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# Multicast in Femtocell Networks: A Successive Interference Cancellation Approach★

Donglin Hu[1], Shiwen Mao[2,*], and Xin Su[3]

[1]AT&T Labs, Inc., San Ramon, CA, USA
[2]Department of Electrical and Computer Engineering, Auburn University, Auburn, AL, USA
[3]Wireless and Mobile Communications Technology R&D Center, Tsinghua University, Beijing, China

## 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 at each user. Minimizing the total BS power consumption achieves the goal of "green" communications. We formulate a Mixed Integer Nonlinear Programming (MINLP) problem, and then reformulate the problem into a simpler form. Upper and lower performance bounds on the total BS power consumption are derived. Finally, we consider three typical connection scenarios, 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.

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**Keywords:** Cross-layer optimization; femtocell networks; green communications; multicast; superposition coding; successive interference cancellation.



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## 1. 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 reduced distance of wireless transmissions, i.e., by *bringing BS's closer to users* [3, 6].

Among many technical challenges, interference management 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 developing interference mitigation techniques for femtocells [6]. In addition, the power consumption is also an important issue [2]. The electricity bill is already a large part of a wireless operator's costs [9]. 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 [20]. 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 have a sizable gross impact.

In this paper, we investigate the problem of multicasting data in femtocell networks. Multicast is an important wireless data application that should be supported. It is not atypical that many users may request for the same content (such as news or stock prices), 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 physical layer (PHY) techniques, for data multicast in femtocell networks [10]. 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

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*Corresponding author. Email: smao@ieee.org.

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) in the same channel. It has been shown that SC with SIC is more efficient than PHY techniques with orthogonal channels [10, 19].

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) [16, 27]. 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 a sufficiently large SNR is achieved for each layer to be decodable with SIC at each user. The overall 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 for the total power consumption. 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 2. In Section 3, we reformulate the problem, and derive performance bounds and solution algorithms. The proposed algorithms are evaluated in Section 4. We review related work in Section 5. Section 6 concludes this paper. The notation used in this paper is summarized in Table 1.

**Table 1.** Notation

| *Symbol* | *Definition* |
|---|---|
| $P_l^m$ | power of BS $m$ transmitting the layer $l$ packet |
| $B_m$ | bandwidth allocated to BS $m$ |
| $\gamma_m^k$ | SNR at user $k$ connecting to BS $m$ |
| $I_m^k$ | indicator of user $k$ connecting to BS $m$ |
| $\tilde{R}$ | target data rate |
| $\Gamma_m^k$ | minimum SNR requirement at user $k$ connecting to BS $m$ |
| $\mathcal{U}_l$ | set of users requesting the level $l$ data |
| $\mathcal{U}_l^m$ | set of users connecting to BS $m$ in $\mathcal{U}_l$ |
| $\mathcal{S}_l^m$ | set of possible users that are *covered* by BS $m$ and request the level $l$ packet |
| $H_m^k$ | channel gain from BS $m$ to user $k$ |
| $Q_l^m$ | partial sum of $P_i^m$'s |
| $M$ | number of the FBS |
| $K$ | number of the users |
| $L$ | number of the packet layers |
| $D_i$ | layer $i$ of the data signal |

## 2. System Model and Problem Statement

### 2.1. System Model

We consider a femtocell network as illustrated in Fig. 1. It is a two-tier femtocell network with an MBS (with index 0) and $M$ FBS's (with indices from 1 to $M$) deployed in the area [16, 27]. 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 (based on the coverage achieved by the peak powers). 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 [10]. 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 [10], as illustrated in Fig. 2. 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 $t$. That is, this set of packets are determined according to the feedback from all the multicast users (i.e., the set of packets they request 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 $D_l(t)$, treating the signals from $D_{l+1}(t)$ to $D_L(t)$ as noise. Note that as the message is divided into

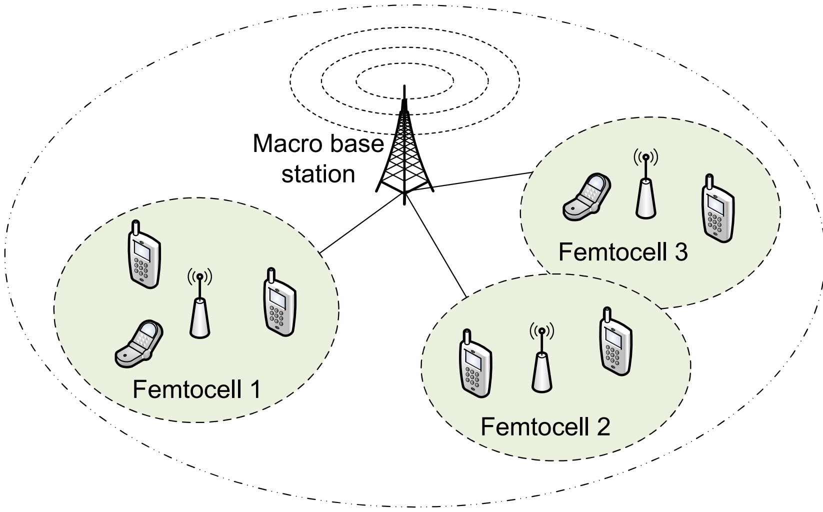


**Figure 1.** The femtocell network model.

many packets (layers), it is possible to allow users to decode the layers in any order to increase the flexibility of the system. However, in this paper, we assume in-sequence decoding for ease of presentation.

## 2.2. Problem Statement

For the SC and SIC scheme to work, the transmitting power for the data levels should be carefully determined, such that there is a sufficiently high SNR for the levels to be decodable at the receivers. It is also important to control the transmit powers of the BS's to reduce interference and leverage frequency reuse. Furthermore, the annual power bill is a large part of a mobile operator's costs [9]. 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 $\tilde{R}$ for each user. Recall that the data file is partitioned into equal-length packets. The target rate $\tilde{R}$ ensures that a packet can be transmitted within a time slot, for given modulation and channel coding schemes.

Define binary indicator $I_m^k$ as

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

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.

$$\text{minimize: } \sum_{m=0}^{M} \sum_{l=1}^{L} P_l^m \tag{2}$$

subject to:

$$B_m \log_2(1 + \gamma_m^k I_m^k) \geq \tilde{R} I_m^k, \forall\, k \tag{3}$$

$$\sum_{m=0}^{M} I_m^k = 1, \forall\, k \tag{4}$$

$$P_l^m \geq 0, \forall\, l, m, \tag{5}$$

where $P_l^m$ is the power of BS $m$ for transmitting the level $l$ packet; $\gamma_m^k$ is the SNR at user $k$ if it connects to BS $m$. Constraint Eq. (3) guarantees the minimum rate at each user. Constraint Eq. (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

$$\gamma_m^k = \frac{H_m^k P_l^m}{N_0 + H_m^k \sum_{i=l+1}^{L} P_i^m}, \tag{6}$$

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

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

The optimization variables in Problem OPT-Power consist of the binary variables $I_m^k$'s and the continuous

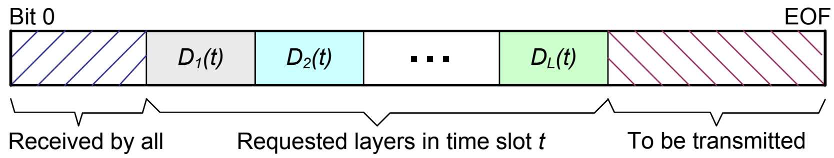


**Figure 2.** Superposition coding and successive interference cancellation.

variables $P_l^m$'s. It is an MINLP problem, which is NP-hard in general. In Section 3, we first reformulate the problem to a obtain a simpler form, and then develop effective algorithms for optimal and suboptimal solutions.

## 3. 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 consumption. The reformulation also leads to a simple heuristic algorithm. Finally, we introduce three more effective power allocation algorithms for three typical connection scenarios, respectively.

### 3.1. Problem Reformulation

Due to monotonic logarithm functions and the binary indicators $I_m^k$, constraint Eq. (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 $\Gamma_m^k = \Gamma_m =: 2^{\tilde{R}/B_m} - 1$ is the minimum SNR requirement at user $k$ that connects to BS $m$. To further simplify the problem, define

$$Q_l^m = \sum_{i=l}^{L} P_i^m, \tag{9}$$

with $Q_{L+1}^m = 0$. Then power $P_l^m$ is the difference as

$$P_l^m = Q_l^m - Q_{l+1}^m. \tag{10}$$

Problem OPT-Power can be reformulated as follows.

$$\text{minimize:} \quad \sum_{m=0}^{M} Q_1^m \tag{11}$$

subject to:

$$\frac{H_m^k (Q_l^m - Q_{l+1}^m)}{N_0 + H_m^k Q_{l+1}^m} I_m^k \geq \Gamma_m I_m^k, \quad \forall\, k \in \mathcal{U}_l, l = 1, \cdots, L \tag{12}$$

$$Q_l^m \geq Q_{l+1}^m, l = 1, \cdots, L \tag{13}$$

$$\sum_{m=0}^{M} I_m^k = 1, \forall\, k. \tag{14}$$

For $l \leq L$, constraint Eq. (12) can be rewritten as

$$Q_l^m I_m^k \geq \left[\frac{N_0 \Gamma_m}{H_m^k} + (1 + \Gamma_m) Q_{l+1}^m\right] I_m^k. \tag{15}$$

Let $\mathcal{U}_l^m$ be the subset of users connecting to BS $m$ in $\mathcal{U}_l$. Since $Q_l^m \geq Q_{l+1}^m$, Eq. (15) can be rewritten as

$$Q_l^m = \max\left\{Q_{l+1}^m, \max_{k \in \mathcal{U}_l^m}\left[\frac{N_0 \Gamma_m}{H_m^k} + (1 + \Gamma_m) Q_{l+1}^m\right]\right\}. \tag{16}$$

From Eq. (16), we define a function $Q_l^m = F_m(Q_{l+1}^m, \mathcal{U}_l^m)$ as

$$F_m(Q_{l+1}^m, \mathcal{U}_l^m) = \begin{cases} Q_{l+1}^m, & \mathcal{U}_l^m = \emptyset \\ \max_{k \in \mathcal{U}_l^m}\left\{\frac{N_0 \Gamma_m}{H_m^k} + (1 + \Gamma_m) Q_{l+1}^m\right\}, & \mathcal{U}_l^m \neq \emptyset. \end{cases} \tag{17}$$

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

$$\begin{aligned} & Q_1^m \\ = \; & F_m(Q_2^m, \mathcal{U}_1^m) \\ = \; & F_m(F_m(Q_3^m, \mathcal{U}_2^m), \mathcal{U}_1^m) \\ = \; & F_m(\cdots(F_m(Q_{L+1}^m, \mathcal{U}_L^m), \mathcal{U}_{L-1}^m), \cdots, \mathcal{U}_1^m) \\ = \; & F_m(\cdots(F_m(0, \mathcal{U}_L^m), \mathcal{U}_{L-1}^m), \cdots, \mathcal{U}_1^m). \end{aligned} \tag{18}$$

If none of the subsets $\mathcal{U}_l^m$ $(l = 1, \cdots, L)$ is empty, we can expand the above recursive term using Eq. (17). It follows that

$$Q_1^m = N_0 \Gamma_m \sum_{l=1}^{L} (1 + \Gamma_m)^{c_l^m} \max_{k \in \mathcal{U}_l^m}\left\{\frac{1}{H_m^k}\right\}, \tag{19}$$

where the exponent $c_l^m$ is defined as

$$\begin{cases} c_1^m = 0 \\ c_{l+1}^m = c_l^m + 1 \end{cases} \tag{20}$$

Otherwise, if a subset $\mathcal{U}_l^m = \emptyset$ for some $m$, we have that

$$Q_l^m = Q_{l+1}^m$$

$$\max_{k \in \mathcal{U}_l^m}\left\{\frac{1}{H_m^k}\right\} = \max_{k \in \emptyset}\left\{\frac{1}{H_m^k}\right\} = 0$$

and

$$c_l^m = c_{l-1}^m.$$

Therefore, Eq. (19) still holds true.

Finally, the objective function Eq. (11) can be rewritten as

$$\sum_{m=0}^{M} N_0 \Gamma_m \sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \max_{k \in \mathcal{U}_l^m} \left\{ \frac{1}{H_m^k} \right\}. \tag{21}$$

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.

## 3.2. Performance Bounds

The above reformulation and simplification allow us to derive upper and lower performance bounds for the total BS power consumption. First, we derive an upper bound for the objective function Eq. (11) by construction. Define a variable $\overline{G}_m$ as

$$\overline{G}_m = \max_{l \in \{1,\cdots,L\}} \max_{k \in \mathcal{U}_l^m} \left\{ \frac{\Gamma_m}{H_m^k} \right\}, \tag{22}$$

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

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

In Eq. (23), 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, Eq. (23) is an upper bound on the objective function Eq. (11).

Furthermore, by defining

$$\overline{G} = \max_{m \in \{0,\cdots,M\}} \left\{ \overline{G}_m \right\} \tag{24}$$

$$\overline{\Gamma} = \max_{m \in \{0,\cdots,M\}} \{\Gamma_m\}, \tag{25}$$

we obtain a looser upper bound from Eq. (23) as

$$\begin{aligned}
\sum_{m=0}^{M} Q_1^m &\le N_0 \overline{G} \sum_{m=0}^{M} [(1+\overline{\Gamma})^L - 1]/\overline{\Gamma} \\
&= N_0 (M+1) \overline{G} \left[ (1+\overline{\Gamma})^L - 1 \right] / \overline{\Gamma}.
\end{aligned} \tag{26}$$

The two upper bounds are summarized in the following theorem.

**Theorem 1.** Both Eqs. (23) and (26) are upper bounds on the objective function Eq. (11).

Next, we derive a lower bound for the objective function Eq. (11) also by construction. Define

$$\underline{G}^l = \min_{m \in \{1,\cdots,M\}} \left\{ \max_{k \in \mathcal{U}_l^m} \left\{ \frac{\Gamma_m}{H_m^k} \right\} \right\} \tag{27}$$

$$\underline{\Gamma} = \min_{m \in \{0,\cdots,M\}} \{\Gamma_m\}. \tag{28}$$

It follows that

$$\begin{aligned}
\sum_{m=0}^{M} Q_1^m &= N_0 \sum_{m=0}^{M} \sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \max_{k \in \mathcal{U}_l^m} \left\{ \frac{\Gamma_m}{H_m^k} \right\} \\
&\ge N_0 \sum_{m=0}^{M} \sum_{l=1}^{L} (1+\Gamma_m)^{c_l^m} \underline{G}^l \\
&\ge N_0 \sum_{l=1}^{L} \underline{G}^l \sum_{m=0}^{M} (1+\underline{\Gamma})^{c_l^m} \\
&\ge N_0 (M+1) \sum_{l=1}^{L} \underline{G}^l (1+\underline{\Gamma})^{\frac{\sum_{m=0}^{M} c_l^m}{M+1}} \\
&\ge N_0 (M+1) \sum_{l=1}^{L} \underline{G}^l (1+\underline{\Gamma})^{\frac{l-1}{M+1}}.
\end{aligned} \tag{29}$$

In Eq. (29), 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, Eq. (29) provides a lower bound for the objective function Eq. (11).

Similarly, by defining $\underline{G} = \min_{l \in \{1,\cdots,L\}} \left\{ \underline{G}^l \right\}$, we obtain a looser lower bound from Eq. (29) as

$$\begin{aligned}
\sum_{m=0}^{M} Q_1^m &\ge N_0 (M+1) \underline{G} \sum_{l=1}^{L} (1+\underline{\Gamma})^{\frac{l-1}{M+1}} \\
&= N_0 (M+1) \underline{G} \frac{(1+\underline{\Gamma})^{\frac{L}{M+1}} - 1}{(1+\underline{\Gamma})^{\frac{1}{M+1}} - 1}.
\end{aligned} \tag{30}$$

The two lower bounds are summarized in the following theorem.

**Theorem 2.** Both Eqs. (29) and (30) are lower bounds on the objective function Eq. (11).

In Fig. 3, we plot the lower and upper bounds for different system parameters. Specifically, we increase the number of femtocells $M$ from 1 to 5 and the number of levels $L$ from 2 to 6, and plot the bounds on the total

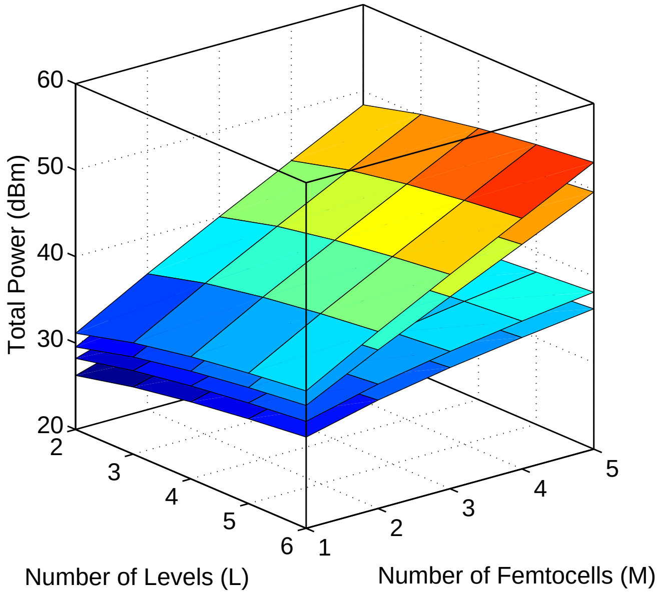


**Figure 3.** The upper and lower bounds for the total power consumption. The four surfaces in the plot are (from top to bottom): the looser upper bound, the tighter upper bound, the tighter lower bound, and the looser lower bound.

power consumption. The parameter *Gamma* ranges from 0.8 to 1.6 and $G$ varies from 900 to 1800, which are from our simulations. In Fig. 3, the four surfaces are the looser upper bound, the tighter upper bound, the tighter lower bound, and the looser lower bound from top to the bottom. It can be seen that the gap between the lower and upper bounds increases as more femtocells are deployed or more levels are adopted. The gap between the two tighter bounds achieves its minimum 1.3274 dBm when the number of levels is 2 and the number of femtocells is 1, which is quite tight and indicative of the global optimal solution.

## 3.3. A Simple Heuristic Scheme

The above reformulation leads to a greedy heuristic algorithm that solves OPT-Power with suboptimal solutions. With this heuristic scheme, 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 known. Starting with $Q_{L+1}^m = 0$, we can apply Eq. (16) iteratively to find the $Q_l^{m'}$'s, for all $l$. Finally, the transmit powers $P_l^m$ can be computed using Eq. (10). The pseudo code for the heuristic algorithm is presented in Algorithm 1.

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 consumption, as will be discussed in Section 3.4.

**Algorithm 1:** A Simple Heuristic Scheme

Each user chooses the BS with the best channel condition to connect to ;
Determine binary variables $I_m^k$ and subsets $\mathcal{U}_l^m$ for all $m$, $k$ and $l$ ;
**for** *m=0:M* **do**
  $Q_{L+1}^m = 0$ ;
  **for** *l=L:1* **do**
    Apply Eq. (16) to find $Q_l^m$ ;
    Compute transmit powers $P_l^m$ using Eq. (10) ;
  **end**
**end**

## 3.4. Power Allocation Algorithms

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

**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 Eq. (17), we can derive the optimal solution as

$$\begin{aligned} Q_l^{m*} &= (1+\Gamma_m)Q_{l+1}^{m*} + \max_{k\in\mathcal{U}_l^m}\left\{\frac{N_0\Gamma_m}{H_m^k}\right\}, \\ &= N_0\Gamma_m\sum_{i=l}^{L}(1+\Gamma_m)^{i-l}\max_{k\in\mathcal{U}_l^m}\left\{\frac{1}{H_m^k}\right\}, \\ & \qquad l = 1, 2, \cdots, L. \end{aligned} \tag{31}$$

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

$$P_l^{m'*} = \begin{cases} Q_l^{m*} - Q_{l+1}^{m*}, & m' = m, \forall\, l \\ 0, & m' \neq m, \forall\, l. \end{cases} \tag{32}$$

**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 Eq. (19), we find that the total power of BS $m$ can be significantly

**Algorithm 2:** 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** $l = 1 : L$ **do**
3     **if** $\Gamma_0(1+\Gamma_0)^{c_l^0} G_l^0 \le \Gamma_1(1+\Gamma_1)^{c_l^1} G_l^0$ **then**
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**
10 **end**
11 **for** $l = L : 1$ **do**
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**

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 Algorithm 2. 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 $\mathcal{O}(L)$.

**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.

$$\bigcup_{m=0}^{M} \mathcal{U}_l^m = \mathcal{U}_l \tag{33}$$

$$\mathcal{U}_l^m \bigcap \mathcal{U}_l^{m'} = \emptyset, \ \forall \ m' \neq m. \tag{34}$$

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.

$$\bigcup_{m=1}^{M} \mathcal{S}_l^m = \mathcal{S}_l^0 = \mathcal{U}_l \tag{35}$$

$$\mathcal{S}_l^m \bigcap \mathcal{S}_l^0 = \mathcal{S}_l^m, \ \forall \ m \neq 0 \tag{36}$$

$$\mathcal{S}_l^m \bigcap \mathcal{S}_l^{m'} = \emptyset, \ \forall \ m' \neq m \text{ and } m, m' \neq 0. \tag{37}$$

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 Algorithm 3. 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 $l$, $\Psi$ 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. $\Delta_l^m$ is the power of BS $m$ for transmitting the level $l$ data packet. In Steps 6–15, the MBS and FBS combination $\Psi$ is determined for transmitting the level $l$ packet, with the lowest power $\Delta_0$. In Steps 16–30, elements in $\mathcal{S}_l^m$ are assigned to $\mathcal{U}_l^m$ according to $\Psi$. 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 $\mathcal{O}(ML)$.

**Algorithm 3:** Power Allocation Algorithm for Case III

Initialize: $c_l^m = 0$ and $Q_{L+1}^m = 0$, for all $l, m$ ;
**for** $l = 1 : L$ **do**
  **for** $m = 0 : M$ **do**
    $\Delta_l^m = \Gamma_m (1+\Gamma_m)^{c_l^m} W_m(\mathcal{S}_l^m)$ ;
  **end**
  Set $\Omega = \{1, \cdots, M\}$ and $\Psi = \emptyset$ ;
  **while** $\Omega \neq \emptyset$ **do**
    $m' = \arg\min_{m \in \Omega} \Delta_l^m$ ;
    Compute $\Delta' = \Gamma_0 (1+\Gamma_0)^{c_l^0} W_0(\bigcup_{m \in \overline{\Psi \cup m'}} \mathcal{S}_l^m)$ ;
    **if** $(\sum_{m \in \Psi \cup m'} \Delta_l^m + \Delta') < \Delta_0$ **then**
      Add $m'$ to $\Psi$ ;
      $\Delta_0 = \sum_{m \in \Psi} \Delta_l^m + \Delta'$ ;
    **end**
    Remove $m'$ from $\Omega$ ;
  **end**
  **if** $\Psi = \emptyset$ **then**
    $\mathcal{U}_l^0 = \mathcal{S}_l^0$ ;
    $c_l^0 = c_l^0 + 1$ ;
    Set $\mathcal{U}_l^m = \emptyset$, for all $m \neq 0$ ;
  **else**
    $\mathcal{U}_l^0 = \bigcup_{m \in \overline{\Psi}} \mathcal{S}_l^m$ ;
    **if** $|\Psi| < M$ **then**
      $c_l^0 = c_l^0 + 1$ ;
    **end**
    **for** $m \in \Psi$ **do**
      $c_l^m = c_l^m + 1$ ;
      $\mathcal{U}_l^m = \mathcal{S}_l^m$ ;
    **end**
  **end**
**end**
**for** $l = L : 1$ **do**
  **for** $m = 0 : M$ **do**
    $Q_l^m = F_m(Q_{l+1}^m, \mathcal{U}_l^m)$ and $P_l^m = Q_l^m - Q_{l+1}^m$ ;
  **end**
**end**

## 4. Performance Evaluation

We evaluate the performance of the proposed power allocation algorithms using MATLAB™. Three scenarios corresponding to the three cases investigated in Section 3 are simulated:

- Case I: a single MBS;
- Case II: one MBS and one FBS; and
- Case III: one MBS and three FBS's.

Since we do not find a suitable and similar scheme in the literature, we compare the performance of the algorithms for different scenarios, and with the heuristic scheme and the upper/lower performance bounds. 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 $\tilde{R}$ is set to 2 Mbps. The channel gain from a base station to each user is exponentially distributed in each time slot.

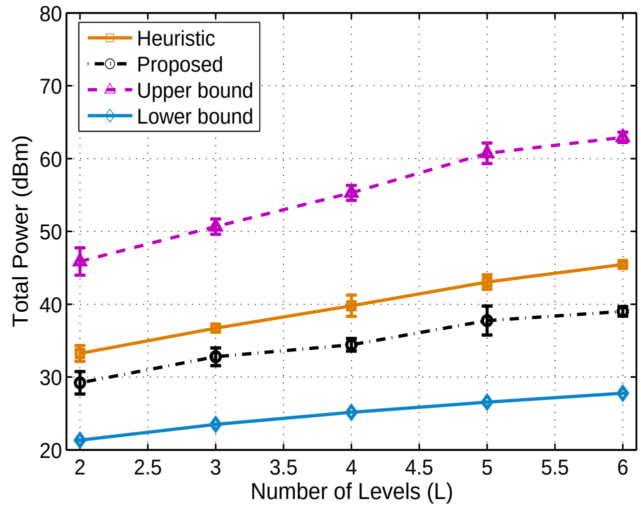


**Figure 5.** Total power vs. number of packet levels.

The interference footprints in the three dimensional space are plotted in Fig. 4. The height $B$ of the cylinders indicates the spectrum used by a BS, while the radius $r$ of the cross section 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. 5 and 7, we plot four curves, each obtained with: (i) the heuristic scheme described in Section 3.3; (ii) The proposed algorithm presented in Section 14; (iii) The upper bound; and (iv) the lower bound derived in Section 3.2. 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.

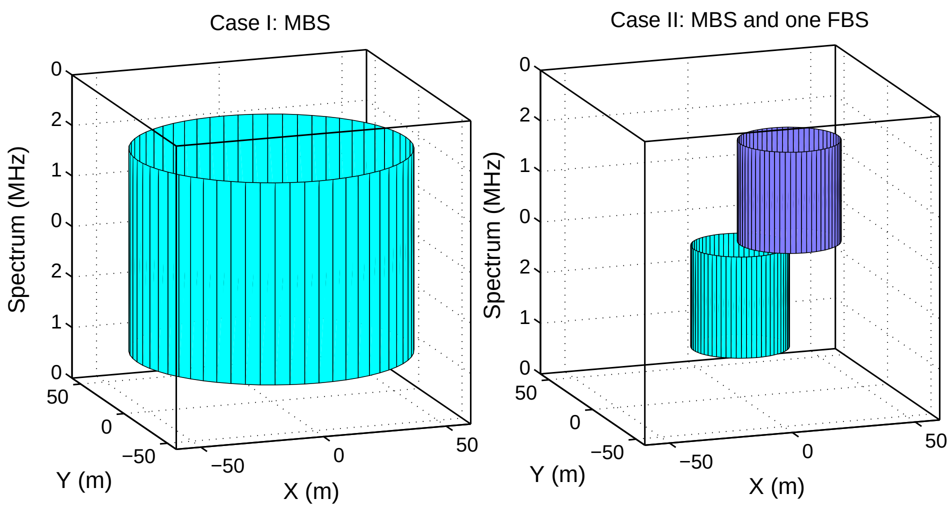


**Figure 4.** Case I vs. Case II: interference footprints.

In Fig. 5, 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. 6, we examine the impact of the number of femtocells, i.e., $M$, on the total power consumption. We increase the number of femtocells $M$ from 1 to 5 and plot the results in Fig. 6. As expected, a larger number of femtocells lead to a higher power consumption. However, the proposed scheme consumes considerable less power than the heuristic scheme. Up to 16.9648 dBm power can be saved by the proposed scheme when the number of femtocells is 1.

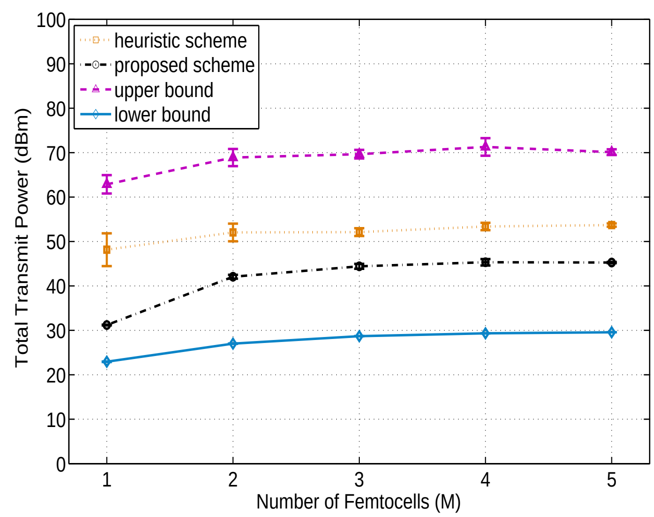


**Figure 6.** Total power vs. number of femtocells.

In Fig. 7, 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.

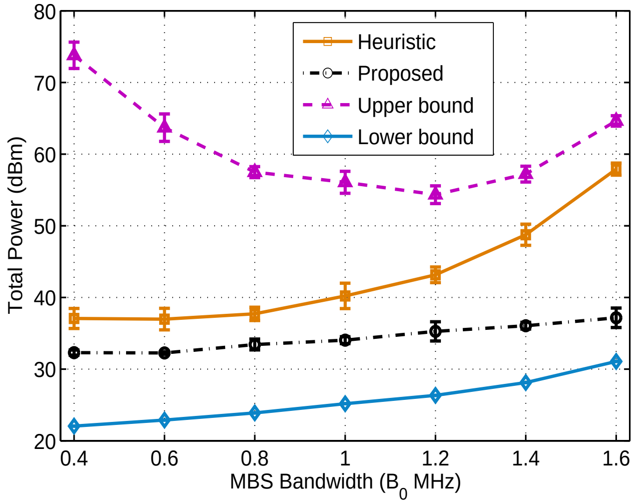


**Figure 7.** Total power vs. bandwidth of MBS.

## 5. 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 [3, 6, 17]. Since FBS's are distributedly located and are able to spatially reuse the same channel, considerable research efforts were made on interference analysis and mitigation [7, 18]. A distributed utility based SINR adaptation scheme was presented in [7] to alleviate cross-tire interference at the macrocell from co-channel femtocells. Lee, Oh and Lee [18] proposed a fractional frequency reuse scheme to mitigate inter-femtocell interference. In our prior work [11, 13], 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.

There are some recent work considering the potential collaborations between femtocells and macrocells. Instead of decoding the signals at the base stations, the work in [8] analyzes the outage rate of joint decoding the signals from macrocell and femtocell in the operator's network. Despite the theoretical benefit, this will make retransmission difficult in case of packet loss or error. In the work of FemtoHall [23], the backhaul networks of the femtocells are used to alleviated the bottleneck effect of the cellular backhaul network. In [28], the femtocell users serve as relays for the macrocell users to facilitate load balancing. In a recent work [15], the authors investigate the impact of access strategies for the femtocells, where spectrum resource is used as an incentive to encourage femtocells to serve more macrocell users. In [29], the cell association problem is studied and a handover algorithm is developed to reduce the number of unnecessary handovers using Bayesian estimation.

Cognitive femtocells have been investigated in a few recent papers, where cognitive radios are exploited [2, 11, 20, 21, 25, 26]. In [21], the authors develop a scheme that femtocells autonomously sense the radio resource usage of the Macrocell so as to mitigate interference. However the unavoidable inaccuracy in the sensing results is not considered. In [26], the authors study effective spectrum sharing among the femtocells assuming that the set of available channels are given and accurate. In a recent work [25], a network with one primary link and one secondary link is considered (although later extended to the case of more than one secondary users). The paper focuses on the scenario that the secondary user can sue cooperation to increase the primary user's data rate. In our recent work [11], CR is exploited to assist multi-user video streaming in femtocell networks. In [20], the problem of cell association is investigated to derive a green resolution, while CR is adopted for sharing spectrum between the MBS and FBS's. In [2], the radio resource and power management problem is investigated in the context of cognitive femtocell networks.

SIC has high potential of sending or receiving multiple signals concurrently, which improves the transmission efficiency. In [19], 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 [24]. Power control for SIC was comprehensively investigated and widely applied to code division multiple access (CDMA) systems [1, 4, 5, 14, 22]. Applying game theory, Jean and Jabbari proposed an uplink power control under SIC in direct sequence-CDMA networks [14]. In [22], 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 [5]. In [1, 4], 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 for achieving the design goals.

## 6. 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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