Narrowband-Internet of Things (NB-IoT): Performance Evaluation in 5G Heterogeneous Wireless Networks

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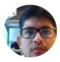

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Narrowband-Internet of Things (NB-IoT): Performance Evaluation in 5G Heterogeneous Wireless Networks

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***Abstract*—Narrowband Internet of Things (NB-IoT) is a promising cellular technology for enabling future low power wireless area networks (LPWANs). NB-IoT aims to provide seamless connectivity to massive IoT devices that require low throughput, low power, and long-range communication. NB-IoT is based on Long Term Evolution (LTE) with a system bandwidth of 180 KHz. Due to such limited bandwidth requirement, NB-IoT can be deployed within the LTE band. However, considering the future heterogeneous wireless networks (HetNet) comprising of multiple small cells operating under a macro cell environment. In this case, when NB-IoT is deployed, the inter-cell interference becomes worse due to the interference from the macro cell users as well. This raises serious concerns on the performance of NB-IoT. Therefore, in this paper, an extensive investigation of NB-IoT performance in terms of throughput and power consumption is presented in different HetNet deployment strategies. Moreover, an evaluation of cooperative resource allocation scheme for NB-IoT is also discussed in detail. The results show a significant impact on the performance of NB-IoT in HetNet environment. It is observed that, with the cooperative scheme, the gains of up to 24% in average throughput and reduction of 72% in energy consumption can be achieved.**

***Index Terms*—NB-IoT, IoT, mMTC, HetNet, Performance Evaluation.**

I. Introduction

Internet of Things (IoT), where massive data from large number of devices is collected and valuable information is extracted to enable communication between products, their environment and the business side. The aim of IoT is to provide seamless connectivity of industrial processes, assets, workforce, and daily user environment to exchange information and make a proactive decision on an upcoming event to better manage production, people lifes and increase profitability. This will enable diverse use-cases in IoT ecosystem which can be classified into two categories namely, non-time critical and time critical. For example, health and safety monitoring, in-house fleet management i.e., mobile-robots have a small amount of data but requires frequent handovers. Furthermore, there are other applications such as monitoring of assets tracking, the output of workstations, stock level, air pressure, electricity consumption, environment factors and the performance of production tools such as precision screwdrivers or condition monitoring. Most of these processes are stationary with a small amount of data and are delay insensitive referred as non-time critical use-cases. Whereas, motion control, process automation, autonomous vehicles, production line automation, etc. belongs to time critical use-cases.

However, with such IoT ecosystem, wireless IoT devices are expected to grow exponentially and to sustain continued growth requires more spectrum or efficient ways of using available spectrum. Therefore, the use of spectrum should be optimal for the long-term sustainability of the future digitalized ecosystem. Stakeholders representing IoT network providers, device manufacturers, users, and federal regulators identified two spectrum-related challenges 1) ensuring the availability of sufficient spectrum and 2) managing the harmful interference from the increasing IoT devices. Moreover, the future wireless networks need to improve Key Performance Indicators (KPIs) required by these diverse IoT use-cases in terms of data rate, device support, latency, coverage and power consumption.

To address these challenges, the Third Generation Partnership Project (3GPP) has introduced a radio access technology called Narrowband Internet of Things (NB-IoT) which provides extended coverage, high capacity, low throughput, reduced device processing complexity and long battery lifetime. NB-IoT is a long-term evolution (LTE) variant designed specifically for massive Machine Type Communication and non-time critical IoT use-cases. LTE already has a global footprint and thus supporting and driving IoT adoption through NB-IoT is considered 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., as standalone, in the guard carriers of existing LTE/UMTS spectrum, or within an existing LTE carrier (in-band) by replacing one PRB.

However, the allocation of frequency band for NB-IoT within LTE band or as a standalone might not be synchronous in all the cell within network, resulting in inter-cell interference from the neighbouring cell LTE users or NB-IoT users (synchronous case). Furthermore, the future wireless networks will be consisting heterogeneous network (HetNet) of multiple small cell operating under a macro cell environment. In this case, when NB-IoT is deployed in a small cell, the inter-cell interference become worse due to the interference from the macro cell users as well. To deploy NB-IoT for practical applications, cell data rate, number of supported devices and power consumption are the key performance measures in which operators are interested. It is necessary to evaluate the performance of NB-IoT in HetNet to realize the impact of inter-cell interference on the above-mentioned KPIs before real deployment.

II. CONTRIBUTION

The main contribution of this paper are as follows:

- Evaluation of NB-IoT performance in 5G HetNet with synchronous and asynchronous deployment of NB-IoT in terms of data rate and power consumption.
- Performance evaluation of NB-IoT with cooperative radio resource allocation scheme in 5G HetNet scenarios along with detailed comparison with non-cooperative approach proposed in [1].

The rest of the paper is structured as follows. Section III presents the state of art and discuss the proposed solutions along with the corresponding limitations. Section IV discuss the possible deployment strategies of NB-IoT in HetNet with both synchronous and asynchronous allocation of frequency resource to NB-IoT. Section V presents the detailed simulation parameters and assumptions under consideration and the evaluation of NB-IoT in HetNet in terms of data rate, power and latency is presented in Section VI. Finally, Section VII presents briefly the conclusion of the paper.

III. MOTIVATION AND STATE OF ART

5G HetNet deployment is one of the promising way to improve the system capacity and coverage. In such deployment, small cells with low transmit powers behave as an underlay network within the macro cell coverage. However, due to the co-existence of NB-IoT within the LTE frequency, raise serious concerns on the performance of NB-IoT in HetNet due to massive inter-cell interference. Moreover, NB-IoT introduces the allocate of uplink resource to **sub-carrier granularity** termed as resource unit (RU) as compared to one complete physical resource block (PRB) allocation in LTE. 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 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 6 tones, 4 ms for 3 tones, 8 ms for a single tone, whereas, for 3.75 kHz numerology, only a single tone is available for 32 ms. Such RU based allocation leads to many scenarios where the uplink transmission wholly or partially overlaps in the frequency and time domains, resulting in severe inter-cell interference (ICI). Moreover, in the 5G HetNet architecture, additional ICI from the macro-cell users is expected to further degrade the performance of NB-IoT.

In order to combat ICI, there has been a remarkable effort in the literature for interference cancellation, estimation and coordination that involve frequency hopping, frequency reuse, power control, etc [2]–[5]. However, the traditional ICI mitigation techniques used in LTE, such as Enhanced Inter-Cell Interference Coordination (eICIC), might not be suitable for NB-IoT [6]. 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. However, in the literature, some efforts has been done to investigate the performance of NB-IoT in terms of device capacity [7]–[9] and coverage [10]–[12] in a single-cell scenario. In addition, in [13], an evaluation of coexistence of LTE and NB-IoT is presented for both in-band and guard-band deployment mode and co-channel interference is modelled due to RF impairments. It is shown that LTE introduces strong interference on NB-IoT. The author in [14] proposes an uplink scheduling scheme based on single-tone allocation at the link-level without ICI consideration. Furthermore, performance of different RU configurations for NB-IoT uplink in terms of user connectivity is presented in [15]. However, the performance evaluation is conducted in a single-cell scenario and the effect of ICI have not been considered. Similarly, in one of our previous work [1], we have presented interference-aware radio resource scheduling for sum-rate maximization in NB-IoT with cooperative scheme in a multi-cell cellular network scenario. To the best of authors knowledge, **the work in this paper is the first work on performance evaluation of NB-IoT in 5G HetNet**.

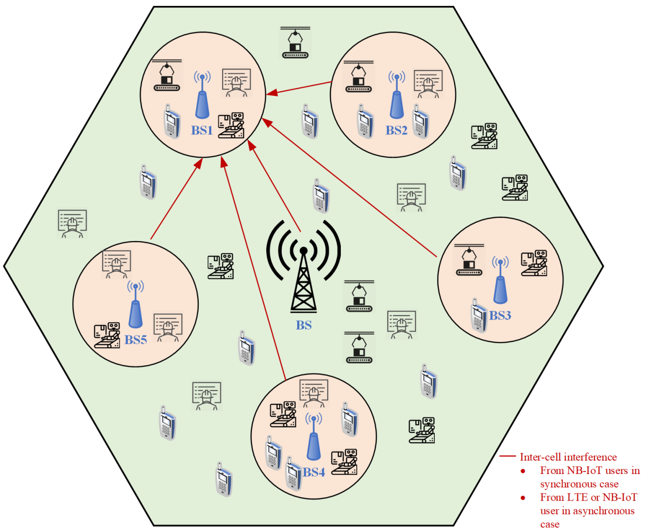


Fig. 1: NB-IoT enabled HetNet.

IV. NB-IOT 5G HETNET DEPLOYMENT STRATEGIES

Next generation 5G wireless networks are expected to support variety of applications with diverse requirements in terms of data rate, connectivity and power consumption. One of the solution to solve the data rate issue is to allow densification of networks by mean of small cell deployment.

Such densification results in higher spectral efficiency and reduction in power consumption due to communication with nearby small cell. In additional, this solution significantly improves network coverage as well. However, the uncoordinated nature of such small cell deployment raise concerns of interference management. Particularly, in case of NB-IoT, as it is expected to coexist with LTE in the same frequency band, interference is one of the major limiting factor for NB-IoT performance in such HetNets. Some of the possible deployment scenarios as shown in Fig. 1 and the corresponding inter-cell interference's that need to be either cancelled or mitigated are as follows:

- **Synchronous deployment in small cells:** In this deployment mode, NB-IoT is configured in each small cell using the same PRB (frequency). This means that, inter-cell interference is only from the neighbouring cell NB-IoT users.
- **Asynchronous deployment in small cells:** The deployment mode in which NB-IoT is enabled in all small cells by using different PRB in each cell. Such deployment may avoid the interference between NB-IoT users from different small cells; however, this results in inter-cell interference from LTE users using the same radio resource in neighbouring cell. As in case of NB-IoT, 3-6 dB power boost is recommended by 3GPP for NB-IoT, therefore, it is expected that interference in this mode is less that the synchronous mode of deployment.
- **Synchronous deployment in small cells and macro cells:** In this mode, NB-IoT is enabled in the small cells as well as in macro cell on the same PRBs. Macrocell users are configured to use higher transmit power as compared to small cell users. Therefore, it is expected that the small cell NB-IoT transmission of edge users are likely to be affected by macro cell NB-IoT users.
- **Asynchronous deployment in small cells and macro cells:** In this mode, the deployment of NB-IoT in both small and macro cell is random, which means different PRBs can be used for NB-IoT in each cell. This will result in interference on NB-IoT users from both NB-IoT users of some neighbouring cell and LTE users of other neighbouring cell. Particularly, the interference from the LTE users of macro cell typically operating on high transmission power is expected to be the major interferer for NB-IoT users in small cell.

V. System Model

To conduct the performance evaluation, we have considered standalone deployment of NB-IoT with in a typical LTE system. The scenario comprises of regular hexagonal macro cell with an inter-site distance of 1000 m and randomly deployed small cells with a radius of 200 m. The simulation parameters are derived from the 3GPP standards [12] as presented in Table I. Furthermore, in this study, the frame transmission of 10 ms and multi-tone transmission with RU configuration of 12 subcarriers with 15 kHz subcarrier spacing is considered. For uplink, multi-tone transmission with 15 kHz subcarrier spacing is known to perform worse than single tone [16]. Therefore, the achieved performance in this study yield the lower bound results. Moreover, the packet size is set to the maximum transport block size (TBS) of 680 bits and 1000 bits for downlink and uplink respectively as in Release 13 of 3GPP specifications.

TABLE I: Simulation Parameters

Parameters	Values
Macro Cell layout	Hexagonal grid
Small Cell layout	Circular grid
Frequency band	900 MHz
LTE Bandwidth	10 MHz
Inter-site Distance	randomly
Macro Cell coverage radius	1 Km
Small Cell coverage radius	200 meters
Macro Cell height	20 meters
Mobile antenna height	2 meters
User distribution	Users dropped uniformly in cell
Macro Cell total transmit power	46 dBm (6 dB boosting applied for NB-IoT)
Small Cell transmit power	40 dBm (6 dB boosting applied for NB-IoT)
User transmit power	23 dBm
For Small Cells Pathloss Model	L= I + 37.6 $\log_{10}(R)$, I=120.9 for the 900 MHz band where R in kilometers
For Macro Cells Pathloss Model	Hata Model
Shadowing standard deviation	8 dB
Shadowing Correlation:	0.5 dB
Base station antenna gain	18 dBi
User antenna gain	-4 dBi
Base station cable loss	3 dB
Building penetration loss	40 dB (Macro Cells)
Noise figure at base station	5 dB
Noise figure at user	3 dB
Noise power spectral density	-174 dBm/Hz

For the analysis, the repetition factor is computed based on MCL as follows [1]:

$$\begin{aligned} \mathrm{SINR} = \mathrm{Tx\ power} + 174 - \mathrm{Noise\ figure} \\ - 10\log_{10}(\mathrm{Bandwidth}) - \mathrm{MCL} \end{aligned} \tag{1}$$

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 in [1].

A. Radio Resource Allocation

In this study, the radio resource allocation scheme presented in [1] for interference mitigation in NB-IoT systems for multi-cell scenario is modified and enhanced for 5G HetNet. The paper assumes a set of small cell base stations $\mathscr{S} = \{1,...,S\}$ and set of macrocell base station $\mathscr{B} = \{1,...,B\}$ that communicates over OFDM to multiple user terminals. The total transmission frame duration is considered to be 10 ms, which consists of set mini time-slots $\mathscr{T} = \{1,...,T\}$ consisting of 1 ms. We assume that there are set of $\mathscr{M} = \{1,...,M\}$ active users in each small cell and set of $\mathscr{N} = \{1,...,N\}$ active users in each macro cell. Using the Shannon-Hartley Theorem, the achievable rate of the m^{th}

user of small cell s in time-slot t can be given by:

$$R_{m,s,t} = \log_2(1 + \frac{P_{m,s,t}\Gamma_{m,s,t}}{N_o + \sum_{k\in S} P_{m,k,t}\Gamma^s_{m,k,t} + \sum_{b\in B} P_{n,b,t}\Gamma^s_{n,b,t}}) \tag{2}$$

where $P_{m,s,t}$ denotes the transmission power of m^{th} user of small cell s in time-slot t, $\Gamma_{m,s,t}$ is the channel gain between small cell base station b and m^{th} user in time-slot t, N_o is the noise power spectral density per PRB. $P_{m,k,t}$ is the transmission power of m^{th} user of neighboring small cell k in time-slot t and $\Gamma^s_{m,k,t}$ is the channel gain between m^{th} user of neighboring small cell k in time-slot t and the base station s. $P_{n,l,t}$ denotes the transmission power of n^{th} user of macro cell b in time-slot t, $\Gamma^s_{n,b,t}$ is the channel gain between n^{th} user of neighboring macro cell b in time-slot t and the small cell s. The sum-rate maximization problem for small cell s with the constraints can be formulated as:

$$\max_{x_{m,s,t},P_{m,s,t}} \sum_{m\in\mathscr{M}} \sum_{b\in\mathscr{B}} \sum_{t\in\mathscr{T}} x_{m,s,t}R_{m,s,t} \quad \forall m\in\mathscr{M}, s\in\mathscr{S}, t\in\mathscr{T} \tag{3}$$

subject to

$$x_{m,b,t} \in \{0,1\} \tag{4}$$

$$\Phi^{sum}_{m,b,t} \leq \Phi^{max}_{m,b,t} \tag{5}$$

$$\sum_{t\in\mathscr{T}} R_{m,b,t} \geq R^{min}_{m,b,t} \tag{6}$$

$$\sum_{t\in\mathscr{T}} P_{m,b,t} \leq P_{max}, \tag{7}$$

$$P_{m,b,t} \geq 0 \tag{8}$$

Where $x_{m,b,t}$ is the binary index and can either be 1 or 0, which indicates that PRBs are exclusively allocated to one user in each time-slot. Constraint (5) represents the maximum tolerable interference threshold constraint to satisfy minimum rate requirement, constraint (6) is the minimum rate requirement of each user. Finally, constraints (7)-(9) indicates the maximum and minimum transmit power of user.

The formulated sum-rate maximization problem is non-convex due to the presence of binary variable $x_{m,b,t}$ and the interference terms in objective function. Therefore, it is not possible to find the the global optimal solution. Hence, in this paper, the interference-aware resource allocation algorithm proposed in [1] is modified for HetNet which is based on heuristically algorithm and comprises of two step namely: time slot allocation and power allocation.

For time slot allocation, the binary variable is relaxed using the well known time sharing property by allowing the binary variable to take any value between 0 and 1 such that $x_{m,s,t} \in [0,1]$ to make the formulated problem as standard convex optimization as in [17], [18]. Using the relaxation property, a greedy time slot allocation procedure is used where time slots are allocated based on the highest channel gain as follow:

$$x_{m,s,t} = 1, if m = \arg\max_{m\in\mathscr{M}}(\Gamma_{m,s,t}) \tag{9}$$

For power allocation, both cooperative and non-cooperative methods are evaluated as follows:

- **Non-cooperative Method**: The power allocation problem for the given time slot allocation is still non convex due to the presence of interference term. Therefore, a lower bound approximation using reference user concept is used so that each user can achieve its minimum rate requirement as outlined in [19]. With such approximation, the problem can be formulated as a standard convex problem with the strong duality [1]. Thus, the efficient power allocation can be obtained using the Lagrangian decomposition method as in [1].
- **Cooperative Method**: In this method, the power allocation problem is formulated as a cooperative game, where each user cooperate with the highest interfering user of the neighboring cell and adjust the power levels accordingly. Each user compute mainly two power levels, power that satisfy the minimum rate constraint and the power based on the maximum tolerable interference threshold constraint using the close form equation as presented in [1]. After that, the appropriate power level is chosen for each user accordingly.

More detailed on non-cooperative and cooperative methods can be found in our previous paper with all the proof and derivation in [1].

VI. Performance Evaluation

In this section, the performance of NB-IoT in HetNet is evaluated with the proposed cooperative algorithm with a Monte Carlo simulation. The performance evaluation is then compared with non-cooperative approach in terms of average throughput per sector and average energy consumption. The simulation is run considering the values stated on Table V.

As mentioned in Section IV, there exist multiple strategies of NB-IoT deployment, therefore, in our analysis we have considered following scenarios for downlink:

- SC1: Only small cell with synchronous deployment of NB-IoT.
- SC2: LTE enabled Macro-cell and small cell with synchronous deployment of NB-IoT.
- SC3: NB-IoT enabled Macro-cell and small cell with synchronous deployment of NB-IoT.
- SC4: Randomly NB-IoT or LTE enabled Macro-cell and small cells.

However, in uplink, only SC1 and SC4 are considered. The reason for such choice is that the maximum transmit power in uplink for both LTE and NB-IoT is 23 dBm as per 3GPP specification. Therefore, in uplink, SC2, SC3 and SC4 are likely to have same impact of inter-cell interference.

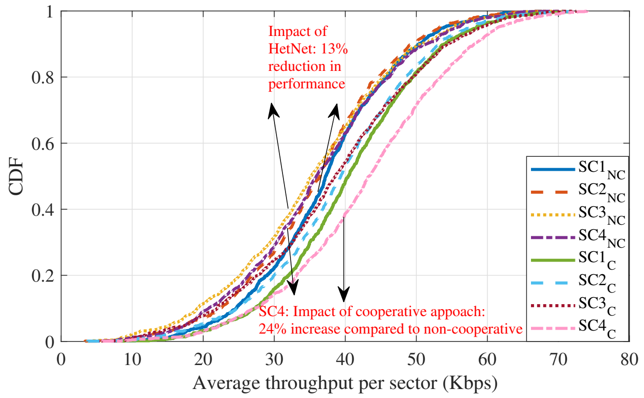
Figure 2a presents a comparison of each of the scenario in-terms of average throughput in downlink as cumulative density function (CDF). It can be seen that, the impact of inter-cell interference is quite significant in HetNet environment (i.e., 13% reduction in average throughput between SC1 with non-cooperative approach ($SC1_{NC}$) and SC3 with non-cooperative ($SC3_{NC}$)). However, the results shows that the cooperative algorithm improves the performance and reliability of the link by diminishing the impact of inter-cell interference. With the cooperative approach, the gain of approx. 24% can be achieved in average throughput per sector between SC4 with non-cooperative approach ($SC4_{NC}$) and SC4 with cooperative ($SC4_C$)).The similar trend of increase in all scenarios is observed in the results.

From the results, the average throughput range is between 2.5 and 75 Kbps approximately. SC1 that does not include Macro-cell gives the higher throughput as expected. On the contrary, the SC2, when both Macro and small cell support NB-IoT, gives the higher interference hence lower throughput achievable. Nevertheless the gap between the results of the scenarios is small. For instance, there is degradation of 5.5%, 13% and 8.4% in SC2, SC3, and SC4 as compared to SC1.

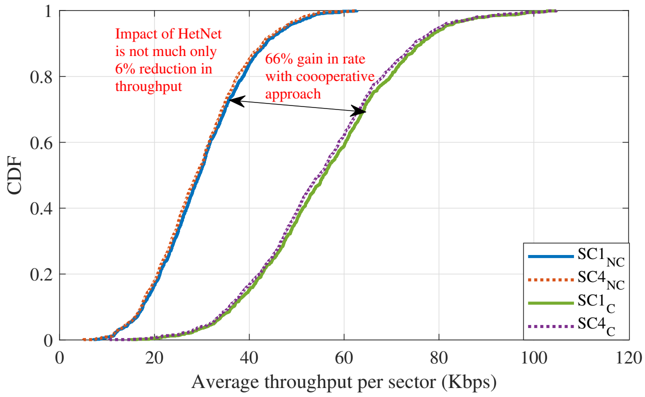
Figure 2b presents the performance evaluation of NB-IoT uplink with SC1 and SC4. It can seen that the impact of inter-cell interference in HetNet when compared to SC1 where only small cell operates. The main reason is that the maximum transmit power in LTE and NB-IoT is set to 23 dBm, therefore only if the user of macro-cell is closed to cell edge users of small cell; in that cases the inter-cell interference will rise. However, it is interesting to note that in uplink, the cooperative approach significantly improve the throughput by 66%.

As seen from the results that cooperative approach performs better in uplink as compared to downlink. This is due to the fact that in downlink the transmit power is significantly than uplink, therefore, downlink users have higher interference tolerance and the chances of cooperation is significantly lower. Whereas in case of uplink, due to lower transmit power, the interference tolerance level is quite low and even small interference will impact more. Therefore, more users cooperate to adjust power level which yield significant improvement. Moreover, reduction in interference with cooperative approach results in reduced repetitions and due to large TBS in uplink, the performance is significantly higher as compared to downlink. Both these factor jointly justify the results presented in Figure 2b.

Figure 3a presents the average energy consumption per sector in all the scenarios with both cooperative and non-cooperative approach in downlink. The results shows that the scenarios with macro-cell have significantly higher energy consumption as compared to SC1 where only small cells operate. Moreover, it can be seen that, cooperative approach significantly reduced the energy consumption in all the scenarios. With cooperative approach, the reduction of 33%, 60%, 72% and 68% in SC1, SC2, SC3 and SC4 in energy consumption is achieved, respectively. The energy consumption is improved due to the inter-cell interference reduction that translates in less repetition reducing the time of transmission. Similarly, figure 3b shows that the average energy consumption per sector in all the scenarios with both cooperative and non-cooperative approach in uplink. It can be seen that the reduction of 57% and 33% in SC1 and SC4, respectively.



(a) Downlink: Average throughput per sector comparison of various scenarios using cooperative and non-cooperative approaches.



(b) Uplink: Average throughput per sector comparison of various scenarios using cooperative and non-cooperative approaches.

Fig. 2: NB-IoT performance in HetNet in terms of average throughput per sector.

VII. Conclusion

The paper presents the evaluation of NB-IoT in HetNet with different deployment strategies. The NB-IoT can be deployed synchronously or asynchronously which results in multiple scenarios where inter-cell interference significantly impact the performance. The results show that significant performance degradation when NB-IoT is deployed in HetNet. However, the proposed cooperative approach is able to provide up to 66% gain in average throughput per sector and 72% in energy consumption. Therefore, it can be concluded that the proposed cooperative approach in [1] can be extended for HetNet and is able to provide significant improvements.

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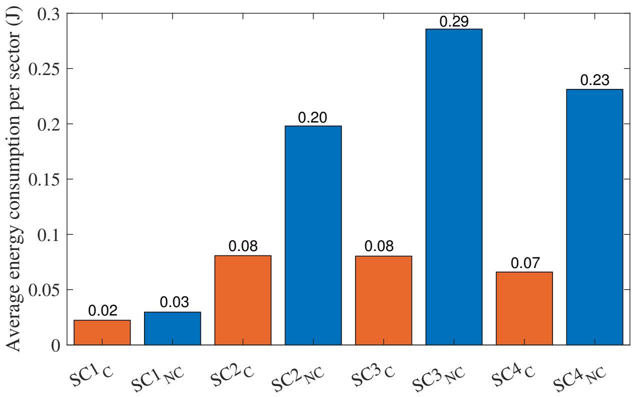
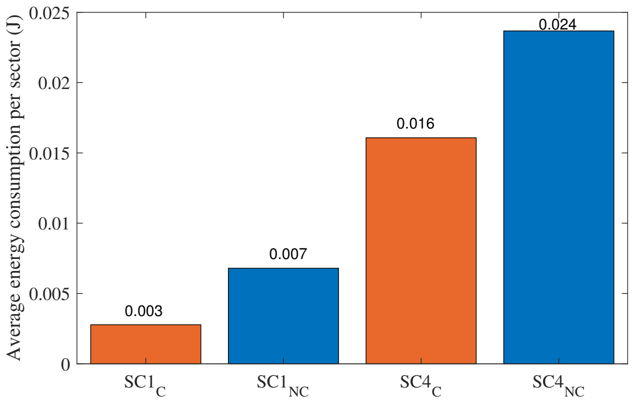


(a) Downlink: Energy consumption per sector comparison of various scenarios using cooperative and non-cooperative approaches.



(b) Uplink: Energy consumption per sector comparison of various scenarios using cooperative and non-cooperative approaches.

Fig. 3: NB-IoT performance in HetNet in terms of average energy consumption per sector.

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