Joint Scheduling and Mobile Edge Computing for Inband NB-IoT Networks

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***Abstract*—In this paper, we perform joint scheduling for cellular users and IoT devices for Inband Narrow Band-IoT networks in the cellular spectrum. The cellular network tries to maximize its communication rate, whereas the IoT network consists of multiple IoT clusters of IoT devices and focuses on a total number of computed bits. Mobile edge computing server is considered to support IoT devices in their computing purpose. We keep provision for multiple physical resource block allocations for a cellular user. However, IoT devices in a cluster may be scheduled at maximum in a physical resource block. The scheduling problem consists of integer and continuous variables, making it non-trivial. We propose a low-complex polynomial-time heuristic algorithm for solving the scheduling problem and show its efficacy.**

I. Introduction

With the advent of different smart applications, e.g., smart city, smart home, smart agriculture, smart healthcare, etc., the Internet-of-Things (IoT) technology has received widespread attention [1]. It is anticipated that a massive number of IoT devices will be deployed in the near future, which will connect wirelessly to cover a wide area. Based on communication distance, IoT communication technologies can be divided into two, i.e., short distance and wide area network. IoT technology with wide area coverage is categorized as Low Power Wide Area Networks (LPWAN), where IoT devices have low power consumption and less complexity. Both cellular and non-cellular radio spectrum are chosen to deploy LPWAN. Non-cellular technology includes Lora, Sigfox, Zigbee, Bluetooth, etc., which operates in unlicensed radio spectrum. Contention issues may arise for unlicensed deployment, which can be avoided for cellular-based LPWAN.

To get access to the modern telecommunication market, mobile network operators together with communication equipment manufacturers, promoted the standardization progress for cellular IoT techniques [2]. A series of radio technology standards named Narrow Band-Internet of Things (NB-IoT) were standardized by the 3rd Generation Partnership Project (3GPP). NB-IoT is designed to operate on the existing cellular networks, e.g., Long Term Evolution (LTE) and Global System for Mobile Communication (GSM) [3]. There are several key performance indicators for NB-IoT, e.g., improved coverage (up to 35km), support for a massive number of devices (50K/cell), ultra-low cost (5 US dollars per device), and energy efficient modules (10 years battery life) [4].

NB-IoT networks can be deployed following either of three different modes, i.e., standalone, guardband, and inband [5]. Dedicated radio spectrum is allotted for the standalone mode, whereas the LTE guardband and operating radio spectrum are allotted for the other two modes, respectively. Dedicated radio spectrum allocation may be inefficient for IoT networks with bursty and smaller amounts of data. On the other hand, it may be challenging to accommodate millions of IoT devices in lower bandwidth guardbands. Inband deployment may be beneficial in this context. NB-IoT devices are scheduled in LTE operating radio spectrum according to their requirements in inband mode.

In this paper, we consider Inband NB-IoT networks. Related literature on scheduling for NB-IoT networks includes [6]–[8]. Authors of [6] have discussed different technical parameters, e.g., latency, coverage, battery life, etc. Though resource allocation has been considered in [7], [8], the question of how to schedule NB-IoT devices efficiently along with LTE users has not been addressed comprehensively there. This motivates us to study scheduling in inband NB-IoT networks. We zest contribution of this paper below:

- Joint scheduling of cellular users and IoT devices in inband NB-IoT networks
- Multiple IoT device scheduling in a single physical resource block to improve radio spectrum efficiency
- Polynomial time efficient algorithm development for solving non-trivial scheduling problem

II. System Model

In Fig. 1, we show the logical diagram of our system model, where we consider a base station (BS), multiple cellular users,

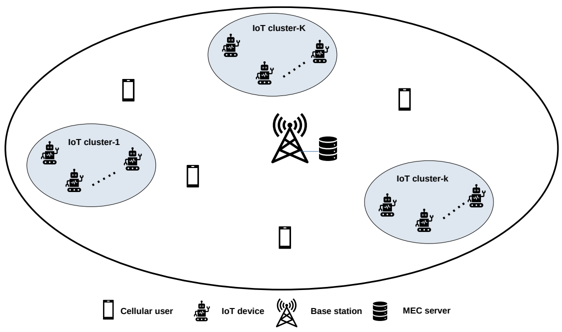

Fig. 1. Logical diagram of system model

and IoT clusters with IoT devices. The base station schedules both cellular users and IoT clusters in orthogonal physical resource blocks (PRBs), which we denote by $\text{PRB}_p, p = 1, .., P$. We denote cellular users by $\text{CU}_l, l = 1, .., L$, and IoT clusters by $\mathcal{I}_j, j = 1, .., J$. IoT devices under $\mathcal{I}_j$ are denoted by $\text{IoT}_{j,m}, m = 1, .., M_j$, where M_j is number of IoT devices under $\mathcal{I}_j$. We consider a scheduler at the BS, which schedules cellular users and IoT devices in the uplink. Each PRB is of duration T sec. and bandwidth B Hz. We allocate maximum a PRB to an IoT cluster; whereas, a cellular user may be allocated multiple resource blocks. In Fig. 2, we show a typical example of our PRB allocation procedure. PRB_1 and PRB_{i+1} are allocated to $\mathcal{I}_1$ and $\mathcal{I}_j$, respectively; PRB_2, PRB_l, and PRB_P are allocated to CUs. IoT devices of cluster $\mathcal{I}_j$ are scheduled in a PRB_{i+1} following TDMA, where we denote allocated time duration to $\text{IoT}_{j,m}$ by $t_{j,m}$.

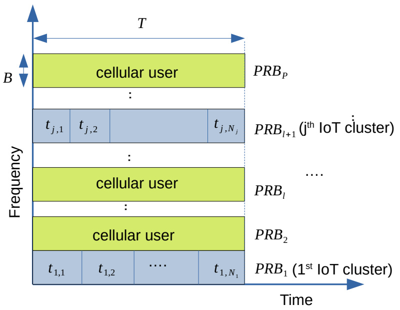

Fig. 2. A typical example of PRB allocation

A. Communication rate for the cellular network

If CU_l is scheduled in PRB_p, then effective received rate at the BS becomes:

$$R_{l,p}^{\text{CU}} = TB \log_2 \left\{ 1 + \frac{P_l^{\text{CU}} \left| h_{l,p}^{\text{CU-BS}} \right|^2 d_{\text{CU}_l}^{-\eta_1}}{\sigma^2} \right\} \tag{1}$$

where P_l^{CU} is CU_l's transmission power, $h_{l,p}^{\text{CU-BS}}$ is the channel gain between CU_l and the BS in PRB_p, d_{CU_l} is distance between CU_l and the BS, η_1 is path-loss factor, and σ^2 is receiver noise power. Therefore, effective communication rate for the cellular network becomes:

$$R^{\text{Comm}} = \sum_{l=1}^{L} \sum_{p=1}^{P} \alpha_{l,p} R_{l,p}^{\text{CU}} \tag{2}$$

where $\alpha_{l,p} \in \{0, 1\}$, is the selection parameter, i.e., $\alpha_{l,p} = 1$ for allocation of PRB_p to CU_l, otherwise, $\alpha_{l,p} = 0$.

B. Computation rate for IoT networks

Typical IoT devices are computation power limited, and hence, they may offload tasks for the computing facility at the BS. Therefore, effective computation rate consists of both local computation and computation at the BS as given below.

1) Local computation at $IoT_{j,m}$: We characterize the computation task of $\text{IoT}_{j,m}$ by a positive parameter tuple $\langle C_{j,m}, f_{j,m} \rangle$, where $C_{j,m}$ is the number of CPU cycles required to compute a bit at $\text{IoT}_{j,m}$ and $f_{j,m}$ is $\text{IoT}_{j,m}$'s CPU frequency (CPU cycles/second). $\text{IoT}_{j,m}$ can compute $R_{j,m}$ bits for the duration $t_{j,m}^{\text{loc}}$, where:

$$R_{j,m}^{\text{loc}} = \frac{t_{j,m}^{\text{loc}} f_{j,m}}{C_{j,m}}. \tag{3}$$

2) Computation at the BS for $IoT_{j,m}$: The BS may schedule IoT devices of a cluster in a PRB for TDMA offloading. Let us consider that cluster $\mathcal{I}_j$ is allocated PRB_p, where $\text{IoT}_{j,m}$ is allocated $t_{j,m,p}$ duration for offloading. Then, for $\text{IoT}_{j,m}$, we can write offloading rate as:

$$R_{j,m,p}^{\text{MEC}} = t_{j,m,p} B \log_2 \left(1 + \frac{e_{j,m,p} |h_{j,m}^{\text{IoT-BS}}|^2 d_{\text{IoT}_{j,m}}^{-\eta_1}}{t_{j,m,p} \sigma^2} \right), \tag{4}$$

where $e_{j,m,p}$, $h_{j,m}^{\text{IoT-BS}}$, and $d_{\text{IoT}_{j,m}}$ are $\text{IoT}_{j,m}$'s offloading energy in PRB_p, channel gain and distance to the BS, respectively.

Under the assumption of negligible computation time at the MEC server at the BS (for high computation power), we can write effective computation rate as:

$$R^{\text{Comp}} = \sum_{j=1}^{J} \sum_{m=1}^{M_j} \left[R_{j,m}^{\text{loc}} + \sum_{p=1}^{P} \beta_{j,p} R_{j,m,p}^{\text{MEC}} \right] \tag{5}$$

where $\beta_{j,p} \in \{0, 1\}$, is the selection parameter, i.e., $\beta_{j,p} = 1$ for allocation of PRB_p to $\mathcal{I}_j$, otherwise, $\beta_{j,p} = 0$.

C. Different Constraints

We consider following constraints in our system model:

1) Guaranteed rate for cellular network: The cellular network mainly focuses on received rate, which we consider in following equation:

$$R^{\text{Comm}} \geq R_{th}. \tag{6}$$

2) Buffer constraint at IoT devices: Typical IoT devices may be tiny, such that, consideration of infinite buffer may not be realistic. Therefore, we consider buffer constraint at IoT devices. If we consider the maximum buffer capacity at $\text{IoT}_{j,m}$ as $B_{j,m}$ bits, then we can write:

$$R_{j,m}^{\text{loc}} + \sum_{p=1}^{P} \beta_{j,p} R_{j,m,p}^{\text{MEC}} \leq B_{j,m}, \forall j, m. \tag{7}$$

3) Energy constraint at IoT devices: IoT devices may be battery driven and there may not be provision of recharging them in a regular interval. Therefore, based on local computation and offloading, we consider following constraint:

$$\frac{w_{j,m} t_{j,m}^{\text{loc}} f_{j,m}^3}{C_{j,m}} + \sum_{p=1}^{P} \beta_{j,p} e_{j,m,p} \leq E_{j,m}, \forall j, m. \tag{8}$$

4) Time constraint for IoT networks: All PRBs are over a particular time duration and we do the scheduling for that time duration. Therefore, we need to consider constraints on both local computation and offloading time durations, i.e.,

$$t_{j,m}^{\text{loc}} \leq T, \forall j, m, \tag{9a}$$

$$\sum_{p=1}^{P} \sum_{m=1}^{M_j} t_{j,m,p} \leq T, \forall j. \tag{9b}$$

5) PRB allocation constraint: We consider orthogonal PRB allocation among CUs and IoT clusters, such that, a PRB is allocated to a CU/IoT cluster at maximum. Following constraints are considered in our system model.

$$\sum_{p=1}^{P} \beta_{j,p} \leq 1, \forall j, \tag{10a}$$

$$\sum_{l=1}^{L} \alpha_{l,p} + \sum_{j=1}^{J} \beta_{j,p} \leq 1, \forall p, \tag{10b}$$

where Equation (10a) means an IoT cluster is allocated a PRB at maximum as we consider narrow-band IoT networks and Equation (10b) signifies that a PRB is either allocated to a CU or an IoT cluster. Please note that in our system model, a CU may be allocated more than a PRB.

III. Scheduling problem

We formulate a metric with both CUs' communication rate and IoT networks' computation rate and try to maximize that under above mentioned constraints. Following is the corresponding optimization problem, from which we find different scheduling parameters.

$$P1: \quad \underset{\boldsymbol{\alpha},\boldsymbol{\beta},\mathbf{t},\mathbf{t}^{\text{loc}},\mathbf{e}}{\text{maximize}} \ \gamma R^{\text{Comm}} + (1-\gamma) R^{\text{Comp}} \tag{11a}$$

$$\text{subject to:} \quad \text{Equation (6)} - \text{(10b)}. \tag{11b}$$

Due to presence of binary variables, i.e., $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, optimization problem $P1$ is not convex. However, we observe that for given values of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, the remaining problem is convex.

A. Feasibility Checking

It can be observed that the optimization problem $P1$ becomes infeasible if Equation (6) does not satisfy. Therefore, our first job is to check the feasibility. We check if the cellular network achieves the required threshold rate, i.e., R_{th}, using all PRBs, which is the best possible case. Corresponding optimization problem becomes:

$$P2: \ \underset{\boldsymbol{\alpha}}{\text{maximize}} \quad \sum_{l=1}^{L}\sum_{p=1}^{P} \alpha_{l,p} R_{l,p}^{\text{CU}} \tag{12a}$$

$$\text{subject to:} \quad \sum_{l=1}^{L} \alpha_{l,p} \leq 1, p = 1,..,P. \tag{12b}$$

We convert the above optimization problem $P2$ to an assignment problem (i.e., balanced bipartite graph problem), such that, it can be solved using efficient Hungarian algorithm.

In Fig. 3, we show a diagram with two partites, i.e., one for PRBs and other for CUs. As a CU may be allocated more than one PRB, we consider P number (i.e., number of PRB) of replicas of a CU on the right partite. In order to make both partites of same size, we include dummy PRBs, i.e., PRB_{P+1} to PRB_{LP}. We show actual and dummy links by blue and red colour, respectively. According to Equation (1), corresponding weight to the link between PRB_l and CU_p becomes $R_{l,p}^{CU}$ (s given in Equation (1)). It is to be noted that for dummy links, weights are zero, i.e., $R_{l,p}^{CU} = 0$, for $p = P+1,..,LP$ and $l = 1,..,L$.

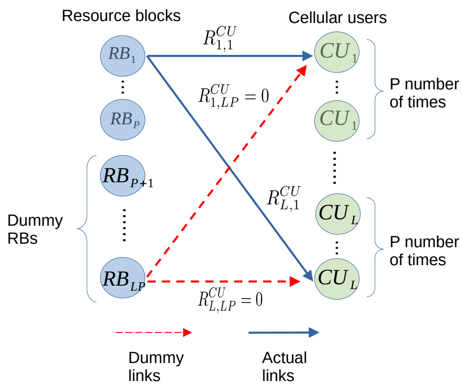

Fig. 3. Mapping between PRBs and CUs

Mathematically, Fig. 3's mapping problem can now be represented as:

$$P3: \ \underset{\boldsymbol{\alpha}}{\text{maximize}} \quad \sum_{l=1}^{LP}\sum_{p=1}^{LP} \alpha_{l,p} R_{l,p}^{\text{CU}} \tag{13a}$$

$$\text{subject to:} \quad \sum_{l=1}^{L} \alpha_{l,p} \leq 1, p = 1,..,LP \tag{13b}$$

$$\sum_{p=1}^{LP} \alpha_{l,p} \leq 1, l = 1,..,L. \tag{13c}$$

We solve the optimization problem $P3$ using Hungarian algorithm. We can say that the optimization problem $P1$ is feasible if Equation (6) satisfies after solving $P3$.

B. Scheduling problem under feasibility

In this section, we analyse the optimization problem $P1$ considering feasibility condition holds as has been discussed in the last section. We provide a heuristic solution for the optimization problem $P1$, which is computationally efficient. In that direction, we map the optimization problem $P1$ with assignment problem, which can be solved by efficient Hungarian algorithm. In Fig. 4, we show a typical example of mapping of PRBs with IoT clusters and CUs. We add dummy PRBs on the left hand side to make it equal with the right hand side which consists of CUs and IoT clusters. We repeat a CU for P number of times on the right hand side according to our previous discussion. Mathematically, we can represent the matching problem of Fig. 4 as:

$$P4: \ \underset{\boldsymbol{\zeta}}{\text{maximize}} \quad \sum_{l \in \{I_1,..,I_J,CU_1,..,CU_L\}} \ \sum_{p=1}^{J+LP} \zeta_{l,p} w_p^l \tag{14a}$$

$$\text{s.t.:} \quad \sum_{l \in \{I_1,..,I_J,CU_1,..,CU_L\}} \zeta_{l,p} \leq 1, p = 1,..,J+LP \tag{14b}$$

$$\sum_{p=1}^{J+LP} \zeta_{l,p} \leq 1, l \in \{I_1,..,I_J,CU_1,..,CU_L\}. \tag{14c}$$

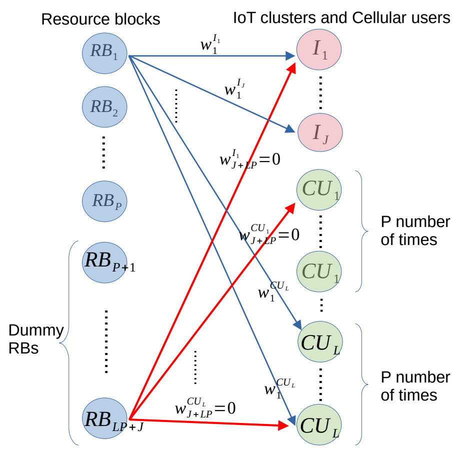

Fig. 4. Mapping of PRBs with CUs and IoT clusters

Associated weights with dummy nodes are zero in Fig. 4, which are shown by red arrows. Procedure for finding remaining weights are discussed below.

1) Evaluation of $w_p^{CU_l}$: When PRB_p is allotted to CU_l, the corresponding weight, i.e, $w_p^{\text{CU}_l}$, becomes:

$$w_p^{\text{CU}_l} = R_{l,p}^{\text{CU}} \tag{15}$$

The above mentioned equation is used to determine the weights for every allocation of PRB_p to CU_l, where $p = 1, .., P$ and $l = 1, .., L$. For dummy PRBs, we consider zero weight values, i.e., $w_p^{\text{CU}_l} = 0, p = P + 1, .., LP + J, \forall l$.

2) Evaluation of $w_p^{IoT_j}$: We find $w_p^{\text{IoT}_j}$ by allocating PRB_p to I_j, i.e., by solving below optimization problem.

$$P5: \underset{\mathbf{t}, \mathbf{t}^{\text{loc}}, \mathbf{e}}{\text{maximize}} \sum_{m=1}^{M_j} [\frac{t_{j,m}^{\text{loc}} f_{j,m}}{C_{j,m}} +$$

$$\sum_{p=1}^{P} t_{j,m,p} B \log_2 \left(1 + \frac{e_{j,m,p} |h_{j,m}^{\text{IoT-BS}}|^2 d_{\text{IoT}_{j,m}}^{-\eta_1}}{t_{j,m,p} \sigma^2}\right)] \tag{16a}$$

$$\text{subject to:} \quad R_{j,m}^{\text{loc}} + \sum_{p=1}^{P} R_{j,m,p}^{\text{MEC}} \leq B_{j,m}, \forall j, m, \tag{16b}$$

$$\frac{w_{j,m} t_{j,m}^{\text{loc}} f_{j,m}^3}{C_{j,m}} + \sum_{p=1}^{P} e_{j,m,p} \leq E_{j,m}, \forall j, m, \tag{16c}$$

$$\text{Equation (9a)} - \text{(9b)}. \tag{16d}$$

We now discuss the solution procedure for $P4$. In that direction, we give the below proposition.

Proposition III.1. *The optimization problem, i.e., $P4$, belongs to the convex optimization family as both the objective function and optimization variable set are convex.*

Proof. From the objective function as given in Equation (16a), it can be observed that the first term is linear to optimization variables. The second term has a form similar to $x \cdot \log_2 \left\{1 + \frac{y}{x}\right\}$ (both x and y are variables), which is convex (can be proved from the Hessian matrix). Hence, the objective function is convex. Among constraints, it can be observed that Equation (16b) has a similar form as the objective function. Hence, from the previous arguments, we can say Equation (16b) is convex. Constraints as given in Equation (16c), (9a), and (9b) are to optimization variables, and hence convex. Therefore, we conclude that $P4$ becomes convex. $\square$

Thanks to Proposition III.1, one can note that the optimal solution for $P4$ can be obtained by utilizing some standard optimization tools, e.g., Gurobi, Mosek, GAMS, CVX, MATLAB. We use "fmincon" in MATLAB to solve $P4$. In Algorithm 1, we present our heuristic algorithm for solving $P1$.

Algorithm 1: Heuristic algorithm for Solving $P1$

1 Initialization: Number of PRBs, CUs, IoT clusters, IoT devices in each cluster, R_{th};
2 Allocate all the PRBs to CUs following Section IV.A ;
3 **if** $R^{Comm} \geq R_{th}$ **then**
4   Go to step 6
else
5   Scheduling problem is not feasible
6 Allocate all the PRBs to IoT clusters and CUs following Section IV.B;
7 **if** $R^{Comm} \geq R_{th}$ **then**
8   Go to last step considering Step-6's result as final one
else
9   From Step 6, identify the following set for PRBs:
$$\mathcal{C} = \{\text{PRB}_p | \text{PRB}_p \text{ is allotted to IoT cluster}, p = 1, .., P\}$$
10 Arrange PRBs in $\mathcal{C} = \left\{\mathcal{C}^{[1]}, \mathcal{C}^{[2]}, .., \mathcal{C}^{[|\mathcal{C}|]}\right\}$, where $\mathcal{C}^{[1]}$ is the PRB in which IoT networks receive least computation rate, $\mathcal{C}^{[2]}$ is associated with second least computation rate, and so on; $|\mathcal{C}|$ is the cardinality of $\mathcal{C}$;
11 $i = 1$;
12 **while** $R^{Comm} < R_{th}$ **do**
13   Allocate $\mathcal{C}^{[i]}$ to CU which gets maximum communication rate in that PRB;
14     $i = i + 1$
15 Result: Scheduled IoT clusters nd CUs in PRBs

Discussion on Algorithm 1 and its complexity: We initially check if there is any possibility that $P1$ becomes infeasible, which is checked in step-3 followed by step-2 (where all PRBs are allotted to CUs to check if Equation (6) satisfies). Step-6 onwards are followed only when the cellular network's communication rate stays above the threshold. In step-6, PRBs are allocated to IoT clusters and CUs and the allocation is considered to be final if the cellular network receives more communication rate than the threshold. Otherwise, the allocation becomes infeasible. As there is a scope to make it feasible, we allot CUs with PRBs from the IoT clusters (which are allotted to IoT clusters in step-6). We form a set for PRBs allotted to IoT clusters in step-9. PRBs are ordered according to IoT clusters' computation rates in step-10. As we aim to maximize weighted sum of communication and computation rates, we try to make the allocation feasible by allotting the cellular network the PRB, in which the IoT network receives least computation rate. This process is continued until we get feasibility, which can be seen in step-12 to 14.

Now, we check the complexity for Algorithm 1. We discuss the complexity of the steps, which contribute mainly. Complexity for step-2 is $O(\max(P, L)^3)$. In step-6, we solve PJ number of convex optimization problems, i.e., $P4$. Considering the ellipsoid method for solving the convex optimization problem, we get complexity as $O(P \sum_{j=1}^{J} M_j^3 \log \frac{R}{r})$. For bipartite matching in step-6, it incurs additional complexity of $O(\max(P, J + LP)^3)$. In step-10, we do sorting, which in the worst case incurs complexity of $O(P \log P)$. Step-12 to 14 causes worst-case complexity of $O(2P)$. Hence, total complexity for Algorithm 1 becomes $O\{\max(P, L)^3 + P\sum_{j=1}^{J} M_j^3 \log \frac{R}{r} + \max(P, J+LP)^3 + P\log P + 2P\}$, which is in polynomial time.

IV. Results and Discussions

In this section, we discuss our received results and show efficacy of our proposed scheduling method. We consider values for different parameters as follows: Channel gains $(|h_{l,p}^{\text{CU-BS}}|^2, |h_{j,m}^{\text{IoT-BS}}|^2, \forall l, p, j, m)$ are exponentially distributed with unit mean, bandwidth (B_w) is of 3 MHz., Distance from BS to CUs, and from BS to IoT devices are uniformly distributed in between 10 to 100 meters, path-loss factor (η_1) is 3, receiver noise power value is -174 dBm/Hz., value for $w_{j,m}, \forall j, m$ is 10^{-26}, buffer capacity $(B_{j,m}, \forall j, m)$ at IoT devices are uniformly distributed in between 1000 to 2000 bits, energy at IoT devices $(E_{j,m}, \forall j, m)$ are uniformly distributed in between 0.5 to 1 joule, time frame duration (T) is 1 msec., number of CPU cycles to compute a bit is 10^6, and IoT devices' CPU frequency $(f_{j,m}, \forall j, m)$ is 10^{10} Hz.

A. Different rates for varying number of PRB

We plot both communication and computation rates for varying number of PRB in Fig. 5, where it can be observed both increases with number of PRB. The result has been generated for four cellular users and three IoT clusters with five, seven, and four IoT devices, respectively. Threshold rate, i.e., value for R_{th}, has been considered to be 5000 bits. For a single PRB, computation rate for the IoT network becomes zero, which happens as the cellular network is allotted the PRB to maintain the rate threshold constraint.

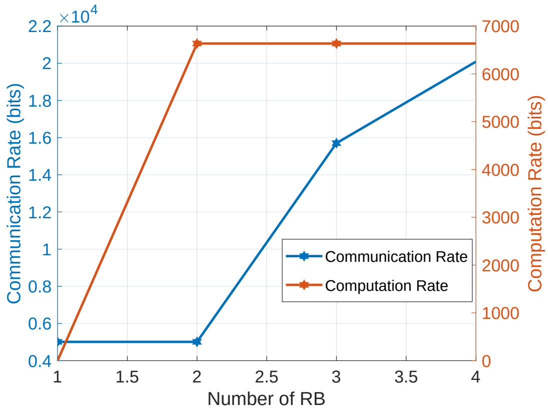

Fig. 5. Communication and Computation Rates for varying number of PRB

B. Spectrum efficiency for our proposed model

We do a comparison in Fig. 6 with conventional approach for scheduling in NB-IoT networks, where an IoT device is allocated a PRB for whole time duration of T sec., in term of number of scheduled IoT devices. The comparative has been generated for four cellular user and two IoT clusters comprising of five and four IoT devices, respectively. The threshold rate i.e, R_{th}, has been kept 5000 bits. We consider same number of IoT devices (i.e., nine) with same values for other paraeters (i.e., buffer data amount, energy, channel, etc.) in both of our proposed and conventional models. It can be observed our proposed scheduling method outnumber the conventional one with increasing value for number of PRB.

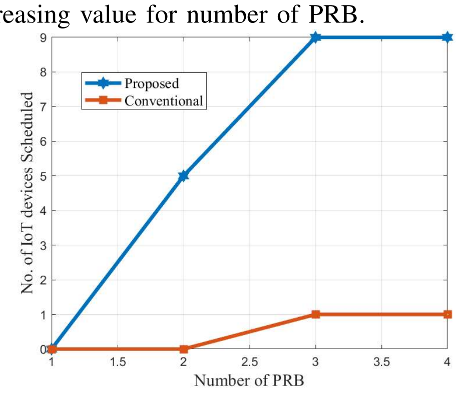

Fig. 6. Scheduled number of IoT devices for varying number of PRB

V. Conclusion and Future Scope

We have studied a scheduling problem for an Inband NB-IoT network with MEC, where CUs and IoT devices are jointly scheduled based on their communication and computation rate. The scheduling problem has been made more general by keeping provision for multiple PRB allocations to a cellular user, whereas an IoT device is allotted a PRB at maximum. More than one IoT device is scheduled in a PRB, unlike the traditional method, which helps in scheduling more buffer-limited IoT devices and improves spectrum efficiency. One possible extension of this work may be consideration of multiple time frame scenario.

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