Radio Resource Management Scheme in NB-IoT Systems

Hassan Malik, Haris Pervaiz, Muhammad Mahtab Alam, Yannick Le Moullec, Alar Kuusik and Muhammad Ali Imran

Abstract*—Narrowband Internet of Things (NB-IoT) is the prominent technology that fits the requirements of future Internet of Things (IoT) networks. However, due to the limited spectrum (i.e., 180 kHz) availability for NB-IoT systems, one of the key issues is how to efficiently use these resources to support massive IoT devices? Furthermore, in NB-IoT, to reduce the computation complexity and to provide coverage extension, the concept of time offset and repetition has been introduced. Considering these new features, the existing resource management schemes are no longer applicable. Moreover, the allocation of frequency band for NB-IoT within LTE band, or as a standalone, might not be synchronous in all the cells, resulting in intercell interference (ICI) from the neighbouring cells' LTE users or NB-IoT users (synchronous case). In this paper, first a theoretical framework for the upper bound on the achievable data rate is formulated in the presence of control channel and repetition factor. From the conducted analysis, it is shown that the maximum achievable data rates are 89.2 Kbps and 92 Kbps for downlink and uplink, respectively. Secondly, we propose an interference aware resource allocation for NB-IoT by formulating the rate maximization problem considering the overhead of control channels, time offset and repetition factor. Due to the complexity of finding the globally optimum solution of the formulated problem, a sub-optimal solution with an iterative algorithm based on cooperative approaches is proposed. The proposed algorithm is then evaluated to investigate the impact of repetition factor, time offset and ICI on the NB-IoT data rate and energy consumption. Furthermore, a detailed comparison between the non-cooperative, cooperative, and optimal scheme (i.e., no repetition) is also presented. It is shown through the simulation results that the cooperative scheme provides up to 8% rate improvement and 17% energy reduction as compared to the non-cooperative scheme.

***Index Terms*—Narrowband Internet of Things (NB-IoT), radio resource allocation, power allocation, repetition factor, system-level evaluation.**

I. Introduction

By 2020, there will be at least 4 internet-connected devices for every person on earth, i.e., approximately 30 billion devices that constitute the Internet of Things (IoT) [1]. These IoT devices will enable application services like smart homes, body/health monitoring, environmental monitoring, and condition-based maintenance, among many others. However, to create such IoT environments, one of the demands is to maintain stable wireless connectivity between IoT devices with limited resource such as power and bandwidth as well as with increasing system complexity. To meet the demands set forth by the IoT applications, Third Generation Partnership Project (3GPP) has introduced a new radio access technology called Narrowband Internet of Things (NB-IoT) which is considered as a promising step towards 5G IoT evolution [2]. Many key industrial players such as Ericsson, Nokia, Intel and Huawei have shown great interest in NB-IoT and have taken active part in the standardization of NB-IoT [3–7]. NB-IoT is able to provide improved coverage with respect to LTE, massive device connectivity, ultra-low device costs or complexity and low device power consumption [8].

NB-IoT is a long-term evolution (LTE) variant designed specifically for IoT. LTE already has a global footprint and thus supporting and driving IoT adoption through NB-IoT is considered to be a promising solution. Like LTE, NB-IoT is based on orthogonal frequency-division multiple access (OFDMA) with 180 kHz system bandwidth, which corresponds to one physical resource block (PRB) in LTE transmission. With 180 kHz of minimum spectrum requirement, NB-IoT can be deployed in three possible operational modes, i.e, i) as standalone, ii) in the guard carriers of existing LTE/UMTS spectrum, iii) within an existing LTE carrier (in-band) by replacing one or more PRBs. In order to support such flexible deployment scenarios, NB-IoT reuses the LTE design extensively, such as OFDM in downlink and single carrier frequency-division multiple access (SC-FDMA) in uplink. In addition, new features are also added to ensure the demands of IoT based applications. Key design changes from LTE include synchronization sequences, random access preamble, time offset between control and data transmission, repetition for coverage extension, etc. These changes are primarily motivated by the fact that NB-IoT is required to operate on a bandwidth of 180 kHz (i.e., 1 PRB), whereas many control channels in LTE were designed to span multiple PRBs occupying greater bandwidth as compared to 180 kHz. These design changes achieve the IoT application requirements while ensuring best co-existence performance with the existing LTE system.

Furthermore, in NB-IoT, considering the limited computing resources in an IoT device, the concept of time offset between the control channel and the data transmission has been introduced. The time offset between the end of a downlink control packet and the beginning of the associated downlink data transmission is at least 4 ms. Similarly, the time offset between the end of a downlink control packet and the beginning of the associated uplink data transmission is at least 8 ms. Due to the time offset, the downlink control channel transmission and uplink data transmission are coupled and thus require the joint

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optimization of downlink and uplink resources. Furthermore, the peak information rate of both downlink and uplink reduce significantly when the time offsets are taken into account.

Moreover, repeating the transmission of data and the associated control signaling several times has been utilized as a base solution to achieve coverage enhancement in NB-IoT. Since more repetitions enhance the transmission reliability but cause spectral efficiency loss, it is crucial to design an appropriate resource allocation scheme integrated with a proper selection of repetition factor for NB-IoT systems.

Additionally, the allocation of frequency band for NB-IoT within LTE band or as a standalone might not be synchronous in all the cells within the network, resulting in intercell interference (ICI) from the neighboring cells LTE users or NB-IoT users (synchronous case). Therefore, a novel interference aware resource allocation scheme that considers the repetition factor and time offset is highly desirable.

A. Motivation and Related Work

Some preliminary studies investigate the device capacity of NB-IoT such as the number of supported devices [3–5] and the coverage aspects [9–11]. The study in [3] presents the capacity evaluation of both NB-IoT downlink and uplink. The study draws a comparison between SC-FDMA and FDMA with Gaussian Minimum Shift Keying (GMSK) uplink capacity and it is shown that SC-FDMA has 3 times higher maximum spectral efficiency, which translates into a device capacity advantage. Furthermore, the downlink with 15 kHz carrier spacing has also been investigated and it is shown that NB-IoT is able to provide the desired capacity of 52K devices per cell. In [4], capacity evaluation of NB-IoT in an in-band deployment is presented with 12 subcarriers at 15 kHz subcarrier spacing in both downlink and uplink. It is shown that the capacity of the in-band deployed NB-IoT system is 71k devices/cell with an information packet size of 32 bytes. Furthermore, a feasibility study for using 15 kHz subcarrier spacing for NB-IoT uplink is presented in [5]. It is shown that using 15 kHz subcarrier spacing, SC-FDMA will meet the 164 dB MCL target. It is also shown that 15 kHz subcarrier spacing has better co-existence with LTE. Similarly, in [12], an overview of data transmission procedure in terms of control and user plane in NB-IoT has been presented along with the energy and coverage analysis. However, all the above-mentioned studies have not considered the impact of control channels and repetition factor on the performance of NB-IoT.

However, so far, few efforts have been done for the radio resource allocation specific to NB-IoT systems. In [13], the author presented a single-tone scheduling mechanism for NB-IoT uplink users. It has been shown that the proposed scheme is only valid for users with good channel conditions and large packet sizes. Furthermore, the proposed scheme has not considered the effect of ICI which is one of the key performance degradation factor in NB-IoT. Similarly, in [14], performance analysis of resource unit configurations for uplink transmission in the NB-IoT is presented. However, the authors have not considered the effect of repetition factor, control data and ICI on the performance. Furthermore, an efficient small data transmission scheme for NB-IoT to reduce the impact of repetition based on control plane solution has been presented in [15]. In the proposed scheme, the NB-IoT radio resource control (RRC) connection setup process is omitted for higher system capacity. However, the side effects of omitting RRC are yet to be studied in detail. In [16], an uplink link adaptation mechanism is proposed to tune the modulation, coding scheme and the repetition number. It has been shown that the proposed mechanism reduces the active time and resource consumption. However, the impact of time offset, and interference has not been considered.

Therefore, in this paper, the factors that affect cell data rate are explored and an interference aware radio resource allocation algorithm is presented with the consideration of repetition factor for each user, time offset and quality of service (QoS) constraints.

B. Summary of Contributions

To deploy NB-IoT for practical applications, cell data rate, number of supported devices and latency are the key performance measures in which operators are interested. Therefore, it is necessary to evaluate **how the performance of NB-IoT is impacted by the repetition factor, time offset, control channel overhead, radio environment, interference and so on?** Furthermore, due to the limited spectrum resource (i.e. 180 kHz) availability for NB-IoT systems, one of the concerns is **how to efficiently allocate resources to massive IoT device in the available spectrum resource?** One of the key issue, in resource allocation of NB-IoT, is that the highest modulation is fixed to Quadrature Phase Shift Keying (QPSK). In traditional resource allocation algorithms such as in LTE, the rate maximization under the ICI is achieved by applying appropriate power allocation algorithms at the interfering nodes, resulting in improve signal-to-interference-plus-noise ratio (SINR). With improved SINR, the nodes are capable to use higher modulation scheme, resulting in improved spectrum efficiency. However, this is not applicable in NB-IoT. On the other hand, improved SINR will help to reduce the repetition factor in NB-IoT, which is one of the factor affecting the performance of NB-IoT and worth investigating.

To the best of our knowledge, the work presented in this paper is the first comprehensive work on the resource allocation of NB-IoT and considers the aspects that affect the overall system performance. The main contributions of this paper are as follows:

- **Firstly**, we formulate an analytical model for the theoretical upper bound on the achievable data rate of NB-IoT network in a single-cell scenario. Furthermore, the effects of repetition factor and control channels overhead on the data rate of NB-IoT along with the trade-off between data rate, latency and number of supported devices are presented.
- **Secondly**, the work is then extended for a multi-cell scenario to investigate the impact of ICI. Furthermore, to improve the spectrum utilization of NB-IoT and to efficiently allocate the resources to the users, this paper presents an efficient radio resource allocation for NB-IoT. The rate maximization problem is formulated taking

into account the overhead of control channels, time offset and repetition factor. Due to the complexity of finding the globally optimum solution, we provide a sub-optimal method by separating the UE timeslot allocation and power allocation procedures, using a heuristic greedy method for UE timeslot allocation, and using cooperative approach for power allocation. Furthermore, the cooperative power allocation procedure adjusts the power of each users to an appropriate level by cooperating with the interfering user of the neighboring cell, so that maximum system gain can be achieved while not violating the maximum power and QoS constraints.

- **Thirdly**, the proposed resource allocation algorithm is then evaluated by extensive simulations to investigate the impact of repetition factor, time offset and ICI. Furthermore, a detailed comparison between the non-cooperative, cooperative and optimal schemes is also presented along with the comparison of single-cell and multi-cell scenario.

The remainder of the paper is organized as follows. Section II presents the general description of NB-IoT downlink and uplink control and data channels. Section III presents the detailed theoretical analysis of cell data rate in downlink and uplink of NB-IoT in a single-cell scenario. Section IV includes the problem formulation for sum-rate maximization in multi-cell scenario and the proposed resource allocation algorithm is presented in detail. Section V describes the simulation scenario with the parameters and channel propagation models. It also highlights the performance evaluation of the proposed algorithm for different system settings and provides a comprehensive comparison between the cooperative and non-cooperative approaches. Finally, concluding remarks are drawn in Section VI.

II. NB-IoT Overview

NB-IoT design exploits synergies with LTE by reusing the higher layers (RLC, MAC, and RRC), for example, and by aligning numerology (the foundation of the physical layer) in both the uplink and downlink. However, the signaling and control channels for NB-IoT are new. Furthermore, in 3GPP Release 13, frequency division duplexing (FDD) half-duplex type-B is chosen as the duplex mode whereas legacy LTE also supports full-duplex mode [17]. FDD half-duplex means that uplink and downlink are separated in frequency and the user either receives or transmits, i.e, does not perform both operations simultaneously. In addition, between every switch from uplink to downlink or vice versa there is at least one guard subframe in between, where the user has time to switch its transmitter and receiver chain.

The detailed frame structure of both downlink and uplink along with the control channels, extracted from the standard TR45.820 [18], are as follows:

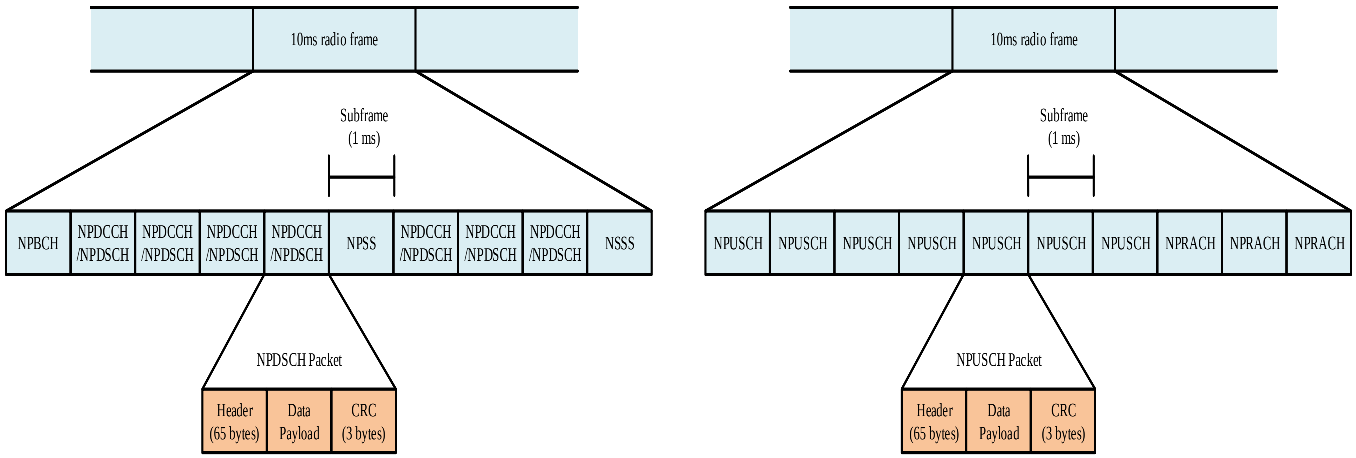
A. Downlink Transmission Scheme

The frame structure of NB-IoT downlink is similar to that of LTE in the time domain with 10 ms length. Each frame consists of 10 subframes of 1 ms length and each subframe consists of two slots with a length of seven OFDM symbols. In the frequency domain, it consists of one PBR with 12 subcarriers having 15 kHz of spacing and normal cyclic prefix (CP). One sub-carrier $\times$ one symbol constitutes one resource element (RE), the smallest transmission unit. RE is the equivalent of one modulation symbol on a subcarrier i.e. 2 bits for QPSK, 4 bits for 16-QAM and 6 bits for 64-QAM. Furthermore, unlike LTE, the NB-IoT downlink physical channels and signals are primarily multiplexed in time. Figure 1a illustrates how the NB-IoT subframes are allocated to different physical channels and signals in downlink. NB-IoT has two physical signals and three physical channels as follows:

1) **Narrowband reference signal (NRS):** NRS is used to provide phase reference for the demodulation of the downlink channel. NRS is transmitted in all subframes that may be used for broadcast or downlink transmission using eight REs per antenna port. For in-band operation, LTE cell-specific reference signals (CRS) are also transmitted in the NB-IoT band, which is not the case in standalone and guard band deployments.
2) **Narrowband primary and secondary synchronization signals (NPSS and NSSS):** NPSS and NSSS are used to perform cell search using time and frequency synchronization and cell identity detection. NPSS is transmitted in subframe 5 in every 10 ms frame, whereas NSSS has a 20 ms periodicity and is transmitted in subframe 9.
3) **Narrowband physical broadcast channel (NPBCH):** NPBCH carries the master information block (MIB) and is transmitted in subframe 0 in every frame. A MIB remains unchanged over the 640 ms transmission time interval (TTI).
4) **Narrowband physical downlink control channel (NPDCCH):** NPDCCH is considered as the core element of the downlink control channels as it carries control information such as paging, UL/DL assignment, random access channel (RACH) response, type of modulation being used for transmission, power control, and so on. It controls the data transmission between the base station (BS) and the user equipment (UE). The size of the control information is fixed at 23 bits, and is encoded over one subframe. Coverage extension is achieved through the use of repetition coding, with support for a maximum of 2048 repetitions.
5) **Narrowband physical downlink shared channel (NPDSCH):** NPDSCH is the main data bearing channel. It consists of user unicast data, some control information and the system information block (SIB). MIB in NPBCH carries all the information to acquire NB-SIB1, whereas NB-SB1 carries all the information to acquire other SIBs. NB-SIB1 is transmitted at a fixed schedule with a periodicity of 2560 ms. If SIB is present in the frame, it always occupies subframe 4 in 16 continuous frames. Repetition coding up to 2048 can be used for coverage enhancement.

B. Uplink Transmission Scheme

In the uplink, NB-IoT supports both single-tone and multi-tone transmissions. Multi-tone transmission uses the same SC-



(a) Downlink Frame Structure

(b) Uplink Frame Structure

Fig. 1: NB-IoT downlink and uplink frame structure

FDMA scheme with a 15 kHz subcarrier spacing and a total bandwidth of 180 kHz with 0.5 ms slot and 1 ms subframe as LTE. However, single-tone transmission supports both 15kHz and 3.75 kHz subcarrier spacing. The 15 kHz mode has similar numerology as in LTE. On the other hand, the symbol duration of the 3.5 kHz subcarrier spacing is four times longer as compared to 15 kHz, which results in a slot length of 2 ms. Each 2 ms slot has 7 OFDM symbols with 48 subcarriers. Furthermore, in NB-IoT uplink, a new resource mapping unit is defined as resource unit (RU). RU is a combination of the number of subcarriers (frequency domain) and number of slots (time domain). For uplink, NB-IoT has one physical signal and two physical channels, as shown in Figure 1b, which are as follows:

- **Demodulation reference signal (DMRS):** In uplink, DMRS are multiplexed with the data so that it is only transmitted in RUs containing data. Depending on the uplink transmission, DMRS is transmitted either in one or three SC-OFDMA symbols per slot.
- **Narrowband physical random access channel (NPRACH):** NPRACH enables the UE to connect to a BS. The BS 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 [19]. NPRACH resource occupy a contiguous set of either 12, 24, 36 and 48 subcarriers and are located on a discrete set of subcarrier ranges. To support coverage extension, the preamble of four symbol groups can be repeated up to 128 times, with a pseudo random frequency separation across repetitions.
- **Narrowband Uplink Shared Channel (NPUSCH):** Contrary to LTE, both the data and 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 hybrid automatic repeat request (HARQ) acknowledgment for downlink data and uses repetition code up to 128.

III. Theoretical Analysis of Cell Achievable Data Rate

In this section, we derive the theoretical upper bound on the data rate of NB-IoT downlink and uplink based on the frames structure presented in the previous section. Data rate is the fraction of the channel capacity used for data transmission. It is a measure of how many units of useful information bits can be communicated in a given amount of time over the communication channel. However, data rate is affected by many parameters, for example, the efficiency of collision avoidance, control overhead, channel utilization and latency. In case of NB-IoT, the data rate is deliberately reduced by expanding the transmission in time with low power. This helps improving the power consumption of the devices but at the same time reduces the coverage area. On the contrary, coverage area extension in NB-IoT is achieved with the help of repetitions. Therefore, in order to accurately model the data rate of NB-IoT, the above mentioned factor needs to be considered. This section presents the theoretical framework for effective data rate analysis of both downlink and uplink in NB-IoT considering the constraint of overhead channels, packet header overheads and repetition codes.

A. Downlink Data Rate

The total effective data rate for NB-IoT downlink is as follows:

$$R_{\text{DL}} = \frac{I_{\text{DL}}}{T_{\text{DL}}} \tag{1}$$

where I_{DL} is the total number of information bits in the downlink and T_{DL} is the total transmission time including all the time taken by downlink overheads and is given as:

$$T_{\text{DL}} = (T_{\text{DSCH}} \times R_{\text{DSCH}} \times T_{\text{CRTL}}) + (T_{\text{CCH}} \times R_{\text{CCH}} \times T_{\text{CRTL}}) \quad (2)$$

Here:

- T_{DSCH} is the time required for the whole NPDSCH including the information bits, header and cyclic redundancy check (CRC) and is given as:

$$T_{\text{DSCH}} = \frac{N_{\text{PKT}} + (N_{\text{PKT}} \times CR)}{(N_{\text{RE}} \times M)} \quad (3)$$

  where N_{PKT} is the total number of transmission bits including header and CRC, CR is the code rate, M is the number of bits per RE and depends on the modulation order such as $M = 2$ for QPSK and $M = 4$ for 16-QAM, N_{RE} is the number of RE available for transmission in a subframe. There is a total of 168 RE's (12 subcarriers $\times$ 14 symbols) in each subframe. However, due to the reference signals, during guard band or standalone operation of NB-IoT, 16 subcarriers are reserved for NRS and therefore, 152 REs are available for transmission. On the other hand, in case of in-band operation, 16 subcarriers are reserved for NRS and 24 subcarriers are for CRS, where it is always assumed that two antenna ports are defined for NRS and 4 antenna ports for CRS. This assumption is necessary because the user gets the actual antenna port information only from reading the MIB-NB. Furthermore, during in-band operation, the first three symbols are reserved for LTE control channels which constitute another 28 subcarriers excluding the RE for reference signals. Therefore, during in-band operation only 100 REs are available for transmission.
- R_{DSCH} is the number of repetitions for NPDSCH, depending on the coverage area.
- T_{CRTL} is the overhead factor due to the control channels of NPSS, NSSS and NPBCH. NPSS and NPBCH have a periodicity of 10 ms while NSSS has a periodicity of 20 ms, therefore, T_{CRTL} is calculated for the frame duration of 20 ms and is given as:

$$T_{\text{CTRL}} = \frac{(T_{\text{frame}})}{T_{\text{frame}} - (T_{\text{PSS}} + T_{\text{SSS}} + T_{\text{BCH}})} \quad (4)$$

  where T_{frame} is the total frame duration, T_{PSS}, T_{SSS} and T_{BCH} are the transmission times required for NPSS, NSSS and NPBCH packets, respectively, during the total frame duration.
- R_{CCH} is the number of repetitions for NPDCCH

Based on Eq.(1)-(4), we have calculated the effective data rate of NB-IoT downlink in standalone and in-band operation with maximum coupling loss (MCL) of 144 dB and 164 dB as presented in Table I. The results presented here consider a maximum supported transport block size (TBS) of 680 bit. According to [18] a header of 65 bytes (520 bits), assuming uncompressed headers, is applied. This means that the block size becomes 1200 bits. Furthermore, a 24 bit cyclic redundancy check (CRC) is appended, resulting in a block size of 1224 bits. The other parameters assumed are also provided in Table I. For example, in order to achieve a coverage of 164 dB MCL in an in-band deployment, the 1224 bits are encoded with a code rate of 1/3, resulting in 1631 bits. These bits are then QPSK modulated, constituting 815 symbols. As there are 100 REs available in each subframe, for simplicity, we assume that 8 subframe are required for the transmission. To achieve the coverage of 164 MCL, it is assumed that these 8 subframes are then repeated 128 times during transmission, resulting in a total of 1024 subframes (1 ms each) with a block error rate (BLER) of 7.43% [9]. Due to the presence of periodic NPSS, NSSS and NPBCH, only 15 subframes are available for transmission during a 20 ms period. Therefore, the transmission time is given by 1024×4/3 = 1362 ms. Furthermore, based on [8], to achieve a coverage of 164 MCL with a BLER of 0.6%, 256 repetitions of NPDCCH are needed, resulting in a transmission time of 256×4/3 = 341 ms. Thus, the total time required for transmission of 680 bits of information with MCL of 164 dB is 341 + 1362 = 1703 ms, achieving an effective data rate of 369.3 bits per second (bps).

TABLE I: NB-IoT downlink effective data rate in different deployment scenarios with a TBS = 680 bits, modulation = QPSK and Code rate = 1/3

Parameters	Standalone		In-band	
MCL (dB)	144	164	144	164
Target SNR (dB)	15.4	-4.6	7.4	-12.6
BLER NPDSCH	8.07 %	9.58 %	9.54 %	7.43 %
BLER NPDCCH	1 %	0.5 %	0.52 %	0.6 %
Repetition NPDSCH	1	32	1	128
Required subframe	6	6	8	8
Duration NPDSCH (ms)	6	250	8	1362
Repetition NPDCCH	1	128	1	256
Duration NPDCCH (ms)	1	165	1	341
Duration Total (ms)	7	415	9	1703
Effective Data Rate (Kbps)	**89.2**	**1.48**	**68.4**	**0.369**

B. *Uplink Data Rate*

In the uplink, the total effective data rate is as follows:

$$R_{\text{UL}} = \frac{I_{\text{UL}}}{T_{\text{UL}}} \quad (5)$$

where, I_{UL} is the total number of information bits in the uplink and T_{UL} is the total transmission time including all the uplink overheads and is given as:

$$T_{\text{UL}} = T_{\text{USCH}} \times R_{\text{USCH}} \times T_{\text{CRTL}} \quad (6)$$

Hereinto:

- T_{USCH} is the time required for the whole NPUSCH including the information bits, header and CRC and is calculated similarly as in downlink with Eq.(3). However, in case of uplink, assuming 15 kHz spacing, due to the presence of DMRS and NPUSCH Format 2 information, the number of REs (N_{RE}) available for transmission are 148 in each subframe, where it is assumed that there are 6 subcarriers for DMRS and 12 subcarriers for NPUSCH Format 2.

- R_{USCH} is the number of repetitions for NPDSCH, depending on the coverage area.
- T_{CRTL} is the overhead factor due NPRACH and NPUSCH Format 2 which contains control information. T_{CRTL} is given as:

$$T_{\text{CTRL}} = \frac{(T_{\text{frame}})}{T_{\text{frame}} - T_{\text{RACH}}} \tag{7}$$

where T_{RACH}, $T_{\text{USCH,2}}$ are the transmission times required for NPRACH and NPUSCH Format 2 packet, respectively, during the total frame duration.

Using the Eq.(5)-(7), Table II presents the effective data rate of NB-IoT uplink in standalone and in-band operation with MCL of 144 dB and 164 dB. The results presented here consider a maximum supported TBS of 1000 bit in uplink as in [18]. The block size with the header and CRC results in 1544 bits. For example, in order to achieve a coverage of 164 dB MCL in an in-band deployment, using the code rate of 1/3 and QPSK modulation results in 1027 symbols. Assuming 15 kHz spacing, there are 148 REs in each subframe, therefore 7 subframes are required for the transmission. To achieve the coverage of 164 MCL with a BLER of 7%, it is assumed that these subframes are then repeated 64 times during transmission, resulting in a total of 448 subframes (1 ms each) [9]. Furthermore, it is assumed that almost 30% uplink resources are reserved for NPRACH as given in [6]. Therefore, based on Eq.(7), the transmission time is $448 \times 1.42 = 637$ ms, achieving an effective data rate of 731.3 bps.

TABLE II: Calculated NB-IoT uplink effective data rate in different deployment scenarios with a TBS = 1000 bits, modulation = QPSK and Code rate = 1/3

Parameters	15 kHz		3.75 kHz	
MCL (dB)	144	164	144	164
Tones	12	12	12	12
Target SNR (dB)	15.4	-4.6	7.4	-12.6
Repetitions NPUSCH	1	64	1	16
Required subframe	7	7	3	3
Duration NPUSCH (ms)	7	448	12	192
Duration Total (ms)	10	637	17	273
Effective Data Rate (Kbps)	**92**	**1.42**	**53.2**	**3.4**

C. Tradeoff between information rate, latency and supported devices

In this section, the system-level performance of the NB-IoT is evaluated through Monte Carlo simulations in terms of effective information rate and latency for a single-cell scenario. The detailed simulation settings along with the traffic model will be presented later in Section V.

First, we evaluate the average information rate per sector that can be achieved by the users in the presence of control channel overhead and repetition factor. Information rate is defined as the number of information bits transmitted per second with all the overhead of control information. Figure 2 shows the cumulative distribution function (CDF) of the average information rate in different deployment scenarios with an information packet size of 45 bytes in uplink and 20 bytes in downlink. The figure reveals that the maximum information rate that can be achieved are 20 Kbps, 32 Kbps and 60 Kbps for in-band, standalone and uplink (15 kHz) scenarios, respectively. However, these rates are significantly lower than the peak data rate of 226.7 Kbps and 250 Kbps in downlink and uplink, respectively, shown in [8]. This is due to the overhead of the control channels, particularly NPDCCH in downlink, which requires an extensive number of repetitions for successful transmission. Furthermore, in uplink, 30% of the resources are reserved for NPRACH and NPUSCH Format 2 packets as in [6]. This results in performance degradation. Moreover, it is also observed that the in-band deployment performance is significantly degraded as compared to the standalone due to the presence of LTE control information.

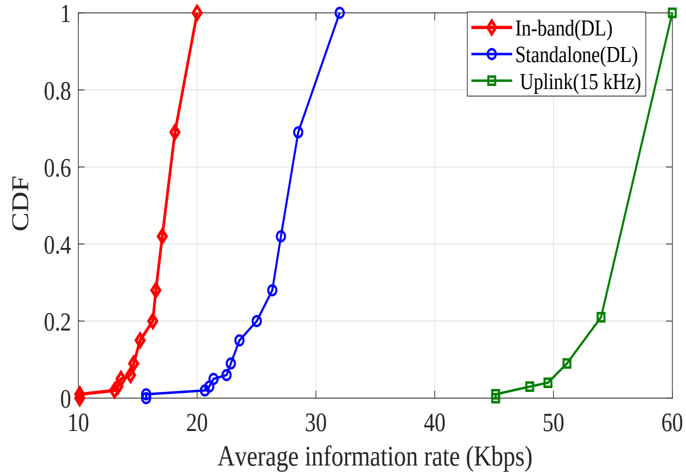


Fig. 2: NB-IoT average information rate per sector in different deployment scenarios

Figure 3 reveals the impact of increase in packet size on the

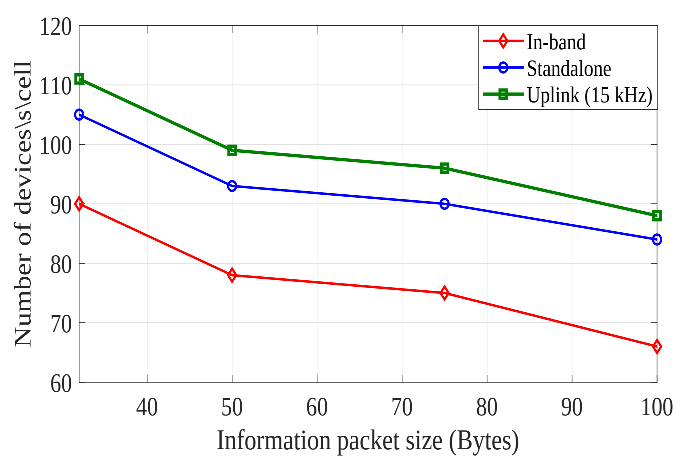


Fig. 3: Number of devices served per second in different deployment scenarios with different information packet sizes

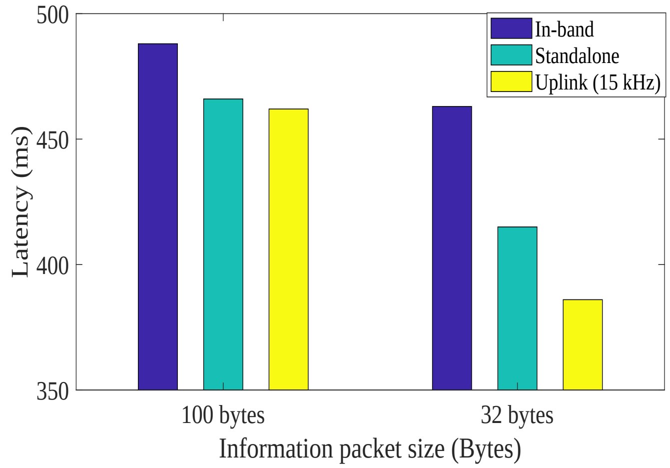


Fig. 4: NB-IoT Latency in different deployment scenarios with different packet sizes

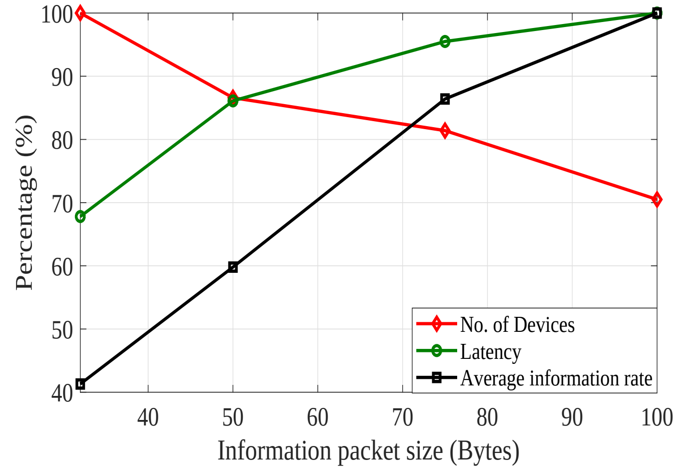


Fig. 5: Percentage increase or decrease in number of supported devices, latency and information rate with varying packet sizes

number of reports per second that a single-cell can successfully support. This corresponds to the number of devices that can be supported by the cell. As a whole, the increase in packet size, no doubt, improves effective data rate by decreasing the overhead cost, but also increases per packet transmission time, resulting in a lower number of supported devices per cell.

Figure 4 presents the latency of NB-IoT deployment in different scenarios with different packet sizes. Latency is defined as the average time required to complete the transmission along with the required overhead control information. It can be seen that with the increase in packet size, the transmission time required for the packet also increases, resulting in increased delay for all the devices in a network. However, increased packet size also improves data rate.

From the above discussion, it is evident that the packet size, number of supported devices, latency and data rate significantly depend on each other. Figure 5 presents the relation between these performance measures in terms of percentage increase or decrease in latency, number of supported devices and data rate with the varying packet sizes as they are in different scales. For this purpose we have assumed that the 32 bytes packet size provide 100% of device support and then plotted the percentage decrease with respect to different packet sizes. Similarly, for latency and data rate, it is assumed that the 100 byte packet size provides 100% latency and data rate. It can be seen that the packet size of 50 bytes is optimal in this case for obtaining a balance between latency and number of supported devices at the cost of data rate. However, the packet size of 70 bytes is the best choice for latency and data rate at the cost of number of supported devices. To obtain an optimal balance of all the three performance measures, namely latency, data rate and number of connected devices, a packet size of 60 bytes is shown to be a more reasonable choice.

IV. Problem Formulation and Solution Approach

In this section, we propose a QoS-aware resource allocation for efficient spectrum utilization of NB-IoT systems in a multi-cell scenario. In the lieu of above discussion, it can be noted that in order to improve the system sum-rate of NB-IoT system, it is crucial to reduce the repetition factor. The repetition factor is based on MCL, where MCL is dependent on SINR and the transmission power of the node is defined similar to Eq.(8) in [6] as follows:

$$\begin{aligned} \text{SINR} &= \text{Tx power} + 174 - \text{Noise figure} \\ &\quad - 10\log_{10}(\text{Bandwidth}) - \text{MCL} \end{aligned} \tag{8}$$

Therefore, the main objective of the resource allocation algorithm is to improve the SINR with the appropriate power level selection in the presence of ICI to reduce the repetition factor required for each user. The scenario assumed in this paper consists of a multi-cell cellular system in which each cell consists of three sectors with a set of BSs $\mathcal{B} = \{1, ..., B\}$ that communicates with NB-IoT user terminals through multicarrier orthogonal channels, such as orthogonal frequency-division multiplexing (OFDM) as shown in Figure 6. For each cell, the total frame duration is divided into a set of time slots $\mathcal{T} = \{1, ..., T\}$, each with 1 ms and consisting of one physical resource block of 180 kHz. Let $\mathcal{I}_b = \{1, ..., I_b\}$ be the set of downlink users of the BS b. The achievable downlink data rate of i_b^{th} user associated with BS b on the t^{th} time slot is given by

$$R_{i_b,t}^b = \log_2\left(1 + \gamma_{i_b,t}^b\right) \tag{9}$$

where $\gamma_{i_b,t}^b$ is the SINR of i_b^{th} downlink user and is given by:

$$\gamma_{i_b,t}^b = \frac{P_{i_b,t}^b h_{i_b,t}^b}{N_0 + I_{i_b,t}}, \forall i_b \in \mathcal{I}_b, b \in \mathcal{B}, t \in \mathcal{T} \tag{10}$$

and where $h_{i_b,t}^b$ is the channel gain between BS b and downlink user of said BS, N_0 is the additive white Gaussian noise (AWGN) and $I_{i_b,t}$ is the inter-cell interference (ICI) received by the user i_b^{th} of BS b in the downlink transmission scheme from the users of the neighboring BSs using the same resource and is given by:

$$I_{i_b,t} = \sum_{k \in \mathcal{B}/b} P_{i_k,t}^k h_{i_b,t}^k, \tag{11}$$

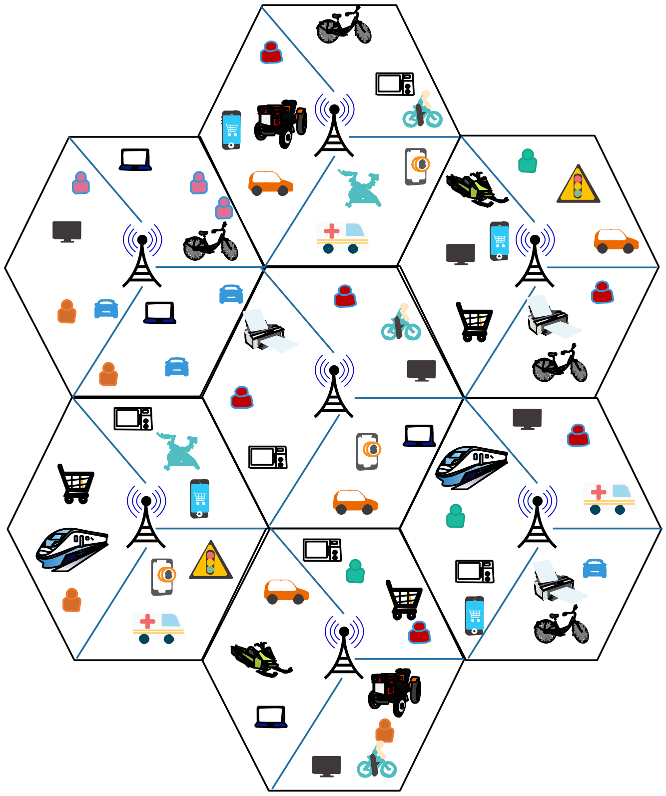


Fig. 6: NB-IoT system scenario

where, $P^k_{i_k,t}$ is the transmit power from the i^{th}_k downlink user of neighboring cell k and $h^k_{i_b,t}$ is the channel gain between the neighboring BS k and the the i^{th}_b downlink user of BS b.

Similarly, let $\mathcal{J}_b = \{1, ..., J_b\}$ be the set of uplink users in the system. The achievable data rate of j^{th}_b user on the t^{th} time slot from the BS b in the uplink transmission scheme is given by

$$R^b_{j_b,t} = \log_2\left(1 + \gamma^b_{j_b,t}\right) \tag{12}$$

where $\gamma^b_{j_b,t}$ is SINR of the j^{th}_b uplink user and is given by:

$$\gamma^b_{j_b,t} = \frac{P^b_{j_b,t} h^b_{j_b,t}}{N_0 + I_{j_b,t}}, \forall j_b \in \mathcal{J}_b, b \in \mathcal{B}, t \in \mathcal{T} \tag{13}$$

where

$$I_{j_b,t} = \sum_{b \in B} P^k_{j_k,t} h^{j_k}_{j_b,t}, \forall j \in \mathcal{J}, k \in \mathcal{B}/b, t \in \mathcal{T} \tag{14}$$

where $h^b_{j_b,t}$ is the channel gain between BS b and the uplink user j_b, N_0 is the AWGN and $I_{j_b,t}$ is the ICI on uplink user j_b of BS b. $h^{j_k}_{j_b,t}$ is the channel gain between uplink user of BS b and uplink user of neighboring BS k. $P^k_{j_k,t}$ is the transmit power of neighboring cell k uplink user j.

With the knowledge of channel state information (CSI), the time slot and power allocation problem that maximizes the system spectral efficiency of both downlink and uplink of a BS b can be formulated as follows:

$$\textbf{P1:} \max_{x_{i_b,t}, x_{j_b,t}, P^b_{i_b,t}, P^b_{j_b,t}} \sum_{i_b \in \mathcal{I}_b} \sum_{j_b \in \mathcal{J}_b} \sum_{t \in \mathcal{T}} x_{i_b,t} R^b_{i_b,t} + x_{j_b,t} R^b_{j_b,t} \tag{15}$$

subject to

$$\sum_{i_b \in \mathcal{I}_b} x_{i_b,t} \leq 1, \ \forall t \tag{16}$$

$$\sum_{j_b \in \mathcal{J}_b} x_{j_b,t} \leq 1, \forall t \tag{17}$$

$$\sum_{t \in \mathcal{T}} x_{i_b,t} R^b_{i_b,t} \geq R_{i_b,\min}, \quad \forall i_b \tag{18}$$

$$\sum_{t \in \mathcal{T}} x_{j_b,t} R^b_{j_b,t} \geq R_{j_b,\min}, \quad \forall j_b \tag{19}$$

$$\sum_{i_b \in \mathcal{I}_b} \sum_{t \in \mathcal{T}} x_{i_b,t} P^b_{i_b,t} \leq P^b_{\max}, \forall b \tag{20}$$

$$\sum_{t \in \mathcal{T}} x_{j_b,t} P^b_{j_b,t} \leq P_{j_b,\max}, \forall j_b \tag{21}$$

where $P^b_{\max}$ and $P_{j_b,\max}$ are the maximum transmission powers of the BS b in the downlink transmission scheme and j^{th}_b user in the uplink transmission scheme, respectively. $x_{i_b,t}$ and $x_{j_b,t}$ are the time slot allocation indicators for the downlink and uplink transmission schemes, where $x_{i_b,t}$ and $x_{j_b,t}$ are equal to 1, if the t^{th} time slot is allocated to the user, and 0, otherwise. $R_{i_b,\min}$ and $R_{j_b,\min}$ are the minimum rate requirements for the downlink and uplink users to ensure quality of service (QoS) requirements.

The problem **P1** formulated in (15)-(21) is a mixed integer non-linear program (MINLP) due to the presence of binary time slot allocation variables. We can solve the problem **P1** in an iterative manner. In the first stage, we evaluate MCL based on the SINR of each user with the maximum possible transmission power and then the corresponding repetition factor is determined. After that, the time slots for NPDCCH and data transmission in both downlink and uplink transmission schemes are assigned with the required repetition factor and also checks the time offset constraint between NPDCCH and data transmissions. In the second stage, we can optimise the power allocation jointly in both downlink and uplink transmission schemes in order to maximise the system sum rate for the given time slot allocation variable.

A. Time Slot Allocation

Furthermore, the aforementioned problem formulated in **P1** is combinatorial in nature due to the binary variables $x_{i,b,t}$ and $x_{j,b,t}$, which makes the formulated problem intractable [20]. It is not possible to find a computationally efficient and tractable optimal solution with a large number of users and time slots. Consequently, instead of seeking the global optimal, we have solved the problem with a sub-optimal iterative algorithms based on heuristic greedy approach for the time slot allocation. In [21], it has been shown that many multi-carrier resource allocation problems satisfy a time sharing property for the sufficiently large number of resource blocks, and the near or upper-bound of the optimal solution can be obtained via dual decomposition method. Unfortunately, the complexity of the dual decomposition technique is still high for practical systems [20]. In order to obtain an efficient solution with suitable complexity, we relax the time slot allocation variable to take any value between 0 and 1 such that $x_{i_b,t} \in [0,1]$ and $x_{j_b,t} \in [0,1]$ in order to make the formulated problem as standard convex optimization [22], [23].

It can also be easily verified that the relaxed problem is convex and has no duality gap [24] [25]. Consequently, the Karush-Kuhn-Tucker conditions are necessary and sufficient for optimality of the relaxed problem [24]. With this time sharing relaxation, a greedy time slot allocation procedure is proposed where time slots are allocated based on the highest channel gain in NB-IoT system as follow:

$$x_{i_b,t} = \begin{cases} 1, & \text{if } \; i_b^* = \arg\max_{i_b \in I_b} h^b_{i_b,t}, \\ 0, & \text{otherwise }, \end{cases}$$
$$x_{j_b,t} = \begin{cases} 1, & \text{if } \; j_b^* = \arg\max_{j_b \in J_b} h^b_{j_b,t}, \\ 0, & \text{otherwise }. \end{cases} \tag{22}$$

B. Joint Downlink/Uplink Power Allocation for Given Time Slot Allocation

For the given time slot allocation, the power allocation problem can be decoupled into downlink power allocation and uplink power allocation problems. Thus, the downlink power allocation can be formulated as follows:

$$\max_{P^b_{i_b,t}} \sum_{t \in \mathrm{T}} \log_2 \left(1 + \frac{P^b_{i_b,t} h^{\sim}_{i_b,t}}{N_0 + \sum_{b \in B} I_{i_b,t}}\right)$$
$$\text{s.t.} \quad (18) \text{ and } (20), \tag{23}$$

where $h^{\sim}_{i_b,t} = \{h^b_{i_b,t} : x_{i_b,t} = 1\}$.

Similarly for uplink,

$$\max_{P^b_{j_b,t}} \sum_{t \in \mathrm{T}} \log_2 \left(1 + \frac{P^b_{j_b,t} h^{\sim}_{j_b,t}}{N_0 + \sum_{b \in B} I_{j_b,t}}\right)$$
$$\text{s.t.} \quad (19) \text{ and } (21), \tag{24}$$

where $h^{\sim}_{j_b,t} = \{h^b_{j_b,t} : x_{j_b,t} = 1\}$.

It can be noted that the problems in (23) and (24) are still non-convex due to the presence of time slot and power allocation variables in the denominator, the expression for achievable rate is still non-convex even with the relaxation of time slot allocation variables and introduction of auxiliary power allocation variable. Hence for better tractability, we take a lower bound approximation such that the user can achieve their minimum rate requirement even when the received aggregate interference is maximum using the reference user concept as outlined in [26], i.e., $\sum_{b \in B} I_{i_b,t} = \arg\max_{i_b \in I_b} I_{i_b,t} = I_t$. This lower bound approximation is commonly used in the literature for better tractability such as [26] [27]. Using the lower bound approximation of the achievable rate, time slot allocation variable and auxiliary power allocation variable, the optimisation problem in (23) and (24) can be reformulated which can be solved using the standard convex optimisation methods with the strong duality [28]. Thus, for a given time slot allocation variable and the maximum interference threshold, I_t, the efficient power allocation can be obtained using the Lagrangian decomposition method as follows:

$$\mathcal{L}(\lambda, \mu, \{P^b_{i_b,t}\}) = \sum_{t \in \mathrm{T}} \log_2 \left(1 + \frac{P^b_{i_b,t} h^{\sim}_{i_b,t}}{N_0 + I_t}\right)$$
$$-\mu\Big(\sum_{i_b \in \mathcal{I}_b} \sum_{t \in \mathcal{T}} P^b_{i_b,t} - P^b_{\max}\Big) - \lambda_{i_b}\Big(R_{i_b,\min} - \sum_{i_b \in \mathcal{I}_b} \sum_{t \in \mathcal{T}} R^b_{i_b,t}\Big) \tag{25}$$

where λ_{i_b} and μ_{i_b} are the Lagrange multipliers. The Kuhn-Tucker condition for the optimal solution is

$$\left.\begin{aligned} \frac{\partial \mathcal{L}}{\partial P^b_{i_b,t}} = 0 \;\; \text{if} \;\; P^b_{i_b,t} > 0 \\ \frac{\partial \mathcal{L}}{\partial P^b_{i_b,t}} \leq 0 \;\; \text{if} \;\; P^b_{i_b,t} = 0 \end{aligned}\right\} \tag{26}$$

Let's define $[x]^+ := \max(0, x)$. The power allocation for the upper bound and lower bound approximation can be expressed respectively, as follow:

$$P^b_{i_b,t}{}^{(opt)} = \left[\frac{1 + \lambda_{i_b}}{\mu \ln(2)} - \frac{N_0}{h^{\sim}_{i_b,t}}\right]^+, N_0 \gg I_t$$
$$P^b_{i_b,t}{}^{(opt)} = \left[\frac{1 + \lambda_{i_b}}{\mu \ln(2)} - \frac{I_t}{h^{\sim}_{i_b,t}}\right]^+, N_0 \ll I_t \tag{27}$$

where the Lagrangian multipliers λ_{i_b} and μ for the $k+1^{th}$ iteration can be updated as follow:

$$\mu^{k+1} = \mu^k - \triangle s \left(\sum_{i_b \in \mathcal{I}_b} \sum_{t \in \mathcal{T}} P^b_{i_b,t} - P^b_{\max}\right), \forall b,$$
$$\lambda^{k+1}_{i_b} = \lambda^k_{i_b} - \triangle s\Big(R_{i_b,\min} - \sum_{i_b \in \mathcal{I}_b} \sum_{t \in \mathcal{T}} R^b_{i_b,t}\Big), \forall i, \tag{28}$$

where $\triangle s$ is the step size. This is an efficient solution if the constraints in (18) and (20) are satisfied.

Similarly, at a given user power allocation of the uplink users for the neighboring cells meaning the maximum interference threshold, i.e., $\sum_{b \in B} I_{j_b,t} = I_t$, an efficient uplink power allocation for the upper bound and lower bound approximation can be obtained, respectively, as follow:

$$P^b_{j_b,t}{}^{(opt)} = \left[\frac{1 + \lambda_{j_b}}{\mu_{j_b} \ln(2)} - \frac{N_0}{h^{\sim}_{j_b,t}}\right]^+, N_0 \gg I_t$$
$$P^b_{j_b,t}{}^{(opt)} = \left[\frac{1 + \lambda_{j_b}}{\mu_{j_b} \ln(2)} - \frac{I_t}{h^{\sim}_{j_b,t}}\right]^+, N_0 \ll I_t, \tag{29}$$

where μ_{j_b} are the Lagrangian multipliers of the jth user that should satisfy the constraint in (19) and (21). The detailed algorithm is listed in Algorithm I.

C. Cooperative Approach

It can be seen that with the increase in transmit power, the interference on the neighboring cell receiver will also increase. In the cooperative approach, we have modeled it as a cooperative game where each transmitter cooperates with the transmitter of the neighboring cell that uses the same time slot and produces highest interference. In this regard, we have imposed a maximum interference threshold constraint I_t such that the total ICI caused by the neighboring cell user sharing the same time slot should always be less than or equal to I_t. The transmit power of the downlink user that can satisfy the minimum rate requirement is calculated as

$$\sum_{t=1}^{|\overline{T}_{i_b}|} \log_2\left(1+\frac{P^b_{i_b,t}h^{\sim}_{i_b,t}}{N_0+\sum_{b\in B} I_{i_b,t}}\right) \geq R_{i_b,\min}, \tag{30}$$

where $|\overline{T}_{i_b}|$ is the total number of time slots allocated to the downlink user i_b and $\sum_{b\in B} I_{i_b,t} = \arg\max_{i_b\in I_b}(I_{i_b,t})$ and for the lower bound solution, it can be assumed that $\sum_{b\in B} I_{i_b,t} = I_t$. The lower bound formulation for (30) in order to satisfy the minimum rate requirement can be achieved at the equality and can be rewritten as,

$$\prod_{t=1}^{|\overline{T}_{i_b}|} \log_2\left(1+\frac{\hat{P}^b_{i_b,t}h^{\sim}_{i_b,t}}{N_0+I_t}\right) = R_{i_b,\min}, \tag{31}$$

From (27), the $P^b_{i_b,t}$ for the interference limited case can be given by $\hat{P}^b_{i_b,t} = \left[\frac{1}{\underline{\lambda}_{i_b}} - \frac{N_0+I_t}{h^{\sim}_{i_b,t}}\right]^+$, where $\underline{\lambda}_{i_b} = \frac{\mu\ln(2)}{1+\lambda_{i_b}}$ is the Lagrangian multiplier corresponding to the case where the downlink user can only attain its minimum rate. (31) can be rewritten as follow:

$$\prod_{t=1}^{|\overline{T}_{i_b}|} \log_2\left(1+\left[\frac{1}{\underline{\lambda}_{i_b}} - \frac{N_0+I_t}{h^{\sim}_{i_b,t}}\right]\times\frac{h^{\sim}_{i_b,t}}{N_0+I_t}\right) = R_{i_b,\min},$$

$$\prod_{t=1}^{|\overline{T}_{i_b}|} \log_2\left(\frac{h^{\sim}_{i_b,t}}{\underline{\lambda}_{i_b}(N_0+I_t)}\right) = R_{i_b,\min},$$

$$\prod_{t=1}^{|\overline{T}_{i_b}|} \left(\frac{h^{\sim}_{i_b,t}}{\underline{\lambda}_{i_b}(N_0+I_t)}\right) = 2^{R_{i_b,\min}},$$

Algorithm I: Iterative Efficient and Reliable Radio Resource Management Procedure for NB-IoT Systems

Initialization:
Set $P^b_{i_b,t} = 0.01$W and $P^b_{j_b,t} = 0.01$W
Set $iter = 1$ and $\mu = 10^{-1}$, $\lambda_{i_b} = 10^{-3}$, $\lambda_{j_b} = 10^{-3}$
Set $\epsilon = 10^{-2}$
Timeslot allocation:
$h^{\sim}_{i_b,t} = \arg\max_{i_b\in I_b}(h^b_{i_b,t})$
$h^{\sim}_{j_b,t} = \arg\max_{j_b\in J_b}(h^b_{j_b,t})$
repeat
Compute $P^b_{i_b,t}$ and $P^b_{j_b,t}$, $\forall i_b, j_b, t$ using (27) and (29), respectively.
Update dual variables μ, λ_{i_b} and λ_{j_b} using subgradient method similarly as given in (28).
$iter = iter + 1$
until Convergence (Stopping Criterion regarding ϵ is satisfied.)

$$\prod_{t=1}^{|\overline{T}_{i_b}|} \left(\frac{y_{i_b,t}}{\underline{\lambda}_{i_b}}\right) = 2^{R_{i_b,\min}},$$

$$2^{-R_{i_b,\min}} \prod_{t=1}^{|\overline{T}_{i_b}|} y_{i_b,t} = \underline{\lambda}_{i_b}{}^{|\overline{T}_{i_b}|}$$

$$\underline{\lambda}_{i_b} = \left(2^{-R_{i_b,\min}} \prod_{t=1}^{|\overline{T}_{i_b}|} y_{i_b,t}\right)^{1/|\overline{T}_{i_b}|} \tag{32}$$

For the given time slot allocation and the interference threshold I_t, the optimal downlink transmission power for BS b can be computed using the following water-filling equations as below:

$$\tilde{P}^b_{i_b,t} = \hat{P}^b_{i_b,t} + \left(\mu - \frac{N_0+I_t}{h^{\sim}_{i_b,t}} - \hat{P}^b_{i_b,t}\right)^+,$$

$$\sum_{i_b\in\mathcal{I}_b}\sum_{t\in\mathcal{T}}\left(\mu - \frac{N_0+I_t}{h^{\sim}_{i_b,t}} - \hat{P}^b_{i_b,t}\right) = P^b_{\max} - \sum_{i_b\in\mathcal{I}_b}\sum_{t\in\mathcal{T}}\hat{P}^b_{i_b,t} \tag{33}$$

As stated the downlink transmit power is computed based on the predetermined interference threshold, I_t. This provision allows for the transmit power to be controlled dynamically as follows:

$$\overline{P}_{i_b,t} \leq \frac{I_t}{h^b_{i_b,t}} \tag{34}$$

Similarly, we can also compute the transmission power for the uplink users j_b on the similar lines as well.

It is important to highlight that our proposed radio resource management procedure for NB-IoT systems can provide a wide range of solutions varying from the upper bound to the lower bound solution, It can be obtained by varying the maximum interference threshold I_t from zero to the acceptable (or practical) values to provide the network operators some design insight to select the appropriate interference mitigation mechanism in correspondence to achieving a specific system performance such as system sum rate.

V. Performance Evaluation

To conduct the performance analysis, we have considered standalone deployments of NB-IoT with a bandwidth of 180 kHz in a typical LTE cell. The scenario is a regular grid of tri-sector sites with inter-site distance of 500 m. The network is assumed to be synchronized, and NB-IoT is deployed with the same PRB in all cells. This means that only the intercell interference from the neighboring cell NB-IoT users affects the system performance in both downlink and uplink.

A. Simulation Setup

The simulation assumptions that closely follows 3GPP standards [18] are presented in Table III. The full 180 kHz bandwidth, i.e. 12 subcarriers at 15 kHz subcarrier spacing in both downlink and uplink, is used for the analysis. For uplink, this is known to perform worse than single tone e.g. 3.75 kHz or 15 kHz, so the achieved performance in this study yields lower bounds as compared to what can be achieved with single

TABLE III: Simulation Assumptions

Parameters	Assumptions
Cell layout	Hexagonal grid, 3 sectors per site
Frequency band	900 MHz
Inter-site Distance	500 m
User distribution	Users dropped uniformly in entire cell
BS transmit power	32 dBm (3 dB boosting applied)
UE Tx power	23 dBm
Pathloss Model	L= I + 37.6 $\log_{10}(R)$, I=120.9 for the 900 MHz band where R in kilometers
Shadowing standard deviation	8 dB
SC distance	110 m
SC between cell-sites	0.5
SC between cell sectors	1.0
BS antenna gain	18 dBi
UE antenna gain	-4 dBi
BS cable loss	3 dB
Building penetration loss	40 dB
Noise figure at BS	5 dB
Noise figure at UE	3 dB
Noise power spectral density	-174 dBm/Hz

tone NB-IoT systems and this is a more realistic assumption when investigating NB-IoT uplink performance [8].

For the simulation, the repetition factor is computed based on MCL, such that the same information is repeated R times. Transmissions are done blindly, i.e. without HARQ feedback. Repetitions are clearly not required when the coupling loss is low since a very robust modulation and coding scheme (MCS) is always used. Moreover, too aggressive repetitions will cause unnecessary interference, hence would have a negative impact on the error rates. Simulations have therefore been run with multiple coverage classes, defined by the coupling loss. The number of repetitions assumed with different MCL values are presented in Table IV.

TABLE IV: Coverage classes with repetition factor

MCL	Repetition
Below 145 dB	1
146 to 148 dB	2
149 to 151 dB	4
152 to 154 dB	8
155 to 157 dB	16
158 to 160 dB	32
161 to 163 dB	64
Above 164 dB	128

1) Traffic Model: The applied traffic models are according to TR45.820 [18] annex E, Mobile Autonomous Reporting (MAR) periodic traffic model. The application payload size is Pareto distributed with parameters: alpha = 2.5, minimum (beta) = 20 bytes, cutoff = 200 bytes. We have assumed an average packet size of 45 bytes for uplink and 20 bytes for downlink as they are usually not very large. According to [18], a header of 65 bytes and 3 bytes CRC field are also applied. Furthermore, all users apply the QPSK and 1/3 coding scheme.

The inter-arrival time is distributed over three categories of periodic transmissions with constant inter-arrival times of one day, two hours, one hour and 30 minutes as in [18]. The respective proportions of devices are 40%, 40%, 15%, and 5%. Assuming, 52K (52547) devices per cell, this gives 143 events (reports) per second as calculated in [4].

B. Simulation Results

In this section, the system-level performance of the NB-IoT system is evaluated through Monte Carlo simulations in terms of effective information rate, average repetition and average energy consumption. With the settings presented in Table III, the simulation is run for different users uniformly distributed over the cell and generates results for over 500 random iterations.

Figure 7 presents the comparison between the single-cell and multi-cell scenarios in downlink (stand-alone mode) and uplink. It can also be noted that, in a multi-cell environment, under the intracell interference, the performance of NB-IoT reduces significantly. For example, it can be seen that the minimum information rate in single-cell downlink with stand-alone mode is 16 Kbps, whereas, in multi-cell scenario, the information rate drops to 6 Kbps. Similarly for uplink, the information rate drops from 45 Kbps to 28 Kbps. As a whole, a performance degradation of 35% and 23 % is observed in downlink and uplink, respectively.

Figure 8 shows the cumulative distribution function (CDF) of the average effective information rate per sector for all the three cases i.e, no repetition, non-cooperative and co-operative schemes of both downlink and uplink. It can be seen that there is a significant degradation in performance with the non-cooperative scheme. This is because each user tries to maximize its SINR and introduces extreme ICI on the neighboring users. This results in an increased number of repetitions. However, with the cooperative scheme, the overall performance of the system is improved by 8% in downlink and uplink for each sector. The gain stems from the reduction in ICI and improved SINR at both cooperative nodes. Furthermore, it can be observed from Figure 8 that the point where the performance of non-cooperative scheme is average, more gain is achieve in the cooperative scheme

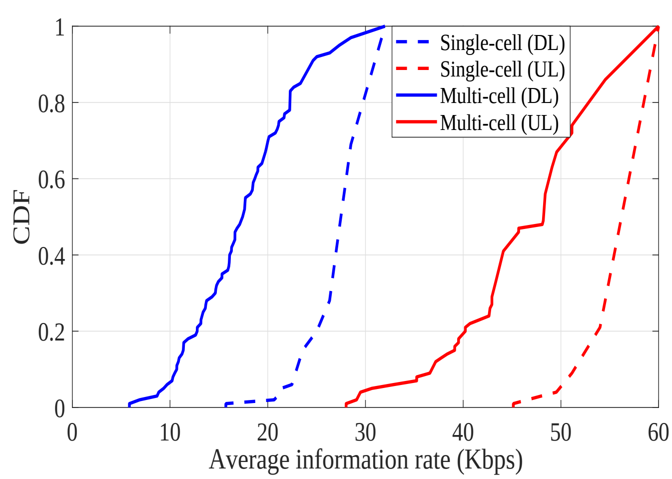


Fig. 7: Comparison between single-cell (downlink (standalone mode) and uplink (15 kHz)) and multi-cell scenario (non-cooperative) to highlight the impact of ICI

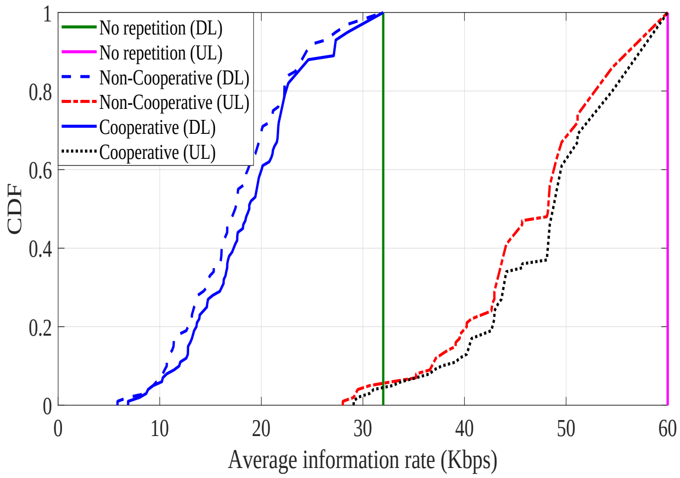


Fig. 8: Effective information rate (Kbps) per sector

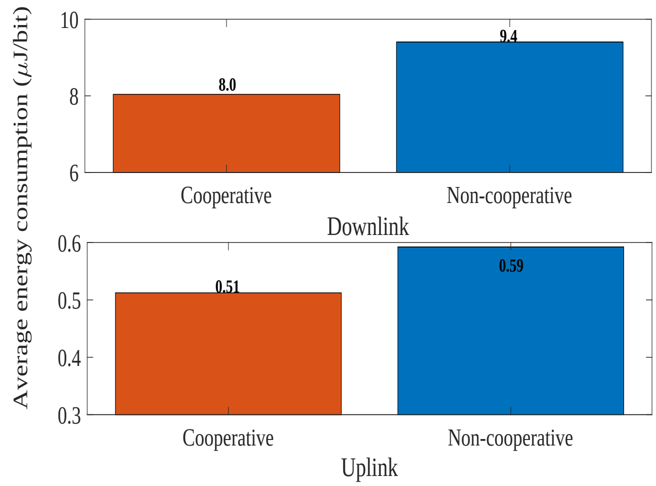


Fig. 10: Average energy consumption per sector

as the SINR of the nodes are in a range where both nodes can cooperate to achieve the best possible repetition factor, resulting in improved transmission rate. For example, in Figure 8, when the average rate in non-cooperative scheme is 45 Kbps, it is around 49 Kbps with the cooperative scheme. Thus results in up to 9% improvement in information rate with the proposed scheme.

Figure 9 presents the average repetition in both non-cooperative and cooperative schemes, it can be seen that with the non-cooperative approach, a significant reduction in repetition is achieved. However, it can be noted that repetition in downlink is higher as compared to uplink. This is because in uplink, the transmission power is significantly lower than in downlink, therefore, the effect of ICI is not that significant. However, it can be seen that in both downlink and uplink, up to 13% reduction in repetition is achieved with the cooperative approach.

Figure 10 presents the average energy consumption per sector in transmission mode by all the users. With the reduction in repetition and improved SINR in the cooperative approach, energy consumption is also significantly reduced. It can been

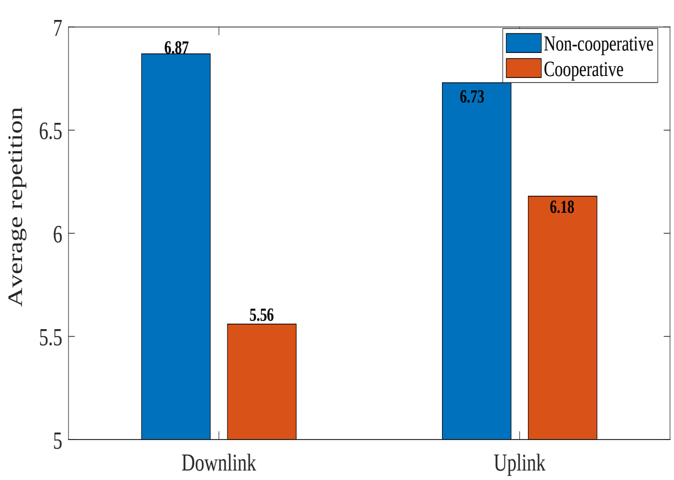


Fig. 9: Average repetition per sector

noted that up to 17% reduction in energy consumption is achieve in downlink and 15% in uplink as compared to the non-cooperative case.

VI. Conclusion

In this paper, we have firstly presented a detailed theoretical analysis of downlink and uplink cell effective data rate based on NB-IoT. From the conducted theoretical analysis, it can be seen that with 144 dB MCL, the maximum achievable effective data rates after adding all the overheads are 89.2 Kbps and 68.4 Kbps for standalone and in-band NB-IoT deployments, respectively. On the other hand, in uplink with 15 kHz spacing, the maximum achievable effective data rate is 92 Kbps. Nevertheless, the results show a degradation of 35% in downlink and 23% in uplink in a multi-cell scenario due to ICI. To address this, we have also presented an efficient resource allocation for NB-IoT with cooperative approaches. It is shown through simulation results that the proposed scheme provides up to 8% improvement in information rate and 17% reduction in energy consumption. These improvements are achieved due to the reduction in the repetition factor. From the results, it can also be concluded that the cost of providing higher data rates with NB-IoT is not only a lower number of supported devices per sector, but also higher delays. Therefore, to provide a suitable solution for the different IoT use-case scenarios, one has to jointly optimize the required data rate, delay, and device density and allocate the resource accordingly.

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