Radio Resource Management in NB-IoT Systems: Empowered by Interference Prediction and Flexible Duplexing

Hassan Malik, Muhammad Mahtab Alam, Haris Pervaiz, Yannick Le Moullec, Anwer Al-Dulaimi, Sven Pärand, and Luca Reggiani

ABSTRACT

NB-IoT is a promising cellular technology for enabling low cost, low power, long-range connectivity to IoT devices. With the bandwidth requirement of 180 kHz, it provides the flexibility to deploy within the existing LTE band. However, this raises serious concerns about the performance of the technology due to severe interference from multi-tier 5G HetNets. Furthermore, as NB-IoT is based on HD-FDD, the symmetric allocation of spectrum band between the downlink and uplink results in underutilization of resources, particularly in the case of asymmetric traffic distribution. Therefore, an innovative RRM strategy needs to be devised to improve spectrum efficiency and device connectivity. This article presents the detailed design challenges that need to be addressed for the RRM of NB-IoT and proposes a novel framework to devise an efficient resource allocation scheme by exploiting cooperative interference prediction and flexible duplexing techniques.

INTRODUCTION

Narrowband-IoT (NB-IoT) is an LTE based cellular technology with a system bandwidth of 180 kHz for supporting massive device connectivity with low-power and low-cost for delay tolerant Internet of Thing (IoT) applications. The limited bandwidth requirement of NB-IoT enables the deployment of this technology in three possible modes, i.e., stand-alone, in-band and guard-band. For a stand-alone deployment, NB-IoT can operate as a dedicated carrier on a GSM channel of 200 kHz. However, for in-band and guard-band deployments, NB-IoT operates on one physical resource block (PRB) within LTE transmission. The in-band deployment mode would be more advantageous as it uses the already existing infrastructure and can be deployed as a firmware upgrade rather than deploying new hardware. Besides the basic LTE structure, some new features have been introduced in NB-IoT in order to meet IoT requirements and ensure the best coexistence with the LTE system. As most of the LTE control channels were designed to span multiple PRBs using larger bandwidth than that of NB-IoT, the synchronization sequences, random access procedure and control channel structures have been modified. Other changes include a time offset between control and data transmission for reducing complexity, the use of the lowest modulation and coding scheme (i.e., maximum allowed Quadrature Phase Shift Keying (QPSK)), retransmissions for extended coverage, and so on. More details on the insight of these design changes for NB-IoT can be found in the standard [1].

Besides the advantages of NB-IoT, some issues still need to be investigated. One of the key issues is: *how to efficiently use the meagre available spectrum resources (i.e., one PRB) for massive user connectivity in NB-IoT systems?* As NB-IoT is expected to operate in the same frequency band as LTE, this raises several design challenges for the allocation of radio resource to the IoT devices, especially in future 5G heterogenous networks (HetNets) comprising multiple small-cells operating under the umbrella of macro-cells. In this article, we describe the most critical design challenges for the radio resource management (RRM) functionalities of NB-IoT, as well as the envisioned solutions in order to describe how the different RRM functionalities should work for addressing the ambitious connectivity of IoT applications. The scope of this article is further extended to provide a novel approach for some of the issues of RRM design (i.e., inter-cell interference and asymmetric traffic between the downlink and uplink) using recently introduced solutions as cooperative interference prediction (CIP) and flexible duplexing techniques.

The rest of the article is structured as follows. The following section includes the open research challenges for the RRM of NB-IoT systems and the associated state-of-the-art solutions. Following that we highlight the CIP and flexible duplexing techniques and describe the proposed radio resource allocation framework for NB-IoT. Then the detailed performance evaluation with the simulation assumptions are described. Finally, the conclusions are presented in the final section.

RESEARCH CHALLENGES FOR RADIO RESOURCE MANAGEMENT FOR NB-IOT

This section presents some of the core issues of the RRM in NB-IoT that should be addressed in order to enable massive device connectivity. In NB-IoT, spectrum allocation is limited to 180

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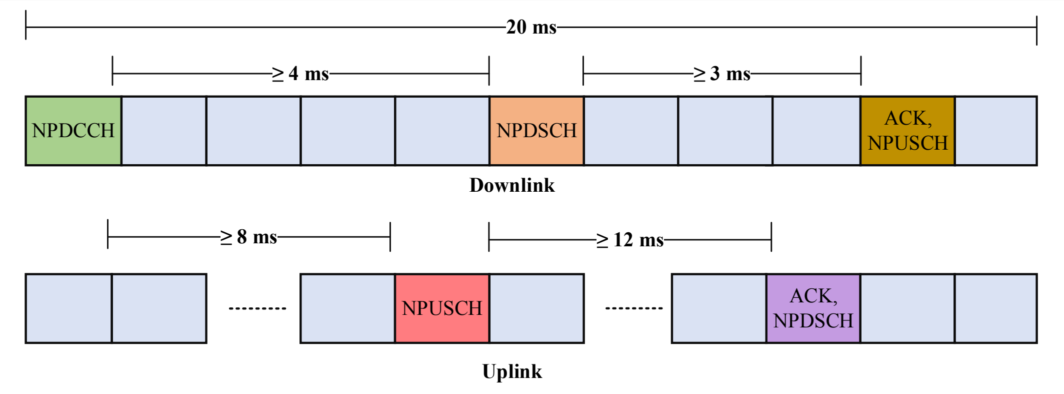


FIGURE 1. Recommended scheduling delay between downlink control and data transmissions by 3GPP with frame duration of 20 ms [5].

kHz mapped to one LTE PRB. As NB-IoT operates within the LTE band, in order to ensure the best coexistence, a standard sub-carrier spacing of 15 kHz with 12 sub-carriers in the frequency domain is recommended. However, the sub-carrier spacing can be reduced to 3.75 kHz with 48 sub-carriers for achieving higher robustness. In the time domain, for 15 kHz sub-carrier spacing, the total frame duration is 10 ms, divided into sub-frames of 1 ms. Each sub-frame comprises two time-slots of 0.5 ms and seven orthogonal frequency-division multiplexing (OFDM) symbols. On the other hand, in the case of 3.75 kHz, each time-slot lasts 2 ms and the complete frame is composed of five time-slots (this set of parameters is one of the numerology options). Moreover, in NB-IoT, Narrowband Physical Broadcast Channel (NPBCH) is always in the sub-frame 0 with 10 ms periodicity. Narrowband Primary Synchronization Signals (NPSS) and Narrowband Secondary Synchronization Signals (NSSS) occupy sub-frames 5 and 9 each 10 ms and 20 ms, respectively. Narrowband Physical Downlink Control Channel (NPDCCH) is transmitted for each user and is encoded over one sub-frame. Coverage extension for NPDCCH is supported through retransmissions within a maximum of 2048 times. Similarly, in the uplink, Narrowband Physical Random-Access Channel (NPRACH), used to connect users to the BS, requires a contiguous set of 12, 24, 36 or 48 sub-carriers, located on a discrete set of sub-carrier ranges. For the sake of simplicity, this article assumes 30 percent of the resources are assigned for NPRACH [2]. The detailed design changes and features in NB-IoT that affect the spectrum efficiency are discussed in the following sections.

RETRANSMISSION → TO PROVIDE EXTENDED COVERAGE AND IMPROVE LINK RELIABILITY

In NB-IoT, retransmission of data and control signals has been introduced in order to improve the coverage and system reliability in terms of packet reception. The decoding of each repeated packet can be done separately, or multiple packets can be combined for improving the rate. NB-IoT defines three coverage classes (i.e., 0 dB, 10 dB and 20 dB for normal, robust, and extreme conditions, respectively) based on the signal strength, which depends on cell deployment, user distribution and propagation channel. Furthermore, with the 5G HetNet deployment where interference is expected to be increased due to multiple sources, the number of retransmissions also increase as the signal strength degrades. The number of retransmissions is evaluated based on the maximum coupling loss (MCL) [1]. The maximum number of retransmissions allowed in the downlink and uplink are 2048 and 128, respectively.

Retransmissions improve undoubtedly the packet reception reliability but at the cost of increased latency, reduced spectrum efficiency and battery life, due to overhead and redundancy. In particular, in NB-IoT, each retransmission adds up to 65 bytes (i.e., without header compression) or 29 bytes (i.e., with header compression). Clearly, improving the packet reception rate with retransmissions is not an optimal choice.

In this regard, in [3], a 2-dimensional link adaptation considering both modulation and coding scheme (MCS) and retransmission selection for NB-IoT is presented. The proposed algorithm reduces the active time and improves spectral efficiency by providing a sub-optimal solution based on a heuristic approach. However, a more robust close-form link adaptation solution for NB-IoT is still missing. Similarly, in [4], dynamic spectrum access for NB-IoT is proposed using reinforcement learning rather than random access. The proposed solution shows significant improvement in terms of retransmission reduction; however, the evaluation is still based on a single user scenario. One of the possible solutions for reducing retransmissions is to improve the channel quality, which is typically degraded because of intra-cell and inter-cell interferences.

SCHEDULING DELAY → TO PROVIDE REDUCED COMPUTATIONAL COMPLEXITY FOR INEXPENSIVE DEVICES

NB-IoT introduces a scheduling delay between the transmissions in order to reduce the computational complexity at the user devices. The NPDCCH contains the scheduling index that allows the device to receive the downlink transmission in Narrowband Physical Downlink Shared Channel (NPDSCH); it starts uplink data transmission in Narrowband Physical Uplink Shared Channel (NPUSCH) with NPUSCH Format 1 and downlink data Acknowledgment (ACK) with NPSUCH Format 2. The recommended minimum scheduling delay thresholds set by 3rd Generation Partnership Project (3GPP) are shown in Fig. 1.

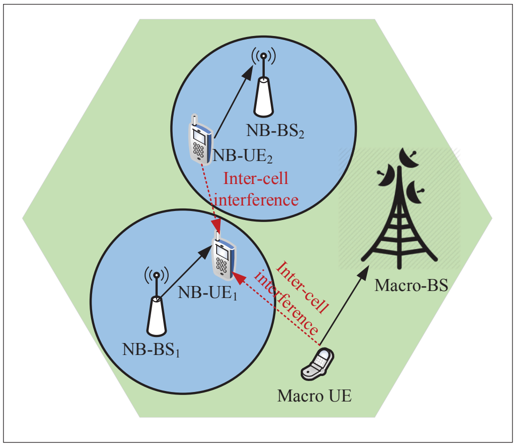


FIGURE 2. Example of uplink inter-cell interference on a NB-IoT user in HetNets, where neighboring small cells have synchronous allocation of NB-IoT band.

In downlink, the scheduling delay between NPDCCH and the associated NPDSCH is recommended to be at least 4 ms. After the reception of NPDSCH, the user sends the associated ACK using NPSUCH Format 2 after 12 ms or more. The reason for such a large delay is to provide ample time for the user to decode and process the NPDSCH consisting of 680 bits compared to 23 bits of NPDCCH. Similarly, in the uplink, the scheduling delay between the NPDCCH and the associated NPUSCH should be at least 8 ms. After the completion of NPUSCH, the user needs to monitor the NPDCCH channel for at least 3 ms in order to receive the ACK before doing retransmission.

The scheduling delay couples the downlink and uplink transmission in NB-IoT, thus requiring joint optimization of the resources. Furthermore, even with the best selection of the scheduling delay, there is still a significant resource wastage due to signalling overhead [6]. To address this issue, the authors in [6] proposed a pre-divided resource allocation that uses a dynamic data slicing technique for splitting the user resource requirements and fitting in the scattered available resources. However, it could incur excessive signal overhead since each sliced data packet requires additional PHY and MAC headers. Therefore, an appropriate scheduling mechanism for the varying payload sizes and scheduling delay selection is a challenging task, particularly for downlink transmission and this needs additional investigation.

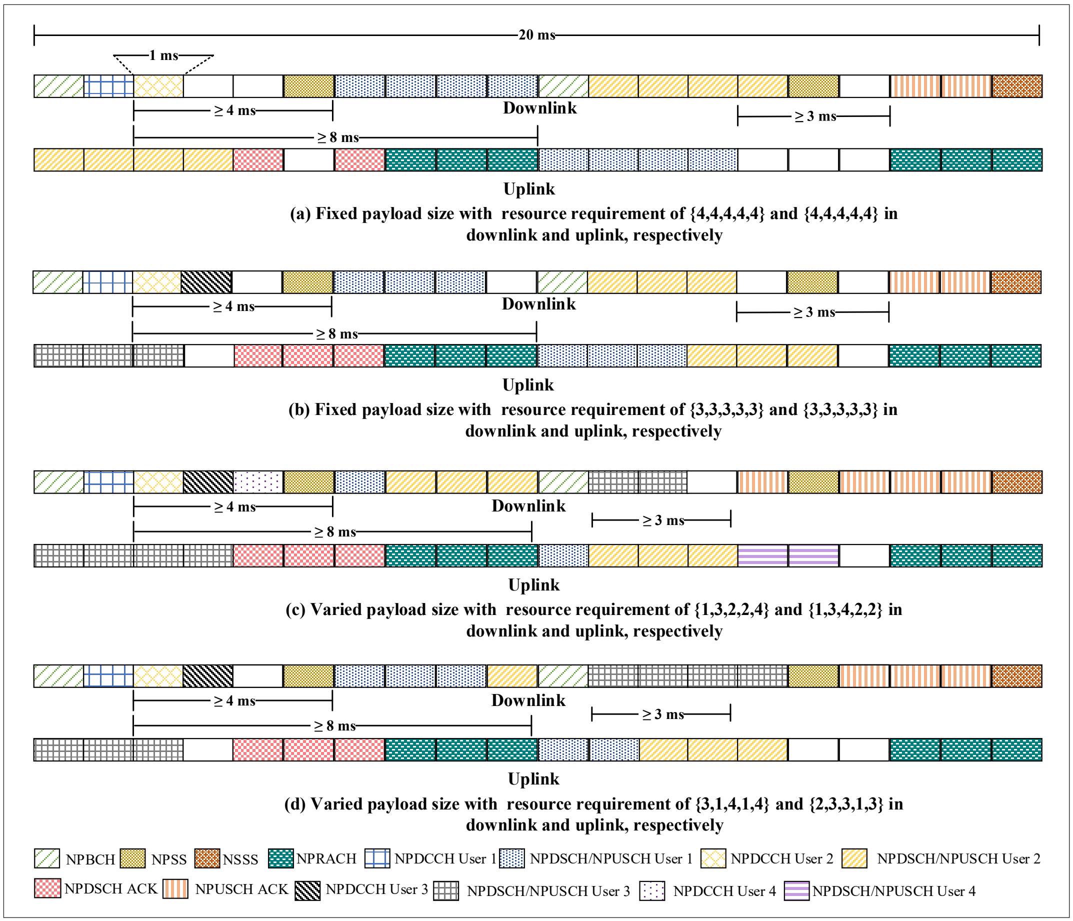
1-Sub-Carrier Granularity ⟶ To Provide Massive Device Support

NB-IoT introduces the concept of resource unit (RU) for the allocation of uplink resources. The RU is defined as the combination of a number of sub-carriers (i.e., tones, the term used in the standard) and a number of symbols grouped together. Unlike traditional LTE, where the smallest allocation unit for the uplink is one PRB, in NB-IoT there is a provision to allocate resources with *1-sub-carrier granularity*. Such allocation provides more degrees of freedom to the base station (BS) for scheduling each uplink user over one available sub-carrier (i.e., a single tone) or a group of sub-carriers (i.e., multi-tone) without limitations. For the sake of simplicity, 3GPP has already recommended pre-defined resource units for both 15 kHz and 3.75 kHz numerologies. The sets of RUs for NPSUCH Format 1 in 15 kHz numerology are 1 ms for 12 tones, 2 ms for six tones, 4 ms for three tones, 8 ms for a single tone, whereas, for 3.75 kHz numerology, only a single tone is available for 32 ms. Furthermore, for NPSUCH Format 2, the recommended single tone allocations are 2 ms and 8 ms for 15 kHz and 3.75 kHz numerologies, respectively.

The allocation of uplink resources with sub-carrier granularity, however, leads to many scenarios where the uplink transmission wholly or partially overlaps in the frequency and time domains with the transmission in the neighboring cell, resulting in severe inter-cell interference (ICI). As NB-IoT operates in the same LTE frequency band, this results in ICI from the neighboring cell NB-IoT users (in the case of synchronous allocation of a band for NB-IoT in the neighboring cell) or from LTE users (in the case of asynchronous allocation) in both the downlink and uplink. Moreover, with the 5G HetNet architecture, multiple small cells operate in the vicinity of a macro-cell on the same frequency band, which adds additional ICI from the macro-cell users as illustrated in Fig. 2. ICI deteriorates the performance of both the downlink and uplink; however, the impact of ICI on the uplink of NB-IoT is expected to be more severe due to the provision of scheduling uplink transmissions with 1-sub-carrier granularity as the transmission might be affected by different users in different sub-carriers.

In order to combat ICI, there has been a remarkable effort in the literature for LTE. However, the traditional ICI mitigation techniques, such as Enhanced Inter-Cell Interference Coordination (eICIC), might not be suitable for NB-IoT. NB-IoT is operating on a single PRB, and therefore resource block muting in this case for NB-IoT might result in a complete system shutdown. On the other hand, resource muting in the macro-cell also reduces spectral efficiency. Specifically, for NB-IoT, the author in [3] proposes an uplink scheduling scheme based on single-tone allocation at the link-level without ICI consideration. Furthermore, the performance of different RU configurations for NB-IoT uplink in terms of user connectivity is presented in [7]. However, the performance evaluation is conducted in a single-cell scenario and the effect of ICI, retransmission, and control channel overhead have not been considered. Moreover, in [8], the authors presented an interference-aware resource allocation based on a cooperative and non-cooperative approach for NB-IoT. It is shown that the cooperative approach improves the information rate by 11 percent compared to the non-cooperative one. However, the cooperative approach also adds the overhead of information sharing among the cells.

It is of utmost importance to evaluate the performance of NB-IoT in HetNets and to devise novel solutions for ICI mitigation, as traditional solutions might not be well suited to NB-IoT due to its limited bandwidth availability.



(a) Fixed payload size with resource requirement of {4,4,4,4,4} and {4,4,4,4,4} in downlink and uplink, respectively

(b) Fixed payload size with resource requirement of {3,3,3,3,3} and {3,3,3,3,3} in downlink and uplink, respectively

(c) Varied payload size with resource requirement of {1,3,2,2,4} and {1,3,4,2,2} in downlink and uplink, respectively

(d) Varied payload size with resource requirement of {3,1,4,1,4} and {2,3,3,1,3} in downlink and uplink, respectively

FIGURE 3. Example of downlink and uplink scheduling in NB-IoT without retransmission in four different scenarios having different RU requests for 5 users.

Half-Duplex Frequency Division Duplexing (HD-FDD) Support Only → To Reduce the Cost of the User Device and Improve Power Efficiency

Currently, NB-IoT only provides HD-FDD support, where transmit and receive data are in a shared channel and in different timeslots, eliminating the need for an expensive duplexer. This also helps to improve the power efficiency of the user devices due to low insertion losses. However, the system with such a symmetric allocation of radio resources between the downlink and uplink results in underutilization of the spectrum due to the asymmetric traffic, as in most IoT based applications the traffic between the downlink and uplink is generally strongly asymmetric.

Four use-case examples with frame duration of 20 ms are presented in Fig. 3 with no retransmission consideration and different packet sizes in order to highlight the impact of asymmetric traffic with 15 kHz numerology and 12 tone allocation in the uplink. Figure 3a assumes five users with maximum allowed transport block size (TBS) of 1000 and 680 bits in the uplink and downlink, respectively. For transmission, each user requires a minimum of four RUs and four sub-frames in the uplink and downlink with in-band deployment due to the presence of LTE control information, as presented in [8]. Similarly, Fig. 3b assumes short packet size, where each user requires a minimum three RUs and three sub-frames in the uplink and downlink, respectively. From Fig. 3a it can be observed that due to the control channel positions, there is a significant chance of resource wastage. One can surely include ACK packets in these sub-frames but, as can be seen in Fig. 3a, only two users in the 20 ms frame can be accommodated. Even after including ACKs for two users, still three sub-frames in downlink and four RU's will be vacant in the downlink and uplink, respectively. Similarly, in Fig. 3b, three users can be accommodated as the packet size is shorter as compared to the Fig. 3a scenario. However, the resource wastage is still significantly higher.

Furthermore, one might argue that in IoT systems the traffic is mostly asymmetric in nature, therefore, the user with less RU requirements will be compensated in the vacant sub-frames as in Figs. 3c and 3d. Even in these cases, there is a significant chance of resource underutilization. Therefore, to fully exploit the spectrum, there is the need for a joint adaptive uplink and downlink allocation with asymmetric traffic.

In traditional LTE, for a HD-FDD system, adaptive cell sizing (ACS) and multi-hop transmission (MHT) techniques were proposed to accommodate asymmetric traffic. ACS uses antenna beamforming to autonomously adjust its coverage area resulting in uniform traffic distribution across all base stations [9], whereas in MHT, a relay station uses the uplink band to improve the downlink capacity. However, due to the deployment of NB-IoT within the LTE system, these techniques might not be a suitable option as they will affect

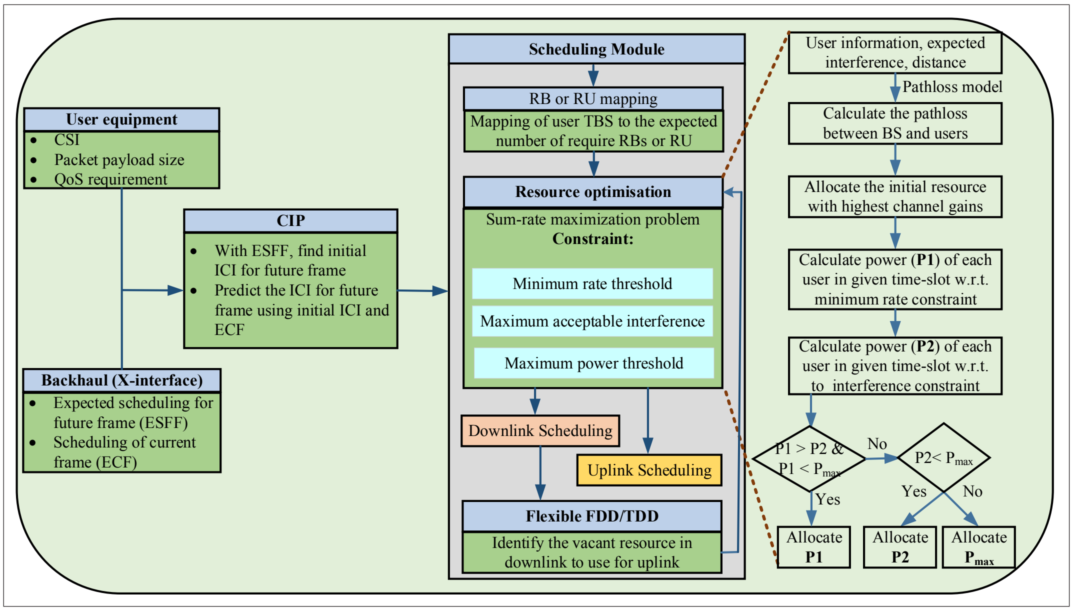


FIGURE 4. Proposed radio resource management framework with cooperative interference prediction, resource optimisation and flexible duplexing module.

the whole network architecture. One of the possible solutions is to use flexible FDD/TDD duplexing within the NB-IoT frame as it will not hamper the LTE transmission [10]. More details on flexible duplexing are presented below.

Summing up, the RRM of NB-IoT needs to be jointly optimized for the downlink and uplink to maximize the spectral efficiency and to address the issue of scheduling delay and asymmetric traffic [6, 8]. In particular, in the case of asymmetric traffic, one of the main concerns is *how to utilize the vacant downlink resource for the uplink*. Beside this, the RRM algorithm in NB-IoT should provide an efficient interference mitigation. Due to the subcarrier level of allocation, the source of interference on each subcarrier might be different as compared to LTE, where the interference on the whole PBR is from a single source. An efficient interference mitigation not only improves the channel quality but also reduces the retransmission, which is main source of spectral efficiency degradation in NB-IoT as stated above. Furthermore, the reduction in retransmission will also result in power and latency improvement [8].

This article addresses these challenges and presents an RRM framework by exploiting flexible duplexing and cooperative interference prediction with an objective to maximize the spectrum efficiency of NB-IoT systems.

PROPOSED RADIO RESOURCE MANAGEMENT FRAMEWORK

This section presents the proposed radio resource management framework which is constituted by three main modules, as shown in Fig. 4: CIP, resource optimization and flexible duplexing.

COOPERATIVE INTERFERENCE PREDICTION

In NB-IoT, the BS is responsible for the allocation of resources and the selection of retransmissions and MCS to its serving users. In order to perform these functions, a BS needs to estimate the channel quality of each user in terms of signal to interference and noise ratio (SINR) using the demodulation reference symbol (DMRS). However, the estimated SINR at time t can be different from the SINR during the actual transmission in $t + \Delta$ (Δ represents time steps ahead), due to the ICI fluctuation. Assuming perfect multi-cell channel state estimation, BSs can perfectly predict ICI if they know the scheduling decisions in the neighboring cells [11]. In particular, in the case of NB-IoT, due to sub-carrier granularity, the probability of having variable interference on the sub-carrier level is significantly higher than in traditional LTE networks. Therefore, it is extremely crucial to estimate accurate ICI in advance for optimal scheduling decisions.

In this regard, CIP schemes are proposed to solve the problem [11, 12]. The core idea of CIP is to cooperate with the neighboring BS and exchange the expected scheduling information of users via backhaul or X-interface before scheduling so that the interference level during the actual transmission can be predictable. For example, consider only small cells in Fig. 2; NB-BS$_2$ estimates the scheduling probabilities of the users in advance by predicting the channel at $t + \Delta$ as in [11]. Then information is shared with NB-BS$_1$ via backhaul or X-interface. As NB-BS$_1$ knows which users will be scheduled at $t + \Delta$ by NB-BS$_2$, NB-BS$_1$ predicts the expected ICI and performs the scheduling of its users accordingly. However, since NB-BS$_2$ estimates the scheduling probabilities at time t, there is a chance that the actual scheduling performed by NB-BS2 at at time instance $t + \Delta$ might differ as for the case in [11].

In order to improve ICI prediction accuracy, in the proposed framework, the CIP scheme presented in [11] has been modified. As in [11], the probability of scheduling is independent from previous scheduling decisions and solely relies on the predicted channel, which is justified due to the non-static position of cellular users. However, considering the static or low mobility behavior of

IoT users, our proposed scheme includes the previous scheduling decision along with the predicted channel to improve the prediction probability.

Resource Optimization Design

In the resource optimization design, with the information of user requirements and the predicted ICI Φ_{pri}, the sum-rate maximization problem of BS b for the downlink and uplink can be formulated as $R = \max_{x,p} \Sigma_{b \in \mathcal{B}} x \log_2(1 + \gamma)$, where x is the time-slot allocation index which indicates allocation is exclusive to one user. The user SINR γ is given as $p\mathcal{H}/(N_o + \Phi)$, where p represents the transmit power of the user, $\mathcal{H}$ is the channel power gain between the user and serving BS, N_o is the thermal noise power, and Φ is the total ICI from all neighboring cell users. The maximization problem formulation should satisfy $x \leq 1$, $p \leq P_{\max}$, $R \geq R_{\min}$ and $\Phi \leq \Phi_{\max}$, where $P_{\max}$ represents the maximum transmit power of each user, $R_{\min}$ is the minimum rate requirement of each user in both the downlink and uplink, and $\Phi_{\max}$ is the maximum tolerable interference threshold by each user, respectively.

The rate maximization problems are well-known and they are non-convex due to the presence of a binary assignment variable and an interference term in the denominator [8]. Therefore, a sub-optimal solution is considered here, consisting of two steps, that is, time-slot and power allocation, as sketched in Fig. 4.

Time-Slot Allocation: The problem is combinatorial due to the binary variables which can be converted to a convex problem using the well known time-sharing property [13]. With this time-sharing relaxation, maximum rate scheduling is employed by each BS for selecting the user with the highest SINR in each time-slot and thus making the best use of multi-user diversity. Each BS b selects the user i, where $i = \arg\max_{i \in I} \gamma_i$; where $\mathcal{I} = \{1, ..., I\}$ is a set of active users in the cell.

Power Allocation: With the given time-slots, the power allocation problem can be simplified as follows: $\max_p \Sigma_{b \in \mathcal{B}} \log_2(1 + \gamma)$. Due to the increase of ICI on the neighboring receivers when transmit power is increased, an interference threshold constraint is imposed so that the aggregate ICI from all the neighboring cells should be less than $\Phi_{\max}$, where $\Phi_{\max} = \Phi_{pri}$ is set to the predicted ICI. The proposed algorithm calculates first the transmit power P_r that satisfies the minimum rate requirement constraint, given by

$$\log_2\left(1 + \frac{p\mathcal{H}}{N + \Phi}\right) \geq R_{\min}.$$

After some mathematical manipulations, $P_r = (1/\mathcal{H})(2^{R_{\min}} - 1)(N + \Phi)$. As stated, the transmit power P_Φ is now computed based on the interference restriction imposed by the neighboring cell users in terms of predicted ICI as $P_\Phi = \Phi_{\max}/\mathcal{H}$. The final power for each user can be calculated as $P = \min(\max(P_r, P_\Phi), P_{\max})$.

Flexible FDD/TDD Duplexing

Flexible duplexing (flexible FDD/TDD) is one of the promising techniques for optimizing the radio resource and coping with the channel and traffic asymmetry in wireless networks [10, 14]. The key idea is to perform adaptive resource allocation in the joint time-frequency domain, without static choices in TDD or FDD. This flexibility enables the ability to match the resources to the traffic even if there is just one paired FDD carrier, that is, one downlink and one uplink carrier. Furthermore, the use of TDD enables the allocation of resources at finer granularity, that is, symbol level rather than carrier level for FDD.

The key idea is to perform adaptive resource allocation in the joint time-frequency domain, without static choices in TDD or FDD. This flexibility enables the ability to match the resources to the traffic even if there is just one paired FDD carrier, that is, one downlink and one uplink carrier.

As a result, flexible duplexing has the advantage of accommodating asymmetric traffic with better spectral efficiency. However, one of the major challenges for exploiting the maximum potential of flexible duplexing is the inter-cell interference between the downlink and uplink users. For example, if a user in a cell performs uplink transmission using downlink resources, it will receive interference from the neighboring cell's downlink users, which might be significantly higher because of the transmit power gap between the downlink and uplink. In order to address this issue, in [14] the authors proposed a resource muting approach within the flexible duplexing framework. However, resource muting might not be a suitable choice for NB-IoT due to limited system bandwidth.

Our proposed radio resource framework exploits the flexible duplex and addresses the ICI interference from the downlink user to the uplink user and vice versa. In this regard, the proposed resource optimization schedules initially the users in the downlink since the downlink traffic is significantly lower than the uplink traffic in the IoT context. Then the downlink scheduling information is used by a flexible duplexing module for calculating the SINR of each uplink user using the predicted ICI from the downlink users in that time-slot as follows: $\gamma_{up} = p\mathcal{H}/(N + \Phi_{pri})$. Then the user with maximum SINR in that time-slot is selected to perform the uplink and the corresponding power level is calculated as presented in the previous section.

Performance Evaluation

This section presents the performance evaluation of the proposed framework through Monte Carlo simulation which runs for 5000 iterations. The scenario is a multi-cell LTE network comprising three sectors and an inter-site distance equal to 500 m with synchronous PRB allocation for NB-IoT users in each cell, in both in-band and stand-alone modes. Furthermore, the total frame duration is assumed to be 20 ms with 15 kHz numerology, where RU is made of 12 tones for 1 ms. A total number of 20 users are deployed randomly and uniformly in each cell with a maximum transmit power of 35 dBm and 23 dBm in the downlink and uplink, respectively. A penetration loss of 35 dB is assumed to ensure that high coupling losses are achieved, as they approximately lie in the range from 8 to 38 dB. The rest of the simulation assumptions follow closely the 3GPP standard and are presented in [15].

Furthermore, considering that in most IoT applications the downlink is only used for control information, the TBS for each downlink and uplink user is randomly generated between [10 20] and [20 50], respectively. In terms of MCS, each user applies QPSK and a 1/3 code rate on all the transmissions. However, the retransmission factor is computed with respect to MCL for different coverage classes as given in [15].

The results are generated for the average information rate per sector, as shown in Fig. 5 through the cumulative distribution function (CDF). Due to the lack of resource allocation schemes for NB-IoT, we have compared the proposed resource allocation with the maximum rate scheduling (MRS), where users are allocated according to the priority given by the maximum channel gain without the interference information, in order to highlight the gain that can be achieved with CIP. It can be seen that the proposed framework significantly improves the downlink and uplink performance in in-band deployment by approximately 11 percent and 14 percent, respectively, and in the standalone mode, by 9 percent and 12 percent. The reason for this improvement is the reduction in retransmissions due to interference-aware scheduling, which helps to reduce the effect of ICI and improves the link reliability. In addition, flexible duplexing enables the uplink to transmit on vacant downlink resources and vice versa, which also contributes to the gain improvement in both the downlink and uplink, as can be seen in Fig. 6. The results show that the proposed RRM framework is able to achieve reductions of approximately 58 percent and 40 percent in resource wastage in the downlink and uplink, respectively, in in-band deployment, and 30 percent and 45 percent in the downlink and uplink, respectively, in the stand-alone deployment.

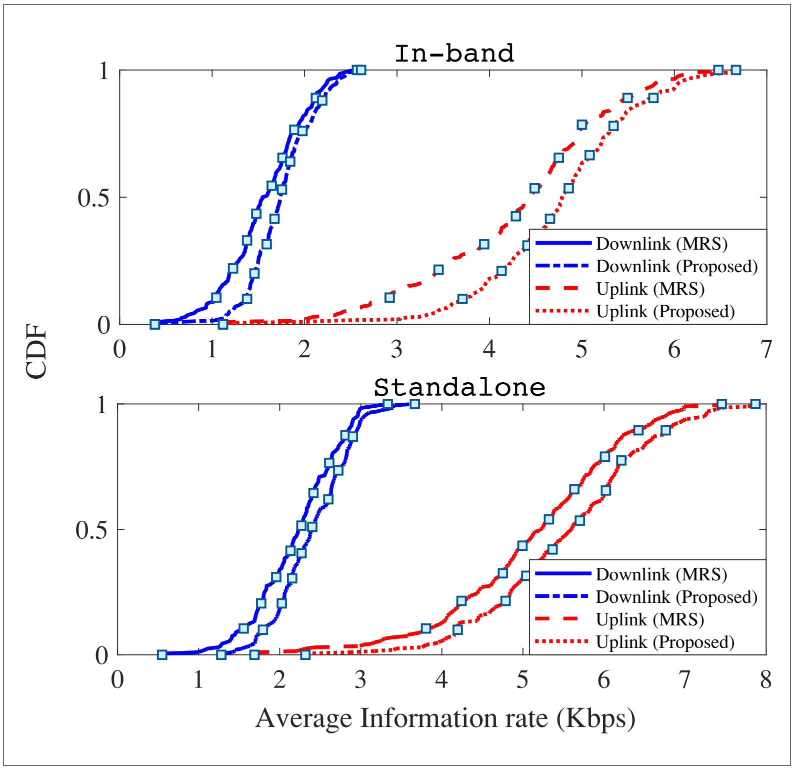


FIGURE 5. Average information rate per sector with in-band and stand-alone deployment and random packet size.

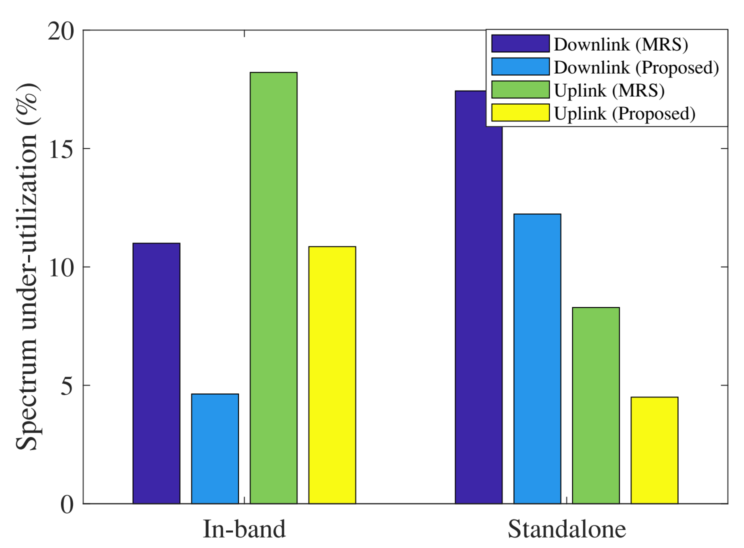


FIGURE 6. Percentage of under-utilized spectrum resource per sector in both in-band and stand-alone deployments.

CONCLUSIONS

NB-IoT is a promising technology for enabling future IoT applications. However, scarce system bandwidth and frequency sharing with LTE raise several challenging issues that need to be addressed in order to fully exploit the potential of this technology. This article highlighted some of the major RRM issues that need to be tackled for achieving the maximum spectral efficiency. Moreover, the article also presented a novel RRM framework specifically designed for NB-IoT and exploiting the CIP and flexible duplexing techniques for addressing those issues. Simulation results show that the proposed framework mitigates significantly the impact of ICI, reduces the retransmissions, accommodates asymmetric traffic, and improves the overall spectrum resource utilization. It is observed that with the proposed RRM framework, up to 14 percent improvement in terms of information rate and 58 percent reduction in resource wastage can be achieved.

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