Scheduling and Adaptive Resource Allocation on ICIC with Testbed Implementation

Chien-Hao Lee[1], Kai-Wen Cheng[1], Kuang-Hsun Lin[2], and Hung-Yu Wei[1,2,*]
[1]Graduate Institute of Electrical Engineering, National Taiwan University, Taipei, Taiwan
[2]Graduate Institute of Communication Engineering, National Taiwan University, Taipei, Taiwan
[*]Email: hywei@ntu.edu.tw

***Abstract*—Inter-Cell Interference Coordination (ICIC) is introduced to mitigate interference at cell-edge User Equipments (UE). A variety of ICIC approaches were proposed in previous literature. However, most of them focused only on resource allocation methods, which were not practical enough for implementation. In our ICIC design, we propose not only a resource allocation scheme but also a scheduling method. The proposed resource optimizer can find an ICIC solution efficiently. The proposed scheduler can maintain the performance of the solution in each Transmission Time Interval (TTI). Both of the resource optimizer and the scheduler are compatible with the testbed. Simulation results shows our proposed schemes outperformed other literature findings in edge throughput and edge UE fairness. Testbed results also shows real gain and the feasibility of our algorithms.**

I. Introduction

To increase the radio resource efficiency, adjacent Base Stations (BS) usually use same frequency band in LTE. However, UE at cell edge may suffer from high interference from neighbor cells. This interference is called Inter-Cell Interference (ICI). ICIC is introduced in 3GPP Release 8 [1]. It points out in high-level that radio resource management is the key to solve ICI problem. Soft Frequency Reuse (SFR) is a well-known static ICIC solution. In each cell, the bandwidth divides into two region: cell center and cell edge. The cell-edge band transmits higher power to increase signal strength and mitigate the effect of interference. The cell configuration of SFR is illustrated in Fig. 1.

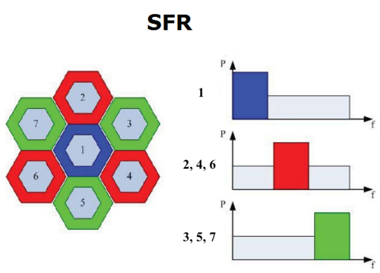

Fig. 1. Frequency division in SFR.

In recent literature findings, [2] jointly considered load imbalance of edge UEs and ICIC. Distributed schemes are proposed to solve ICI problem in [3] and [4]. In [5] [6], the resource allocation is in time domain. [7] uses game theory in Hetrogeneous Network (HetNet) scenario. However, mobility management, distributed schemes, and time-domain ICIC are not compatible with our testbed. Two others ICIC methods in centralized frequency-domain scheme [8] [9] are more feasible on our testbed. Therefore, we take these two methods as benchmarks and compare several performance metrics with our proposed algorithm. [10] optimizes specific traffic type in ICI environment. In simulation, we simplify the problems to theoretical throughput only.

The remaining of this paper is organized as follows. Section II describes the problems modeling. Section III presents the design of our algorithms. Section IV shows the performance of our algorithms and the comparison with previous ICIC solutions by simulation. Section V gives the discussion of results from testbed experiments. Finally, conclusions are drawn in Section VI.

II. Problem Description

The ICI problem can be described as an integer programming optimization problem. In previous work, the optimization object is usually the overall throughput, subject to a minimal cell-edge throughput. However, two drawbacks of such optimization can not be ignored. The first one is that the average cell-edge throughput is probably still low after optimization. The second one is that the throughput is likely to have great difference in each cell-edge UE because of the unbalanced distribution of cell-edge UE in each cell.

In each TTI, the number of serving UE is limited, and the maximum value is four in our testbed. If there are more than four UEs waiting for transmitting, eNB should do scheduling. Since the object of optimization is focused on single TTI and the network topologies are probably dissimilar in each TTI, the default round-robin scheduler is not able to maintain the performance in each TTI. On the basis of these problems, the design of our ICIC solution included two aspect: scheduler and resource optimizer. A classification algorithm and an efficient optimization algorithm are designed for scheduler and resource optimizer respectively.

III. Proposed ICIC Algorithm

We propose a centralized ICIC algorithm, including a classification algorithm and an efficient optimization algorithm, and implement these algorithms in the central controller. The flow of overall algorithm is illustrated in Fig. 2. The input into the central controller is Reference Signal Received Power (RSRP) of each UE in each cell. The classification algorithm classifies UE type, and generates network topology for the input to next stage algorithm. In the meantime, each UE is grouped to a type and this information is sent back to corresponding eNB. The schedule function in eNB schedules serving UEs in each TTI. After the network topology is generated, the efficient optimization algorithm produces a command for each eNB. The command sets the Resource Block (RB) allocation and UE power configuration. The RB allocation function in eNB allocates RB for serving UEs according to the command.

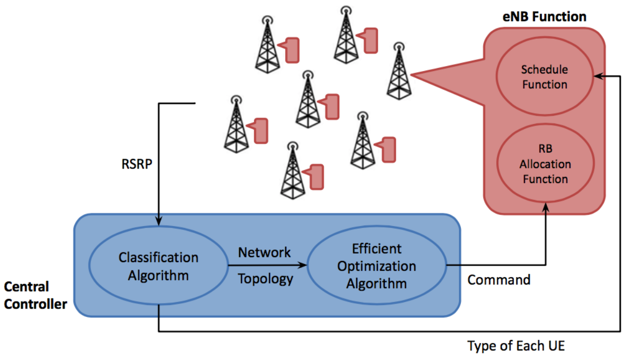

Fig. 2. Proposed ICIC solution overview.

A. *Classification Algorithm: classifySch*

Before scheduling, all UEs in one cell are classified as cell-center UE, cell-middle UE, or cell-edge UE by their RSRP value. For a UE, if the difference between RSRP from the serving eNB i ($RSRP_i$) and RSRP from the neighbor eNB j ($RSRP_j$) is lower a threshold (I_{th}), that UE will be classified as a cell-edge UE. If the UE is not a cell-edge UE, RSRP from the serving eNB will be compared with the other threshold (I_{tt}) to classify the UE as a cell-center UE or a cell-middle UE.

$$\begin{cases} RSRP_i - RSRP_j < I_{th}, & \text{cell-edge} \\ RSRP_i - RSRP_j > I_{th}, RSRP_i < I_{tt}, & \text{cell-middle} \\ RSRP_i - RSRP_j > I_{th}, RSRP_i > I_{tt}, & \text{cell-center.} \end{cases} \quad (1)$$

The main goal of the scheduler is to produce a network topology and the type of each UE. The network topology should be able to represent the serving UEs in each TTI, making commands generated by the central controller take effect and maintain their performance in each TTI. The UE type defines the serving UEs in each TTI. The number of UE type is equal to N_t, the number of maximum serving UE per cell in single TTI. In each TTI, the serving UEs are chosen from each UE type. The type of UE includes several edge types and non-edge type. The edge types include the information of its neighbor cells. Different edge types include different neighbor cells. Moreover, the classification algorithm also increases the number of edge type even when there are only a few cell-edge UEs. This ensures the scheduler work in scenarios that the number of cell-edge UE is low. Several steps are designed to generate UE type. The algorithm executes independently for each cell.

At first, the scheduler determines representatives of neighbor eNB by the distribution of cell-edge UE. The algorithm can identify which neighbor cells that cell-edge UEs concentrate at, and take those cells as groups. There may be one or more than one neighbor eNB in each group. For clear description, some vectors are defined as follows and illustrated in Fig. 3.

- eNB vector: The size and the number of eNB vector are the number of neighbor cell. Each neighbor eNB forms an eNB vector. In each eNB vector, the index corresponding to its eNB is 1, and the index corresponding to its adjacent eNB is a value between 0 and 1, which is predetermined by the distance between two eNBs.
- Group vector: Group vector is normalization of linear combination of eNB vectors that in a group.
- UE vector: The size of UE vector is also same as the number of neighbor cell. UE vector is determined by the neighbor cell information of UE. If eNB j is one of the neighbor cell of UE i, the index j of UE vector i is set to 1. Otherwise, it is set to 0.

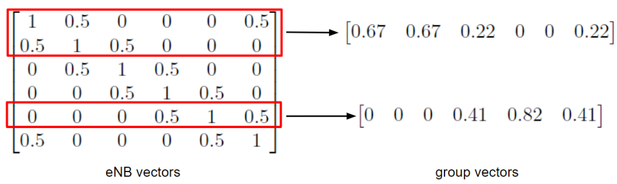

Fig. 3. Example of group vector construction.

After constructing group vectors and UE vectors, the algorithm starts to group UE. For each cell-edge UE, the inner product of UE vector and each group vector is calculated, and the cell-edge UE will be put to a group with the maximum result. There is also the maximum size of each group. If the number of UE in a group is more than the upper limit, that group will be divided into two groups with equal size. Several conditions for grouping are included in the algorithm so that the number of cell-edge group is certainly lower than N_t.

Then, cell-middle UEs and cell-center UEs are going to be grouped in order. Some new groups will be added until the number of group reaches N_t. The remaining UEs are assigned to a group with the smallest size one by one. Overall, the grouping order of cell-middle UE is prior to cell-center UE. The reason is that the UE which is assigned to a group earlier is more likely to be served in the same TTI with cell-edge UE, and the resource assigned to cell-edge UE is fewer (but with higher power level to boost its throughput). Therefore, the cell-middle UE, whose RSRP is lower than that of cell-center UE, is more possibly assigned with more resource than cell-center UE.

B. *Efficient Optimization Algorithm: bfsOpt*

Since the complexity of ICI optimization problem is proved to be NP-hard [11] [12], the goal of proposed efficient optimization algorithm is to generate a RB allocation command with better performance at cell-edge UEs for each eNB efficiently. Due to the testbed characteristics, the proposed scheme includes two aspects: (1) base station RB mask, (2) base station downlink data channel power control. A Resource Block Group (RBG), which consists of few RBs, is the minimum unit allocated to an UE. The downlink data channel to UE can be boosted or attenuated by $\{-6$ dB, -4.77 dB, -3 dB, -1.77 dB, 0 dB, 1 dB, 2 dB, 3 dB$\}$ compared with the reference signal power, which is defined in 3GPP LTE standard [13].

The overall procedure is (1) to determine RBGs allocated to cell-edge UE, (2) to determine RBGs allocated to cell-middle UE, (3) to allocate remaining RBGs to cell-center UE, and (4) to construct a command for each eNB. The step (1) in the procedure is implemented by a graph-based approach. We use a weighted graph to solve the optimization problem. Our algorithm follows the graph theory [14] and some heuristic coloring techniques [15] [16]. In the graph $G = (V, E)$, each node represents a cell-edge UE, and the weight on each edge represents an interference level when two cell-edge UEs using the same subchannel. There are two interference level considered in our work, including (a) edge-to-edge interference and (b) neighbor-to-edge interference. The edge-to-edge interference means that two UEs served in different neighbor cells are connected on the same edge. The neighbor-to-edge interference means that one UE is not on the edge of two neighbor cells but the other one is. An example for constructing weighted graph is illustrated in Fig. 4. The red thick line means two UEs are in same serving eNB, and must be allocated with different RBGs. The blue fine line means two UEs are in adjacency, i.e. edge-to-edge interference, and should be allocated with different RBGs. The other neighbor-to-edge interference is not shown in Fig. 4 for clear illustration.

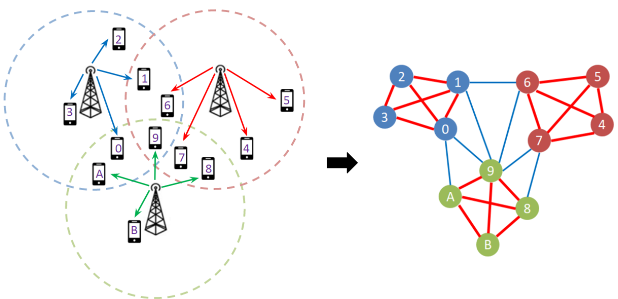

Fig. 4. Example of graph construction.

After the interference graph is constructed, we need to assign each node to a cluster (i.e. coloring). The goal is to separate two nodes with high weight edge as much as possible. In other words, the total interference in all clusters will be minimized. The number of cluster used in this work is corresponding to the total RBG number. To reduce the time complexity of optimization procedure, a greedy algorithm is adopted in this work. However, it is known that the performance of greedy algorithm is affected by the order of node selection. Instead of random selection, we use Breadth-First Search (BFS) to determine the order of cell-edge UE on graph. At first, a cell-edge UE is chosen randomly as the search key. Then, other cell-edge UEs in the same cell and neighbor cell-edge UEs on the same edge are the next level nodes to be explored. The search continues until all cell-edge UEs have been explored once. After BFS, the order for the greedy algorithm is determined. Fig. 5 illustrates an example of BFS on graph.

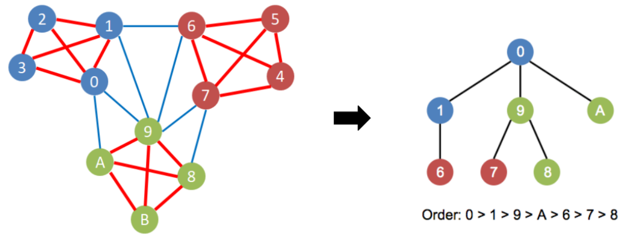

Fig. 5. Example of BFS on graph.

According to the order produced by BFS, the greedy algorithm takes a cell-edge UE at each time. The cell-edge UE chooses three clusters with minimal increasing total interference, subject to a constraint that every UE in the same cell can not use the same subchannel. After all cell-edge UEs are allocated with resource, the algorithm starts to determine RBGs allocated to cell-middle UE. Each cell-middle UE chooses four clusters with minimal increasing total interference. This will separate the RBGs used by cell-middle UEs and their neighboring cell-edge UEs as possible as it can, and mitigate the interference to those cell-edge UEs. At the end, the remaining RBGs are allocated to cell-center UEs. A command is generated for each eNB. An example of resource allocation is described in Table I. PA means the power level of data channel to a UE. In RBG allocation, “O” means the RBG is allocated to the UE, and “X” means the RBG is not allocated to the UE.

TABLE I
EXAMPLE OF RESOURCE ALLOCATION.

Order	**UE Index**	**UE Type**	**PA**	**RBG Allocation**
1	0	edge	7	OOOXXXXXXXXXXXXXX
2	1	edge	6	XXXOOOXXXXXXXXXXX
3	9	edge	7	XXXXXXOOOXXXXXXXX
4	A	edge	6	XXXOOOXXXXXXXXXXX
5	6	edge	7	OOOXXXXXXXXXXXXXX
6	7	edge	6	XXXOOOXXXXXXXXXXX
7	8	edge	5	OOOXXXXXXXXXXXXXX
8	2	middle	3	XXXXXXXXXOOOOXXXX
9	4	middle	3	XXXXXXXXXOOOOXXXX
10	5	middle	3	XXXXXXXXXXXXXOOOO
11	3	center	0	XXXXXXOOOXXXXOOOO
12	B	center	0	XXXXXXXXXOOOOOOOO

Legend	
PA	Transmit power level (0-7)
RBG Allocation	O: The RBG is allocated to the UE. X: The RBG is not allocated to the UE.

IV. SIMULATION RESULT

In this section, we use simulation to evaluate the performance of proposed algorithms. All results in this section are the average of 50 times simulation.

A. Simulation Scenario

The simulation scenario is a 5×5 grid deployment with uniform UE distribution. In this scenario, the ratio of cell-edge UE is high (more than 40%), which is able to test ICIC schemes in dense edge user case. The simulation setup is described in Table II. The system model follows the testbed characteristics.

TABLE II
SIMULATION PARAMETERS

Model	Parameter	Assumption
System Model	Cell deployment	5×5 grid deployment
	Cell distance	50 m
	Carrier DL frequency	2.66 GHz
	Bandwidth	10 MHz; 50 RBs
	Resource allocation type	Type 0
	Max serving UE per cell	4 (single TTI); 32 (total)
	Reference signal power	−7 dBm
Channel Model	Pass loss model	3GPP urban micro [17]
	Thermal noise density	−174 dBm/Hz
Traffic Model	User distribution	Uniform
	User density	4-32 users per cell
	Data generation	Full buffer

B. Compared Schemes

The performance of bfsOpt is compared with six benchmarks, which are (1) Middle-Power-Enhanced SFR (MPESFR), (2) SFR, (3) Q-learning ICIC, (4) Hypergraph-based ICIC (Hgraph), (5) full power scheme, and (6) no ICIC scheme. In addition, our proposed scheduler (classifySch) is compared with Round-Robin scheduler (RR). Several combinations of scheduler and resource optimizer are evaluated for the comparison of these two schedulers.

- SFR is described in Fig. 1.
- MPESFR is similar with SFR, but the power of cell-middle UE is enhanced.
- Q-learning ICIC [8] learns two parameters (1) cell-center power, (2) edge-to-center boundary. The eNB band division configuration is similiar to SFR pattern referring to Fig. 1. It is claimed that the higher of total SINR is the minor ICI.
- Hgraph was proposed in [9]. It considers cumulative interference to construct a hypergraph, use the hypergraph to divide neighbor cells into different clusters, and allocate orthogonal subchannels to cells in the same cluster. It is claimed that the higher of total CQI is the minor ICI.
- Full power scheme boosts the transmit power of all UEs to the highest power level that eNB can transmit.
- No ICIC scheme allocates all UEs with the same transmit power and the same number of RBs.

C. Simulation Result: 4 UEs per cell

The performance of different resource allocation schemes can be compared by the scenario with only four UEs in each cell. Fig. 6 and Fig. 7 show the CQI and throughput in the seven schemes. The edge throughput in bfsOpt is higher than those in other schemes, since it can maintain the edge CQI at certain level and allocate more resource to cell-edge UE in the dense edge user scenario. Hgraph divides RBs used in neighbor cells entirely, and therefore it has the highest CQI but poor throughput. Q-learning ICIC tends to assign cell-center UE with higher power level and more resource than other methods, leading to extremely high throughput of center UE.

Fig. 8 shows the fairness of cell-edge UE in the seven schemes. We make use of Jains fairness index [18] to evaluate

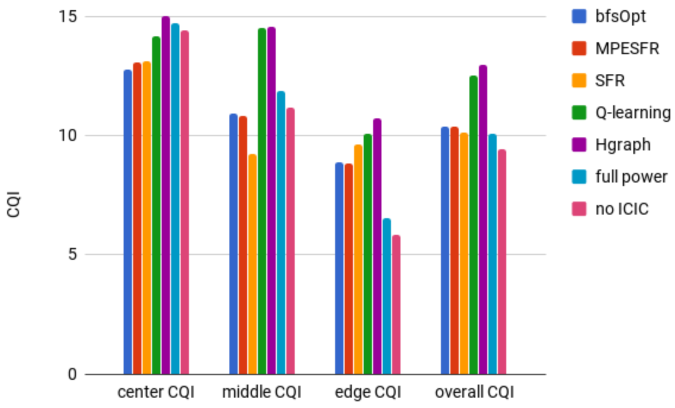

Fig. 6. Downlink CQI in 4 UEs per cell.

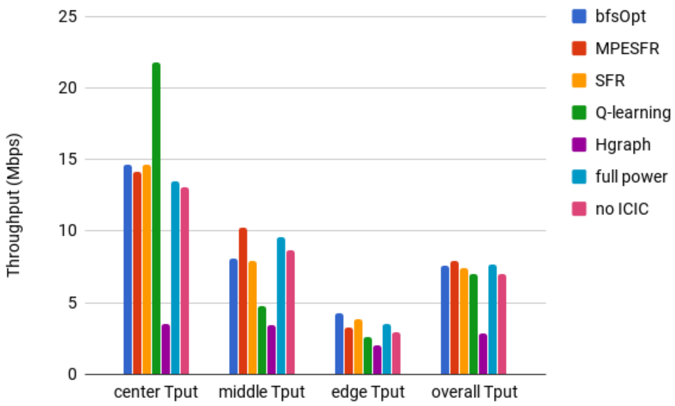

Fig. 7. Downlink throughput in 4 UEs per cell.

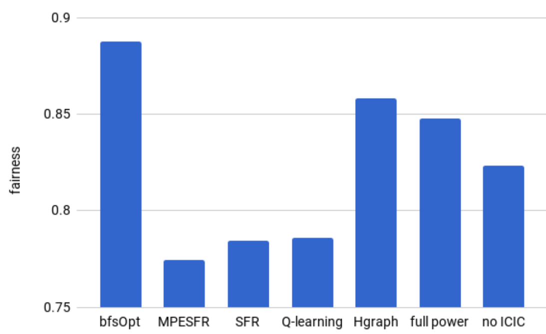

Fig. 8. Downlink edge fairness in 4 UEs per cell.

fairness. The formula of Jains fairness index is given by

$$J(x_1, x_2, ..., x_n) = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} {x_i}^2} \tag{2}$$

where J is the fairness index of cell-edge UE throughput and K is the total number of cell-edge UE. The closer the throughput, the higher fairness index. Since the resource division of cell-edge UE is fixed in SFR and Q-learning ICIC, they might have trouble when the number of UE is unbalanced in each cell. We solve this problem by increasing the fairness of cell-edge UE.

D. Simulation Result: 8-32 UEs per cell

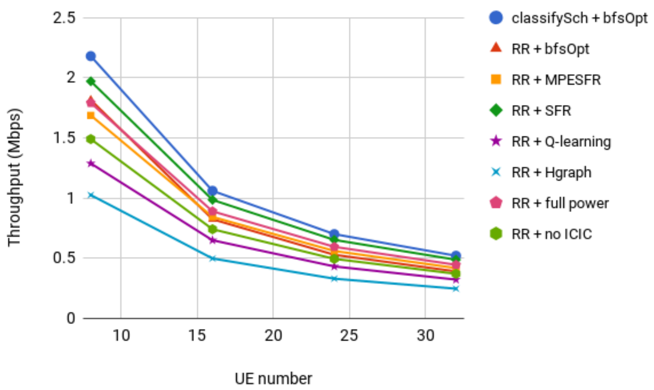

Fig. 9. Downlink edge throughput in 8-32 UEs per cell.

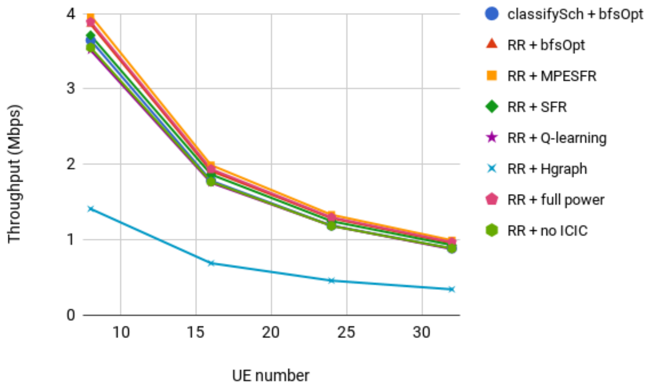

Fig. 10. Downlink overall throughput in 8-32 UEs per cell.

The performance of the combination of different schedulers and different resource allocation schemes can be compared by the scenario with more than four UEs in each cell. Fig. 9, Fig. 10, and Fig. 11 show the edge throughput, the overall throughput, and the edge fairness of the eight schemes respectively. After adding classifySch, the edge throughput of bfsOpt increases, while the overall throughput of that decreases. The scheme of classifySch with bfsOpt has the highest edge throughput because it can maintain the edge CQI at certain

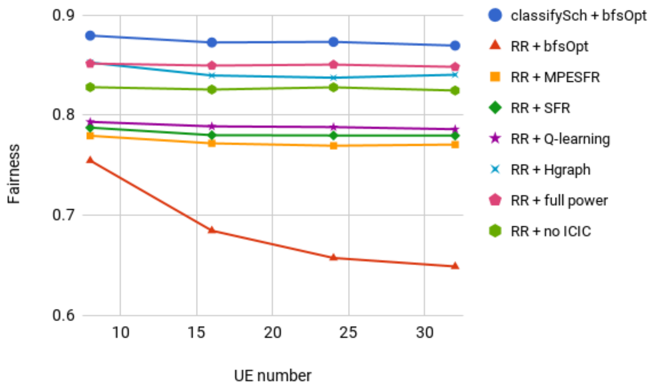

Fig. 11. Downlink edge fairness in 8-32 UEs per cell.

level in dense edge UE scenario. The scheme of RR with MPESFR has the highest overall throughput because the ratio of cell-middle UEs and cell-edge UEs are high in this scenario. The scheme of classifySch with bfsOpt has the highest fairness because each cell-edge UE are allocated with the same number of RB by bfsOpt and the edge CQI is maintained in each TTI by classifySch.

V. Testbed Result

Beyond simulation, we conduct several experiments on the testbed to verify the feasibility of the proposed algorithms. As shown in Fig. 12, the testbed includes following elements: (1) LTE small cell, (2) Evolved Packet Core (EPC), (3) Router, (4) UE, (5) Central Controller. The eNB and UE deployment is shown in Fig. 13.

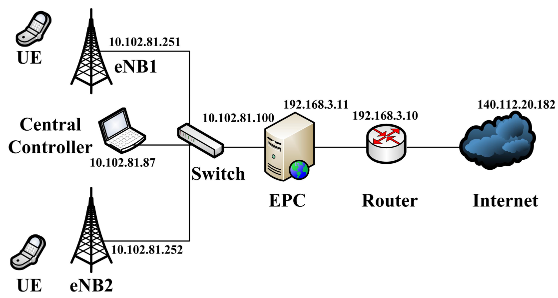

Fig. 12. Testbed architecture.

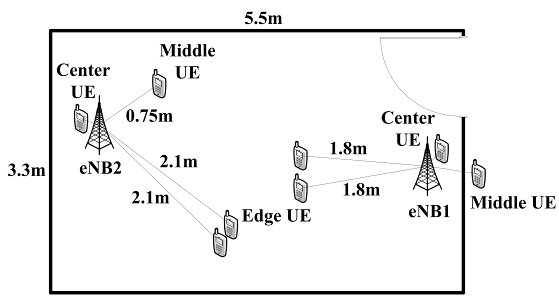

Fig. 13. Testbed scenario.

Fig. 14 describes downlink throughput of cell-middle UEs and the average of four cell-edge UEs. The downlink data is full buffer and transmitted by iPerf. As shown in Fig. 14, bfsOpt outperforms other schemes in the throughput of eNB2 cell-middle UE and the average throughput of cell-edge UEs. The interference at eNB1 cell-middle UE is relatively low. Since MPESFR and SFR allocate more resource to cell-middle UE than that to cell-edge UE, MPESFR and SFR have the higher throughput than bfsOpt in eNB1 cell-middle UE.

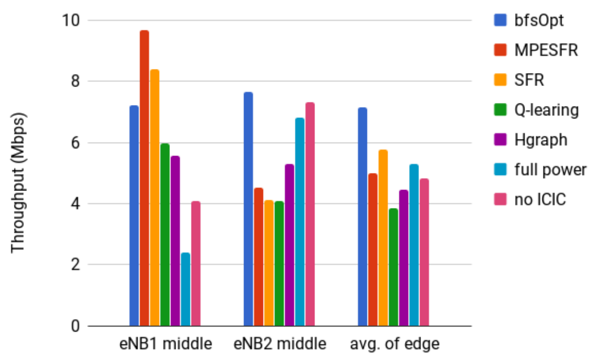

Fig. 14. Downlink throughput of different type UE.

Adaptive Modulation and Coding (AMC) in LTE is a mechanism in change of Modulation and Coding Scheme (MCS) to adapt the channel variation. The higher MCS value means the channel quality is better (i.e. higher CQI). Fig. 15 shows the cumulative percentage of MCS selection of all cell-edge UEs. According to the figure, Hgraph has the highest MCS value. The others four ICIC methods also improved the MCS selection of cell-edge UEs. The MCS curves of no ICIC and full power are lower than others. Band division and power control are effective in mitigating ICI.

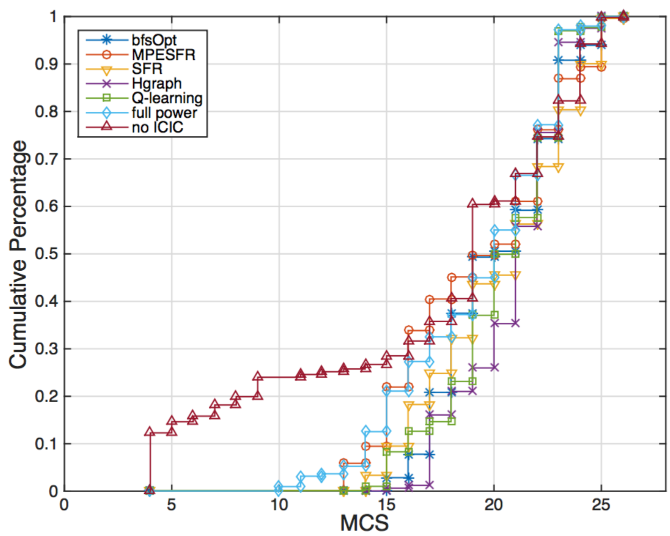

Fig. 15. CDF curve for MCS of all cell-edge UEs.

VI. Conclusion

In this work, we design a classification algorithm as scheduler and an efficient optimization algorithm as resource optimizer to realize ICIC on the testbed. For the sake of implementation, our design is compatible with the testbed. We use simulation to compare the performance of proposed algorithms and other schemes in the large scale. Furthermore, we conduct testbed experiments to verify that the proposed algorithms have the feasibility to be implemented practically.

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