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Multicast in Femtocell Networks: A Successive Interference Cancellation Approach

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***Abstract*—A femtocell is a small cellular base station (BS), typically used for serving approved users within a small coverage. In this paper, we investigate the problem of data multicast in femtocell networks that incorporates *superposition coding* (SC) and *successive interference cancellation* (SIC). The problem is to decide the transmission schedule for each BS, as well as the power allocation for the SC layers, to achieve a sufficiently large SNR for each layer to be decodable with SIC. The objective is to minimize the total BS power consumption. We formulate a Mixed Integer Nonlinear Programming (MINLP) problem, which is NP-hard in general. We then reformulate the problem into a simpler form, and derive upper and lower performance bounds. Finally, we consider three typical connection scenarios in the femtocell network, and develop optimal and near-optimal algorithms for the three scenarios. The proposed algorithms have low computational complexity, and outperform a heuristic scheme with considerable gains in our simulation study.**

I. INTRODUCTION

A femtocell is a small cellular base station (BS), typically used for serving approved users within a small coverage (e.g., a house). Femtocells usually have broadband wireline connections to the service provider network, which can be exploited to coordinate the transmissions of multiple femtocells for improved network-wide performance. Among many benefits, femtocells can be used to extend coverage, improve capacity, and reduce both power consumption and interference. Most of the benefits are achieved by the reduced distance of wireless transmissions, i.e., by bringing BS's closer to users [1].

Among many technical challenges, interference is an important problem for the success of this technology, since femtocells usually use the same spectrum as conventional cellular networks. There has been considerable effort on interference mitigation techniques for femtocells [1]. In addition, the power consumption is also an important issue. The electricity bill is already a large part of a wireless operator's costs [2]. Minimizing BS power consumption can reduce not only the owner's operating expense (or, OPEX), but also the global CO_2 emission, thus achieving the goal of "green" communications. Considering the envisioned wide deployment of femtocells and the predicted huge increase in wireless data traffic in the near future, even a small reduction in the BS power consumption will be magnified and may have a sizable gross impact.

In this paper, we investigate the problem of data multicast in femtocell networks. It is not atypical that many users may request for the same content, as often observed in wireline networks. By allowing multiple users to share the same downlink multicast transmission, significant spectrum and power savings can be achieved.

In particular, we adopt *superposition coding* (SC) and *successive interference cancellation* (SIC), two well-known PHY techniques, for data multicast in femtocell networks [3]. With SC, a compound signal is transmitted, consisting of multiple signals (or, layers) from different senders or from the same sender. With SIC, a strong signal can be first decoded, by treating all other signals as noise. Then the decoder will reconstruct the signal from the decoded bits, and subtract the reconstructed signal from the compound signal. The next signal will be decoded from the residual, by treating the remaining signals as noise. And so forth. A special strength of the SC with SIC approach is that it enables simultaneous unicast transmissions (e.g., many-to-one or one-to-many). It has been shown that SC with SIC is more efficient than PHY techniques with orthogonal channels [3], [4].

In this paper, we adopt SC and SIC for the unique femtocell network environment, and investigate how to enable efficient data multicast from the femtocells to multiple users. We consider a femtocell network consisting of one macro base station (MBS) and multiple femto base stations (FBS). The MBS and FBS's cooperatively multicast a data file to users in the network. The data is coded with SC. Each user connects to either the MBS or an FBS and uses SIC to decode the received compound signal. The problem is to decide the transmission schedule for each BS, as well as the power allocation for the SC layers, such that there is a sufficiently large SNR for each layer to be decodable with SIC. The objective is to minimize the total BS power consumption.

We formulate a Mixed Integer Nonlinear Programming (MINLP) problem, which is NP-hard in general. Then we reformulate the MINLP problem into a simpler form, and derive upper and lower performance bounds. We also derive a simple heuristic scheme that assigns users to the BS's with a greedy approach. Finally, we consider three typical connection scenarios in the femtocell network, and develop optimal and near-optimal algorithms for the three scenarios. The proposed algorithms have low computational complexity, and are shown to outperform the heuristic scheme with considerable gains.

The remainder of this paper is organized as follows. We present the system model and problem statement in Section II. In Section III, we reformulate the problem, and derive performance bounds and solution algorithms. The proposed algorithms are evaluated in Section IV. We review related work

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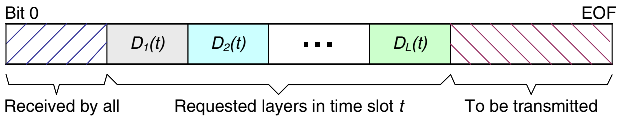


Fig. 1. Superposition coding and successive interference cancellation.

in Section V. Section VI concludes this paper.

II. SYSTEM MODEL AND PROBLEM STATEMENT

A. System Model

Consider a femtocell network with an MBS (indexed 0) and M FBS's (indexed from 1 to M) deployed in the area. The M FBS's are connected to the MBS and the Internet via broadband wireline connections. Furthermore, we assume a spectrum band that is divided into two parts, one is allocated to the MBS with bandwidth B_0 and the other is allocated to the M FBS's. The bandwidth allocated to FBS m is denoted by B_m. When there is no overlap between the coverages of two FBS's, they can spatially reuse the same spectrum. Otherwise, the MBS allocates disjoint spectrum to the FBS's with overlapping coverages. We assumed the spectrum allocation is known a priori.

There are K mobile users in the femtocell network. Each user is equipped with one transceiver that can be tuned to one of the two available channels, i.e., connecting to a nearby FBS or to the MBS. The network is time slotted. We assume block-fading channels, where the channel condition is constant in each time slot [3]. We focus on a multicast scenario, where the MBS and FBS's multicast a data file to the K users. The data file is divided into multiple packets with equal length and transmitted in sequence with the same modulation scheme. Once packet l is successfully received and decoded at the user, it requests packet $(l+1)$ in the next time slot.

We adopt SC and SIC to transmit these packets [3], as illustrated in Fig. 1. In each time slot t, the compound signal has L *layers* (or, levels), denoted as $D_1(t)$, $\cdots$, $D_L(t)$. Each level $D_i(t)$, $i=1,\cdots,L$, is a packet requested by some of the users in time slot t. A user that has successfully decoded $D_i(t)$, for all $i=1$, $\cdots$, $l-1$, is able to subtract these signals from the received compound signal and then decodes $D_l(t)$, while the signals from $D_{l+1}(t)$ to $D_L(t)$ are treated as noise.

B. Problem Statement

For the SC and SIC scheme to work, the transmit powers for the levels should be carefully determined, such that there is a sufficiently high SNR for the levels to be decodable. It is also important to control the transmit powers of the BS's to reduce interference and leverage frequency reuse. The annual power bill is a large part of a mobile operator's costs [2]. Minimizing BS power consumption is important to reduce not only the operator's OPEX, but also the global CO$_2$ emission; an important step towards "green" communications.

Therefore, we focus on BS power allocation in this paper. The objective is to minimize the total power of all the BS's, while guaranteeing a target rate R_{tar} for each user. Recall that the data file is partitioned into equal-length packets. The target rate R_{tar} ensures that a packet can be transmitted within a time slot, for given modulation and channel coding schemes.

Define binary indicator I_m^k, for all m and k, as:

$$I_m^k = \begin{cases} 1, & \text{if user } k \text{ connects to BS } m \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Consider a general time slot t when L data packets, or levels, are requested. We formulate the optimal power allocation problem (termed OPT-Power) as follows.

$$\begin{aligned} \text{minimize:} \quad & \textstyle\sum_{m=0}^{M}\sum_{l=1}^{L} P_l^m & (2)\\ \text{subject to:} \quad & B_m \log_2(1+\gamma_m^k I_m^k) \geq R_{tar} I_m^k, \ \text{ for all } k & (3)\\ & \textstyle\sum_{m=0}^{M} I_m^k = 1, \text{for all } k & (4)\\ & P_l^m \geq 0, \ \text{ for all } l, m, & (5) \end{aligned}$$

where P_l^m is the power of BS m for transmitting the level l packet; γ_m^k is the SNR at user k if it connects to BS m. Constraint (3) guarantees the minimum rate at each user. Constraint (4) is due to the fact that each user is equipped with one transceiver, so it can only connect to one BS.

Let $\mathcal{U}_l$ denote the set of users requesting the level l packet. A user $k \in \mathcal{U}_l$ has decoded all the packets up to D_{l-1}. It subtracts the decoded signals from the received signal and treats signals $D_{l+1}, \cdots, D_L$ as noise. The SNR at user $k \in \mathcal{U}_l$, for $l = 1, \cdots, L-1$, can be written as:

$$\gamma_m^k = H_m^k P_l^m \Big/ \left(N_0 + H_m^k \textstyle\sum_{i=l+1}^{L} P_i^m\right), \tag{6}$$

where H_m^k is the random channel gain from BS m to user k and N_0 is the noise power. For user $k \in \mathcal{U}_L$ that requests the last packet D_L, the SNR is

$$\gamma_m^k = H_m^k P_L^m / N_0. \tag{7}$$

The optimization variables in Problem OPT-Power consist of the binary variables I_m^k's and the continuous variables P_l^m's. It is an MINLP problem, which is NP-hard in general. In Section III, we first reformulate the problem to a obtain a simpler form, and then develop effective algorithms for optimal and suboptimal solutions.

III. REFORMULATION AND POWER ALLOCATION

In this section, we reformulate Problem OPT-Power to obtain a simpler form, and derive an upper bound and a lower bound for the total BS power. The reformulation also leads to a simple heuristic algorithm. Finally, we introduce power allocation algorithms for three connection scenarios.

A. Problem Reformulation

Due to the monotonic logarithm functions and the binary indicators I_m^k, constraint (3) can be rewritten as:

$$\gamma_m^k I_m^k \geq \Gamma_m^k I_m^k, \quad m = 0, 1, \cdots, M, \tag{8}$$

where $\Gamma_m^k = \Gamma_m =: 2^{R_{tar}/B_m} - 1$ is the minimum SNR requirement at user k that connects to BS m. To further simplify the problem, define $Q_l^m = \sum_{i=l}^{L} P_i^m$, with $Q_{L+1}^m = 0$. Then power P_l^m is the difference

$$P_l^m = Q_l^m - Q_{l+1}^m. \tag{9}$$

Problem OPT-Power can be reformulated as:

$$\begin{aligned} \text{minimize}\ & \textstyle\sum_{m=0}^{M} Q_1^m && (10)\\ \text{subject to:}\ & H_m^k(Q_l^m - Q_{l+1}^m)/\left(N_0 + H_m^k Q_{l+1}^m\right) I_m^k \ge \Gamma_m I_m^k, && \\ & \qquad\qquad \text{for all } k \in \mathcal{U}_l, l = 1, \cdots, L && (11)\\ & Q_l^m \ge Q_{l+1}^m, l = 1, \cdots, L && (12)\\ & \textstyle\sum_{m=0}^{M} I_m^k = 1, \text{ for all } k. && (13) \end{aligned}$$

For $l \le L$, constraint (11) can be rewritten as:

$$Q_l^m I_m^k \ge \left[N_0 \Gamma_m / H_m^k + (1+\Gamma_m) Q_{l+1}^m\right] I_m^k. \tag{14}$$

Let $\mathcal{U}_l^m$ be the subset of users connecting to BS m in $\mathcal{U}_l$. Since $Q_l^m \ge Q_{l+1}^m$, (14) can be rewritten as,

$$Q_l^m = \max\left\{Q_{l+1}^m, \max_{k \in \mathcal{U}_l^m} \left[N_0 \Gamma_m / H_m^k + (1+\Gamma_m) Q_{l+1}^m\right]\right\}. \tag{15}$$

From (15), we define a function $Q_l^m = F_m(Q_{l+1}^m, \mathcal{U}_l^m)$ as:

$$\begin{aligned} & F_m(Q_{l+1}^m, \mathcal{U}_l^m) \qquad\qquad\qquad\qquad (16)\\ &= \begin{cases} Q_{l+1}^m, & \mathcal{U}_l^m = \emptyset \\ \max_{k \in \mathcal{U}_l^m} \left\{\frac{N_0 \Gamma_m}{H_m^k} + (1+\Gamma_m) Q_{l+1}^m\right\}, & \mathcal{U}_l^m \neq \emptyset. \end{cases} \end{aligned}$$

Obviously, $F_m(Q_{l+1}^m, \mathcal{U}_l^m)$ is non-decreasing with respect to Q_{l+1}^m. It follows that

$$\begin{aligned} Q_1^m &= F_m(Q_2^m, \mathcal{U}_1^m) = F_m(F_m(Q_3^m, \mathcal{U}_2^m), \mathcal{U}_1^m) \\ &= F_m(\cdots(F_m(Q_{L+1}^m, \mathcal{U}_L^m), \mathcal{U}_{L-1}^m), \cdots, \mathcal{U}_1^m) \\ &= F_m(\cdots(F_m(0, \mathcal{U}_L^m), \mathcal{U}_{L-1}^m), \cdots, \mathcal{U}_1^m). \end{aligned} \tag{17}$$

If none of the subsets $\mathcal{U}_l^m$ ($l = 1, \cdots, L$) is empty, we can expand the above recursive term using (16). It follows that

$$Q_1^m = N_0 \Gamma_m \textstyle\sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \displaystyle\max_{k \in \mathcal{U}_l^m} \left\{1/H_m^k\right\}, \tag{18}$$

where the exponent c_l^m is defined as $c_1^m = 0$ and $c_{l+1}^m = c_l^m + 1$. Otherwise, if a subset $\mathcal{U}_l^m = \emptyset$ for some m, we have that $Q_l^m = Q_{l+1}^m$, $\max_{k \in \mathcal{U}_l^m}\left\{1/H_m^k\right\} = \max_{k \in \emptyset}\left\{1/H_m^k\right\} = 0$, and $c_l^m = c_{l-1}^m$. Eq. (18) still holds true.

Finally, the objective function (10) can be rewritten as

$$\textstyle\sum_{m=0}^{M} N_0 \Gamma_m \sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \displaystyle\max_{k \in \mathcal{U}_l^m} \left\{1/H_m^k\right\}. \tag{19}$$

Since $(1+\Gamma_m) > 0$, it can be seen that to minimize the total BS power, we need to keep the c_l^m's as low as possible.

B. Performance Bounds

The reformulation and simplification allow us to derive performance bounds for the total BS power consumption. First, we derive the upper bound for the objective function (10). Define a variable

$$\overline{G}_m = \max_{l \in \{1,\cdots,L\}} \max_{k \in \mathcal{U}_l^m} \left\{\Gamma_m / H_m^k\right\}, \tag{20}$$

which corresponds to the user with the worst channel condition among all users that connect to BS m. It follows that:

$$\begin{aligned} \textstyle\sum_{m=0}^{M} Q_1^m &= N_0 \textstyle\sum_{m=0}^{M} \sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \displaystyle\max_{k \in \mathcal{U}_l^m} \left\{\Gamma_m / H_m^k\right\} \\ &\le N_0 \textstyle\sum_{m=0}^{M} \sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \overline{G}_m \\ &\le N_0 \textstyle\sum_{m=0}^{M} \overline{G}_m \sum_{l=1}^{L} (1+\Gamma_m)^{l-1} \\ &= N_0 \textstyle\sum_{m=0}^{M} \overline{G}_m \left[(1+\Gamma_m)^L - 1\right] / \Gamma_m. \end{aligned} \tag{21}$$

In (21), the first inequality is from the definition of $\overline{G}_m$. The second inequality is from the definition of c_{l+1}^m. Specifically, $c_1^m = 0$; when $\mathcal{U}_l^m \neq \emptyset$, we have $c_l^m = c_{l-1}^m + 1$; when $\mathcal{U}_l^m = \emptyset$, we have $c_l^m = c_{l-1}^m$. It follows that $c_l^m \le l - 1$. Therefore, (21) is an upper bound on the objective function (10).

Next, we derive a lower bound for (10). Define

$$\begin{cases} \underline{G}^l = \min_{m \in \{1,\cdots,M\}} \max_{k \in \mathcal{U}_l^m} \left\{\Gamma_m / H_m^k\right\} \\ \underline{\Gamma} = \min_{m \in \{0,\cdots,M\}} \left\{\Gamma_m\right\}. \end{cases} \tag{22}$$

We have that

$$\begin{aligned} \textstyle\sum_{m=0}^{M} Q_1^m &= N_0 \textstyle\sum_{m=0}^{M} \sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \displaystyle\max_{k \in \mathcal{U}_l^m} \left\{\Gamma_m / H_m^k\right\} \\ &\ge N_0 \textstyle\sum_{m=0}^{M} \sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \underline{G}^l \\ &\ge N_0 \textstyle\sum_{l=1}^{L} \underline{G}^l \sum_{m=0}^{M} (1+\underline{\Gamma})^{c_l^m} \\ &\ge N_0 (M+1) \textstyle\sum_{l=1}^{L} \underline{G}^l (1+\underline{\Gamma})^{\frac{\sum_{m=0}^{M} c_l^m}{M+1}} \\ &\ge N_0 (M+1) \textstyle\sum_{l=1}^{L} \underline{G}^l (1+\underline{\Gamma})^{\frac{l-1}{M+1}}. \end{aligned} \tag{23}$$

In (23), the first inequality is from the definition of $\underline{G}^l$. The second inequality is due to the definition of $\underline{\Gamma}$. The third inequality is due to the fact that $(1+\Gamma)^{c_l^m}$ is a convex function. The fourth inequality is because that each level must be transmitted by at least one BS. Thus for each level l, there is at least one $c_l^m = c_{l-1}^m + 1$ for some m. It follows that the sum $\sum_{m=0}^{M} c_l^m$ should be greater than $l - 1$. Therefore, (23) provides a lower bound for (10).

Furthermore, by defining $\underline{G} = \min_{l \in \{1,\cdots,L\}} \left\{\underline{G}^l\right\}$, we can obtain a looser lower bound from (23) as

$$\textstyle\sum_{m=0}^{M} Q_1^m \ge N_0 \underline{G} (M+1) \displaystyle\frac{(1+\underline{\Gamma})^{\frac{L}{M+1}} - 1}{(1+\underline{\Gamma})^{\frac{1}{M+1}} - 1}. \tag{24}$$

C. A Simple Heuristic Scheme

We first describe a greedy heuristic algorithm that solves OPT-Power with suboptimal solutions. With this heuristic, each user compares the channel gains from the MBS and the FBS's. It chooses the BS with the best channel condition to connect to, thus the values of the binary variables I_m^k are determined. Once the binary variables are fixed, all the subsets $\mathcal{U}_l^m$'s are determined. Starting with $Q_{L+1}^m = 0$, we can apply (15) iteratively to find the Q_l^m's. Finally, the transmit powers P_l^m can be computed using (9).

With this approach, among the users requesting the level l packet, it is more likely that some of them connect to the MBS and the rest connect to some FBS's, due to the random channel gains in each time slot. In this situation, both MBS and FBS will have to transmit all the requested data packets.

Such situation is not optimal for minimizing the total power, as will be discussed in Section III-D2.

D. Power Allocation Algorithms

In the following, we develop three power allocation algorithms for three different connection scenarios with a more structured approach.

1) Case I–One Base Station: We first consider the simplest connection scenario where all the K users connect to the same BS (i.e., either the MBS or an FBS). Assume all the users connect to BS m. Then we have $I_m^k = 1$ for all k, and all the subsets $\mathcal{U}_l^m$ are non-empty; $I_{m'}^k = 0$ for all k and all $m' \neq m$, and all the subsets $\mathcal{U}_l^{m'}$ are empty for $m' \neq m$.

From (16), we can derive the optimal solution as:

$$\begin{aligned} Q_l^{m*} &= (1+\Gamma_m)Q_{l+1}^{m*} + \max_{k\in\mathcal{U}_l^m}\left\{N_0\Gamma_m/H_m^k\right\}, \\ &= N_0\Gamma_m \textstyle\sum_{i=l}^{L}(1+\Gamma_m)^{i-l}\max_{k\in\mathcal{U}_l^m}\left\{1/H_m^k\right\}, \\ &\qquad\qquad l = 1, 2, \cdots, L. \qquad (25) \end{aligned}$$

Recall that $Q_{L+1}^{m*} = Q_{L+1}^m = 0$, the optimal power allocation for Problem OPT-Power in this case is:

$$P_l^{m'*} = \begin{cases} Q_l^{m*} - Q_{l+1}^{m*}, & m' = m, \text{ for all } l \\ 0, & m' \neq m, \text{ for all } l. \end{cases} \qquad (26)$$

2) Case II–MBS and One FBS : We next consider the case with one MBS and one FBS (i.e., $M = 1$), where each user has two choices: connecting to either the FBS or the MBS.

Recall that $\mathcal{U}_l^0$ and $\mathcal{U}_l^1$ are the subset of users who connected to the MBS and the FBS, respectively, and who request the level l packet. Examining (18), we find that the total power of BS m can be significantly reduced if one or more levels are not transmitted, since the exponent c_l^m will not be increased in this case. Furthermore, consider the two choices: (i) not transmitting level l, and (ii) not transmitting level $l' > l$ from BS m. The first choice will yield larger power savings, since more exponents (i.e., $c_l^m, c_{l+1}^m, \cdots, c_{l'-1}^m$) will assume smaller values. Therefore, we should let these two subsets be empty whenever possible, i.e., either $\mathcal{U}_l^0 = \emptyset$ or $\mathcal{U}_l^1 = \emptyset$. According to this policy, all the users requesting the level l packet will connect to the same BS. We only need to make the optimal connection decision for each subset of users requesting the same level of packet, rather than for each individual user.

Since not transmitting a lower level packet yields more power savings for a BS, we calculate the power from the lowest to the highest level, and decide whether connecting to the MBS or the FBS for users in each level. Define $G_l^0 = \max_{k\in\mathcal{U}_l}\left\{1/H_0^k\right\}$ and $G_l^1 = \max_{k\in\mathcal{U}_l}\left\{1/H_1^k\right\}$. The algorithm for solving Problem OPT-Power in this case is given in Table I. In Steps 2–10, the decision on whether connecting to the MBS or the FBS is made by comparing the expected increments in the total power. The user subsets $\mathcal{U}_l^0$ and $\mathcal{U}_l^1$ are determined in Steps 4 and 7. In Steps 11–14, Q_l^m's and the corresponding P_l^m's are computed in the reverse order, based on the determined subsets $\mathcal{U}_l^0$ and $\mathcal{U}_l^1$.

The computational complexity of this algorithm is $\mathcal{O}(L)$.

TABLE I
POWER ALLOCATION ALGORITHM FOR CASE II

```
1:  Initialize all $c_l^0$, $c_l^1$, $Q_{L+1}^0$ and $Q_{L+1}^1$ to zero;
2:  FOR $l = 1$ TO $L$
3:    IF $(\Gamma_0(1+\Gamma_0)^{c_l^0}G_l^0 \leq \Gamma_1(1+\Gamma_1)^{c_l^1}G_l^0)$
4:      Set $\mathcal{U}_l^0 = \mathcal{U}_l$ and $\mathcal{U}_l^1 = \emptyset$;
5:      $c_l^0 = c_l^0 + 1$;
6:    ELSE
7:      Set $\mathcal{U}_l^0 = \emptyset$ and $\mathcal{U}_l^1 = \mathcal{U}_l$;
8:      $c_l^1 = c_l^1 + 1$;
9:    END IF
10: END FOR
11: FOR $l = L$ TO 1
12:   $Q_l^0 = F_0(Q_{l+1}^0, \mathcal{U}_l^0)$ and $P_l^0 = Q_l^0 - Q_{l+1}^0$;
13:   $Q_l^1 = F_1(Q_{l+1}^1, \mathcal{U}_l^1)$ and $P_l^1 = Q_l^1 - Q_{l+1}^1$;
14: END FOR
```

3) Case III–MBS and Multiple FBS's : Finally, we consider the general case with one MBS and multiple FBS's in the network. Each user is able to connect to the MBS or a nearby FBS. Recall that we define $\mathcal{U}_l$ as the set of users requesting the level l packet, and $\mathcal{U}_l^m$ as the subset of users in $\mathcal{U}_l$ that *connect* to BS m. These sets have the following properties.

$$\begin{cases} \bigcup_{m=0}^{M}\mathcal{U}_l^m = \mathcal{U}_l \\ \mathcal{U}_l^m \bigcap \mathcal{U}_l^{m'} = \emptyset, \quad \text{for all } m' \neq m. \end{cases} \qquad (27)$$

The first property is due to the fact that each user must connect to the MBS or an FBS. The second property is because each user can connect to only one BS. The user subsets connecting to different BS's do not overlap. Therefore, $\mathcal{U}_l^m$'s is a *partition* of $\mathcal{U}_l$ with respect to m.

In addition, we define $\mathcal{S}_l^m$ as the set of possible users that are *covered* by BS m and request the level l packet. These sets have the following properties.

$$\begin{cases} \bigcup_{m=1}^{M}\mathcal{S}_l^m = \mathcal{S}_l^0 = \mathcal{U}_l \\ \mathcal{S}_l^m \bigcap \mathcal{S}_l^0 = \mathcal{S}_l^m, \quad \text{for all } m \neq 0 \\ \mathcal{S}_l^m \bigcap \mathcal{S}_l^{m'} = \emptyset, \quad \text{for all } m' \neq m \text{ and } m, m' \neq 0. \end{cases} \qquad (28)$$

The first property is because all users in each femtocell are covered by the MBS. The second property indicates that the users covered by FBS m are a subset of the users covered by the MBS. The third property shows that the user subsets in different femtocells do not overlap. We can see that the $\mathcal{S}_l^m$'s, for $m = 1, \cdots, M$, are also a partition of $\mathcal{U}_l$.

Define $W_m(\mathcal{U}) = \max_{k\in\mathcal{U}}\left\{1/H_m^k\right\}$, where $\mathcal{U}$ is the set of users and $m = 0, \cdots, M$. If the set $\mathcal{U}$ is empty, we define $W_m(\emptyset) = 0$. For example, consider Case II where $M = 1$. We have $\mathcal{S}_l^0 = \mathcal{S}_l^1 = \mathcal{U}_l$, $W_0(\mathcal{U}_l) = G_l^0$, and $W_1(\mathcal{U}_l) = G_l^1$.

The power allocation algorithm for Case III is presented in Table II. The algorithm iteratively picks users from the *eligible* subset $\mathcal{S}_l^m$ and assigns them to the *allocated* subset $\mathcal{U}_l^m$. In each step l, Ψ is the subset of FBS's that will transmit the level l packet; the complementary set $\overline{\Psi}$ is the subset of FBS's that will not transmit the level l packet. The expected increment in total power for each partition is computed, and the partition with the smallest expected increment will be chosen. Δ_l^m is the power of BS m for transmitting the level l data packet. In Steps 6–15, the MBS and FBS combination Ψ is determined for transmitting the level l packet, with the lowest power Δ_0.

TABLE II
POWER ALLOCATION ALGORITHM FOR CASE III

```
1:  Initialize: $c_l^m = 0$ and $Q_{L+1}^m = 0$, for all $l$, $m$;
2:  FOR $l = 1$ TO $L$
3:      FOR $m = 0$ TO $M$
4:          $\Delta_l^m = \Gamma_m (1 + \Gamma_m)^{c_l^m} W_m(\mathcal{S}_l^m)$;
5:      END FOR
6:      Set $\Omega = \{1, \cdots, M\}$ and $\Psi = \emptyset$;
7:      WHILE ($\Omega \neq \emptyset$)
8:          $m' = \arg\min_{m \in \Omega} \Delta_l^m$;
9:          Compute $\Delta' = \Gamma_0 (1 + \Gamma_0)^{c_l^0} W_0(\bigcup_{m \in \overline{\Psi \cup m'}} \mathcal{S}_l^m)$;
10:         IF $((\sum_{m \in \Psi \cup m'} \Delta_l^m + \Delta') < \Delta_0)$
11:             Add $m'$ to $\Psi$;
12:             $\Delta_0 = \sum_{m \in \Psi} \Delta_l^m + \Delta'$;
13:         END IF
14:         Remove $m'$ from $\Omega$;
15:     END WHILE
16:     IF ($\Psi = \emptyset$)
17:         $\mathcal{U}_l^0 = \mathcal{S}_l^0$;
18:         $c_l^0 = c_l^0 + 1$;
19:         Set $\mathcal{U}_l^m = \emptyset$, for all $m \neq 0$;
20:     ELSE
21:         $\mathcal{U}_l^0 = \bigcup_{m \in \overline{\Psi}} \mathcal{S}_l^m$;
22:         IF ($|\Psi| < M$)
23:             $c_l^0 = c_l^0 + 1$;
24:         END IF
25:         FOR $m \in \Psi$
26:             $c_l^m = c_l^m + 1$;
27:             $\mathcal{U}_l^m = \mathcal{S}_l^m$;
28:         END FOR
29:     END IF
30: END FOR
31: FOR $l = L$ TO 1
32:     FOR $m = 0$ TO $M$
33:         $Q_l^m = F_m(Q_{l+1}^m, \mathcal{U}_l^m)$ and $P_l^m = Q_l^m - Q_{l+1}^m$;
34:     END FOR
35: END FOR
```

In Steps 16–30, elements in $\mathcal{S}_l^m$ are assigned to $\mathcal{U}_l^m$ according to Ψ. In Steps 31–35, power sums Q_l^m and the corresponding power allocations P_l^m are calculated in the reverse order from the known $\mathcal{U}_l^m$'s.

The complexity of the algorithm is $\mathcal{O}(ML)$.

IV. PERFORMANCE EVALUATION

We evaluate the performance of the proposed power allocation algorithms using MATLAB$^{\text{TM}}$. Three scenarios corresponding to the three cases in Section III are simulated: (i) Case I: a single MBS; (ii) Case II: one MBS and one FBS; and (iii) Case III: one MBS and three FBS's.

Since we do not find any similar schemes in the literature, we made the following comparisons. First, we compare Cases I and II with respect to BS power consumption and interference footprint. In both cases, there are $K = 8$ users and $L = 4$ levels. In Case I, the MBS bandwidth is $B_0 = 2$ MHz. In Case II, the MBS and the FBS share the 2 MHz total bandwidth; the MBS bandwidth is $B_0 = 1$ MHz and the FBS bandwidth is $B_1 = 1$ MHz. The target data rate R_{tar} is set to 2 Mbps. The channel gain from a base station to each user is exponentially distributed in each time slot.

The interference footprints in the three dimensional space are plotted in Fig. 2(a). The height B of the cylinders indicates the spectrum used by a BS, while the radius r is proportional to the BS transmit power. In Case I when only the MBS is used, the total BS power is 45.71 dBm and the volume of the cylinder is $\pi r^2 B = 18,841$ MHz m^2. In Case II when both the MBS and FBS are used, the total BS power is 34.58 dBm and the total volume of the two cylinders is $2,378$ MHz m^2. Using an additional FBS achieves a 11.13 dB power saving and the interference footprint is reduced to 12.62% of that in Case I. This simple comparison clearly demonstrate the advantages of femtocells achieved by bringing BS's closer to users.

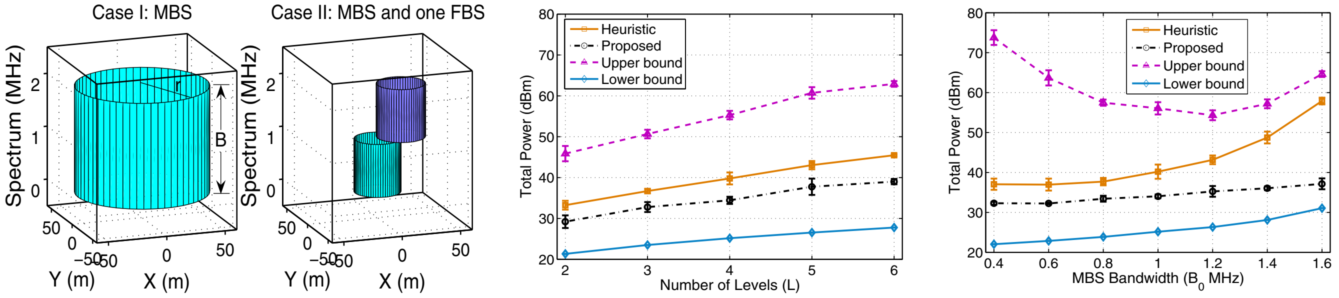
We next consider the more general Case III, using a femtocell network of one MBS and three FBS's. The MBS bandwidth is $B_0 = 1$ MHz and each FBS is assigned with bandwidth $B_m = 1$ MHz, $m = 1, 2, 3$. The target data rate is still 2 Mbps. In Figs. 2(b) and 2(c), we plot four curves, each obtained with: (i) the heuristic scheme described in Section III-C; (ii) The proposed algorithm presented in Section III-D3; (iii) The upper bound; and (iv) the lower bound derived in Section III-B. Each point in the figures is the average of 10 simulation runs. The 95% confidence intervals are plotted as error bars, which are all negligible.

In Fig. 2(b), we examine the impact of the number of packet levels L on the total BS transmit power. We increase L from 2 to 6, and plot the total power of base stations. As expected, the more packet levels, the larger the BS power consumption. Both the proposed and heuristic curves lie in between the upper and lower bound curves. When L is increased from 2 to 6, the power consumption of the heuristic scheme is increased by 12.22 dB, while the power consumption of the proposed algorithm is increased by 9.94 dB. The power savings achieved by the proposed algorithm over the heuristic scheme range from 3.92 dB to 6.45 dB.

In Fig. 2(c), we show the impact of the BS bandwidths. The number of levels is $L = 4$. We fix the total bandwidth at 2 MHz, which is shared by the MBS and FBS's. We increase the MBS bandwidth from 0.4 MHz to 1.6 MHz in steps of 0.2 MHz, while decrease the bandwidth of FBS's from 1.6 MHz to 0.4 MHz. We find that the total power consumption is increased as B_0 gets large. This is due to the fact that as the FBS bandwidth gets smaller, the FBS's have to spend more power to meet the minimum data rate requirement. The curve produced by the proposed algorithm has a smaller slop than that of the heuristic scheme: the overall increase in the total power of the proposed algorithm is 4.86 dB, while that of the heuristic scheme is 20.84 dB. This implies that the proposed scheme is not very sensitive to the bandwidth allocation between the MBS and FBS's. The proposed algorithm also achieves consider power savings over the heuristic scheme. When $B_0 = 1.6$ MHz, the total power of the proposed algorithm is 20.75 dB lower than that of the heuristic scheme.

V. RELATED WORK

Femtocells have attracted considerable interest from both industry and academia. Technical and business challenges, requirements and some preliminary solutions to femtocell networks are discussed in [1]. Since FBS's are distributedly located and are able to spatially reuse the same channel,



(a) Case I vs. Case II: interference footprints (b) Case III: impact of number of levels L (c) Case III: impact of MBS bandwidth B_0

Fig. 2. Simulation results of the power allocation algorithms for SIC-based multicast.

considerable research efforts were made on interference analysis and mitigation [5], [6]. A distributed utility based SINR adaptation scheme was presented in [5] to alleviate cross-tire interference at the macrocell from co-channel femtocells. Lee, Oh and Lee [6] proposed a fractional frequency reuse scheme to mitigate inter-femtocell interference. In our prior work [7], the problem of streaming scalable videos in cognitive radio femtocell networks was investigated. We developed a greedy algorithm to compute near-optimal solutions and proved a closed-form lower bound for its performance.

SIC has high potential of sending or receiving multiple signals concurrently, which improves the transmission efficiency. In [4], the authors developed MAC and routing protocols that exploit SC and SIC to enable simultaneous unicast transmissions. Sen, et al. investigated the possible throughput gains with SIC from a MAC layer perspective [8]. Power control for SIC was comprehensively investigated and widely applied to code division multiple access (CDMA) systems [9]–[13]. Applying game theory, Jean and Jabbari proposed an uplink power control under SIC in direct sequence-CDMA networks [9]. In [10], the authors introduced an iterative two-stage SIC detection scheme for a multicode MIMO system and showed the proposed scheme significantly outperformed the equal power allocation scheme. A scheme on joint power control and receiver optimization of CDMA transceivers was presented in [11]. In [12], [13], the impact of imperfect channel estimation and imperfect interference cancellation on the capacity of CDMA systems was examined.

In this paper, we consider the challenging problem of data multicast in femtocell networks with an SC/SIC approach, aiming to minimize the overall BS power consumption. We propose a simple heuristic scheme and a near-optimal power allocation scheme with low computational complexity and proven performance bounds. The proposed algorithms are shown to perform well in achieving the design goals.

VI. CONCLUSIONS

In this paper, we investigated data multicast in femtocell networks consisting of an MBS and multiple FBS's. We adopted SC and SIC for multicast data and investigated how to assign transmit powers for the packet levels. The objective was to minimize the total BS power consumption, while guaranteeing successful decoding of the multicast data at each user. We developed optimal and near-optimal algorithms with low computational complexity, as well as performance bounds. The algorithms were evaluated with simulations and are shown to outperform a heuristic with considerable gains.

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