Why user swapping could be the best coordination mechanism in a cellular network?

Dariush Fooladivanda, and Catherine Rosenberg, *Fellow, IEEE*
Dept. of Electrical and Computer Engineering, University of Waterloo, Canada
Email:{dfooladi, cath}@uwaterloo.ca

Abstract*—We propose a technique that can be used to improve the throughput offered to cellular users, in particular cell-edge users. Often, base stations (BSs) of different network operators are not co-located. Because of this, more spatial diversity is available by considering multiple cellular networks. Users who do not have a high SINR in their home network might see a much better SINR in another network because of the spatial diversity. Hence, to improve the performance of their cell-edge users, network operators can "swap" (exchange) them. In essence, we want to allow roaming between operators for other reasons than pure coverage. This paper aims at quantifying the gains that can be obtained by such swapping techniques. We propose a swapping scheme, "Operator-Based Swapping", in which a central controller decides which users should be exchanged between two operators assuming the number of users served by an operator does not change. Although implementing such a centralized scheme would be difficult, it helps us to understand the potential gain of such a "swapping" technique. Our numerical results show that high throughput gains (e.g., 80%) are achievable for the 10% worst users for both operators if the two networks are spatially diverse. We then propose a second swapping technique, called "BS-Based Swapping", that restricts the number of exchanged users to be equal on a pair of BS-basis. We believe that this scheme might be easier to implement. We compare the performance of this scheme under different configurations representing different levels of spatial diversity and allocated resources including time and frequency. Our numerical results show that this second swapping technique works almost as well as the first one. Our results show the potential of a technique based on a generalization of roaming as a mean to improve user performance.

I. INTRODUCTION

Cellular operators are exploring several options to improve the efficient usage of their licensed band in a context where data traffic is growing much faster than anticipated. The options go from very sophisticated physical layer technologies (e.g., MIMO, cooperative relaying, etc.) and planning options (e.g., fractional frequency reuse) to heterogeneous infrastructure (e.g., pico, femto, etc.) and to very complex cooperative schemes between base stations (BS). The goal is to take full advantage of spatial diversity and interference management techniques to improve the throughput offered to cellular users. We investigate another technique that could be used to improve the throughput offered to cellular users which we believe has the advantage of being relatively simple (when compared to the level of sophistication (e.g., synchronization) required by some of the techniques proposed so far) and based on our results, seem to be very promising. This technique is based on a different type of cooperation, a cooperation between cellular network operators to "swap" (i.e., exchange) users for their mutual benefits. The main reason for proposing this technique is that typically (though not always) BSs from different operators are not co-located and hence more *spatial diversity* is available by considering multiple cellular networks than being restricted to one. In other words, if a given subscriber of a cellular operator *A* does not receive a good signal from any of the BSs belonging to *A*, the user might be better off selecting a BS from operator *B* if he/she happens to be close to such a BS. Hence, what we propose is to extend the idea of roaming (i.e., select a BS from another operator) to cases other than lack of coverage (i.e., a subscriber can roam out of its own operator's network even if that network could have serviced him) but to do so in a cost neutral fashion to avoid making the system much more complex. By swapping users (i.e., the operators are exchanging the same number of users), the operators are entering into some kind of peering agreement and will make sure that the user exchange does not negatively affect the performance of their own users.

Cellular operators are trying to fulfill multiple requirements that are often in opposition, such as trying to maximize the total throughput while being fair, i.e., offering reasonable services to edge users. The reality in a cellular system is that the throughput seen by a user on a downlink (we focus in this paper on the downlink) depends on the quality of the received radio signal which is a function of its position with respect to its BS, the radio environment (fading, shadowing, interference), the bandwidth allocated to its BS, the scheduling policy and the number of users in the same cell. We say that a user belonging to operator *A* is an edge user if it receives a poor Signal to Interference and Noise Ratio (SINR) from its BS and there is no BS from operator *A* that could offer him a better service. While our swapping scheme is used to improve a global objective function without discriminating any users, our numerical results show that it significantly improves the throughput of edge users. It is worth noting that even if a user sees a better SINR from BS b belonging to operator *B* than from BS a belonging to his operator *A*, he might not always receive a better throughput if he selects BS b. Indeed, the possible reasons for this are that BS b might have been allocated limited resources (i.e., a small frequency band) and/or has too many users currently associated with it. Hence, a swap should only be performed if the user's throughput would increase with a change of BS.

We consider an urban area in which two network operators have deployed many BSs. We first quantify the potential benefits of our swapping scheme under the assumption that all subscribers' information (for both operators) is available at a central controller, and the central controller decides which users should be exchanged among the operators when the objective function is a global Proportional Fairness objective function and the only constraint is that the number of users being exchanged should be the same for the operators (but not necessarily the same on a per BS-basis). We call this "Operator-Based Swapping". Our numerical results show that "Operator-Based Swapping" scheme improves subscribers' throughput significantly. In particular, it improves cell edge users' throughput although we allow all users to be exchanged. We show that significant gains are achievable for the 10% worst users (in terms of *throughput*) for both operators if the networks are spatially diverse. This gives us the stimulus to take the next step towards a practical implementation of our user swapping idea.

Implementing an "Operator-Based Swapping" scheme in a non-centralized way would be difficult. We aim at designing a distributed swapping scheme that requires limited exchange of information between BSs. To do so, we propose a second swapping technique that restricts the number of exchanged users to be equal on a pair of BS-basis, i.e., two BSs (each one belonging to a different operator) will have to exchange the same number of users. We believe that this scheme can be implemented more easily in a practical way. We compare the performance of this new scheme (computed at the central controller assuming complete information) with the original swapping scheme for different scenarios representing different levels of heterogeneity of BSs in terms of allocated resources and number of users. These results show that our "BS-Based Swapping" scheme works very well even for large systems. This study aims at understanding the advantages of user swapping.

II. LITERATURE REVIEW

In the literature, several techniques have been proposed to improve users' throughput in cellular systems. For example, the MIMO technique is proposed to increase users' rates by improving users' radio signal quality in cellular networks. Due to several reasons such as low SNR, inter-cell interference (because of using low frequency reuse factor), and signal correlation among different antennas, MIMO is unable to improve cell-edge users' rates. To solve this problem, multi-site MIMO (MS-MIMO) is proposed [8]. In a MS-MIMO system, a cell-edge user is served by more than one BS [9]-[11]. Multi-site Single-user MIMO is a MS-MIMO technique in which BSs perform cooperative MIMO transmission for only one user. Extensive studies have been done on MS-SU-MIMO [11], [12]. MS-MIMO improves users' rates, in particular cell-edge users' rates, in the cost of using additional frequency resources from neighboring BSs. This could reduce available resources for cell-interior users in each BS. In [13], Kaneko *et al.* propose a scheduling algorithm to improve cell-edge users' throughput while all users' throughput are improved. These cooperative techniques are complex, and in some cases this complexity is not worth the insufficient performance gains.

Heterogeneous cellular networks (HetNets) are designed to improve spectral efficiency per unit area [14]. The mixture of different BSs, e.g., macro, pico, and femto, enables operators to offer higher data rates and eliminate coverage holes. For example, the LTE-Advanced improves network-wide spectral efficiency by employing a mix of low-power BSs [15]- [16]. In such networks, users should associate with low-power BSs if they can. This association can improve their throughput if resource allocation and interference management among different types of BSs are performed optimally [17]- [18]. Note that in HetNets performance gains are obtained by adding new infrastructure while the performance gains shown in this work are obtained without adding any new infrastructure.

III. SYSTEM MODEL

We consider a geographical area in which two network operators have deployed many BSs. We assume that the operators are allocated orthogonal licensed frequency channels so that there is no interference among the corresponding networks. Let $\mathcal{Q} = \{1, 2\}$ denote the set of network operators in the area. Let $\mathcal{Z}_q$ denote the set of BSs deployed by the operator $q \in \mathcal{Q}$. We study the downlink and focus on a static setting (i.e., a snapshot of the system). We make the following assumptions for each network operator q:

- The network is based on OFDM with M_q sub-channels, each of bandwidth b. The operator assigns these sub-channels to its BSs based on a certain channel allocation strategy. Let K_j denote the number of sub-channels allocated to BS $j \in \mathcal{Z}_q$.
- The total transmit power of a BS j is fixed and equal to P_j. The BSs transmit all the time.
- $\mathcal{U}_q$ is the set of subscribers for operator q. For each user, the channel gains and hence the SINR from all base stations in $\mathcal{Z}_1$ and $\mathcal{Z}_2$ are assumed known.
- Each subscriber can associate with only one BS. The default association rule is Received Signal Power[1] (though our framework would work with any other association rule). This means that in the benchmark system without our swapping scheme, each operator handles its own subscribers using an Received Signal Power rule.
- All BSs use Proportional Fairness (PF) scheduling to allocate resources to their users and all users are greedy, i.e., they want the largest possible throughput.
- The rate function $f(\cdot)$ for each BS is known so that given an SINR, the user's throughput can be computed. We do not make any restricting assumptions on f. We assume that f is the same for each BS (though our framework is independent of this assumption).

Our channel gain model accounts for path loss and slow fading. To model slow fading correctly, we consider shadowing correlation including autocorrelation and cross-correlation [1]-[2]. More information is provided in Section V.

In our benchmark (i.e., the case without swapping scheme), users are associated with one of the BSs of their network operator using the default association rule. Let $x_{i,j}^{(o)} = 1$ if user $i \in \mathcal{U}_q$ is associated with BS $j \in \mathcal{Z}_q$, and let it be 0, otherwise. The superscript (o) means "benchmark". Note that for our benchmark $x_{i,j}^{(o)} = 0$ for all $i \in \mathcal{U}_q$ and $j \in \mathcal{Z}_{q'}$,

---

[1] A user i associates with BS $j^\star$ that provides the highest downlink received signal power.

i.e., a subscriber of operator q cannot associate with a BS of operator q' ($q' \neq q$). Let $\mathcal{C}_j$ and $N_j^{(o)}$ denote the set of users and the number of users associated with BS j in the benchmark (i.e., $|\mathcal{C}_j| = N_j^{(o)}$), respectively. Moreover, let $\lambda_i^{(o)}$ denote user i's rate in the benchmark. To compute $\lambda_i^{(o)}$, let $\lambda_{i,j}$ and $\gamma_{i,j}$ denote the user i's rate and SINR from BS j, respectively. Then, the PF scheduling implies [3]:

$$\lambda_{i,j} = \frac{K_j b f(\gamma_{i,j})}{N_j^{(o)}}. \tag{1}$$

Recall that K_j and b denote the number of sub-channels allocated to BS $j \in \mathcal{Z}_q$ and the bandwidth of each sub-channels, respectively. Hence, $\lambda_i^{(o)} = \sum_{j \in \mathcal{Z}_1 \cup \mathcal{Z}_2} \lambda_{i,j}\, x_{i,j}^{(o)}$ since $\sum_{j \in \mathcal{Z}_1 \cup \mathcal{Z}_2} x_{i,j}^{(o)} = 1$ for all i, and $x_{i,j}^{(o)} = 0$ for all $i \in \mathcal{U}_q$ and $j \in \mathcal{Z}_{q'}$ ($q' \neq q$). In the next section, we discuss our user swapping schemes in more detail.

IV. THE SWAPPING SCHEMES

A. *Operator-Based Swapping*

We assume that there is a central controller in the system which has access to all users' information including SINRs and rates from all the subscribers to all BSs. This means that $\lambda_{i,j}$ can be computed beforehand for all $i \in \mathcal{U}_1 \cup \mathcal{U}_2$ and $j \in \mathcal{Z}_1 \cup \mathcal{Z}_2$. In the proposed swapping scheme, the central controller will decide which users should be exchanged among the operators. Our user swapping scheme is as follows:

- We allow each user i to be associated with any of the BSs in $\mathcal{Z}_1 \cup \mathcal{Z}_2$. Let $x_{i,j}^{(s)} = 1$ if user i is associated with BS j after performing the swapping scheme, and let it be 0, otherwise. The superscript (s) means "swap".
- We impose that no users should do worse with our scheme. Hence, $\lambda_i^{(s)} \geq \lambda_i^{(o)}$ for all i. Note that according to (1) we will have $\lambda_i^{(s)} < \lambda_i^{(o)}$ for user i who is associated with BS j (i.e., $x_{i,j}^{(o)} = 1$) if $\sum_{i \in \mathcal{U}_1 \cup \mathcal{U}_2} x_{i,j}^{(s)} > N_j^{(o)}$. Therefore, $\lambda_i^{(s)} \geq \lambda_i^{(o)}$ for all i imposes the following constraint:

  $$\sum_{i \in \mathcal{U}_1 \cup \mathcal{U}_2} x_{i,j}^{(s)} = N_j^{(o)}, \qquad \forall j \in \mathcal{Z}_1 \cup \mathcal{Z}_2 \ . \tag{2}$$

  This constraint implies that in our swapping scheme the operators exchange the same number of subscribers irrespective of the objective function. This constraint also means that no BS can increase its number of users.
- We select proportional fairness as our global objective function, i.e., the centralized controller maximizes $\sum_{i \in \mathcal{U}_1 \cup \mathcal{U}_2} \log(\lambda_i^{(s)})$ where $\lambda_i^{(s)}$ is the rate of user i after performing our swapping scheme, i.e., $\lambda_i^{(s)} = \sum_{j \in \mathcal{Z}_1 \cup \mathcal{Z}_2} \lambda_{i,j}\, x_{i,j}^{(s)}$.

Hence, given the set of users $\mathcal{U}_1$, $\mathcal{U}_2$, and all $\lambda_{i,j}$'s, we want to compute $\{x_{i,j}^{(s)}\}$ to solve the following problem:

$$\mathbf{P}_0(\mathcal{Q}) : \max_{\{x_{i,j}^{(s)}\}} \sum_{i \in \mathcal{U}_1 \cup \mathcal{U}_2} \log(\lambda_i^{(s)})$$

$$\text{s.t} \quad \lambda_i^{(s)} = \sum_{j \in \mathcal{Z}_1 \cup \mathcal{Z}_2} x_{i,j}^{(s)}\, \lambda_{i,j}, \qquad \forall i \in \mathcal{U}_1 \cup \mathcal{U}_2 \tag{3a}$$

$$\lambda_i^{(s)} \geq \lambda_i^{(o)}, \qquad \forall i \in \mathcal{U}_1 \cup \mathcal{U}_2 \tag{3b}$$

$$\sum_{j \in \mathcal{Z}_1 \cup \mathcal{Z}_2} x_{i,j}^{(s)} = 1, \qquad \forall i \in \mathcal{U}_1 \cup \mathcal{U}_2 \tag{3c}$$

$$\sum_{i \in \mathcal{U}_1 \cup \mathcal{U}_2} x_{i,j}^{(s)} = N_j^{(o)}, \qquad \forall j \in \mathcal{Z}_1 \cup \mathcal{Z}_2 \tag{3d}$$

$$x_{i,j}^{(s)} \in \{0, 1\}, \qquad \forall i \in \mathcal{U}_1 \cup \mathcal{U}_2,\ j \in \mathcal{Z}_1 \cup \mathcal{Z}_2 \tag{3e}$$

where all $\lambda_{i,j}$'s, $\lambda_i^{(o)}$'s, and $N_j^{(o)}$'s are computed beforehand and used as inputs to the optimization problem.

Problem $\mathbf{P}_0(\mathcal{Q})$ is a non-linear integer program (because of the nonlinear objective function). This type of problem is in general difficult to solve. Fortunately, we can transform $\mathbf{P}_0(\mathcal{Q})$ into an equivalent linear integer problem for which we can obtain exact solutions. We transform $\mathbf{P}_0(\mathcal{Q})$ into a linear integer program that has the same set of exact solutions as the original problem. We will show that the new problem is a linear integer program with the same set of exact solutions as $\mathbf{P}_0(\mathcal{Q})$. Noting that all $x_{i,j}^{(s)}$'s are binary variables and $\sum_{j \in \mathcal{Z}_1 \cup \mathcal{Z}_2} x_{i,j}^{(s)} = 1$ for all $i \in \mathcal{U}_1 \cup \mathcal{U}_2$, each term in the objective function of $\mathbf{P}_0(\mathcal{Q})$ can be rewritten as follows:

$$\log\left(\lambda_i^{(s)}\right) = \log\left(\sum_{j \in \mathcal{Z}_1 \cup \mathcal{Z}_2} x_{i,j}^{(s)}\, \lambda_{i,j}\right) = \sum_{j \in \mathcal{Z}_1 \cup \mathcal{Z}_2} x_{i,j}^{(s)}\, \log\left(\lambda_{i,j}\right) \tag{4}$$

Using this property, $\mathbf{P}_0(\mathcal{Q})$ can be reformulated into a linear integer program (since the $\lambda_{i,j}$'s are inputs to the problem) which can be solved efficiently for relatively large systems.

We were able to compute exact solutions to $\mathbf{P}_0(\mathcal{Q})$ for relatively large systems composed of two network operators with many BSs each. Although the results are promising in that significant increase in throughput can be achieved for edge users (see Section V), this scheme is not conducive to a distributed implementation. Next, we propose a second swapping scheme between pairs of BSs. We believe that this scheme can be implemented in a practical way.

B. *BS-Based Swapping*

As mentioned earlier, in our proposed "Operator-Based Swapping", no user should do worse than with the benchmark. This implies that for any feasible swapping $\{x_{i,j}^{(s)}\}$, (2) should hold, i.e., the operators exchange the same number of subscribers (and each BS keeps the same number of users though exchanges do not have to be equal on a pair of BSs basis). We now restrict the exchange between any pair of BSs (j, j') with $j \in \mathcal{Z}_1$ and $j' \in \mathcal{Z}_2$ to be symmetric, i.e., $\sum_{i \in \mathcal{C}_j} x_{i,j'}^{(s)} = \sum_{i \in \mathcal{C}_{j'}} x_{i,j}^{(s)}$ where $\mathcal{C}_j$ denotes the set of users associated with BS j before performing our user swapping scheme. Our second swapping scheme is then as follows:

- We allow each user i to be associated with any BSs in $\mathcal{Z}_1 \cup \mathcal{Z}_2$.

- We impose that no users should do worse with our scheme than with the benchmark.
- We impose that each pair of BSs should exchange the same number of subscribers, i.e., $\sum_{i\in\mathcal{C}_j} x_{i,j'}^{(s)} = \sum_{i\in\mathcal{C}_{j'}} x_{i,j}^{(s)}$ for all $j \in \mathcal{Z}_1$ and $j' \in \mathcal{Z}_2$.
- We select proportional fairness as our global objective function, i.e., we maximize $\sum_{i\in\mathcal{U}_1\cup\mathcal{U}_2} \log(\lambda_i^{(s)})$.
- We use a similar central controller as in the previous section (i.e., one that can compute all $\lambda_{i,j}$'s beforehand).

Given the set of users $\mathcal{U}_1$, $\mathcal{U}_2$, and all $\lambda_{i,j}$'s, we want to compute $\{x_{i,j}^{(s)}\}$ so as to solve the following problem:

$$\mathbf{P}_1(\mathcal{Q}): \max_{\{x_{i,j}^{(s)}\}} \sum_{i\in\mathcal{U}_1\cup\mathcal{U}_2} \log(\lambda_i^{(s)})$$

$$\text{subject to} \quad (3a), (3b), (3c), (3d), \ (3e)$$

$$\sum_{i\in\mathcal{C}_j} x_{i,j'}^{(s)} = \sum_{i\in\mathcal{C}_{j'}} x_{i,j}^{(s)}, \ \forall j \in \mathcal{Z}_1, \ j' \in \mathcal{Z}_2, \tag{5a}$$

where all $\lambda_i^{(o)}$'s and $N_j^{(o)}$'s are computed beforehand and used as inputs to the optimization problem. Note that $\mathbf{P}_1(\mathcal{Q})$ can also be transformed into a linear integer program which can be solved for relatively large systems.

Next, we compare the performance of two large networks when one of the swapping schemes is enabled with the performance of the two networks without user swapping. The results show that there is a significant gain in users' throughput when the operators exchange some of their users. The results also show that there is no significant difference in users' throughput when the operators use our second swapping scheme instead of the first swapping scheme.

V. NUMERICAL RESULTS

We consider a system composed of two networks belonging to two independent operators in a large geographical area. Each operator has deployed some macro BSs in the system area as shown in Fig. 1. Each network has an inter-cell distance of 500 m. We study a square area of length $L = 1600\ m$ inside the whole system area as shown in Fig. 1. Let K_A and K_B denote the number of sub-channels allocated to operator *A* and operator *B*, respectively. We consider a reuse factor of "three", i.e., each BS in *A* (resp. in *B*) has access to $\frac{K_A}{3}$ (resp. $\frac{K_B}{3}$) sub-channels. We assume that there are N_A and N_B subscribers with operator *A* and operator *B*, respectively, and that these subscribers are distributed uniformly in the square area.

We use an SINR model that accounts for path loss and slow fading [4]. To model slow fading correctly, we consider shadowing correlation including autocorrelation and cross-correlation [1]- [2]. In particular, since users and BSs are fixed in our system model, we only need to consider cross-correlation among shadowing paths between each user and multiple BSs [2]. What we want to model is the fact that fading from two base stations to a user are correlated and that correlation is a function of the distance Δd between the 2 base stations. In particular, the fading should be the same if the base station are co-located. Several shadowing models have been proposed in the literature [2]. We use the LTE shadowing model. In LTE, the log-normal slow fading ψ in the logarithmic scale around the mean path loss (dB) is characterized by a Gaussian distribution with zero mean, standard deviation $\sigma = 8$dB, and the autocorrelation function $A_\psi(\Delta d) = \sigma^2 e^{\frac{-\Delta d}{d_c}}$ where d_c is is the de-correlation distance [5]. We take $d_c = 50$ meters [5].

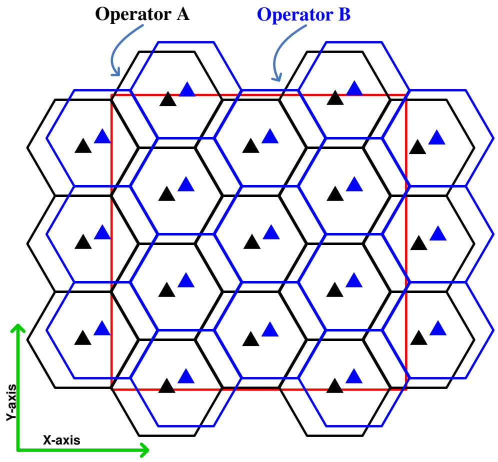

Fig. 1. Two network operators (operator *A* and operator *B*) have deployed some macro BSs in a large geographical area. The area that we study is the red square. These networks are not co-located. The network of operator *B* is considered as a 75 meters shift of the network of operator *A* along the x-axis and y-axis.

The SINR of user i at distance d_i^j from BS $j \in \mathcal{Z}_q$ is computed by the formula

$$SINR_i^j = \frac{\frac{3P_j}{K_q}\ G_j\ \delta_i^j(d_i^j)}{N_0 + \sum_{h\in I_j} \frac{3P_h}{K_q}\ G_h\ \delta_i^h(d_i^h)} \tag{6}$$

where I_j is the set of macro BSs in $\mathcal{Z}_q$ (not including j) that use the same channel set as j, P_j is the transmit power of BS j, and N_0 is the noise power. G_j is a factor which accounts for transmitter/receiver gains, equipment losses, and slow fading. We assume that the transmit power P_j is shared equally among all channels allocated to BS j. Path loss for the BSs is computed using the formula

$$\delta_i^j(d_i^j) = 128 + 37.6\ \log_{10}(d_i^j/1000), \ d_i^j \geq 35m\ .$$

We assume that the system uses adaptive modulation with discrete rates. Table II taken from [6] and [7] gives us the mapping between the SINR and the efficiency e for the modulation and coding scheme (MCS) for LTE. In this table, there are 15 MCSs. Let ℓ be such a MCS. Hence the bit rate seen by a user that has a SINR between level ℓ and level $\ell+1$ is $r = \theta e_\ell = \frac{\mathrm{SC}_{\mathrm{ofdm}}\mathrm{SY}_{\mathrm{ofdm}}}{T_{\mathrm{subframe}}} e_\ell$ where e_ℓ is the efficiency (in bits/symbol) of the corresponding level ℓ, θ is a constant that depends on the system configuration, $\mathrm{SC}_{\mathrm{ofdm}}$ is the number of data subcarriers per sub-channel bandwidth, $\mathrm{SY}_{\mathrm{ofdm}}$ is the number of OFDM symbols per subframe, and T_{subframe} is the frame duration in time units. We take the values of $\mathrm{SC}_{\mathrm{ofdm}}$, $\mathrm{SY}_{\mathrm{ofdm}}$, T_{subframe}, and the sub-channel bandwidth to be 12, 14, 1ms, and 180KHz, respectively.

We compare the performance of three systems: the system without any user swapping, the system with the "Operator-Based Swapping" scheme, and the system with "BS-Based

TABLE I
PHYSICAL LAYER PARAMETERS

Noise Power	$-110\ dBm$	P_{macro}	$46\ dBm$
Carrier Frequency	$2\ GHz$	Channel Bandwidth	$180\ KHz$
BS Cable Loss	$6\ dB$	User Noise Figure	$9\ dB$
Penetration Loss	$20\ dB$	Shadowing s.d.	$8\ dB$

Swapping". The system without any user swapping is considered as the benchmark. For a given operator q, we only consider users in the red square. To compare the performance of these systems, we define the following metrics for each operator:

$$G^q_{Op}(x) = \frac{\mathrm{R}^q_{\text{Operator-Based}}(x) - \mathrm{R}^q_{\text{Benchmark}}(x)}{\mathrm{R}^q_{\text{Benchmark}}(x)}$$

$$G^q_{BS}(x) = \frac{\mathrm{R}^q_{\text{BS-Based}}(x) - \mathrm{R}^q_{\text{Benchmark}}(x)}{\mathrm{R}^q_{\text{Benchmark}}(x)}$$

where $\mathrm{R}^q_{\text{Benchmark}}(x)$, $\mathrm{R}^q_{\text{BS-Based}}(x)$, and $\mathrm{R}^q_{\text{Operator-Based}}(x)$ denote the mean throughput of the $x\%$ worst users (i.e., the $x\%$ of users with the lowest throughput) in the red square in the benchmark, in the system with "BS-Based Swapping", and in the system with "Operator-Based Swapping", respectively. The physical layer parameters are shown in Table I. These parameters are used to compute G_j in (6) [4].

We consider three different system configurations:

Configuration 1: In this configuration, operators *A* and *B* have the same number of users (i.e., $N_A = N_B = 400$) and the same amount of resources (i.e., $K_A = K_B = 90$).

Configuration 2: In this configuration, $N_A = 400$ and $N_B = 250$ users, and $K_A = 60$ and $K_B = 90$.

Configuration 3: In this configuration, $N_A = 250$ and $N_B = 400$ users, and $K_A = 60$ and $K_B = 90$.

Via these configurations, we are comparing the performance of the proposed user swapping schemes and the benchmark when the operators have different number of subscribers and different number of sub-channels. In configuration 1, the two operators have similar networks while in configuration 2, operator *A* is serving more users than operator *B*, and operator *A* has access to fewer sub-channels than operator *B*. In configuration 3, although operator *A* has access to fewer sub-channels than operator *B*, it is serving fewer users than operator *B*.

For each configuration, we computed the users' SINRs for the three systems (the benchmark, "Operator-Based Swapping", and "BS-Based-Swapping") for 100 realizations. For each realization, the users are uniformly placed in the region, the channel gains (including path loss and shadowing) are computed, the user are assigned to the BSs using the Received Signal Power rule, and then the users' throughput are computed.

As mentioned earlier, we assume that the operators use the Received Signal Power association rule. Note that the optimal user association problem is an NP-hard problem [17]. Because of this, it is hard to compute the optimal user association for relatively large systems. To compare the performance of the Received Signal Power rule with the optimal association, we use the method proposed in [17]. Let GM_A denote the geometric mean rate [2] of the users of operator *A*, i.e., $\sqrt[N_A]{\prod_{i=1}^{N_A} \lambda_i^{(o)}}$, when operator *A* uses the Received Signal Power association rule, and let GM_{opt} denote the upper bound on the geometric mean rate of the users of operator *A* computed by using the method proposed in [17]. To compare the performance of Received Signal Power rule with the optimal association, we define the metric $G = \frac{GM_{opt} - GM_A}{GM_{opt}}$. Our numerical results show that the average of G (over 100 realizations) for configurations 1, 2, and 3 is 1.7647%, 1.7368%, and 1.8224%, respectively. These results show that the Received Signal Power rule is performing very well in these configurations, and that no user is suffering with low data rate because of the non-optimal user association.

We show in Fig. 2 (resp. Fig. 3 and Fig. 4) for configuration 1 (resp. for configurations 2 and 3) the relative gains as a function of x (averaged over the 100 realizations). These results show that the proposed swapping schemes improve the worst users' rates significantly as shown in Figures 2 to 4. In configuration 1, the average rate improvement seen by the 10% worst users is 80% with the "Operator-Based Swapping" scheme and 70% with the "BS-Based Swapping" scheme. In other words, the results show that to reach optimality, the proposed schemes swap edge users among the operators even though we allow all users to be exchanged. This explains why the curves are decreasing in some configurations (e.g., configurations 1 and 3). Note that in some configurations the proposed schemes would swap users who already have high data rates. In such scenarios, the curves are not necessarily decreasing. For example, in configuration 2, since there are more time and frequency resources with BSs of operator *B*, users of operator *A* who have higher data rates than other users of *A*, are the best candidates for the exchange. In this case, to achieve optimality, the proposed schemes exchange some users of operator *A* who have higher data rates than other users of *A*. This explains why the curve in Fig. 3 is not decreasing and the gain for the 10% worst user is 25%.

In Fig. 5, we show the cumulative distribution function (CDF) of the throughput for the 10% worst users of operator *A* in configuration 1. This figure shows that "Operator-Based Swapping" and "BS-Based Swapping" improve the 10% worst users' throughput significantly. Figure 5 shows that 80% of the worst users of operator *A* have a rate less than or equal to 2.5×10^5 (bits/sec) before performing the user swapping scheme while only 20% of the worst users have a rate less than or equal to 2.5×10^5 after exchanging users. We have seen the same improvement for operator *B*.

In configuration 2, operator *A* has more subscribers than operator *B*, and has allocated fewer number of sub-channels to its BSs than operator *B*. Therefore, users of operator *B* have access to more time and frequency resources than users of operator *A*. Cell-edge users of operator *B* might receive a much stronger radio signal from one of the BSs of operator *A*. However, these users might not receive a higher rate from operator *A* since operator *A* assigns less time and frequency

---

[2] Note that for fixed N, maximizing the geometric mean rate is equivalent to maximizing the proportional fairness objective function.

TABLE II
MODULATION AND CODING SCHEMES-LTE

SINR thresholds (in dB)	-6.5	-4	-2.6	-1	1	3	6.6	10	11.4	11.8	13	13.8	15.6	16.8	17.6
Efficiency (in bits/symbol)	0.15	0.23	0.38	0.60	0.88	1.18	1.48	1.91	2.41	2.73	3.32	3.9	4.52	5.12	5.55

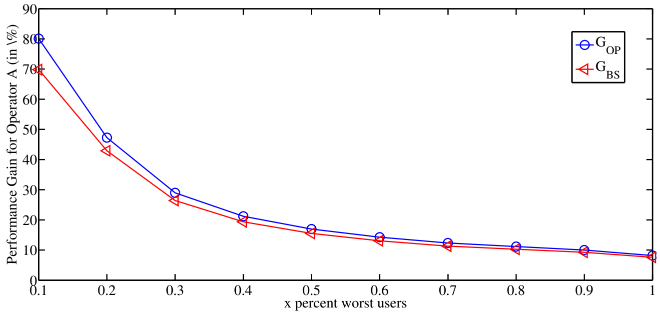

Fig. 2. $G_{Op}(x)$ and $G_{BS}(x)$ in Configuration 1 for operator A. The gains are averaged over 100 realizations.

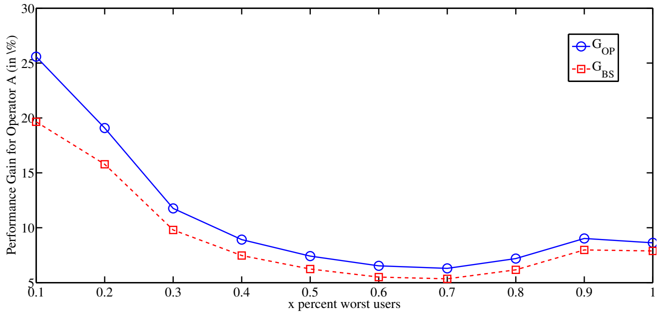

Fig. 3. $G_{Op}(x)$ and $G_{BS}(x)$ in Configuration 2 for operator A. The gains are averaged over 100 realizations.

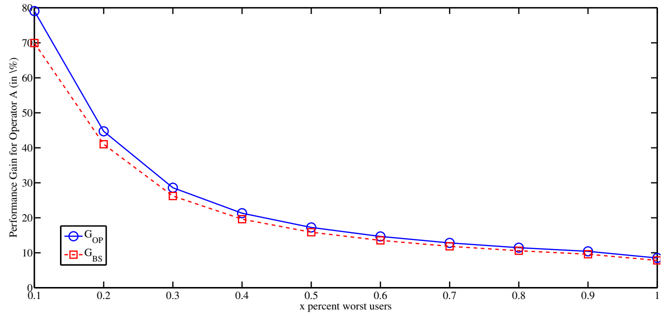

Fig. 4. $G_{Op}(x)$ and $G_{BS}(x)$ in Configuration 3 for operator A. The gains are averaged over 100 realizations.

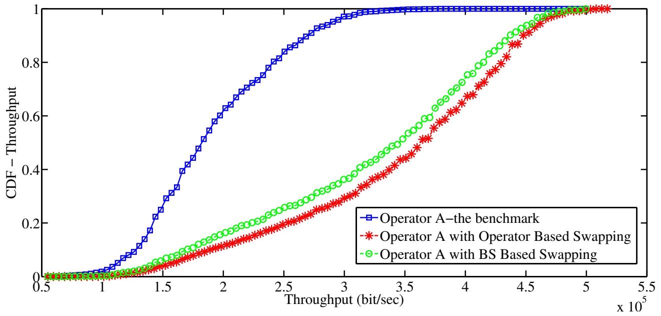

Fig. 5. CDF for the 10% worst users in Configuration 1 for operator A. The CDF is obtained over 100 realizations.

resources to his users. Hence, fewer users will be exchanged between these operators. This is shown in Figure 3. This figure shows that the improvement in users' throughput is less than the improvement in configuration 1 and configuration 3. Note that in configuration 3, operator A has access to fewer number of sub-channels than operator B, and it is serving fewer number of users than operator B. This explains why the proposed swapping schemes can improve users' throughput significantly in configuration 3 as shown in Figure 4.

These results show that both schemes yield similar performance which will allow us to focus on the per-BS swapping scheme, since it is much simpler to implement. They also show that the performance of the proposed swapping schemes depends on the resources available on a per user basis including time and bandwidth at each BS. In other words, achievable gains in users' throughput depend on K_A, N_A, K_B, and N_B. To understand this relationship, we fix K_A and N_A, and change the number of subscribers and the number of sub-channels of operator B. In particular, we fix $K_A = 60$ and $N_A = 400$, and we vary K_B between $K_A - 30$ and $K_A + 30$ and N_B between $N_A - 300$ and $N_A + 100$. The results for "Operator-Based Swapping" are shown in Fig. 6 where the y-axis is K_B and the x-axis is N_B (the larger circle represents the symmetric case). Note that in each configuration the 10% worst users are considered. In this figure, we show the points for which the gains for both operators are greater than 25%. These results show that for a wide range of K_B and N_B, a gain of at least 25% is achievable for the 10% worst users for both operators. Hence, even when the operators have different number of subscribers and different number of sub-channels (i.e., the systems are asymmetric though not too much) gains can be obtained. We also show the points for which the gains for the 10% worst users of both operators are greater than 45% in Fig. 7. This result shows that larger gains are achievable for both operators if their networks are more similar.

Altogether these results show that the proposed user swapping schemes improve worst users' rates significantly (i.e., average gain larger than 25%) even if the operators have different systems in terms of the number of allocated sub-channels and the number of subscribers. However, higher gains are achievable if the systems are more symmetric. Note that the performance of the proposed schemes also depends on the spatial diversity among BSs of the operators. To understand this dependence, we fix the network of operator A, and we consider the network of operator B as a shift of the network

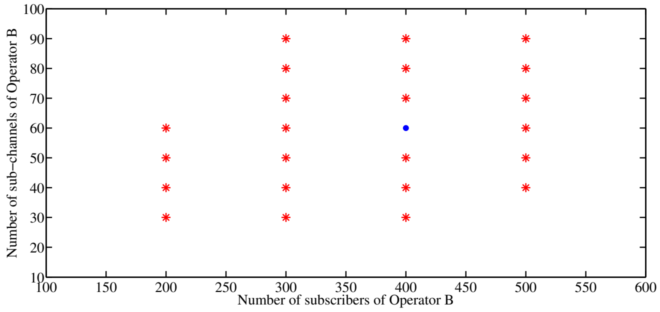

Fig. 6. The points for which the gains $G_{Op}(10)$ for both operators are greater than 25%. The blue point corresponds to a pure symmetric case. The gains are averaged over 100 realizations.

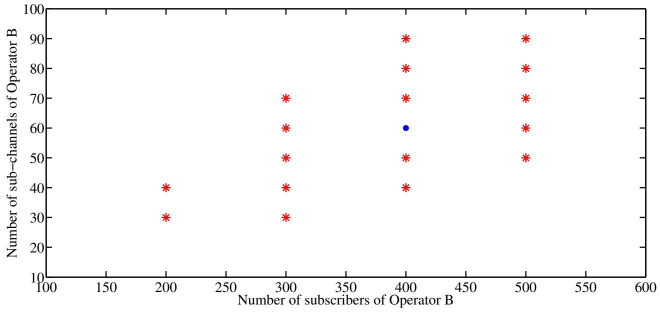

Fig. 7. The points for which the gains $G_{Op}(10)$ for both operators are greater than 45%. The blue point corresponds to a pure symmetric case. The gains are averaged over 100 realizations.

of operator A along the x-axis and y-axis, as shown in Fig. 1. We have considered several locations for operator B (corresponding to different shifts along the x-axis and y-axis). In particular, we consider $x_0 = r \times cos(\theta)$ meters shift along the x-axis, and $y_0 = r \times sin(\theta)$ meters shift along the y-axis where $r \in \{0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, 200\}$ and $\theta \in \{\frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}, \frac{7\pi}{4}\}$. The average gain $G_{Op}(10)$ in configurations 1 for operator A is shown in Fig. 8. The results are striking. Significant gains can be achieved for the 10% worst users as long as there is some level of spatial diversity between the 2 networks.

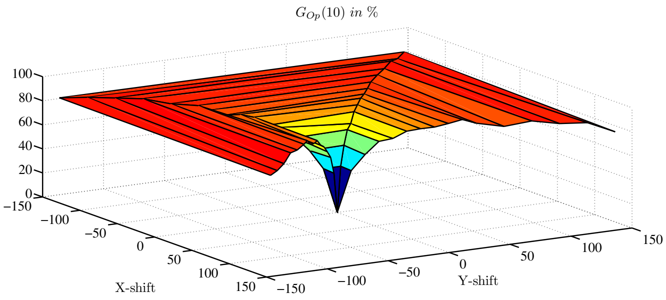

Fig. 8. $G_{Op}(10)$ in Configuration 1 for operator A. The gain is averaged over 100 realizations.

VI. CONCLUSIONS

We have proposed two user exchange schemes for wireless cellular networks. The proposed schemes improve cell-edge users' rates without decreasing other users' rates at each BS. We have shown that the proposed swapping schemes enable cellular network operators to improve their cell-edge users' rates *significantly* if their networks are spatially diverse. Our numerical results show that the performance of our schemes depends on the BSs' diversity in a given geographical area (the placement of BSs of different operators), the users' distribution, and the available bandwidth at each BS. These results are promising, but more work is needed to produce a practical distributed swapping mechanism. This is part of our future work.

REFERENCES

[1] F. Graziosi and F. Santucci, "A general correlation model for shadow fading in mobile radio systems," *in IEEE Commun. Lett.*, vol. 6, no. 3, pp. 102-104, Mar 2002.

[2] S. S. Szyszkowicz, H. Yanikomeroglu, and J. S. Thompson, "On the Feasibility of Wireless Shadowing Correlation Models," *in IEEE Trans. on Vehicular Tech.*, vol. 59, no. 9, Nov. 2010.

[3] L. Li, M. Pal and Y. R. Yang, "Proportional Fairness in Multi-Rate Wireless LANs," *in Proc. INFOCOM*, pp. 1004–1012, May 2008.

[4] A. Goldsmith, Wireless Communications, *Cambridge Univ. Press*, 2005.

[5] 3GPP TR 36.814, "Further advancements for E-UTRA Physical layer aspects," (Release 9).

[6] D. Lopez-Perez, A. Ladanyi, A. Juttner and J. Zhang, "Optimization Method for the Joint Allocation of Modulation Schemes, Coding Rates, Resource Blocks and Power in Self-Organizing LTE Networks," *in Proc. INFOCOM*, pp. 111–115, Apr. 2011.

[7] C. Mehlfuhrer, M. Wrulich, J. Ikuno, D. Bosanska and M. Rupp, "Simulating the Long Term Evolution physical layer," *in Proc. European Signal Processing Conference*, Aug. 2009.

[8] H. Zhang and H. Dai, "Cochannel interference mitigation and cooperative processing in downlink multicell multiuser MIMO networks," *EURASIP, Journal on Wireless Communications and Networking*, vol. 2004, No. 2, pp. 222–235, 2004.

[9] Y. Hatakawa, T. Oseki, M. Nakano, T. Suzuki, and T. Inoue, "A Study of the Combination Use of Transmit Diversity and Spatial Multiplexing in Multisite MIMO," *in Proc. IEICE General Conference*, Kitakyushu, Japan, Mar. 2008, B-5-190 (in Japanese).

[10] A. Yoshimoto and T. Hattori, "Evaluation of Ergodic Capacity Taking into Account of Area Coverage in a Multilink MIMO Cellular Network for Supporting Guaranteed QoS," *IEICE Trans. Fund.*, vol. E90-A, No.7, pp.1292–1299, July, 2007.

[11] K. Sakaguchi, "Base Station Cooperation MIMO for Spatial Spectrum Sharing," *IEICE Technical Report*, Japan, Mar., 2008, Vol. 107, No. 519, SR2007-103, pp. 123-128 (in Japanese).

[12] L. Xu, K. Yamamoto, H. Murata, and S. Yoshida, "Adaptive Base Station Cooperation and Subchannel Reallocation at Cell Edge in Cellular Networks with Fractional Frequency Reuse," *in Proc. PIMRC*, Tokyo, Japan, Sept. 2009.

[13] Shoji Kaneko, Masashi Fushiki, Masayuki Nakano, and Yoji Kishi, "BS-Cooperative Scheduler for a Multi-site Single-User MIMO Cellular System," *in Proc. VTC*, pp. 1–5, Sept. 2010.

[14] R1-081957, "Categorization of technical proposals for the PHY layer of LTE-A," Qualcomm Europe.

[15] 3GPP TR 36.912 V2.0.0, "3GPP; Technical Specification Group Radio Access Network; Feasibility study for Further Advancements for E-UTRA (Release 9)," Aug. 2009.

[16] R. Bendlin, V. Chandrasekhar, R. Chen, A. Ekpenyong, and E. Onggosanusi, "From Homogeneous to Heterogeneous Networks: A 3GPP Long Term Evolution Rel. 8/9 Case Study," *in Proc. CISS*, 2011.

[17] D. Fooladivanda and C. Rosenberg, "Joint Resource Allocation and Association for Heterogeneous Cellular Networks", *in IEEE Trans. on Wireless Communications*, vol. 12, pp. 248-257, Oct 2012.

[18] J. Ghimire and C. Rosenberg, "Resource Allocation, Transmission Coordination and User Association in Heterogeneous Networks: a Flow-based Unified Approach", *in IEEE Trans. on Wireless Communications*, vol. 12, pp. 1340-1351, Dec. 2012.