Opportunistic Joint Decoding with Scheduling and Power Allocation in OFDMA Femtocell Networks

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Abstract—**One of the major challenges in deploying femtocells is the management of interference between neighboring femtocells and between the femtocells and the macrocells. This paper explores the use of opportunistic multiuser detection for interference mitigation in the downlink of an orthogonal frequency division multiple access (OFDMA) femtocell network. In particular, we focus on the use of joint decoding (JD) at the receiver, where a macro or femto user may jointly decode both the desired message and the message from a selected interfering user in order to achieve a higher overall transmission rate. It is shown that to take the full advantage of opportunistic multiuser detection, the selection of JD pairs needs to be jointly optimized with scheduling, power allocation, and rate adaptation. This paper adopts a network utility maximization framework and proposes an iterative algorithm for such a joint optimization across the network. Simulation results show that multiuser detection can significantly benefit the femto-users, while maintaining the performance of macro-users. Further, although the lower-complexity successive interference cancellation (SIC) scheme can already reap significant benefit of multiuser detection, JD can further improve upon SIC.**

I. INTRODUCTION

Femtocells, which are short-range, low-cost, and low-power base stations (BSs) introduced to improve system capacity and wireless coverage, have received considerable attention in both academic research [1] and recent cellular standards such as 3GPP. Due to the fact that femtocells and macrocells can heavily overlap with each other, methods for efficient mitigation of intra/inter-cell interference will likely play a key role in future femtocell deployments. A number of recent works have treated the topic of interference avoidance in femtocell networks, a collection of which is surveyed in [2] and [3]. This paper focuses on one possible way for managing interference: the use of opportunistic multiuser detection (MUD), where a macro or femto user attempts to decode and cancel some or all of the signals emitting by the interfering users, thereby reducing its own effective interference level, whenever such detection is feasible.

There are two main classes of MUD algorithms. With successive interference cancellation decoding (SIC), each receiver decodes and cancels the interfering messages from other transmitters before decoding its desired messages. With joint decoding (JD), the receiver jointly decodes both the desired and the interfering messages at the same time, effectively treating the network as a multiple access channel (MAC). Although in a traditional MAC, the rate region achievable with JD is identical to that with SIC, this paper shows that when multiple transmitter-receiver pairs are involved, JD can offer superior performance as compared to SIC. This is consistent with information theoretical result of [4], which shows that when the transmitters use point-to-point codes in a network, the optimal performance is achieved by a combination of single-user decoding (SD) and JD. Further, this paper shows that to effectively take advantage of multiuser detection, the use of JD must be closely incorporated and jointly optimized with user scheduling and power allocation in both the macrocell and the femtocell. Toward this end, this paper considers an orthogonal frequency-division multiple-access (OFDMA) femtocell network, and proposes a network utility maximization approach for coordinating the scheduling of users in each time-frequency slot, and the allocation of power spectrum density (PSD) across the frequencies and across the network. Scheduling and power allocation are crucial as they are capable of not only facilitating, but also creating opportunities for multiuser detection.

The use of interference cancellation techniques in OFDMA femtocell and picocell networks has been studied previously in the literature. For example, SIC decoding is considered in [5] and [6] and JD is considered in [7], where multiuser detection is applied after scheduling and rate/power adaptation. In particular, [6] considered pathloss based power control and signal-to-noise-and-interference ratio (SINR) based channel assignment, while [7] considered a subband scheduling method based on frequency reuse. The information theoretical considerations of femtocell system have been given in [8] and [9] where JD is implicitly included in the rate region characterization. Opportunistic multiuser detection has also been considered in cognitive radio systems [10] and in more general multiuser networks [11] where water-filling-like power allocation schemes are proposed.

This paper differs from previous works in several aspects. Instead of characterizing rates at a link level (as in [10], [11]) or using abstract network models (as in [8], [9]), this paper takes a system-level perspective, and optimizes scheduling, power allocation, and the selection of MUD pairs jointly for specific channel realizations under a network utility maximization framework. In doing so, it is assumed that macro- and femtocells are capable of coordinating these decisions. This paper shows that such coordination is crucial in achieving optimized performance. For example, in contrast to what is found in [7] where SIC is shown to provide only marginal benefit when scheduling and MUD are sequentially optimized, this paper shows that with joint optimization SIC is already capable of providing considerable improvement to the femto users while maintaining the macrocell performance. Moreover, instead of considering SIC only as in [5] [6], this paper shows that JD can further improve the SIC performance under a network utility maximization setup.

II. OPTIMIZED OPPORTUNISTIC JOINT DECODING

A. System Model

This paper considers the downlink of a macro/femtocell environment with L_M macrocells, L_F femtocells, K_M users per macrocell, and K_F users per femtocell employing an OFDMA scheme with N tones over a fixed bandwidth. For convenience in terminology, in the rest of the paper, a "cell" can be referred to as either a macro or femtocell. Assuming an OFDMA implementation, the frequency assignments for users within each cell are non-overlapping. Thus, users experience intercell interference only and no intracell interference. Let $h^n_{l,mk}$ denote the channel response between the lth base-station and the kth mobile user (MU) in mth cell in nth tone for the downlink. The downlink user schedules are determined by the assignment functions $f(l,n)$, which assign a user k to the lth cell in the nth tone for the downlink, i.e. $k = f(l,n)$. The PSD used by the l-th base-station in nth tone is denoted as P^n_l.

The network is assumed to employ an initial channel estimation and synchronization phase, in which the multi-path fading channel information is obtained between nearby transmitter and receiver in the network, including downlink direct channels within each cell as well as the interfering channels between the BSs and the MUs in neighboring cells. The channel-state information (CSI) is supposed to be perfect. Further, femto BSs and macro BSs coordinate with each other through backhaul to exchange channel-state and control information. These are fairly strong assumptions, but the resulting optimization indicates that such coordination provides crucial benefits, as this paper aims to benchmark. Closed access mode is adopted in this paper, where only subscribed users within radio range are allowed to establish connections with the femtocell.

B. SIC vs JD

In each time-frequency slot, the MU receivers can perform either SD where the interference is treated as noise, or SIC where the interference is decoded first then subtracted, or JD where the interference and the desired signals are decoded jointly. Suppose that in the nth frequency tone, the scheduled user k in the lth cell wishes to decode its own message and is interfered by the message transmitted from the BS of the mth cell to its scheduled user k'. Let r^n_{lk} denote the instantaneous downlink rate for the kth user in the lth cell in the nth tone. With SD, the achievable rate is

$$\tilde{r}^n_{lk} = \log\left(1 + \frac{P^n_l |h^n_{l,lk}|^2}{\sum_{j \neq l} P^n_j |h^n_{j,lk}|^2 + \sigma^2}\right), \tag{1}$$

where σ^2 is the background noise. With MUD, the user k in cell l may decode the message of user k' in cell m in tone n. In this case, we denote the 5-tuple (l,k,m,k',n) as a MUD pair. With SIC, the achievable rates are

$$\begin{cases} r^n_{lk} & \leq \log\left(1 + \frac{P^n_l |h^n_{l,lk}|^2}{\sum_{j\neq l,m} P^n_j |h^n_{j,lk}|^2 + \sigma^2}\right) \\ r^n_{mk'} & \leq \min\left\{\log\left(1 + \frac{P^n_m |h^n_{m,mk'}|^2}{\sum_{j\neq m} P^n_j |h^n_{j,mk'}|^2 + \sigma^2}\right),\right. \\ & \qquad \left.\log\left(1 + \frac{P^n_m |h^n_{m,lk}|^2}{\sum_{j\neq m} P^n_j |h^n_{j,lk}|^2 + \sigma^2}\right)\right\} \end{cases} \tag{2}$$

where the minimization of the two terms comes from the fact that the message from base-station m is decoded at both users k and k'. Finally, with JD the achievable rates are

$$\begin{cases} r^n_{lk} & \leq \log\left(1 + \frac{P^n_l |h^n_{l,lk}|^2}{\sum_{j\neq l,m} P^n_j |h^n_{j,lk}|^2 + \sigma^2}\right) \\ r^n_{mk'} & \leq \log\left(1 + \frac{P^n_m |h^n_{m,mk'}|^2}{\sum_{j\neq m} P^n_j |h^n_{j,mk'}|^2 + \sigma^2}\right) \\ r^n_{lk} + r^n_{mk'} & \leq \log\left(1 + \frac{P^n_l |h^n_{l,lk}|^2 + P^n_m |h^n_{m,lk}|^2}{\sum_{j\neq l,m} P^n_j |h^n_{j,lk}|^2 + \sigma^2}\right) \end{cases} \tag{3}$$

Note that the BSs l, m, and the MU k form a MAC, but the rate constraints on r^n_{mk} can be replaced by that of $r^n_{mk'}$ since the MU k is not interested in the message from BS m, but only MU k' is. The SD, SIC and JD points are illustrated in Fig. 1. Let $C_1(x) = \log\left(1 + \frac{x}{\sum_{j\neq l,m} P^n_j |h^n_{j,lk}|^2 + \sigma^2}\right)$ and $C_2(x) = \log\left(1 + \frac{x}{\sum_{j\neq m} P^n_j |h^n_{j,mk'}|^2 + \sigma^2}\right)$. It is easy to verify that the rate region given in (2) is contained in that given in (3). Thus, JD should perform at least as well as SIC. Further, depending on the channel gains and the power allocation, there are cases in which JD may be strictly superior to SD. In fact, JD offers additional trade-off of rates between r^n_{lk} and $r^n_{mk'}$. This flexibility is crucial in network optimization.

C. Optimization Problem Formulation

This paper adopts a network-utility maximization framework with a proportionally fair log-utility function, i.e.,

$$\begin{aligned} \max \quad & \sum_{l,k} \log \bar{R}_{l,k} \\ \text{s.t.} \quad & 0 \leq P^n_l \leq S^{max}_l \; \forall l, n \end{aligned} \tag{4}$$

where S^{max}_l is the transmit PSD constraint in the lth cell, and $\bar{R}_{l,k}$ is the long-term average rate of MU k in cell l, which is typically updated exponentially by $\bar{R}_{l,k} = \alpha \bar{R}_{l,k} + (1-\alpha) R_{l,k}$ with some $0 < \alpha < 1$. The instantaneous rate $R_{l,k}$ is

$$R_{l,k} = \sum_{n \in D_{lk}} r^n_{lk} \tag{5}$$

where D_{lk} is the set that all the frequency tones assigned to the kth user in the lth cell, where r^n_{lk} is given by (1), (2) or (3) corresponding to the cases of SD, SIC or JD respectively. The above utility maximization problem can be reduced to a maximization of the marginal increase of the utility function in each time epoch, which can be decomposed in a tone-by-tone basis in the frequency domain:

$$\max \sum_{l,k} w_{l,k} r^n_{l,k}, \quad \text{where } w_{l,k} = \frac{1}{\bar{R}_{l,k}} \tag{6}$$

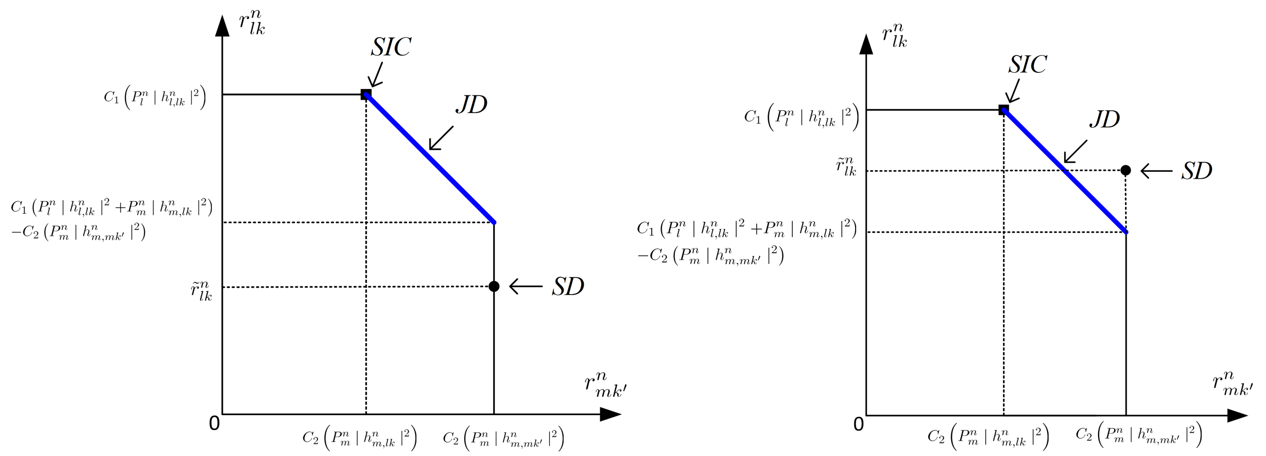

Fig. 1. Achievable rates for two cases with different channel parameters of JD vs. SIC vs. SD. Left: JD offers additional flexibility as compared to SIC. Right: either SIC or SD is always superior to JD.

This is a mixed discrete and continuous optimization problem over scheduling, power allocation, and the selection of MUD pairs. Finding the globe optimal solution to this problem is expected to be rather challenging. To provide a practical solution to this problem, we decouple the problem into several subproblems: scheduling, selection of MUD pairs, and power allocation with MUD, then solve the subproblems separately and iteratively to achieve at least a local maximum of the target objective function. As mentioned earlier, such a solution needs macro and femto BSs to coordinate with each other to share channel-state and transmission-rate information in each time-frequency slot.

The proposed algorithm maintains a list of MUD pairs in the network, then proceeds with scheduling assuming that MUD pairs and the powers are fixed, then MUD pair selection assuming a fixed schedule and power, then power control assuming the fixed schedule and MUD pairs, and finally iterates among the three steps. The detailed descriptions of the steps are as follows.

D. Scheduling

The conventional proportionally fair scheduling step involves assigning user k in the lth cell as

$$f^i(l,n) = \arg\max_k \left\{ w_{l,k} \log\left(1 + \frac{P_l^n |h_{l,lk}^n|^2}{\sum_{j \neq l} P_j^n |h_{j,lk}^n| + \sigma^2}\right)\right\}$$

in the ith iteration of the algorithm. This can be implemented in each cell independently. The scheduling operation is slightly more complicated when the previously scheduled user in the cell is involved in a MUD pair. In this case, the new user should only replace the previously scheduled user only if doing so results in increased network utility. In the proposed algorithm, the newly scheduled user is assumed not to be involved in MUD, at least initially.

More precisely, if the kth user in lth cell and the k'th user in mth cell forms a MUD-pair in the $(i-1)$th iteration, we record

$$J_{l,m,n}^{(i-1)} = \max\left\{ w_{l,k} r_{lk}^n + w_{m,k'} r_{mk'}^n \right\} \tag{7}$$

as the utility of the pair in the $(i-1)$th iteration. Then, the scheduler replaces the assigned user in cell l by $f^i(l,n)$ and replaces the assigned user in cell m by $f^i(m,n)$ if

$$w_{l,f^i(l,n)} \tilde{r}_{l,f^i(l,n)}^n + w_{m,f^i(m,n)} \tilde{r}_{m,f^i(m,n)}^n > J_{l,m,n}^{(i-1)} \tag{8}$$

where $\tilde{r}_{l,f^i(l,n)}^n$ and $\tilde{r}_{m,f^i(m,n)}^n$ here are SD rates. In doing so, the weighted rate-sum $\sum_{l,k} w_{l,k} r_{l,k}^n$ is guaranteed to be nondecreasing in the scheduling step.

E. MUD Pair Selection

Next, MUD pairs are selected among the scheduled users in each frequency tone. Clearly, this is a combinatorial search, however, its complexity is manageable in practice since each cell only has a limited number of neighbors. To further reduce the search complexity, this paper assumes that the MAC channel formed with either SIC or JD is limited to between two users, i.e., each user's signal can only be detected by at most one additional user, and each receiver can detect only at most one interferer. Further, no overlap between two different MUD pairs is allowed, i.e., if a user's signal is already being decoded by another user, then its receiver cannot participate in the decoding of some other user.

The basic algorithm is to go through all possible user pairs among the SD users. Note that when MUD is used at the receivers, $r_{l,k}^n$ depends not only on its transmit PSD, but also on the transmission rates of the BS in its neighbour cell. Specifically, MUD is applied between the kth user in the lth cell and the k'th user in the mth cell in the nth tone, if $J_{l,m,n}^i > w_{l,k}\tilde{r}_{lk}^n + w_{m,k'}\tilde{r}_{mk'}^n$ where $\tilde{r}_{lk}^n, \tilde{r}_{mk'}^n$ are given by the SD rate (1). In case of SIC, $J_{l,m,n}^i$ is computed assuming (2). In case of JD, $J_{l,m,n}^i$ is computed assuming (3), which involves a comparison between the two corner points of the pentagon region shown in Fig. 1.

This part of the algorithm also tests all existing MUD pairs to see if reverting any of them back to SD results in a net increase in utility. Overall, the algorithm works in a greedy fashion. The forming or breaking of the pair that results in the largest increase in weighted sum rate is done first. Algorithm proceeds until no new pairing or unpairing results in a net utility increase.

F. Power Control based on Joint Detection

The power allocation step assumes a fixed user schedule and a fixed set of MUD-pairs to find the optimal transmit PSD in the downlink. The objective is again the weighted rate sum:

$$\max \sum_{l,k} w_{l,k} r_{l,k}^n \quad s.t. \quad 0 \le P_l^n \le S_l^{max} \tag{9}$$

where $r_{l,k}^n$ is given by (1) if SD is applied, (2) if SIC is applied, and (3) if JD is applied.

In the following, we assume the case of JD, and illustrate how a local optimum of the above nonconvex optimization problem can be found numerically. Dualizing the optimization problem with respect to the instantaneous rates constraints (3) of JD, the optimization problem (9) can be rewritten as

$$\begin{aligned} \max \quad & \sum_{l' \notin \Pi} w_{l',\tilde{k}} \tilde{r}_{l',\tilde{k}}^n + \sum_{(l,m)\in\Pi} \{w_{l,k} r_{lk}^n + w_{m,k'} r_{mk'}^n\} \\ & - \sum_{l,m:(l,m)\in\Pi} \{\lambda_l^1 \left(\tilde{r}_{lk}^n - r_{lk}^n\right) + \lambda_m^2 \left(\tilde{\tilde{r}}_{mk'}^n - r_{mk'}^n\right) \\ & + \lambda_{l,m}^3 (\bar{r}_{l,k,m,k}^n - r_{lk}^n - r_{mk'}^n)\} \\ \text{s.t.} \quad & 0 \le P_l^n \le S_l^{max} \end{aligned} \tag{10}$$

where Π is the set of JD pairs, $\tilde{r}_{l',\tilde{k}}^n$ is given by the SD achievable rate (1), $\tilde{\tilde{r}}_{mk'}^n = \log\left(1 + \frac{P_l^n |h_{l,lk}^n|^2}{\sum_{j\neq l,m} P_j^n |h_{j,lk}^n|^2 + \sigma^2}\right)$, and $\bar{r}_{l,k,m,k}^n = \log\left(1 + \frac{P_l^n |h_{l,lk}^n|^2 + P_m^n |h_{m,lk}^n|^2}{\sum_{j\neq l,m} P_j^n |h_{j,lk}^n|^2 + \sigma^2}\right)$.

Note that the purpose of $\{\lambda_l^i\}$ is to ensure that the rate constraints in (3) are satisfied. Appropriate $\{\lambda_l^i\}$ can be found by a subgradient search. For fixed $\{\lambda_l^i\}$, we can find a local optimum of the optimization problem (10) using a Newton's method. Specifically, assuming that there are $L_M + L_F$ cells in total and let $g(P_1^n, \ldots, P_{L_M+L_F}^n)$ denote the objective function in (10), which is a function of transmit power $(P_1^n, \ldots, P_{L_M+L_F}^n)$. Then, one variant of the Newton's method [12] is to let each base-station iteratively update its power allocation according to $P_l^n(\kappa+1) = [P_l^n(\kappa) + \mu \triangle P_l^n]_0^{S_l^{max}}$ where the power update direction is given by

$$\triangle P_l^n = \frac{\partial g / \partial P_l^n + \sum_{j\neq l} \left|\partial g / \partial P_j^n\right|}{|\partial^2 g / \partial (P_l^n)^2|} \tag{11}$$

As the Newton's direction is an ascent direction, the convergence can be ensured with an appropriate step size μ.

G. Summary of the Algorithm

The scheduling, the MUD-pair set selection, and the power allocation steps are iterated until convergence. Each step is a nondecreasing step in network utility. Thus, the iterations converge to at least a local optimum solution. The entire algorithm is summarized below:

1) Initialize $P_l^n = S_l^{max}, \forall l, n$, and the MUD set $\Pi = \emptyset$.
2) Fix P_l^n and the set of MUD-pairs, perform scheduling of users for each cell in each frequency tone.
3) Fix the user schedule, update the set of MUD-pairs.

Cellular Layout	Hexagonal, 1 macro -cell, 3 femtocells
Macro cell radius	1.6 km
Femto cell radius	320 m
Frequency Reuse	1
Channel Bandwidth	10 MHz
Number macro MUs	40 per cell
Number femto MUs	5 per cell
Macro BS Max Transmit Power	43 dBm
Macro BS Max PSD	-27 dBm/Hz
Femto BS Max Transmit Power	23 dBm
Femto BS Max PSD	-47 dBm/Hz
Antenna Gain	15 dBi
Background Noise	-169 dBm/Hz
Transmitter/Receiver Antenna No.	1
Multipath Time Delay Profile	ITU-R M.1225 PedA
Distance-dependent path loss	$128.1 + 37.6 \log_{10}(d)$
FFT Size	64

TABLE I
FEMTOCELL CHANNEL MODEL PARAMETERS

4) Fix the user schedule and the set of MUD-pairs, repeat the following steps until $\{\lambda_l^i\}$ converge
   a) Optimize the power spectra $\{P_l^n\}$ by solving (10) by Newton's method and update the rates of each MUD-pairs.
   b) Update $\{\lambda_l^i\}$ using subgradient method, i.e. if $(l, k, m, k', n) \in \Pi$,

$$\begin{aligned} \lambda_l^1 &= \left[\lambda_l^1 - s\left(\tilde{r}_{l',\tilde{k}}^n - r_{l,k}^n\right)\right]_+, \\ \lambda_m^2 &= \left[\lambda_m^2 - s\left(\tilde{\tilde{r}}_{mk'}^n - r_{m,k'}^n\right)\right]_+, \\ \lambda_{l,m}^3 &= \left[\lambda_{l,m}^3 - s\left(\bar{r}_{l,k,m,k}^n - r_{lk}^n - r_{mk'}^n\right)\right]_+, \end{aligned}$$

   where s is the step-size and $[a]_+ = \max(0, a)$.
5) Update the proportional-fairness weights $\{w_{l,k}^n\}$, stop if network utility converges; otherwise, go to Step 2).

In practice, Step 4) can be implemented with a fixed number of iterations. In addition, in the procedure for updating Lagrangian multipliers, we keep only the values of power spectra $\{P_l^n\}$ which increase the objective in (10) to ensure the convergence of the algorithm.

III. SIMULATION RESULTS

The performance of the proposed algorithm is evaluated on a macro-femto overlaid network with one macro BS and three femto BSs, with maximal frequency reuse, and where three femto BSs are deployed on the edge of macrocell's region at distances $0.8R$ from the the macro base-station, where $R =$ 1.6km is the macrocell radius. Each femto-station serves a coverage area of radius $0.2R$. All the macro or femto MUs are randomly located within the macro or femto region. Each MU establishes connection with the BS with the highest received SINR. System parameters are outlined in Table I.

Fig. 2 shows the log utility achieved with constant PSD with JD (label as CP-JD) and constant PSD with SD (labeled as CP) vs. that achieved with dynamic power allocation with SIC and JD (labeled as DP-SIC and DP-JD respectively) and dynamic power control with SD (labeled as DP). In

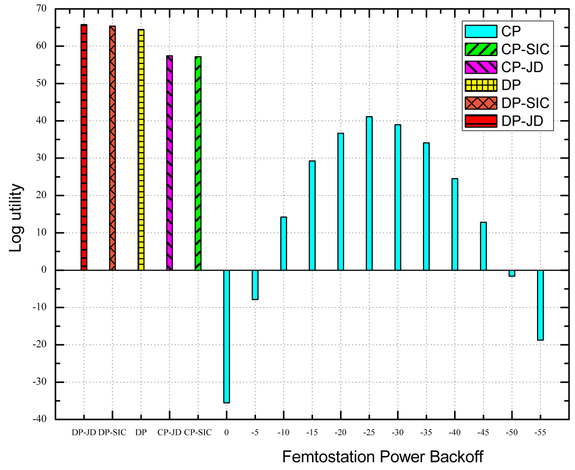

Fig. 2. Comparison of log-utility achieved by constant PSD with SD, SIC, and JD vs. dynamic PSD with SD, SIC, and JD.

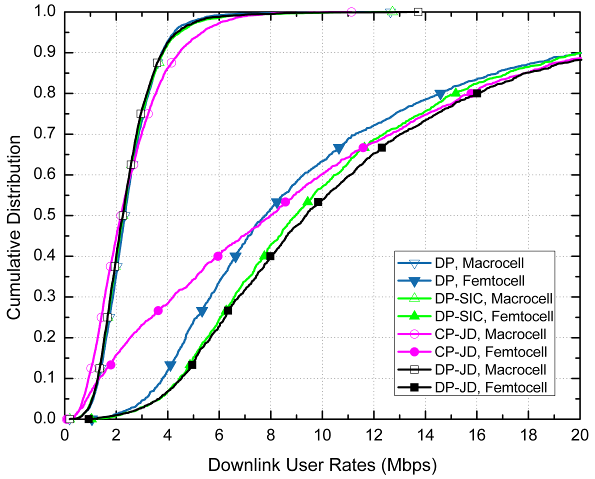

Fig. 3. Cumulative distribution of user rates for dynamic power allocation with and without MUD.

the constant PSD with SD case, power backoff at the femto BS is implemented with backoff values ranging from -5dB to -50dB. As can been seen from the figure, the optimal power backoff values are -25dB for this particular topology. It is shown that dynamic power control always outperforms constant PSD, and JD is slightly superior to SIC, which is in term slightly superior to SD.

The advantage of MUD is more evident in Fig. 3, which shows the cumulative distribution of rates for the macro users (labeled as Macrocell) and the femto users (labeled as Femtocell) for dynamic power allocation with SIC (labeled as DP-SIC), with JD (labeled as DP-JD), and with SD (labeled as DP), and constant power allocation with JD (labeled as CP-JD). Femtocell users achieve higher average rates because they are on average closer to the femto-stations than macro-users are to the macro base-stations in this topology. The figure demonstrates that the proposed scheduling, power allocation and MUD scheme brings significant benefit to the femto-users, while essentially maintaining the performance of the macro-users. In addition, SIC already brings in significant benefits of MUD, while JD further enlarges the improvements. Specifically, for the 50-percentile femto-users, as compared to conventional scheduling and dynamic power control scheme using SD, the SIC scheme achieves 15% improvement on the rate for the femto-users (7.8Mbps vs. 9Mbps), with further 5% improvement possible with JD (9.4Mbps). The percentage improvement is even larger for cell-edge users. The figure also shows that the DP-JD scheme achieves better performance than the CP-JD scheme for cell-edge users, which highlights the importance of power allocation.

IV. CONCLUSION

This paper considers interference mitigation with opportunistic MUD in femtocell networks. A numerical algorithm is proposed to solve the joint scheduling, power allocation, and MUD set selection problem iteratively to maximize the overall network utility. It is shown that by coordinating the macro and femto base-stations for exchanging CSI and control information, significant throughput improvement can already be obtained using SIC, and further improvement is possible using JD, as compared with the conventional SD scheme.

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