the updated equalization coefficients will in turn affect the noise power unexpectedly.

Assuming Zero Forcing (ZF) based equalization is implemented. The noise power after equalization can be written as $\mathbf{P}_n = \mathbb{E}(|\mathbf{E}_q \mathbf{n}_I|^2) = \mathbb{E}(|\frac{1}{\mathbf{\Gamma H}_I}|^2)N_0 = |\frac{1}{\mathbf{\Gamma}}|^2 N_0$, where $\mathbf{E}_q$ is the equalization factor and N_0 is the power density of noise $\mathbf{n}_I$. Fig. 8 is depicted in order to have a clear view on how the equalization process could change the noise power. By averaging the coefficients of noise power (i.e., $\frac{1}{|\mathbf{\Gamma}|^2}$) over all the NB-IoT sub-carriers, it can be observed that the average noise power changing with different NB-IoT sample length and reaching to its smallest point when $b = 17 \sim 19$. Note that the state-of-the-art case in [11] is not the optimal scenario in terms of the noise enhancement in NB-IoT signal.

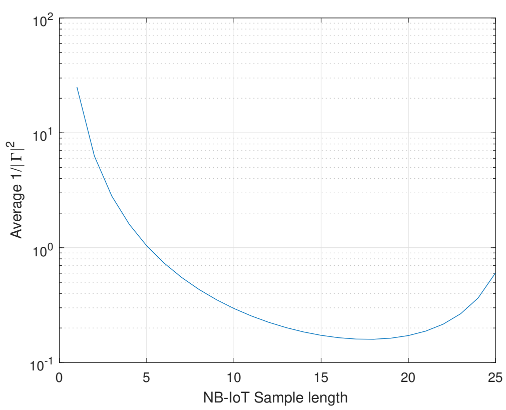


Fig. 8. Average $\frac{1}{|\mathbf{\Gamma}|^2}$ v.s NB-IoT sample length.

The BER v.s E_b/N_0 performance of NB-IoT system is illustrated in Fig. 9 with different $B_{G,N}$ and b. It is apparent that the performance of NB-IoT system is insensitive to the guard band, which is aligned with the derived equation (16). In addition, the worst and the best BER curves occur when b is equal to 1 and 10, respectively. This can be explained by Fig. 8, i.e., larger noise power results in worse SNR with fixed signal power.

V. Conclusion

In this paper, a comprehensive uplink LTE/NB-IoT co-existence system model was established, where an arbitrary NB-IoT sample duration was assumed. Based on this model, the mathematical derivations were carried out to investigate the influence caused by the mismatched sampling rate between the low-end NB-IoT device and LTE UE (and BS). It is revealed that LTE UE suffers from interference generated by NB-IoT signal, and the power of interference is a close-form function of NB-IoT sample length and guard band between assigned LTE and NB-IoT sub-carriers. For NB-IoT signal, although it is free of interference from LTE UE, the desired

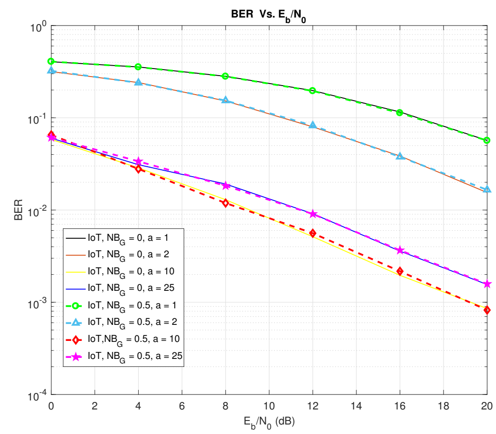


Fig. 9. BER v.s E_b/N_0 of NB-IoT with different $N_{B,G}$ and b.

signal at the receiver side is altered due to the sampling rate mismatching. More specifically, the equivalent CFR of the NB-IoT signal is composed of the multiplication of a phase shift factor and the CFR. Numerical results were performed to show the effectiveness of the proposed system model and derivations. The work in this paper can serve as a valid guidance for NB-IoT deployment and co-existence analysis.

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