Cooperative Interference Avoidance Scheduler for Radio Resource Management in NB-IoT Systems

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***Abstract*—The design changes on the physical (PHY) layer, i.e. the limited system bandwidth of one physical resource block (PRB), single antenna support, lower-order modulations, etc. inhibit the mapping of traditional long term evolution (LTE) radio resource management techniques to narrowband internet of things (NB-IoT) systems. Consequently, possible interference due to massive connectivity may severely degrade the expected system performance.**

In this regard, we propose an interference avoidance scheduling algorithm for NB-IoT systems. The algorithm entails a cooperative strategy in which the base stations share their respective scheduling tables which are then used to compute the interference for future transmitting user equipment (UEs). The computed interference values are then used as input to individual base station schedulers to perform scheduling. Each base station's scheduler then allocates the radio resources to the UEs with the lowest possible interference.

Extensive simulations are carried out to analyze the performance of our proposed algorithm and compare it to the conventional Round-Robin scheduling scheme. The results show that our proposed algorithm provides up to 36% throughput improvement to the NB-IoT UE as compared to Round-Robin. Similarly, for the same device's locations, the UEs are experiencing relatively better maximum coupling loss (MCL) which results in lower repetition numbers per coverage class.

***Index Terms*—NB-IoT, LPWAN, Interference Avoidance, Resource Scheduler, Radio Resource Management, mMTC**

I. Introduction

Narrow-Band Internet of Things (NB-IoT) is one of the enablers of the IoT use-cases such as environmental monitoring, smart gas metering, smart grids, smart water metering, smart waste management, etc. These use-cases are normally associated with different sensors installed in a fixed location to facilitate the corresponding expected services with low or no human intervention. The diversity of use-cases enforces different UE requirements including reporting circle, energy efficiency, payload size, nature of traffic, etc. For example, in a small-medium sized city, it is expected to have an average of 40 devices per household equipped with sensors to service different applications [1]. In this regard, such massive connections demand proactive radio resource management techniques to offer the required quality of service to the corresponding applications.

To cope with the growing demand for IoT use-cases, the 3rd Generation Partnership Project (3GPP) introduced the NB-IoT as a licensed IoT cellular technology to support the massive Machine-Type connections (mMTC). NB-IoT is a variant of the Long Term Evolution (LTE) with reduced complexity to enable low-cost devices. NB-IoT is classified as a Low-Power Wide-Area Networks (LPWAN) technology intended to enhance coverage for IoT use-cases especially for applications in hard-to-reach areas.

As per 3GPP, the design changes are as follows; NB-IoT's system bandwidth is a maximum of 200 kHz and can offer peak data rates of 250 $kbps$ and 226.7 $kbps$ in downlink and uplink, respectively. NB-IoT performs up to 128 repetitions to enable extended coverage, can tolerate a delay of up to 10 s during its transmissions, utilizes low order modulations i.e. Binary Phase Shift Keying (BPSK), support up to 52000 devices per cell and can transmit at maximum coupling loss (MCL) of 164 dB. More design changes are presented in [2].

Despite the advantages they bring, these changes hinder the effective implementation of traditional radio resource management techniques to NB-IoT systems because i) supporting massive devices with merely 200 kHz of radio resources is challenging even with low payload transmission, and additionally ii) when NB-IoT is deployed in in-band, guard-band or stand-alone mode, the limited system bandwidth hinders the traditional techniques such as carrier aggregation, inter-cell interference coordination (ICIC) with physical resource block (PRB) muting, etc. This is because PRB muting means shutting down the complete NB-IoT system bandwidth, and ICIC involves power and frequency partitioning between the competing/interfering base stations. Similarly, the Network Assisted Interference Cancellation and Suppression (NAICS) technique is no longer applicable. With NAICS, the network is required to provide the UEs with additional information on scheduled transmissions and hence enhance the performance of the receiver; however, NAICS is not a spectrum efficient technique and requires a complex receiver for interference mitigation [3]. Therefore, it is necessary to propose novel radio resource management techniques adapted to NB-IoT systems.

Previous studies such as [4] proposed an interference mitigation algorithm by considering the coexistence between NB-IoT and LTE; the proposed algorithm uses the channel frequency response (CFR) to mitigate the sampling mismatch between the NB-IoT UE and the base station / enhanced Node-B (eNB). The authors of [5] proposed an algorithm that leverages the average device delay and processing time to optimize NB-IoT resource management through basic scheduling. In [6], the authors presented a novel interference aware resource management for NB-IoT. Power control in a cooperative manner was proposed to minimize the interference impact. In [7], the authors proposed an algorithm to enhance the cell capacity; the optimal scheduling involves offset index selection and UE search spaces in NB-IoT networks. In [8], the authors proposed a link adaptation algorithm to enhance coverage; the algorithm uses a mathematical analysis of Shannon theorem. In [9], the authors proposed a link adaptation scheme that dynamically adjusts the maximum coupling loss (MCS) to optimize the block error rate (BLER) and Bit Error Rate performance.

However, the existing state of the art does not consider yet the inter-cell interference avoidance strategies to cope with the growing demand of IoT use-cases under stringent radio resources.

In this regard, we propose an inter-cell interference-avoidance scheduling algorithm to optimize the usage of limited NB-IoT radio resources and enhance the overall throughput. Our algorithm relies on the utilization of a cooperative strategy between NB-IoT's base stations by sharing the expected scheduling tables among themselves in advance. Each base station then computes the possible inter-cell interference that may arise between the prospective devices during their transmissions. The tables along with the computed interference information are then used as input to local schedulers. Proactive scheduling is then performed, avoiding to assign devices whose interference impact can lower the expected throughput. A Round-Robin algorithm is used as a benchmark and exhaustive simulations are performed. The results show that our proposed algorithm enhances the device achievable throughput up to 36% and reduces the number of repetitions per coverage class.

To the best of the authors' knowledge, this is the first work that entails the cooperative interference avoidance strategy to optimize the radio resources usage for NB-IoT systems.

The rest of the paper is organized as follows; section II presents our proposed cooperative interference-avoidance scheme, section III presents the simulation and performance evaluation, and section IV concludes the paper.

II. Proposed Cooperative Interference-Avoidance Strategy for NB-IoT System

In our proposed cooperative strategy the base stations share (over the X2-interface) the channel quality information (CQI) (i.e. SNR, location, path-loss, cell ID, expected payload, etc.), for the devices (UE) to be scheduled for the next radio frame. The proposed scheduler then uses this information to calculate the interference possibilities among shared UEs. The calculated interference values are hence used as input to the individual base station. Proactive scheduling is then performed

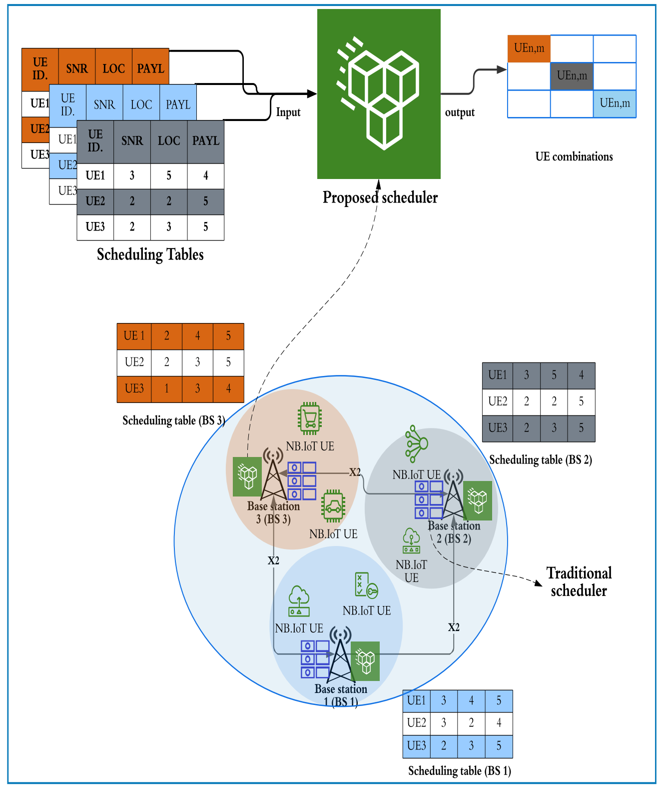

Fig. 1. Proposed cooperative interference-avoidance strategy for NB-IoT system

by providing the available resources to UEs whose impact in terms of inter-cell interference is the lowest.

The proposed scheduler comprises three main parts i.e. collection center, computing center, and scheduling center. The collection center receives and registers the scheduling tables from the individual base-stations. The computing center computes the inter-cell interference between UEs. The scheduling center makes the final decision about the UEs that have the best throughput performance when scheduled in the same slots. The system under study is considered to be a small and medium sized city based on the Okumura-Hata channel model whereby the UE path-loss model can then be expressed as in Equation (1), [10].

$$PL = A + B\ log(d) + C \tag{1}$$

where A, B and C depend on the antenna height and the frequency.

$$A = 69.55 + 26.16\ log(fc) - 13.82\ log(hb) - a(hm) \tag{2}$$

$$B = 44.9 - 6.55\ log(hb) \tag{3}$$

where fc and d are given in MHz and km, respectively, a and C depend on environmental factors, and hb and hm are heights for the base-station and UE, respectively.

The interference impact is based on the SINR which is calculated as shown in Equation (4), [11].

$$SINR^{DL}_{k,n} = \frac{p_{k,n}|h_{k,n}|^2}{\sum_{m=1}^{M} \omega_{n,m} p_{m,n} |h^C_{m,n}|^2 + N_0 B} \quad (4)$$

where $SINR^{DL}_{k,n}$, k, $p_{k,n}$, and $|h_{k,n}|^2$ are the down-link signal to interference-plus-noise ratio, the transmit power, and channel response of user n from base station k, respectively. $\omega_{n,m}$, $p_{m,n}$, and $|h^C_{m,n}|^2$ are the power classes, transmit power, and channel response of user m from base station n, respectively. N_0B is the channel noise which is considered constant.

The proposed scheduler functions as follows: it receives the scheduling tables from the individual base stations and then checks for inter-cell interference; if there is interference, it checks the interference weight with all the other UEs to be scheduled in the same radio frame. If the UEs have the best throughput performance, it forwards that combination (UE identities) to be used by the individual base stations. The flowchart of the proposed inter-cell interference-avoidance algorithm for the NB-IoT system is as depicted in Fig. 2.

III. Simulation and Performance Evaluation

TABLE I
Main simulation parameters for the proposed cooperative strategy for NB-IoT system [12]

Simulation Parameters	
Name	Value
(a) Transmit power of base station, UE (dBm)	46 , 23
(b) Modulation scheme	BPSK
(c) Carrier frequency (MHz)	900
(d) Receiver Thermal Noise density (dBm/Hz)	−174
(e) No. cooperating base station	3
(f) Interference Margin (dB)	0
(g) Channel model	Okumura Hata
(h) Effective Noise Power (dBm)	d + q + f + 10log(r)
(i) Required / calculated SINR (dB)	
(j) Receiver sensitivity	h + i
(k) MCL (dB)	a - j
(l) Modulation scheme	BPSK
(m) No. of antenna support per UE	1
(o) Height of base station, UE (m)	100, 1
(p) Radius of a cell	1 km
(q) Noise figure of base station, UE	9, 5 dB
(r) Occupied System bandwidth (kHz)	180

1) Simulation Setup: Extensive system-level simulations are performed to analyze the proposed approach, as depicted in Fig.1. The simulation setup is considered close to the one presented in [12]; however, it is well adapted to fit the NB-IoT system. The NB-IoT UEs are considered fixed and hence the impact of Doppler spread on UE mobility is negligible. This suits well the use cases such as smart grid, smart water, smart gas metering, smart waste management, etc. [1].

The Round-Robin algorithm, as presented in [13], is used to compare the performance of the proposed algorithm. In Round-Robin, each eNB assigns the radio resources to UEs in a first-come-first-served way. That is, the first detected UE is given the available resources regardless of the impact of interference it may cause/face.

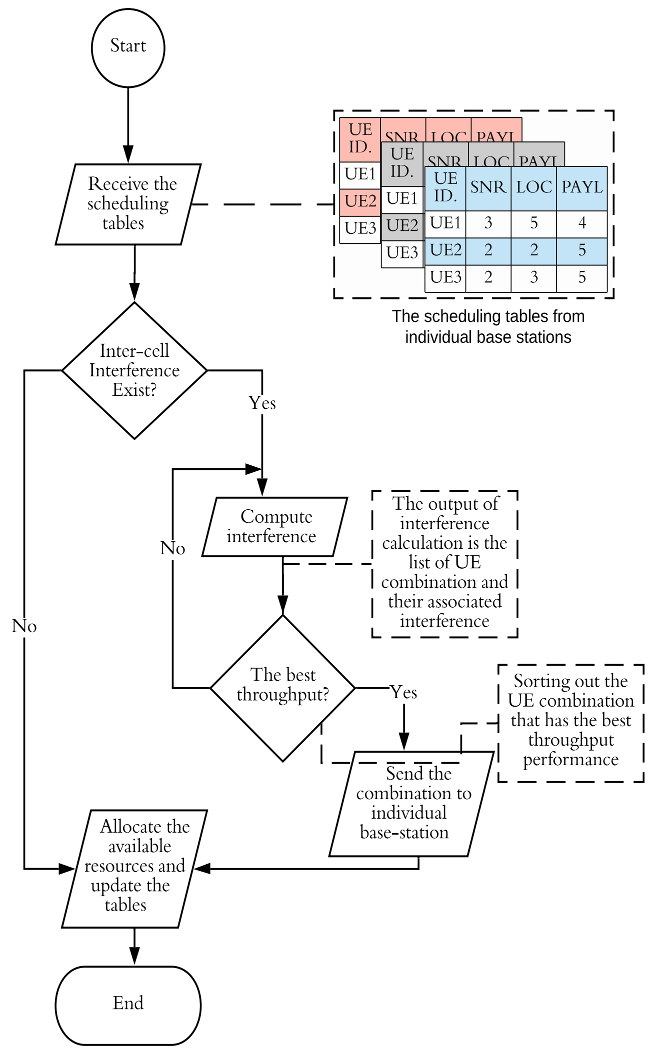

Fig. 2. Flowchart of our proposed NB-IoT inter-cell interference avoidance algorithm

For the interference-aware scheduling algorithm to better function, it is crucial to perform proper estimation of channel parameters to effectively sort out the UEs under possible interference. This is achieved by fixing the base stations and UEs while evaluating their corresponding channel conditions based on the defined model. The important simulation parameters are as presented in Table I [14].

2) Simulation Results: In Fig. 3, it can be observed that with the Round-Robin approach, the maximum achievable throughput per device is 60 $kbps$. The devices located at the center of the cell experience better throughput as compared to those towards the edge. This is due to the low path-loss which increases when moving from the center. It is also observed that the devices on the cell edge experience relatively high inter-cell interference as compared to those located at the center. Consequently, the achieved throughput is very low on the

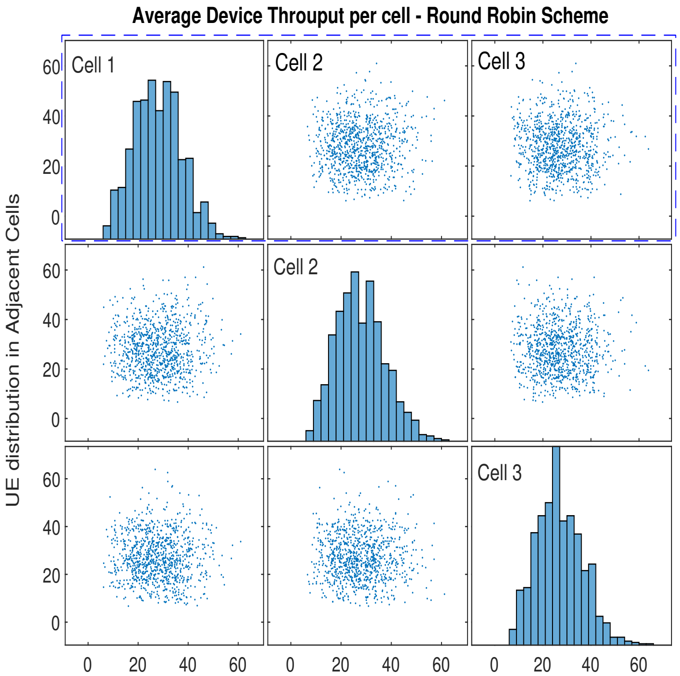

Fig. 3. Throughput distribution of NB-IoT UEs from the evaluation of the three cells when the Round-Robin scheduling algorithm is used. For example, when evaluating cell 1 the interference impact is considered from UEs from cell 2 and cell 3 and the same method is done for all cells. The dots represent the UEs distribution in adjacent cells

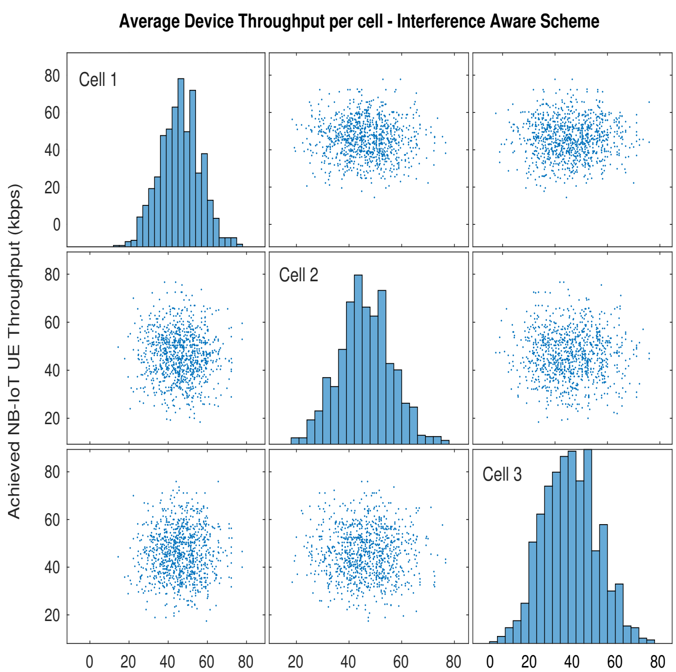

Fig. 4. Throughput distribution of NB-IoT UEs from the evaluation of the three cells when the proposed interference-aware scheduling algorithm is used. The dots represent the UEs distribution

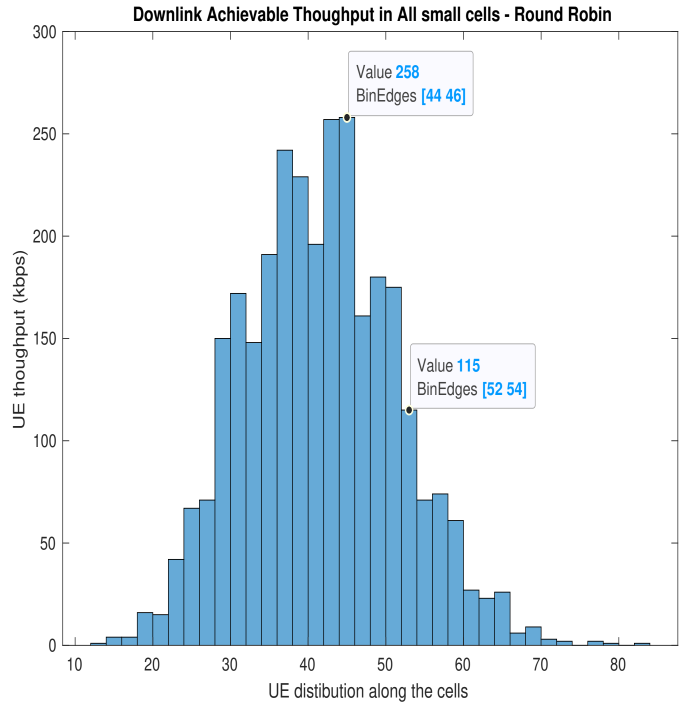

Fig. 5. Total achievable throughput for NB-IoT in the cells after using the Round-Robin scheduling algorithm

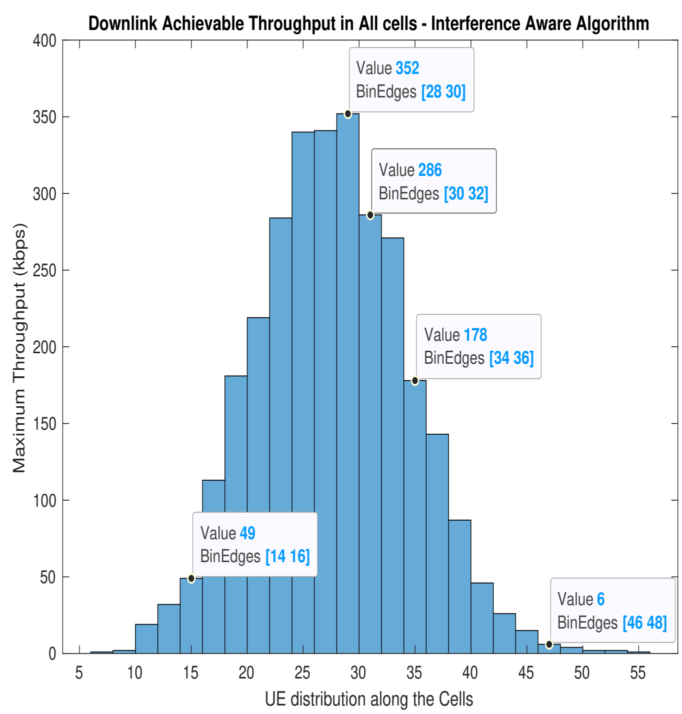

Fig. 6. Total achievable throughput for NB-IoT in the cells after using the proposed interference-avoidance scheduling algorithm

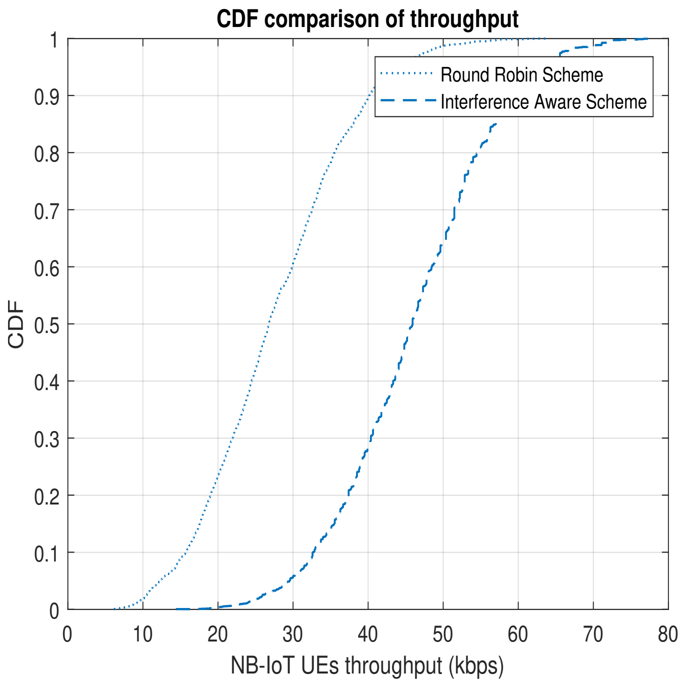

Fig. 7. Cumulative distribution functions (CDF) that represents the gain in throughput of the proposed intercell interference avoidance scheduling algorithm as compared to the Round Robin scheduling algorithm

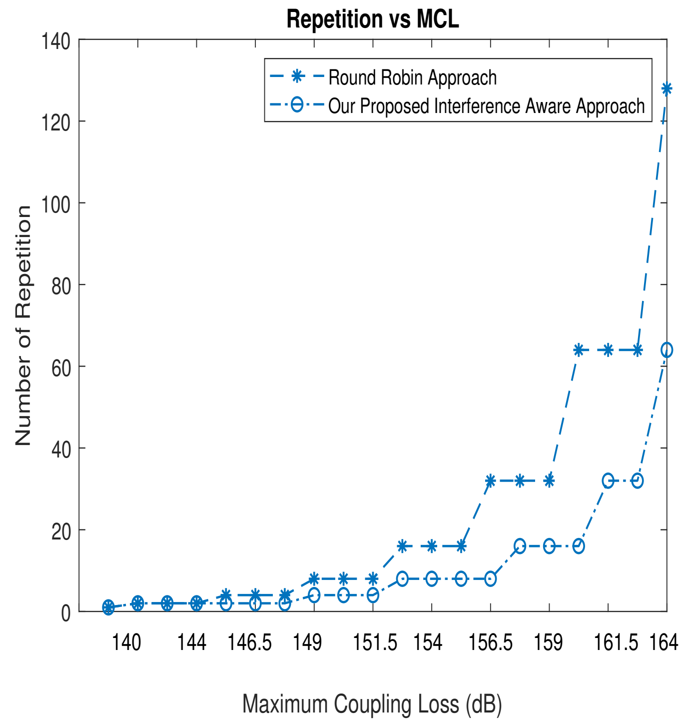

Fig. 9. Maximum number of repetitions experienced by the NB-IoT UEs under the two approaches

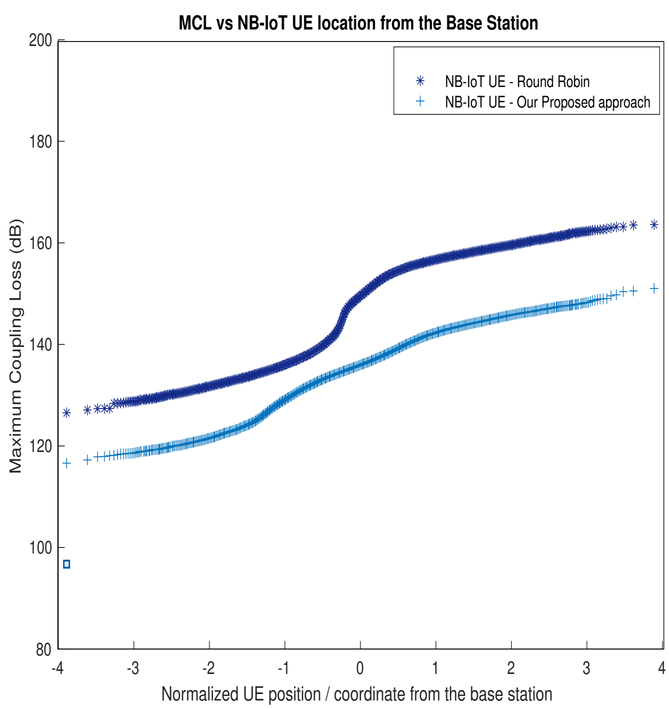

Fig. 8. Comparison of the maximum coupling loss between our proposed approach and Round-Robin for the UEs served in the same fixed locations.

edges of the cell.

In Fig. 4, with our proposed approach, it is observed that the overall UE throughput has relatively raised and the devices located at the center of the cell can experience a throughput of up to 80 $kbps$. Similarly, as the devices get farther from the center, the throughput drops; this is due to the increase in the experienced path-loss. The overall relative increase in throughput as compared to the Round-Robin algorithm is due to avoidance of interference and hence the NB-IoT UEs could guarantee better transmission with minimum errors.

Figure 5 presents the NB-IoT UE's maximum achievable throughput over the three cells. It is observed that the UEs that are exactly at the center of the cell can achieve an average throughput of about 250 $kbps$. This peak value corresponds to the 3GPP proposed framework as presented in [14] which is used during system modeling. However, some UEs that are exactly at the center of the cell can experience relatively lower throughput compared to UEs at a distant location. This is due to the inter-cell interference that these UEs may experience when scheduled at the same time.

Figure 6 presents the NB-IoT UE's maximum achievable throughput over the three cells after implementing the interference-aware scheduling algorithm. It is observed that the maximum achievable total NB-IoT UE throughput over the three cells is 350 $kbps$, while gradually decreasing as UEs are located far from the center. (Please note that 3GPP has given 250 $kbps$, but in our simulation, we considered that the impact of control channel overhead is negligible). However, this peak value is only possible when the impact of interference is considered negligible. As moving farther from the cell center, the throughput uniformly drops due to shadowing, fading and increase in path-loss.

Figure 7 presents the comparison of the cumulative distribution function (CDF) of achievable throughput for the two approaches under study. For the same number of devices per cell, it can be observed that the proposed approach outerperforms the Round-Robin approach and about 50 percentile of devices are experiencing almost twice the minimum achievable throughput.

Figure 8 presents the comparisons of MCL between our proposed approach and Round-Robin, it is observed that for the same device locations under the three coverage classes (i.e. MCL = 144 dB, MCL = 158 dB and MCL = 164 dB) the devices are served with relatively lower MCL as compared to the Round Robin approach. This is due to reduced interference impact and hence improving the receiver sensitivity. As a result, our approach makes the devices experience a relatively lower number of repetitions in all coverage classes, as shown in Fig. 9.

In general, it is observed that significant system gains in throughput and repetition reduction per coverage class are achieved when our proposed algorithm is used.

IV. Conclusion

This paper has presented a novel inter-cell interference aware scheduling algorithm for NB-IoT systems. Our proposed scheme utilizes the information shared in advance between the cooperating base stations to compute the interference weight, and hence schedules UEs with the minimum possible interference for the next transmissions. Unlike previous studies, our scheme considers the NB-IoT devices reduced complexity which may lead to poor channel estimation. Exhaustive simulations are carried to analyze the performance improvements of our approach. It is observed that our approach could guarantee a throughput improvement up to 36% as compared to the conventional Round-Robin approach. Furthermore, maximum achievable total NB-IoT UE throughput over the three cells is around 350 $kbps$ for devices at the cell center; however, as the UE moves far from the center, the throughput relatively drops due to channel variations and inter-cell interference impact on cell edge UEs. It is also observed that our proposed approach serves UEs at the same positions with better MCL as compared to the conventional scheme hence can reduce the number of repetitions per coverage class. The future outlook involves further studies on dynamic traffic models, energy efficiency, latency and mobility analysis for NB-IoT systems.

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