Distributed Resource Allocation with Inter-cell Interference Coordination in OFDMA Uplink

Shuhui Liu, Yongyu Chang, Guangde Wang, Dacheng Yang

Abstract—**In this paper, we propose a distributed resource allocation mechanism with inter-cell interference (ICI) coordination for practical orthogonal frequency division multiple access (OFDMA) uplink. The designed scheme combines soft frequency reuse (SFR) and interference limited power control of neighboring cells. It avoids severe interference to neighboring cells through adjusting the interference limited power constraints according to the load variations across cells. The computational complexity is greatly lowered by decomposing a multi-cell optimization problem into distributed single-cell sub-problems. The simulation results demonstrate that the proposed scheme not only guarantees the cell-edge UEs' quality of service (QoS) but also improves the overall system performance significantly. Moreover, this scheme can adapt to the load variations in a certain cell or across cells.**

Keywords-distributed resource allocation; inter-cell interference coordination; OFDMA uplink; SFR; inteference limited power control

I. INTRODUCTION

Orthogonal frequency division multiplexing access (OFDMA) has emerged as one of the prime access schemes for broadband wireless networks, such as 3GPP Long Time Evolution (LTE), IEEE802.16 and Ultra Mobile Broadband (UMB), benefiting for its intrinsic advantages including high spectral efficiency and anti multi-path capacity. Since OFDMA supports intra-cell orthogonality, the main interference comes from the inter-cell.

In order to protect the cell-edge users from ICI, fractional frequency reuse (FFR) techniques, such as in [1]-[3] are proposed, but FFR suffers from poor spectrum efficiency. The soft frequency reuse (SFR) technique is provided in [4] to improve the spectrum efficiency, but it is only effective in static scenarios. Tracing the user distribution and traffic load in real time remains a challenge. The authors in [5] develop an adaptive SFR scheme which can adapt to the semi-statically changing traffic load and user distribution among neighboring cells. However, it only considers the frequency resource allocation but not the power allocation which is critical to mitigate ICI.

In this paper, we propose a dynamic distributed resource allocation with ICI coordination in OFDMA uplink system. To achieve the efficient frequency reuse and improved power efficiency, the scheme is designed to combine SFR and interference limited UL power control [6]. Differing from SFR in frequency resource allocation aspect, the proposed scheme allows cell-edge UEs using cell-interior sub-channels. Thus, cell-edge UEs' performance is ensured while the load distribution between cell-edge and cell-interior is unbalanced. Moreover, the UE's transmit power is adaptively adjusted according to the interference constraints of the neighboring cells rather than set a fixed transmit power for the cell-edge and cell-interior UEs respectively as in SFR. Compared to [6], the resource allocation optimization problem in this paper is formulated with considering both the UEs' QoS and the interference power constraints. Besides, this scheme sets different initial interference constraints on different RB ranges based on SFR. Furthermore, the interference constraints are dynamically modified according to the load variations. This adaptive interference power constrains scheme only requires minor coordination between cells. Finally, the proposed scheme decomposes the multi-cell resource optimization problem into a distributed single-cell problem, which makes it more suitable for practical use.

The paper is organized as follows. Section II provides the system model and problem formulation. The specific distributed resource allocation algorithm is given in Section III and the simulation model and results are generalized in Section IV. Finally the conclusions are drawn.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SFR Model

We introduce the SFR firstly since the proposed scheme is based on the SFR. As depicted in Fig. 1, the SFR scheme divides the available spectrum into two reserved parts: a cell-edge bandwidth and a cell-center bandwidth. UEs within each cell are also divided into two groups, interior cell-center UEs and exterior cell-edge UEs, depending on which type of bandwidth they are assigned or have access to. Cell-edge UEs are restricted to the reserved cell-edge bandwidth while cell-center UEs have exclusive access to the cell-center bandwidth and can also have access to the cell-edge bandwidth but with less priority than cell-edge UEs.

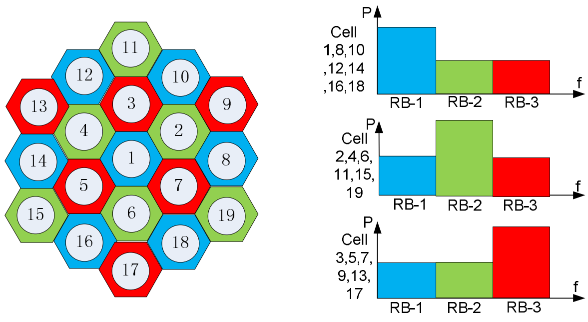

Figure 1. Cell layout of SFR

Resource block (RB) is used to denote the smallest unit of resource and the overall bandwidth B is divided into three ranges: RB-1, RB-2 and RB-3. Usually, the cell-edge bandwidth in one cell/sector is fixed to one third of the entire available bandwidth (i.e., RB-1 for "blue" cells, RB-2 for "green" cells and RB-3 for "red" cells) with the aim of ensuring that adjacent cells can allocate non-overlapping frequency bands for their cell-edge traffic to avoid ICI.

B. Problem Formulation

We consider an OFDMA uplink system which consists of N cells. And K users are distributed in the region served by N cells. U_n denotes the UE set belongs to the cell n and $|U_n|$ is the number of UE in cell n. Therefore, the total number of UEs in the system is $K=\sum_{n=1}^{N}|U_n|$. The system has M RBs which are divided into three RB ranges as in Figure 1. We define the assignment matrix of cell n as $\mathbf{A}^n=[a_{mk}^n]_{M\times|U_n|}$, where a_{mk}^n is 1 if RB m is assigned to user k and 0 otherwise. Each RB in one cell is assigned to only one user. The vector $\mathbf{p}^n=(p_1^n,...,p_M^n)$ denotes the UEs' transmission power in cell $n\,(1\le n\le N)$, with p_m^n denoting the transmission power of a particular UE allocated on RB m. If RB m is not allocated, p_m^n is assigned 0. Note that, the UE who transmits data on RB m of cell n has been determined by the assignment matrix $\mathbf{A}^n$. So it is not denoted explicitly in the transmission power vector. In addition, we denote the network power vector by $\mathbf{P}=[\mathbf{p}^1,\mathbf{p}^2,...,\mathbf{p}^N]$, a concatenation of the transmission power vectors of the N cells in the integrated region.

The signal to interference plus noise ratio (SINR) of user k in RB m of cell n for the given network power vector $\mathbf{P}$ can be expressed by,

$$\gamma_{mk}^n(\mathbf{P})=\frac{G_{mk}^n p_m^n}{\sum_{l=1,l\ne n}^{N}\sum_{j\in U_l} a_{mj}^l G_{mj}^l p_m^l+\sigma^2} \tag{1}$$

where G_{mk}^n denotes the channel gain between user k and the cell n on RB m and σ^2 is the noise power. Then the achievable data rate of user k is given by,

$$R_{mk}^n(\mathbf{P})=\frac{B}{M}\log_2\left(1+\frac{\gamma_{mk}^n(\mathbf{P})}{\Gamma}\right) \tag{2}$$

where $\Gamma=-\ln(5\text{BER})/1.5$ for the bit error rate requirement BER [7].

The total data rate of UE k, R_k, depends on the power allocation in other cells as well as the RBs assignment and the power allocation in the corresponding serving cell. Specifically, R_k is determined by $\mathbf{P}$ and $\mathbf{A}^n$ as follows,

$$R_k(\mathbf{P},\mathbf{A}^n)=\sum_{m=1}^{M} a_{mk}^n R_{mk}^n(\mathbf{P}) \quad k\in U_n \tag{3}$$

Assume each UE k has a minimum target data rate R_k^{target}. To guarantee the quality of service (QoS) and fairness of UEs in the overall system, each UE requires to satisfy the minimum target data rate and the total transmit power of each UE is bounded by the UE maximum transmit power $P^{\max}$. The remaining resources are used to maximize the system throughput. The resource allocation optimization in the multi-cell networks can be formulated as follows,

$$\begin{aligned}&\max_{\mathbf{A}^n,\mathbf{P}}\sum_{n=1}^{N}\sum_{k\in U_n}R_k(\mathbf{P},\mathbf{A}^n)\\ &\text{s.t.}\begin{cases}R_k\ge R_k^{\text{target}},\forall k\in U_n,n\in C\\ 0\le\sum_{m=1}^{M}a_{mk}^n p_m^n\le P^{\max}\ \ \forall k\in U_n,n\in C\end{cases}\end{aligned} \tag{4}$$

III. PROPOSED DISTRIBUTED RESOURCE ALLOCATION SCHEME

A. Dynamic Interference Limited Power Control (DILPC)

In SFR, two fixed transmission power levels are imposed on cell-interior and cell-edge UEs generally which lowers the power allocation flexibility and may incur severe interference in the OFDMA uplink due to not considering users' location. In this paper, based on the SFR in Figure 1, we designate different levels of preferences (i.e. receiving power constraints) to particular RB types. Set a low threshold for one set of RBs, which allows low interference from other cells and these RBs are preferred by the cell-edge UEs. The cell-interior UEs can behave at a relative high SINR on high interference RBs since they have low path loss. For example, in Figure 1 we can say that for the "blue" cells, uplink transmission RB-1 is the most preferred, RB-2 and RB-3 would be less preferred. Here, the sets of "blue", "green" and "red" cells in the system region are denoted as C_b,C_g,C_r respectively. For simplicity, two interference constraints are considered, so we put the initial interference constraints for "blue" cells as $T_b=[T_L,T_H,T_H]$ for RB-1, RB-2 and RB-3, similarly, $T_g=[T_H,T_L,T_H]$ for "green" cells and $T_r=[T_H,T_H,T_L]$ for "red" cells respectively. Considering the load variations between cells, a further level of dynamic interference limited power control is developed. We introduce an offset for each cell n denoted by Δ_n to modify the power constraints which adapts to the load variations among cells. The update process of Δ_n value in dB will be shown in table I. We introduce two transmit time interval (TTI) counters θ_n^{Up} and θ_n^{Down} to register the TTI number that all UEs are satisfied to the target data rate and that not all UEs are satisfied to the target data rate respectively. A threshold of TTI number is denoted as D which control the updating frequency of Δ_n. Initialize $\theta_n^{Up}=\theta_n^{Down}=0$, $\Delta_n=0$.

We can conclude from the above process that the interference constraints offset for each cell will be updated for each TTI according to its load. If the load is high, that is, some of the UEs in this cell cannot achieve their target data rate, the interference constraints should be reduced to mitigate severe interference from neighboring cells. When the load is low, the interference constraints can be set a higher value to coordinate other cells' load since this cell can tolerate higher ICI. Note that, we introduce the threshold of TTI number D to reduce the signaling overhead and also avoid the system instability. When the offset need not be changed and there are no signaling exchanges of course. And when the interference constraints have just been modified, it's necessary to reserve a time interval to guarantee the system stable through adaptive resource allocation adjustment.

TABLE I UPDATING PROCESS OF POWER CONSTRAINTS OFFSET

For a certain TTI t in cell *n*,
if (all UEs in cell *n* are satisfied to the target data rate)
$\theta_n^{Up} = \theta_n^{Up} + 1$;
if (there exist UEs that are not satisfied to the target data rate)
$\theta_n^{Down} = \theta_n^{Down} + 1$;
if (θ_n^{Up} is equal to the threshold of TTI number D)
{ Δ_n is increased by ΔUp ; $\theta_n^{Up} = 0$;}
else if (θ_n^{Down} is equal to the threshold of TTI number D)
{ Δ_n is decreased by $\Delta Down$; $\theta_n^{Down} = 0$;}
else Δ_n keeps the same.

When the offset is changed, it should be conveyed to neighboring cells through the interface between NodeBs, such as X_2 interface in LTE system, and only 1 bit is needed. The signaling overhead is tolerable since the updating frequency is not very fast and there is only 1 bit to be conveyed to only neighboring cells each time. The decreasing step $\Delta Down$ should be much larger than the incremental step ΔUp because the QoS guarantee is more critical. In this paper, through extensive simulation we designate $\Delta Down$ is 50 times of ΔUp .

Then the interference constraint for a particular cell *n* can be expressed as,

$$T_n = \begin{cases} [T_L + \Delta_n, T_H + \Delta_n, T_H + \Delta_n],\ for\ n \in C_b \\ [T_H + \Delta_n, T_L + \Delta_n, T_H + \Delta_n],\ for\ n \in C_g \\ [T_H + \Delta_n, T_H + \Delta_n, T_L + \Delta_n],\ for\ n \in C_r \end{cases} \tag{5}$$

For a particular UE *k* in the uplink transmission, it takes a measurement of the path loss between the serving and neighboring cells to implement the handover procedure. We can make use of this existing measurement results and the UE *k* reports these results to its serving cell. The speed of reporting need not be especially fast and as such, downlink path loss measurements is used to infer mean uplink path loss.

For a certain RB *m*, the interference constraint of neighboring cell *n* can be obtained by checking the type of RB *m* (RB-1, RB-2 and RB-3). The value can be got in formula (5) which is noted as T_n^m .The following formula is used to calculate transmit power constraints P_{km}^{th} of UE *k* on RB *m*,

$$P_{km}^{th} = \min_{n \in \Psi_k} \{PL(k,n) \bullet T_n^m\} \tag{6}$$

where $PL(k,n)$ denotes the path loss plus shadowing fading between the UE *k* and its neighboring cell n , ψ_k is the set of neighboring cells for UE *k*. Note that T_n^m is transformed into real value form dB value. We use the maximum interference that neighboring cells can tolerate to restrict the UE's transmission power.

B. Adaptive Distributed Interference Coordination

In this part, we solve the problem in formula (4) in a distributed manner. As the problem in formula (4) is NP-hard [8], a heuristic and suboptimal algorithm is developed to solve this problem. We make use of the dynamic interference limited power control scheme to decouple the power allocation from the resource allocation since the interference to the neighboring cells is considered. The new proposed algorithm solves the problem in a distributed manner that each cell allocates its own resource and power to UEs while prohibits high interference to neighboring cells by limiting UE transmission power.

In each cell, the problem continues to decompose into two sub-problems. Since the QoS guarantee is a crucial issue, the first sub-problem is minimizing the number of RBs demanded to satisfy the minimal target data rate. The second one is maximizing the capacity using remaining RBs from sub-problem 1. The sub-problem of minimization the sum RBs number for UEs in cell *n* is formulated as follows,

$$\begin{aligned} &\min \sum_{k \in U_n} \sum_{m=1}^{M} a_{mk}^n \\ &s.t.\ R_k \ge R_k^{\text{target}} \\ &\quad p_m^n a_{mk}^n \le P_{km}^{th} \\ &\quad \sum_{m=1}^{M} p_m^n a_{mk}^n \le P_{\max}, \forall k \in U_n \end{aligned} \tag{7}$$

The set of remaining RBs that has not been allocated after solving the problem (7) in cell *n* is denoted as $\mathfrak{M}^n$. And the capacity maximization for the remaining RBs is formulated as follows,

$$\begin{aligned} &\max \sum_{k \in U_n} \sum_{m \in \mathfrak{M}^n} a_{mk}^n R_{mk}^n \\ &s.t.\ p_m^n a_{mk}^n \le P_{km}^{th} \\ &\quad \sum_{m=1}^{M} p_m^n a_{mk}^n \le P_{\max}, \forall k \in U_n \end{aligned} \tag{8}$$

It's worthwhile to note that the sub-problems clarified in (7) and (8) are still hard to get analytical solution. We develop practical algorithms to solve them based on the transmit power constraints from which we can have more accurate SINR estimation. The SINR for the UE *k* in cell *n* on RB *m* can be further estimated,

$$\gamma_{mk}^n(\mathbf{P}) = \frac{G_{mk}^n p_m^n}{\sum_{l=1, l \ne n}^{N} \sum_{j \in U_l} a_{mj}^l G_{mj}^l p_m^l + \sigma^2} \approx \frac{P_{km}^{th} / PL(k,n)}{I_{mk}^n + \sigma^2} \tag{9}$$

The P_{km}^{th} can be obtained through (6) and the uplink received interference I_{mk}^n of UE *k* on resource *m* should be estimated from the previous interference levels experienced on RB *m*, using an appropriate filtering mechanism. Thus, the

SINR of each UE on each RB can be estimated using (9), and the estimated data rate on RB m can be obtained. The following algorithm solves sub-problems in (7) and (8) sequentially.

For the cell n in one TTI,

1. Initialization
   For each user $k \in U_n$, set $\tilde{R}_k = 0$ as the estimated achievable data rate, $\mathfrak{M}^n = \{1,2,...,M\}$ denotes the available RB set for cell n and the transmission power of user k is $\tilde{P}_k^{Tx}$ =0.
2. Finding appropriate UE-RB-pair (k,m) by checking all these UE-RB pairs that satisfying
   $(k,m) = \arg \max_{k \in U_n, m \in \mathfrak{M}^n} R_{mk}^n$;
   Update $\tilde{R}_k$, $\tilde{P}_k^{Tx}$, $\mathfrak{M}^n$ as follows,
   $\tilde{R}_k = \tilde{R}_k + R_{mk}^n$, $\tilde{P}_k^{Tx} = \tilde{P}_k^{Tx} + P_{km}^{th}$, $\mathfrak{M}^n = \mathfrak{M}^n - \{m\}$;
   if ($\tilde{R}_k > R_k^{\text{target}}$ or $\tilde{P}_k^{Tx} > P_{\max}$) $U_n = U_n - \{k\}$;
   if (U_n or $\mathfrak{M}^n$ is empty) break;
   else go to step 2.
3. If $\mathfrak{M}^n$ is not empty, then allocates remaining RBs uniformly to users with the best channels, that is finding k satisfying $k = \arg\max_k R_{mk}^n$ and $\tilde{P}_k^{Tx} < P_{\max}$, such that both resource allocation efficiency and the overall system capacity can be improved.
4. Update interference constraints offset by implementing updating process of power constraints offset in Table I;
   Update transmission power constraints P_{km}^{th} through (5) (6).

In step 2, we first allocate RBs to UEs to achieve the target data rate and minimize the RBs' number subjecting to the interference limited power control scheme. And in step 3, the remaining RBs from step 2 are used to maximize the system capacity. The step 4 completes the update of interference limited power constraints.

Remark 1: The proposed algorithm here minimizes used RB number to guarantee UEs' QoS. Then the remaining RBs are used to maximize the overall system throughput to get the improved system performance by making use of the frequency scheduling flexibility. Also, we set a transmit power threshold to each UE to eliminate severe interference to neighboring cells. Moreover, the transmit power constrains are adapted to the load variations between cells. Different from SFR, the cell-edge UEs are allowed to use the cell-interior RBs to guarantee the cell-edge UEs' QoS when the cell load in one cell is unbalanced and provide more flexibility for frequency resource allocation.

IV. SIMULATIONS AND RESULTS ANALYSIS

A. Simulation Models and Parameters

To evaluate the merits of the proposed resource allocation scheme, a dynamic system simulator is established. We adopt the 19-cell layout with wrap around as shown in Figure 1 and the main simulation parameters are listed in Table II.

TABLE II
PARAMETERS FOR SYSTEM-LEVEL SIMULATION

Parameter	Setting
System bandwidth	10MHz
Subcarrier per PRB	12
Inter-site distance	500m
Maximum UE transmit power	21dBm
Channel model	Vehicular A [9]
UE speed	3km/h
Slow fading standard variance	8dB
Thermal noise density	-174dBm/Hz
Threshold of TTI number D	30

B. Simulation Results and Analysis

We will simulate different schemes to compare the performance of proposed scheme.

For conventional SFR scheme, the interior-to-edge power ratio is fixed to $1/4$. The fixed interference limited power constraints scheme is abbreviated as FILPC which consists of two situations that $T_H = T_L = 15dB$ and $T_H = 15dB$, $T_L = 0dB$ where the threshold value is normalized by noise power. Note that the spectrum access manner for FILPC is the same as SFR and only the power allocation manner is different. The last one is the proposed DILPC scheme in this contribution with the interference power constraints initial value $T_H = 15dB$, $T_L = 0dB$.

Figure 2 and Figure 3 are average cell-edge user throughput and average UE throughput with respect to the number of UE per cell respectively. As expected, the proposed scheme DILPC achieves the best performance among the evaluated schemes. From Figure 2, we can see that the proposed scheme can get significant gains in views of cell-edge user throughput compared to SFR and FILPC. The reason is that when the load is high, the SFR and FILPC schemes limit the cell-edge users to access the cell-interior bandwidth which results in the QoS degradation of cell-edge UEs. The proposed scheme provides more flexibility to access frequency resource for cell-edge users. Moreover, the dynamic interference limited constraints can avoid severe interference among cells which can make the UE pick the best RB to transmit to get the target data rate.

In Figure 3, the proposed algorithm provides significant gains when comes to the average UE throughput. The schemes with interference constraints can perform better than the SFR with fixed transmission power since the former scheme takes the ICI coordination into consideration by setting different interference thresholds to different RB ranges. The new proposed scheme performs best which not only considers the ICI coordination but also makes each UE to select the best RB to get frequency scheduling gain.

Finally, to verify the efficiency of DILPC, we introduce a load unbalance scenario that the central cell's load is high (30 UEs/cell) and the neighboring cells of this central cell have low load (10 UEs/cell). Define the unsatisfied UE ratio by the number of UEs with unsatisfied data rate to the overall number. The unsatisfied UE here is the one with the data rate less than the target data rate. In addition, the proposed scheme with unchanged interference constrains $T_H = 15dB, T_L = 0dB$ is as the reference scheme which in figure 4,5 denoted by proposed 1 and the proposed scheme DILPC is called as proposed 2.

From Figure 4 we can find that the proposed DILPC scheme achieves the best performance in views of unsatisfied ratio. Compared to proposed 1, the DILPC will reduce the central cell's constraints since the high load causes the UEs cannot achieve the target rate and thus, the UEs in neighboring cells will lower their transmit power to avoid severe interference to the central cell. To some degree, this scheme can balance the load across cells by adaptively adjusting the interference thresholds. In this way, the unsatisfied UEs can be reduced in the high load cells while not deteriorating neighboring cells UEs' QoS. Figure 5 shows the average UE throughput of neighboring cells in this load unbalance scenario. The neighboring cells throughput lowers not much compared with FILPC. So the proposed scheme DILPC can achieve the load balance and guarantee the UE's QoS in high load cell while not deteriorates the performance of low load cells.

V. CONCLUSIONS

In this paper, we develop a new low complexity and low overhead distributed resource allocation scheme. The new scheme makes use of limiting interference power to neighboring cells to avoid severe ICI based on SFR. Moreover, this new scheme is suitable to any load variation no matter in a certain cell or across cells. Through the comprehensive simulation, the results show that the new proposed scheme can guarantee the UEs' QoS while enhance the system throughput whatever in load balance or unbalance scenarios.

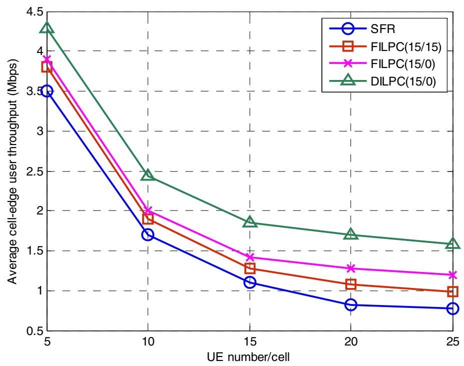

Figure 2. Average cell-edge user throughput

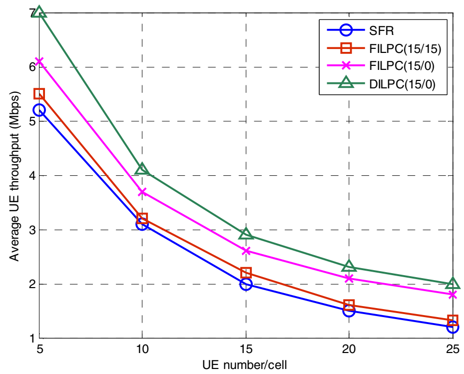

Figure 3. Average UE throughput

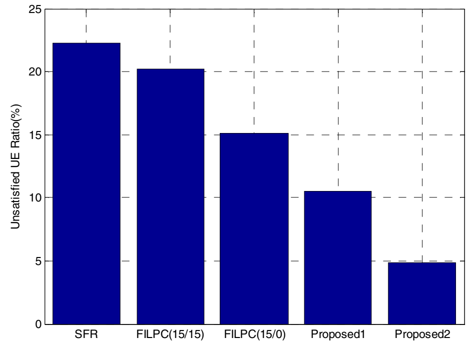

Figure 4. Unsatisfied UE Ratio

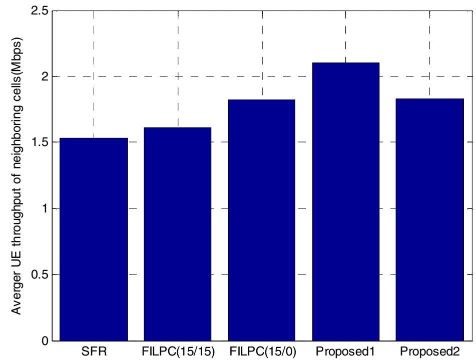

Figure 5. Average UE throughput of neighboring cells

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