

Joint Spectrum and Power Allocation for Multi-node Cooperative Wireless Systems

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Joint Spectrum and Power Allocation for Multi-node Cooperative Wireless Systems

Xueqing Huang, *Student Member, IEEE*, and Nirwan Ansari, *Fellow, IEEE*

Abstract—Energy efficiency is a growing concern for wireless networks, not only due to the emerging traffic demand from smart devices, but also because of the dependence on the traditional unsustainable energy and the overall environmental concerns. The urgent call for reducing power consumption while meeting system requirements has motivated increasing research efforts on green radio. In this paper, we investigate a new joint spectrum and power allocation scheme for a cooperative downlink multi-user system using the frequency division multiple access scheme, in which arbitrary M base stations (BSs) coordinately allocate their resources to each user equipment (UE). With the assumption that multi-BS UE (user being served by multi-BS) would require the same amount of spectrum from these BSs, we conclude that when the number of multi-BS UEs is limited by $M - 1$, the resource allocation scheme can always guarantee the minimum overall transmit power consumption while meeting the throughput requirement of each UE and also each BS's power constraint. Then, to decide the clusters of multi-BS UEs and the clusters of individual-BS UEs (users being served by individual BSs), we propose a UE-BS association scheme and a complexity reduction scheme. Finally, a novel joint spectrum and power allocation algorithm is proposed to minimize the total power consumption. Simulation results are presented to verify the optimality of the derived schemes.

Index Terms—Joint spectrum and power allocation, cooperative transmission, frequency division multiple access, UE-BS association, complexity reduction.



1 INTRODUCTION

TO improve the system performance and make the best use of the system resource, cooperative transmissions have recently attracted much attention [1], [2]. The basic idea is to take advantage of the broadcast nature of wireless communications such that some nodes in wireless networks can help each other to transmit signals for better quality via spatial diversity or higher data rates through spatial multiplexing [3].

The next-generation cellular networks, including cloud radio access networks (C-RAN) and software defined wireless networks (SDN), have proposed to enable cooperative transmission through the base band unit pool [4] and the controller [5]. One typical technology that has already been adopted by 3GPP Long Term Evolution is coordinated multi-point (CoMP) transmission [6]. As illustrated in Fig. 1a, the adjacent outer cells and cell edge users can be considered as a new virtual cell (shaded area). This virtual cell is surrounded by multiple inner cells, has multiple base stations (BSs) serving as power sources, and works on the outer band (allocated by the fractional frequency reuse scheme [7]) or major subcarriers (allocated by the soft frequency reuse scheme [8]). The features of multiple power sources and shared spectrum have motivated the coordination transmission, which is considered as an effective tool to improve the coverage of high data rates and the cell-edge throughput.

In addition to the cellular networks with simultaneous multiple data transmissions, cooperative communications has been widely adopted in ad-hoc networks and cognitive networks [9], where cooperative sequential data transmissions play a major role. As illustrated in Fig. 1b, destination node (DN) combines the signal transmitted by source node (SN) in the first time slot and the forwarding signal transmitted by the relay node in the second time slot. Network coding based two-way relay schemes with decoding (decode-and-forward) and without decoding (amplify-and-forward, denoise-and-forward, compress-and-forward) are introduced to implement cooperative communications [10]. Although the capacity of the relay network and point-to-point cellular network are different, the inherent cooperative diversity of relay network can save energy by combining the signals received from different spatial paths and consecutive time slots [11]. Without loss of generality, we focus on the cellular network in this paper.

Capitalizing on the internal flexibility of FDMA/OFDMA in power loading across the frequency channels/subcarriers, and the external flexibility in multiple nodes serving as power sources, the resource allocation scheme for cooperative wireless systems can dynamically assign the limited resources (spectrum and power) to deliver the best quality of service to customers at the lowest cost; that is, the available resources are allocated to the user who can best exploit the resources according to the current channel state information (CSI). This multi-node multi-UE diversity gained from dynamic resource allocation improves the performance of cooperative wireless systems.

In cellular networks, a couple of research works on

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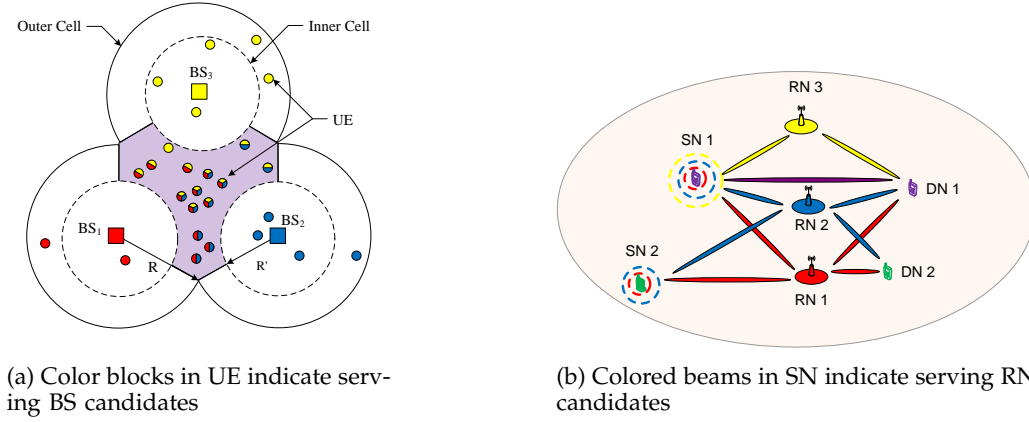


Fig. 1: Cooperative wireless system model.

optimal power allocation [12], [13] have been conducted to maximize the system throughput with power constraints. Kivanc *et al.* [14] investigated the subcarrier assignment problem to minimize the total power consumption while meeting data rate requirements. In ad-hoc networks and cognitive radio (CR) networks, to maximize the system capacity, Gong *et al.* [15] studied the optimal bandwidth and power allocation in a FDMA CR network. Chen and Wang [16] presented a joint subcarrier and power allocation algorithm for multiuser OFDMA CR systems. Using the Lambert-W function, Brah *et al.* [17] derived the closed form solution for subcarrier allocation in OFDMA based wireless mesh network. In wireless networks with hybrid energy supplies (an energy harvester and a constant energy source driven by a non-renewable resource), to minimize the on-grid energy consumption, Ng *et al.* [18] proposed the energy-efficient resource allocation for OFDMA systems. Han and Ansari [19], [20] developed an energy aware cell size adaptation algorithm. However, the power source of each UE is limited to only one BS in the above works, i.e., each UE can only associate with one BS at any time.

In relay networks, for a given total power budget/time duration of the SN and RN, Mo *et al.* [21] optimized the power/time variables such that the outage probability of the cooperative relaying protocol is minimized. Assuming equal-time allocation for the SN and RN, Zhang *et al.* [22] investigated joint subcarrier and power allocation schemes to optimize the sum rate of downlink multi-UE transmission. For the system with node-specific power constraint, Luo *et al.* [23] presented the joint water-filling (Jo-WF) power allocation algorithm to maximize the system throughput with two BSs jointly transmitting their constrained power to the multiple orthogonal sub-channels.

Note that although various resource allocation algorithms have been extensively investigated to maximize the efficiency of cooperative wireless systems, most existing works, similar to the ones mentioned above, considered the scenario with only one or two serving nodes, and there are rather limited studies on the scenario with multiple serving nodes. Zhu and Wang [24] studied

the downlink throughput maximization problem for the multi-UE distributed antenna system. With a system-specific power budget, the maximal ratio transmission (MRT) scheme is adopted to allocate power among multiple distributed antennas, where each antenna can be considered as a BS. Sadek *et al.* [25] minimized the symbol error rate (SER) of the system with multiple sequential RNs, where each RN coherently combines the signals received from all of the previous RNs in addition to the signal from SN. They proposed a power allocation scheme with a system-specific budget on the total transmission power. Cui *et al.* [26] proposed the joint minimization power consumption (JMPC) algorithm to minimize the total power consumption subject to the system-specific throughput requirement and BS-specific power budget.

For the scenario with multiple cooperative nodes and node-specific power budget, we further extend the JMPC algorithm, and analyze the joint spectrum and power allocation problem in this paper. That is, using a new approach with “power shifting” and “common candidate vector”, we aim to minimize the total transmission power consumption of the system while guaranteeing the UE-specific QoS requirement in terms of throughput.

The contributions of this paper include 1) we have proven the conjecture that for the system with arbitrary M cooperative BSs and N UEs, the minimum total power consumption can always be achieved when the number of *multi-BS UEs* (UEs that are powered by multi-BS) is limited by $M - 1$; 2) we have derived the UE-BS association scheme to determine the clusters of multi-BS UEs as well as the clusters of *individual-BS UEs* (UEs that are powered by individual BSs); 3) we have proposed a complexity reduction scheme to improve the efficiency of the joint spectrum and power allocation algorithm (JSPA).

The major features that distinguish our work from the previous state-of-the-art works with similar system scenarios are summarized in Table 1. Since JSPA does not require UEs to have the capability to be served by all of the BSs, it is applicable to any cooperative networks where mobile UEs can move out of the coverage of

certain BSs. Since JSPA is proven to be optimal, it outperforms the existing algorithms, and its low-complexity is desirable for the practical operation of the cooperative networks, such as the online resource allocation schemes which cope with mobile UEs.

TABLE 1: Comparison between JSPA and existing works

BS No.	Alg.	Maximum Multi-BS UE	Serving BS Candidates	OPT	CPX
2	MRT	N	2	Sub-opt	Low
	JMPC	1		Opt	High
	JSPA		Varying		Low
M	MRT	N	M	Sub-opt	Low
	JMPC	1			High
	JSPA	$M - 1$	Varying	Opt	Low

2 COORDINATED TRANSMISSION MODEL

Consider a cooperative downlink multi-user system, in which M BSs coordinately assign spectrum and allocate power to N users located in the coordinative zone, as depicted in Fig. 1a. Each user feeds back the instantaneous CSI to its corresponding BS via a feedback channel. Through the back-haul channels, which can be optical fiber or out of band microwave links, each BS has access to the data and control information (such as CSI) of associated users [27]. Note that when M or N is very large, acquirement of CSI and data information of each UE at each cooperative BS is very challenging for the back-haul links and feedback channels. Therefore, we assume BSs have partial access to control and data information, i.e., the data transmission of the user is dynamically coordinated only among those BSs who have gained access to this UE.

To simplify the mathematical derivation, we assume each BS has the same power constraint P_0 and share the same overall bandwidth B_0 . Since multiple access technologies based on frequency division allocate orthogonal spectrum among UEs to avoid interference, B_0 is divided into N distinct and nonoverlapping flat fading channels with various bandwidths, one for each UE. As compared with the co-channel separation method such as zero-forcing in [28], the orthogonal spectrum sharing method is not necessarily less efficient in terms of spectrum usage. This is due to the fact that the cell edge users are highly likely to be in the low SINR region caused by inter-cell interference. In addition, for the central area of each cell, they can all utilize the same spectrum resources, such as inner band and minor subcarriers in [7], [8], [29]. However, to ensure tractability of our analysis, the joint resource allocation of UEs located in the coordinated zone and central area is left for our future work.

Furthermore, if UE j is a multi-BS UE, the serving BSs would allocate the same channel to this UE, so that without shifting frequency, UE j can optimally receive

its information from the assigned channel with maximal-ratio combining (MRC) [30], [31]. Thus, the achievable throughput of the j -th user given by the AWGN Shannon Capacity (sum rate) is expressed as

$$R_j = B_j \log_2 \left(1 + \frac{\sum_{i=1}^M P_{i,j} |H_{i,j}|^2}{\sigma_j^2} \right) \quad (1)$$

where B_j is the bandwidth assigned to the j -th channel, $\sigma_j^2 = N_0 B_j$ represents the power of additive white Gaussian noise at the j -th channel, $P_{i,j}$ denotes the allocated transmission power from BS i to the j -th channel, and $H_{i,j}$ denotes the corresponding channel gain between BS i and the j -th channel.

The goal here is to minimize the total transmission power of the system while meeting each user's throughput requirement R_j^S as well as each BS's power and spectrum constraints. The circuit energy consumption associated with data reception in the UE side is generally modeled as a constant, especially with given data rate and no frequency shifting in each UE [32]. For the circuit energy consumption incurred by data transmission at the BS side, we also adopt the simplified constant model [33]; this is due to the fact that in addition to the UEs in the coordinated zone, each BS has to serve the UEs located in the central area of each cell, and so BSs are likely to remain active. As a result, only the transmission power of all of the BSs is considered in the following problem formulation.

$$\begin{aligned} P_{\text{overall}} &= \min \sum_{i=1}^M \sum_{j=1}^N P_{i,j} \\ \text{s.t. } R_j &= R_j^S, j \in \mathcal{N} \\ \sum_{j=1}^N P_{i,j} &\leq P_0, i \in \mathcal{M} \\ \sum_{j=1}^N B_j &= B_0 \end{aligned} \quad (2)$$

where $\mathcal{M} = \{1, \dots, M\}$, $\mathcal{N} = \{1, \dots, N\}$. Owing to the limitation in the feedback/back-haul channels or severe channel attenuation, if UE j cannot be associated with BS i or has moved out of the coverage of BS i , then we set $H_{i,j} = 0$.

For the sake of mathematical abbreviation, we denote $\gamma_{i,j} = (P_0 |H_{i,j}|^2) / (N_0 B_0)$, $x_{i,j} = P_{i,j} / P_0$ and $y_j = B_j / B_0$. Note that $\gamma_{i,j}$ is the signal to noise ratio (SNR) associated with BS i over the total bandwidth B_0 when the entire power P_0 is allocated to the j -th UE. $x_{i,j}$ and $y_{i,j}$ represent the power and bandwidth allocation ratio, and $R_j^S / B_0 = R'_j$. Since the logarithm is monotonically increasing, the objective function (2) combined with the

constraints can be described as follows:

$$\begin{aligned}
Z &= \min_{\{\mathbf{X}, \mathbf{Y}\}} \sum_{i=1}^M \sum_{j=1}^N x_{i,j} \\
s.t. \quad &\sum_{i=1}^M \gamma_{i,j} x_{i,j} = (2^{R_j^t/y_j} - 1)y_j, \quad j \in \mathcal{N} \\
&\sum_{j=1}^N x_{i,j} \leq 1, \quad i \in \mathcal{M} \\
&\sum_{j=1}^N y_j = 1
\end{aligned} \tag{3}$$

where $\mathbf{X} = \{x_{i,j} | i \in \mathcal{M}; j \in \mathcal{N}\}$, $\mathbf{Y} = \{y_j | j \in \mathcal{N}\}$, and $Z = P_{\text{overall}}/P_0 \leq M$ represents the total power consumption ratio.

3 PROBLEM ANALYSIS

As discussed in [26], finding the global optimal solution of the power allocation problem is very complicated. Solving (3) is even more challenging due to the non-convexity of the joint optimization of spectrum and power. In order to achieve the minimum power consumption, we first decouple the power allocation problem from the spectrum allocation problem.

3.1 Power allocation scheme

The main result of this paper is the number of multi-BS UEs in the optimal solution is limited by $M-1$, as stated in the following Lemma.

Lemma 1: For any spectrum allocation scheme \mathbf{Y} , there exists an optimal power allocation with at least $(M-1)(N-1)$ elements of \mathbf{X} being zero.

The proof of Lemma 1 is provided in Appendix A. The observation presented in Lemma 1 simplifies the joint spectrum and power allocation problem greatly, because 1) the power allocation is decoupled from the spectrum allocation, which enables versatile access technologies, such as FDMA or OFDMA system; 2) the number of BS-UE links in the system, i.e., the number of non-zero elements in \mathbf{X} , is limited within the range of $[N, N+M-1]$.

Remark 1: Define the SNR ratio between (BS i , UE j) link and (BS i' , UE j) link as

$$\gamma_{i,i'}^j = \frac{\gamma_{i,j}}{\gamma_{i',j}} \tag{4}$$

According to the *power shifting argument* in Appendix A, if $\gamma_{i,i'}^j$ allows a feasible power shifting that will decrease the total power consumption, then the corresponding power allocation is not optimal. So, power shifting argument can be used as an initial assessment to determine whether UE j should be associated with BS i , i' or both, and we will elaborate this in the next section.

3.2 UE-BS association scheme

To satisfy the QoS requirements, each user j should be associated with at least one BS i such that $x_{i,j}y_j > 0$. Since the number of non-zero elements in \mathbf{X} is limited (Lemma 1), the majority of UEs will be associated with

one BS only. According to the channel conditions, we will address the UE-BS association problem such that the complexity of finding the zero elements is further decreased.

Suppose there is no power limit for each BS, to minimize the power consumption of the system, the intuitive association scheme for each UE is to find the BS with the best channel condition. With this scheme, UE j will be powered by BS i only, where

$$i = \arg \max_{k \in \{1, 2, \dots, M\}} \{\gamma_{k,j}\} \tag{5}$$

So, UEs will be divided into M clusters denoted by *initial disjoint clusters* $\{J_i^0 | i \in \mathcal{M}\}$, where the i -th cluster, J_i^0 , consists of UEs, which prefer to be powered by BS i .

With the introduction of BS-specific power budget, BS i may not be able to power all of the UEs in cluster i , and other BSs will provide power coordination. Let $J_i^{i'}$ be the cluster consisting of UEs that 1) belong to J_i^0 , and 2) are powered by BS i' (partially or being taken over completely). Then, *new disjoint clusters* $\{J_i | i \in \mathcal{M}\}$ will be formed, where J_i consists of UEs that are powered by BS i only.

Remark 2: Since $J_i^{i'} \neq \Phi$ implies there is power shortage in BS i , $J_i^{i'} = \Phi$. Let $\overline{J_i^{i'}} = J_i^0 \setminus J_i^{i'}$ be the UE cluster which consists of UEs that are not taken over by BS i' . If $\bigcup_{i' \in \mathcal{M} \setminus i} \overline{J_i^{i'}} \subset J_i^0$, then BS i would not take UEs from any other BSs, i.e., $\bigcup_{i' \in \mathcal{M} \setminus i} J_i^{i'} = \Phi$, so $J_i = \bigcap_{i' \in \mathcal{M} \setminus i} \overline{J_i^{i'}}$.

Since the stability of clusters depends on the SNR ratio $\gamma_{i,i'}^j$ in (4), a *common candidate (CC) vector* \mathbf{J}^{CC} can be defined for the disjoint clusters

$$\mathbf{J}^{\text{CC}} = \begin{bmatrix} j_{1,2}, & j_{1,3}, & \cdots & j_{1,M}, \\ & j_{2,3}, & \cdots & j_{2,M}, \\ & & \ddots & \vdots \\ & & & j_{M-1,M} \end{bmatrix}$$

where each element $j_{i,i'}$ is the multi-BS UE candidate that is commonly powered by BS i and i' .

For any $i \in \{1, \dots, M-1\}$ and $i' \in \{i+1, \dots, M\}$, we require $j_{i,i'}$ in \mathbf{J}^{CC} to satisfy the following inequality

$$\min_{j \in J_i} \gamma_{i,i'}^j \geq \gamma_{i,i'}^{j_{i,i'}} > \max_{j \in J_{i'}} \gamma_{i,i'}^j \tag{6}$$

where for the initial cluster J_i^0 and $J_{i'}^0$, the corresponding $j_{i,i'}$ satisfies $\gamma_{i,i'}^{j_{i,i'}} \geq 1 > \gamma_{i,i'}^{1+j_{i,i'}}$.

Lemma 2: To minimize the power consumption, the CC vector which satisfies (6) always exists for the optimal clusters $\{J_i | i \in \mathcal{M}\}$.

The proof of Lemma 2 is provided in Appendix B. A very important point to be noticed from Lemma 2 is that multi-BS UEs are all in \mathbf{J}^{CC} because at most one UE will be associated with both BS i and BS i' . So

$$|\text{UNI}(\mathbf{J}^{\text{CC}})| \leq M-1$$

where $\text{UNI}(\bullet)$ consists of unique elements in \bullet .

Let J_i^{mul} be the multi-BS UE candidates that are simultaneously powered by BS i and other BSs, Then, we will have

$$J_i^{mul} = \left(\bigcup_{i'=i+1}^M J_{i',i} \bigcup_{i'=1}^{i-1} J_{i',i} \right) \setminus \left(\bigcup_{i'=1}^M J_{i'} \right) \quad (7)$$

$$\begin{cases} x_{i,j} = (2^{R'_j/y_j} - 1)y_j/\gamma_{i,j}, & j \in J_i \\ x_{i,j} = 0, & j \notin J_i \cup J_i^{mul} \end{cases} \quad (8)$$

As we can see, by revealing the relationship between J_i and J^{CC} , Lemma 2 can further differentiate the non-zero and zero variables of \mathbf{X} .

3.3 Complexity reduction scheme

Instead of iteratively solving (3) for every J^{CC} that satisfies (6), we try to find the possible optimal J^{CC} by considering the model of a 2-BS system, which can be used as the reference for the more complicated cooperative system involving three or more BSs.

For the initial disjoint clusters, suppose we relax the power constraint for BS i_1 and set the power limit of the other BS i_2 , $\{i_1, i_2\} = \{1, 2\}$, (3) becomes:

$$\begin{aligned} Z = \min & \sum_{j \in J_1^0} \frac{2^{R'_j} - 1}{\gamma_{1,j}} y_j + \sum_{j \in J_2^0} \frac{2^{R'_j} - 1}{\gamma_{2,j}} y_j \\ \text{s.t.} & \sum_{j \in J_{i_1}^0} (2^{R'_j/y_j} - 1)y_j/\gamma_{i_1,j} \leq +\infty \\ & \sum_{j \in J_{i_2}^0} (2^{R'_j/y_j} - 1)y_j/\gamma_{i_2,j} \leq 1 \\ & \sum_{j=1}^N y_j = 1 \end{aligned} \quad (9)$$

where $x_{i,j} = 0$ if $j \notin J_i^0$, and $x_{i,j}$ is given in (8) if $j \in J_i^0$.

As we can see, (9) is convex over \mathbf{Y} . By Lagrange dual function, we can derive the closed form solution expressed in the Lambert-W function [17], or utilize various algorithms designed for the convex problem to approach the optimal solution [34].

As shown in Fig. 2, the relaxed solutions can be represented in the two dimensional coordinates $S_i = (\sum_{j \in J_1^0} x_{1,j}, \sum_{j \in J_2^0} x_{2,j})$, where S_i is the solution to (9) with BS i having no power budget. $S_i > (1, 1)$ means the power consumption of BS i is greater than 1, i.e., S_i is located outside of the square region bound by $(1, 1)$. $S_i \leq (1, 1)$ implies S_i is located within the region bound by $(1, 1)$.

Lemma 3: Suppose UEs are sorted in the descending order of $\gamma_{1,2}^j$, $J^{CC} = [j_{1,2}]$.

1) If $S_1 = S_2$, then S_i is the optimal solution.

2) If $S_1 > (1, 1)$, then there exists $j'_1 \in J_1^0$ such that $\sum_{j=1}^{j'_1-1} x_{1,j} \leq 1$, $\sum_{j=1}^{j'_1} x_{1,j} > 1$, then $j_{1,2} \geq j'_1$.

3) If $S_2 > (1, 1)$, then there exists $j'_2 \in J_2^0$ such that $\sum_{j=j'_2+1}^N x_{2,j} \leq 1$, $\sum_{j=j'_2}^N x_{2,j} > 1$, then $j_{1,2} \leq j'_2$.

The proof of Lemma 3 is provided in Appendix C. By relaxing the power constraint of a BS, Lemma 3 can limit the range of $j_{1,2}$, so that the complexity of finding the optimal solution is much lower than iterating through every possible J^{CC} .

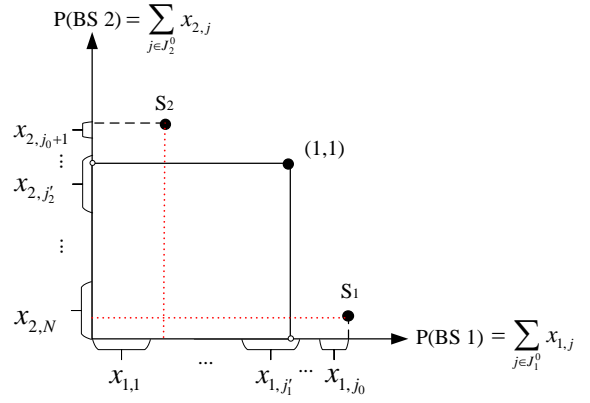


Fig. 2: Coordination with relaxed power constraint.

Remark 3: For any disjoint clusters $\{J_i | i \in \mathcal{M} \setminus \{i_1, i_2\}\}$ with $M \geq 3$, we can limit the range of j_{i_1, i_2} by using Lemma 3. The details of how to apply Lemma 3 are provided in the next section.

4 JOINT SPECTRUM AND POWER ALLOCATION ALGORITHM

Since $J_i^0 \subseteq J_i$ implies BS i may provide power coordination to other BSs, $M - \sum_{i=1}^M 1\{J_i^0 \subseteq J_i\}$ BSs will receive power coordination, where $1\{\bullet\} = 0$ if \bullet is false and 1 otherwise. So, for any $\{J_i, J_i^{mul} | i \in \mathcal{M}\}$ which satisfies Lemma 2, the objective function in (3) can be

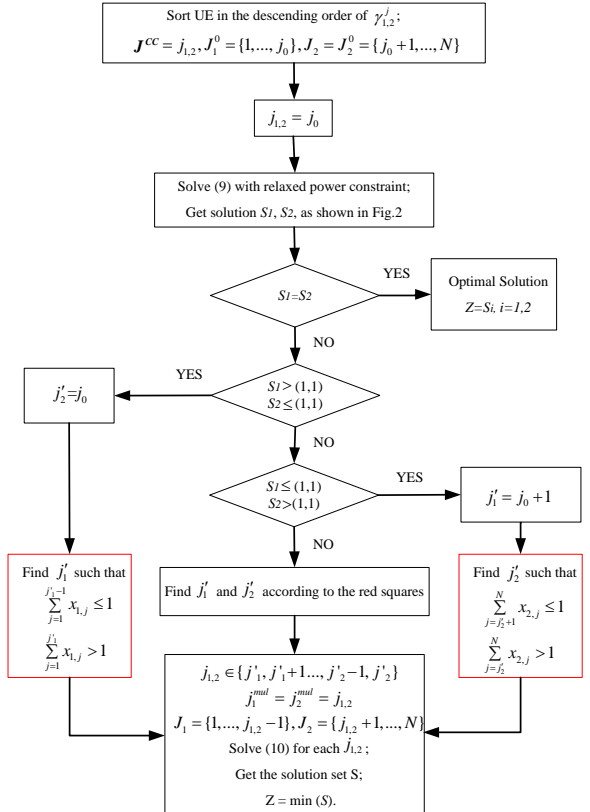


Fig. 3: JSPA algorithm, $M = 2$.

transformed into

$$\begin{aligned}
\min & \sum_{i=1}^M \left(\sum_{j \in J_i} \frac{R'_j}{(2^{y_j})} y_j + \sum_{j \in J_i^{mul}} x_{i,j} \right) 1\{J_i^0 \subseteq J_i\} + \\
& M - \sum_{i=1}^M 1\{J_i^0 \subseteq J_i\} \\
\text{s.t.} & \sum_{j \in J_i} \frac{R'_j}{(2^{y_j})} y_j + \sum_{j \in J_i^{mul}} x_{i,j} \leq 1, \quad i \in \mathcal{M} \\
& \sum_{i=1}^M \gamma_{i,j} x_{i,j} = (2^{R'_j/y_j} - 1) y_j, \quad j \in \bigcup_{i=1}^M J_i^{mul} \\
& \sum_{j=1}^N y_j = 1
\end{aligned} \tag{10}$$

where $x_{i,j}$ is given in (8), and if $1\{J_i^0 \subseteq J_i\} = 0$, the first constraint is satisfied with equality, i.e., $\sum_{j \in J_i} (2^{R'_j/y_j} - 1) y_j / \gamma_{i,j} + \sum_{j \in J_i^{mul}} x_{i,j} = 1$.

Based on Lemmas 1-3, we first present the joint spectrum and power allocation (JSPA) algorithm with $M = 2$. Similar to (9), for each $j_{1,2}$ in Fig. 3, (10) is also a convex optimization problem with $N+2$ variables $\{\mathbf{Y}, x_{1,j_{1,2}}, x_{2,j_{1,2}}\}$. With arbitrary M , the two procedures to achieve the optimal resource allocation are given in Alg. 1 and Alg. 2, where Alg. 1 is used to find the multi-BS UE candidates that satisfy Lemma 2, and Alg. 2 will iterate the output candidates that satisfy Lemma 3 until the corresponding optimal UE-BS association scheme that minimizes the overall power consumption is found.

Algorithm 1 JSPA algorithm: UE-BS association

```

1: for  $\mathcal{J}^{CC}$  with  $|\text{UNI}(\mathcal{J}^{CC})| \leq M - 1$  do
2:    $\mathcal{M} = \{1, \dots, M\}, \mathcal{N} = \{1, \dots, N\}$ 
3:   According to (5), get  $J_i^0, i \in \mathcal{M}, j \in \mathcal{N}$ 
4:    $\overline{J}_i^{i'} = J_i^0, i \in \mathcal{M}, i' \in \mathcal{M} \setminus i$ 
5:    $J_i, J_i^{mul} = \Phi, i \in \mathcal{M}$ 
6:   while  $\bigcup_{i \in \mathcal{M}} J_i \cup_{i \in \mathcal{M}} J_i^{mul} \neq \mathcal{N}$  do
7:      $\mathcal{N} \leftarrow \mathcal{N} \setminus \bigcup_{i \in \mathcal{M}} J_i$ 
8:      $\mathcal{M} \leftarrow \mathcal{M} \setminus \{i \in \mathcal{M} : \bigcup_{i' \in \mathcal{M} \setminus i} \overline{J}_i^{i'} \subset J_i^0\}$ 
9:     Update  $J_i^0, i \in \mathcal{M}, j \in \mathcal{N}$ 
10:    for  $i \in \mathcal{M}$  do
11:       $\mathcal{M}' = \{1, \dots, M\} \setminus i$ 
12:       $\overline{J}_i^{i'} = \{j \in J_i^0 : \gamma_{i,i'}^j > \gamma_{i,i'}^{j_{i,i'}}\}, i' \in \mathcal{M}'$ 
13:       $J_i \leftarrow J_i \cup \{\bigcap_{i \in \mathcal{M}'} \overline{J}_i^{i'}\}$ 
14:    end for
15:    According to (7), get  $J_i^{mul}, i \in \mathcal{M}, j \in \mathcal{N}$ 
16:  end while
17:  return  $\{\mathcal{J}^{CC}, J_i, J_i^{mul} | i \in \{1, \dots, M\}\}$ 
18: end for

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5 SIMULATION RESULTS

We assume that 20 independent and identically distributed (i.i.d.) Rayleigh-faded users are uniformly located within the shaded zone (see Fig. 1). R is 1000

Algorithm 2 JSPA algorithm: Complexity reduction

```

1:  $Z = M$ 
2: for  $i_1, i_2 \in \{1, \dots, M\}, i_2 > i_1$  do
3:    $\mathcal{M} \leftarrow \{1, \dots, M\} \setminus \{i_1, i_2\}$ 
4:   for  $\{J_i, J_i^{mul} | i \in \mathcal{M}\}$  returned by Alg. 1 do
5:      $\mathcal{N} \leftarrow \{1, \dots, N\} \setminus \{\bigcup_{i \in \mathcal{M}} J_i \cup_{i \in \mathcal{M}} J_i^{mul}\}$ 
6:     Sort UE in the descending order of  $\gamma_{i_1, i_2}^j$ 
7:     Update  $J_i^0, i \in \{i_1, i_2\}, j \in \mathcal{N}$ 
8:     In (10),  $J_i \leftarrow J_i^0, i \in \{i_1, i_2\}$ 
9:     Keep power budgets of BSs other than  $i_1/i_2$ 
10:    Get the relaxed solutions to (10):  $S_{i_1}/S_{i_2}$ 
11:    if  $S_{i_1} > (1, 1), S_{i_2} \leq (1, 1)$  then
12:      Get  $j'_{i_1}$  according to Lemma 3
13:       $j'_{i_2} = \max_{j \in J_{i_1}^0} \{j\}$ 
14:    else if  $S_{i_2} > (1, 1), S_{i_1} \leq (1, 1)$  then
15:      Get  $j'_{i_2}$  according to Lemma 3
16:       $j'_{i_1} = \max_{j \in J_{i_2}^0} \{j\} + 1$ 
17:    else if  $S_{i_1} > (1, 1), S_{i_2} > (1, 1)$  then
18:      Get  $j'_{i_1}, j'_{i_2}$  according to Lemma 3
19:    else if  $S_{i_1} \leq (1, 1), S_{i_2} \leq (1, 1)$  then
20:       $j'_{i_1} = j'_{i_2} = \max_{j \in J_{i_1}^0} \{j\}$ 
21:    end if
22:    for  $\{J_i, J_i^{mul}\}$  returned by Alg. 1 do
23:      if  $j_{i_1, i_2} \in \{j'_{i_1}, \dots, j'_{i_2}\}$  then
24:        Get the solution to (10):  $S$ 
25:         $Z \leftarrow \min\{Z, S\}$ 
26:      end if
27:    end for
28:  end for
29: end for
30: return  $Z$ 

```

m and the inner cell radius R' is 600 m. The distance-dependent path loss model is $L(d) = 128.1 + 37.6 \lg(d)$ dB, d in km, and $N_0 = -174$ dBm/Hz. For the sake of simplicity, we assume $B_0 = 1$, and each BS's power constraint is $P_0 = 1$.

The performances of the proposed JSPA algorithm and JMPC algorithm in [26] are averaged over 1,000 independent snapshots by Monte-Carlo simulation. The throughput requirement of each UE is defined as

$$R_j = \epsilon R_j^0, \epsilon > 0 \tag{11}$$

where R_j^0 is generated according to (1), with all of the N users being assigned equal spectrum and power (ESP) from each BS.

5.1 Two-node system

As pointed out in Table 1, for $M = 2$, both JSPA and JMPC are optimal in the sense of power allocation. For easy comparison, we assume the system-specific throughput requirement of JMPC is divided among all of the UEs, i.e., UE-specific R_j^S in (11). Then, as we can see in Fig.4, JSPA outperforms JMPC in the total power consumption. The reason is that JSPA supports

flexible spectrum allocation, while JMPC adopts equal bandwidth allocation for all UEs.

Fig. 5 indicates that with $\epsilon > 1$, there will be loss, i.e., the system fails to support all of the N users' throughput requirements with its maximum power and spectrum resources. Apparently, the loss rate must be zero with $\epsilon \leq 1$ and the loss rate will increase with ϵ . Since JSPA always consumes less or equal power, the loss rate is smaller accordingly.

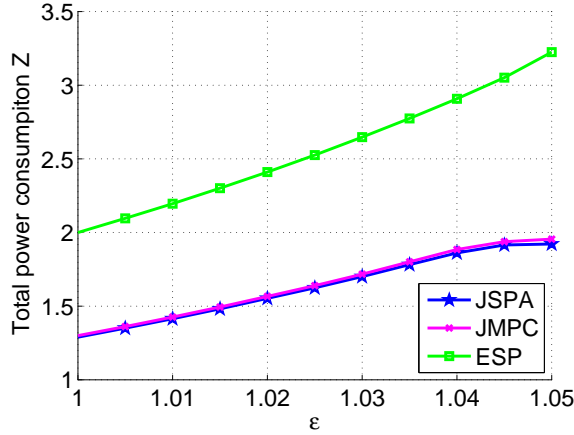


Fig. 4: Total power consumption of the 2-BS cooperative system.

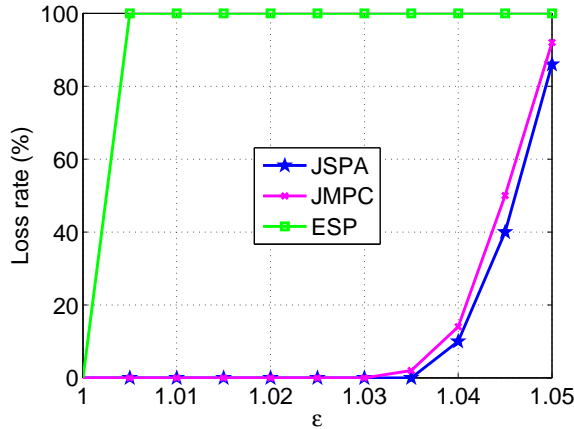


Fig. 5: Loss rate of the 2-BS cooperative system.

5.2 Multi-node system

To verify the point that for $M \geq 3$, JSPA is optimal while JMPC is sub-optimal in the sense of power allocation, we assume instead of UE-specific throughput requirement and spectrum allocation, JSPA requires UE-common bandwidth allocation and system-specific throughput requirement (sum of R_j in (11)).

As we can see in Figs. 6 and 7, JSPA always achieves the best performance, both in total power consumption and the loss rate, even when it does not enable flexible spectrum allocation. The gain will increase with the randomness of R_j rather than with the simultaneous

increase/decrease with bigger/smaller ϵ . The randomness make it less likely for one BS to exceed the power limit, when it provides spectrum or power to help the overloaded BS. Since JSPA and JMPC are compared in the same environment, we can conclude that under the perfect coordinated transmission between the multiple BSs, the proposed JSPA algorithm provides a significant reduction in the power consumption.

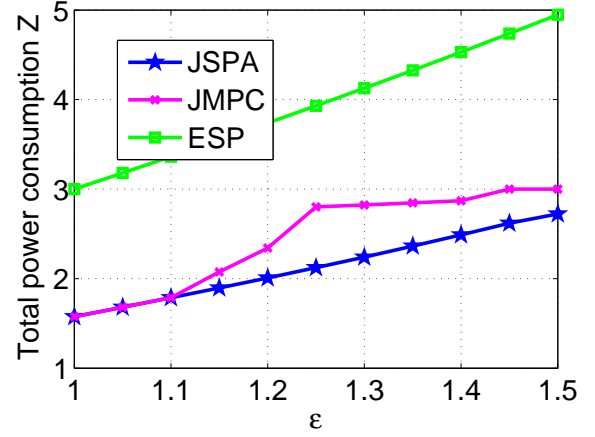


Fig. 6: Total power consumption of the 3-BS cooperative system.

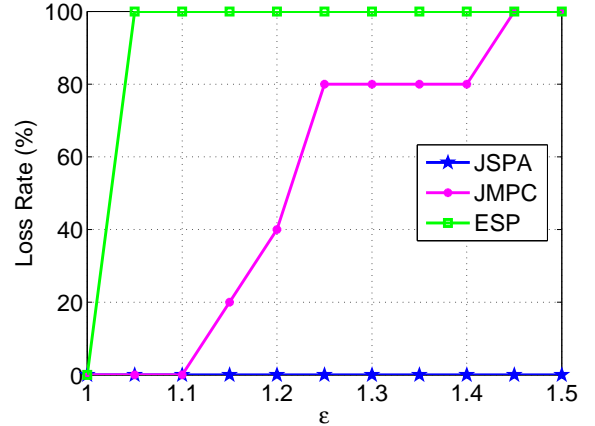


Fig. 7: Loss rate of the 3-BS cooperative system.

6 CONCLUSION

In this paper, we have investigated the joint spectrum and power allocation problem in minimizing the overall transmit power consumption while meeting the throughput requirements of each UE and each BS's power constraint for a cooperative downlink multi-user system. We have shown analytically that the number of multi-BS UE should be limited by the number of BSs. Moreover, we have also proposed the UE-BS association scheme and the corresponding complexity reduction scheme, which determines the serving BSs for each UE based on channel conditions and the constraints in the optimization problem. Finally, a novel joint spectrum

and power allocation algorithm, proven to yield the minimum total power consumption, is proposed. In the future, the capacity of the feedback/back-haul channel, the resource allocation scheme for the users located in the non-coordinated zone, and more sophisticated circuit energy consumption model of both BSs and UEs can be taken into consideration in which case the theoretical results can be directly applied to the realistic wireless communication system. Meanwhile, although the system model is based on the downlink cellular network, the derived results are applicable for various networks with cooperative features: multiple power sources and shared spectrum.

APPENDIX A PROOF OF LEMMA 1

First, we will prove that Lemma 1 is true for $M = 2$. Then, mathematical induction is used to prove the scenario for $M \geq 3$.

A.1 $M = 2$

Since all of the N users need power, either from BS 1, BS 2, or both, then at least N elements of \mathbf{X} are non-zero. To prove Lemma 1, we need to prove that the minimum power consumption can be guaranteed when at most one of the N users is served by two BSs simultaneously.

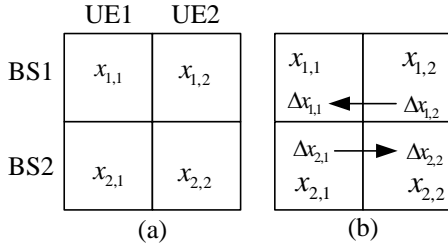


Fig. 8: Power shift in the 2-BS cooperative wireless system.

We use reductio ad absurdum here. Suppose in the optimal solution $\{\mathbf{X}, \mathbf{Y}\}$, both UE 1 and UE 2 are powered by BS 1 and BS 2, i.e., $x_{i,j} > 0$, ($i, j = 1, 2$). Then, any power shift $\Delta x_{i,j} \neq 0$, ($i, j = 1, 2$) in Fig. 8 (b) will result in higher total power consumption.

$$\begin{aligned} x'_{1,1} &= x_{1,1} + \Delta x_{1,1}, x'_{1,2} = x_{1,2} - \Delta x_{1,2} \\ x'_{2,1} &= x_{2,1} - \Delta x_{2,1}, x'_{2,2} = x_{2,2} + \Delta x_{2,2} \end{aligned}$$

To guarantee the throughput requirement, $\sum_{i=1}^M \gamma_{i,j} x_{i,j}$ should remain the same after the power shift, which yields

$$\begin{aligned} \gamma_{1,1} \Delta x_{1,1} - \gamma_{2,1} \Delta x_{2,1} &= 0 \\ \gamma_{2,2} \Delta x_{2,2} - \gamma_{1,2} \Delta x_{1,2} &= 0 \end{aligned}$$

If $\gamma_{1,1} \gamma_{2,2} - \gamma_{1,2} \gamma_{2,1} \geq 0$, there always exists a power shift to ensure $\Delta x_{1,2} + \Delta x_{2,1} - \Delta x_{1,1} - \Delta x_{2,2} \geq 0$, where

$$\begin{cases} \Delta x_{2,1} \geq \Delta x_{2,2} \geq 0, \Delta x_{1,1} = \Delta x_{1,2} \geq 0 \\ \Delta x_{1,2} \geq \Delta x_{1,1} \geq 0, \Delta x_{2,1} = \Delta x_{2,2} \geq 0 \end{cases}$$

Similarly, for $\gamma_{1,1} \gamma_{2,2} - \gamma_{1,2} \gamma_{2,1} \leq 0$, the following $\Delta x_{i,j}$ is always feasible such that the total power consumption will decrease after the power shifting.

$$\begin{cases} \Delta x_{2,2} \leq \Delta x_{2,1} \leq 0, \Delta x_{1,1} = \Delta x_{1,2} \leq 0 \\ \Delta x_{1,1} \leq \Delta x_{1,2} \leq 0, \Delta x_{2,1} = \Delta x_{2,2} \leq 0 \end{cases}$$

This contradicts with the assumption.

If there is a set consisting of more than two users powered by BS 1 and 2 simultaneously, we can iteratively group these users into pairs, and do power shifting as in the two-user case. The remaining users that are powered by two BSs form a new user set. Finally, we will get at most one user being served by the two BSs simultaneously.

Note 1: 1) For $\gamma_{1,1} \gamma_{2,2} - \gamma_{1,2} \gamma_{2,1} < 0$, it is always more power efficient if BS 1 schedules more power to UE 2, while UE 1 prefers BS 2; the optimal power allocation must be the case when at least one of $x'_{1,1}$ and $x'_{2,2}$ is zero. 2) For $\gamma_{1,1} \gamma_{2,2} - \gamma_{1,2} \gamma_{2,1} > 0$, the optimal power allocation must be the case when at least one of $x'_{1,2}$ and $x'_{2,1}$ is zero. 3) For $\gamma_{1,1} \gamma_{2,2} - \gamma_{1,2} \gamma_{2,1} = 0$, if the power keeps shifting until at least one of $x_{i,j}$ ($i, j = 1, 2$) becomes zero, it can still guarantee the minimum power consumption because power shifting brings no increment in the total power consumption.

A.2 $M \geq 3$

Assume Lemma 1 is true for the scenario with $M - 1$ BSs.

For the scenario with M BSs and N UEs, we represent the power allocation solution as an $M \times N$ area, similar to the 3×4 area in Fig. 9 (a).

Suppose there are more than $MN - (M - 1)(N - 1) = M + N - 1$ non-zero cells in the $M \times N$ area, taking $M + N$ non-zero cells for example. Since each UE, i.e., column, has at least one non-zero cell, then at least $N - M$ UEs will be powered by individual BSs.

Suppose columns $\{M + 1, \dots, N\}$ of the $M \times N$ area represent UEs that are powered by individual BSs, then there must be $2M$ non-zero cells in the $M \times M$ square formed by the first M columns of the $M \times N$ area (similar to the first 3×3 square in Fig. 9 (b)).

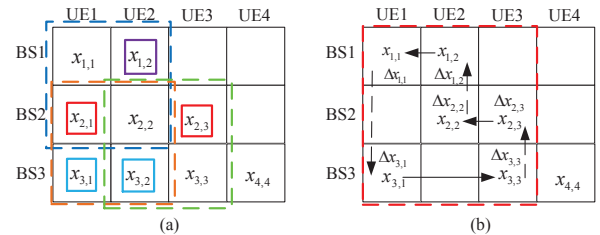


Fig. 9: Power shift in the 3-BS cooperative wireless system.

Denote T_i , $i \in \{1, \dots, M\}$ as the number of non-zero elements in the i -th row of the $M \times M$ square. Since

$\sum_{i=1}^M T_i \leq 2M$ and Lemma 1 is true for $M - 1$ BSs, then in the $M \times M$ square, we can get

$$2M - T_i \leq (M - 1) + (M - 1), \forall i \in \{1, \dots, M\}$$

The above equation implies $T_i = 2, \forall i \in \{1, \dots, M\}$, i.e., each row has two non-zero cells in the $M \times M$ square. If there are columns that have only one non-zero cell, delete these columns and the corresponding rows where these non-zero cells are located. Finally, an $m \times m$, ($M \geq m \geq 2$) sub-square which has two non-zero cells in each column and each row must exist. Divide the $2m$ non-zeros cells into two groups, each with m non-zero elements. Within each group, each row is distinct and so is each column.

Taking the 3×3 dotted sub-square in Fig. 9 (b) for example. Group 1 includes $\{x_{1,1}, x_{2,2}, x_{3,3}\}$ and group 2 includes $\{x_{3,1}, x_{1,2}, x_{2,3}\}$. It can be proved that in the optimal solution, the number of non-zero elements in the 3×3 sub-square should be no greater than $2 \times 3 - 1$ [35].

In summary, if the product of $\gamma_{i,j}$ of cells in group 1 is greater than the product of SNR of group 2, then a power shift from group 2 to group 1 that will decrease the total power consumption exists. If the product of group 1 is no more than the group 2's product, then there exists a power shift from group 1 to group 2 that will bring no increment to the total power consumption.

In either case, the power shifting will continue until at least one of the cells becomes zero. So, the number of non-zero cells in the $m \times m$ square will be no more than $2M - 1$. The number of non-zero cells in the $M \times N$ area will be no more than $(2M - 1) + (N - M) = M + N - 1$. Accordingly, the number of zeros cells will be greater than $MN - (M + N - 1) = (M - 1)(N - 1)$.

When there are more than $M + N$ non-zero cells in the $M \times N$ area, we can always iteratively take $M + N$ non-zero cells and do power shifting to make the number of the non-zero cells no more than $M + N - 1$.

APPENDIX B PROOF OF LEMMA 2

We will prove that Lemma 2 is true for the scenarios for $M = 2, 3$. For scenarios with $M > 3$, the same argument can be utilized to arrive at the same conclusion.

B.1 $M = 2, \mathcal{J}^{CC} = [j_{1,2}]$

To prove Lemma 2, we need to show in the optimal clusters J_1 and J_2 , when users are sorted in descending order of $\gamma_{1,2}^j$,

$$\max_{j \in J_1} \{j\} < \min_{j \in J_2} \{j\} \quad (12)$$

For the initial clusters $J_1^0 = \{1, \dots, j_0\}$ and $J_2^0 = \{j_0 + 1, \dots, N\}$, let $j_{1,2} = j_0$.

For the optimal clusters, suppose there are two users $j_1^* \in J_1, j_2^* \in J_2$, and $j_1^* > j_2^*$, as shown in Fig. 10. Since $\gamma_{1,j_1^*} \gamma_{2,j_2^*} - \gamma_{2,j_1^*} \gamma_{1,j_2^*} < 0$, power shifting between the two users will result in only one of the following scenarios (Note 1):

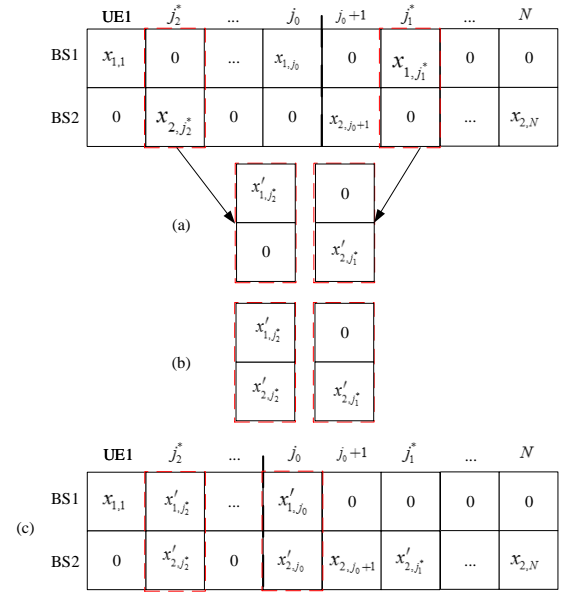


Fig. 10: UE-BS association in the 2-BS cooperative wireless system.

Scenario 1: As shown in Fig. 10 (a), $J_1 = J_1^0, J_2 = J_2^0$.

Scenario 2: One of the users is powered by two base stations; take j_2^* for example, as shown in Fig. 10 (b). Then, the power shifting between UE j_2^* and j_0 will result in Fig. 10 (c), where $x'_{2,j_2^*} x'_{1,j_0} = 0$.

1) If $x'_{2,j_2^*} = 0$, we will have $J_1 = \{1, \dots, j_0 - 1\}, \{j_0 + 1, \dots, N\} \subset J_2$.

2) If $x'_{2,j_2^*} > 0, x'_{1,j_0} = 0$, then UE j_2^* will continue to do power shifting with UE $\{j_0 - 1, j_0 - 2, \dots, j_2^* + 1\}$, until either $x'_{2,j_2^*} = 0$ or $J_2 = \{j_2^* + 1, \dots, N\}$. In either case, for any $j_1 \in J_1$ and $j_2 \in J_2$, there will be $j_1 < j_2$.

Furthermore, at least $N - 1$ UEs will belong to J_1 or J_2 (Lemma 1), if $J_1 \cup J_2 = \{1, \dots, N\}$, $j_{1,2} = \max_{j \in J_1} \{j\}$. If UE j^* is powered by both BS 1 and BS 2 simultaneously, $j_{1,2} = j^*$.

B.2 $M = 3, \mathcal{J}^{CC} = [j_{1,2}, j_{1,3}, j_{2,3}]$

The UE-BS association scheme in the optimal solution must fall in one of the categories in Fig. 11, where a solid arrow represents power coordination (providing power for other BS's UE), and a dashed line means spectrum coordination only (increasing the transmission power of its own UE to spare more spectrum for other BSs).

For each category, we can find the corresponding \mathcal{J}^{CC} which satisfies Lemma 2. Readers are referred to [35] for details.

APPENDIX C PROOF OF LEMMA 3

If $S_1 = S_2$, then they must be the optimal solution because relaxing the constraints by limiting the transmit power of only one BS brings no benefits to the total power consumption.

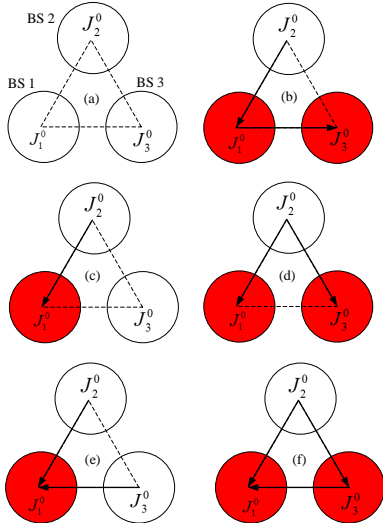


Fig. 11: Spectrum and power coordination in the 3-BS cooperative wireless system (red BS means power consumption is 1).

Then, we only prove part 2) with $S_1 > (1, 1)$, as part 3) can be similarly proved. Suppose in the CC vector \mathbf{J}^{CC} which corresponds to the optimal solution $\{x_{i,j}^*\}$, we have $j_{1,2} < j'_1$, then the optimal cluster $J_1^* \subseteq \{1, \dots, j'_1 - 2\} \subset J_1^0$.

1) For the optimal solution $\{x_{i,j}^*\}$, we can find the corresponding mapping $\{x'_{i,j}\}$ by relaxing the constraint of BS 1 as follows:

$$\begin{aligned} x'_{1,j} &= x_{1,j}^* + \gamma_{2,1}^j x_{2,j}^*, & x'_{2,j} &= 0, & j &\in J_1^0 \setminus J_1^* \\ x'_{1,j} &= x_{1,j}^*, & x'_{2,j} &= x_{2,j}^*, & j &\in J_1^* \cup J_2^0 \end{aligned} \quad (13)$$

Since $\{x_{i,j}\}$ in S_1 is the optimal relaxed solution, $\{x'_{i,j}\}$ must fall into the shadowed region of Fig. 12,

$$\sum_{j \in J_1^0} x'_{1,j} + \sum_{j \in J_2^0} x'_{2,j} > \sum_{j \in J_1^0} x_{1,j} + \sum_{j \in J_2^0} x_{2,j} \quad (14)$$

Based on (14), we have the following result

$$\sum_{j=1}^{j'_1-1} (x'_{1,j} - x_{1,j}) > \sum_{j=j'_1}^{j_0} (x_{1,j} - x'_{1,j}) + \sum_{j \in J_2^0} (x_{2,j} - x'_{2,j}) \quad (15)$$

2) For $\{x_{i,j}\}$, the relaxed solution in S_1 , we can find the corresponding mapping $\{x_{i,j}^*\}$ by considering the power constraint of BS 1. The power allocation with power constraints for each BS becomes

$$\begin{aligned} x_{1,j}^* &= x_{1,j}, & x_{2,j}^* &= 0, & j &\in \{1, \dots, j'_1 - 1\} \\ x_{1,j}^* &= \beta x_{1,j}, & x_{2,j}^* &= \gamma_{1,2}^j (1 - \beta) x_{1,j}, & j &= j'_1 \\ x_{1,j}^* &= 0, & x_{2,j}^* &= \gamma_{1,2}^j x_{1,j}, & j &\in \{j'_1 + 1, \dots, j_0\} \\ x_{1,j}^* &= 0, & x_{2,j}^* &= x_{2,j}, & j &\in J_2^0 \end{aligned} \quad (16)$$

where $\beta = (1 - \sum_{j=1}^{j'_1-1} x_{1,j}) / x_{1,j'_1}$. From (13) and (16), we

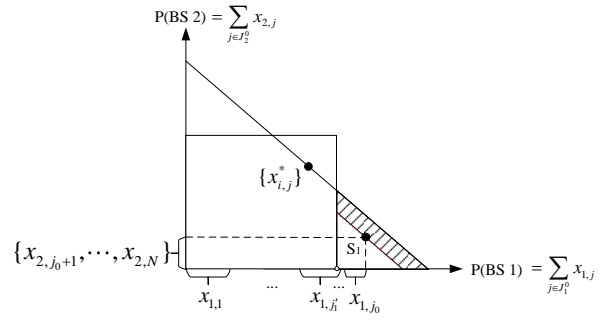


Fig. 12: Solution Mapping, straight slop=1.

have

$$\begin{aligned} &\sum_{i=1}^2 \sum_{j=1}^{j'_1-1} (x_{i,j}^* - x_{i,j}^*) \geq \\ &\left(\sum_{j=1}^{j'_1-1} x_{1,j}^* + \left(\sum_{j=1}^{j'_1-1} x'_{1,j} - \sum_{j=1}^{j'_1-1} x_{1,j}^* \right) \gamma_{1,2}^{j'_1-1} \right) - \sum_{j=1}^{j'_1-1} x_{1,j} \\ &\sum_{i=1}^2 \sum_{j=j'_1}^N (x_{i,j}^* - x_{i,j}^*) = \left((1 - \gamma_{1,2}^{j'_1}) \beta x_{1,j'_1} + \right. \\ &\left. \sum_{j=j'_1}^{j_0} \gamma_{1,2}^j x_{1,j} + \sum_{j \in J_2^0} x_{2,j} \right) - \left(\sum_{j=j'_1}^{j_0} \gamma_{1,2}^j x'_{1,j} + \sum_{j \in J_2^0} x'_{2,j} \right) \end{aligned} \quad (17)$$

Substituting $\sum_{j=1}^{j'_1-1} x_{1,j}^* = 1 = \sum_{j=1}^{j'_1-1} x_{1,j} + \beta x_{1,j'_1}$ into (17), we can see

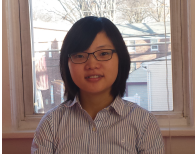
$$\begin{aligned} &\sum_{i=1}^2 \sum_{j=1}^{j'_1-1} (x_{i,j}^* - x_{i,j}^*) \geq \beta x_{1,j'_1} + \\ &\left(\sum_{j=1}^{j'_1-1} (x'_{1,j} - x_{1,j}) - \beta x_{1,j'_1} \right) \gamma_{1,2}^{j'_1-1} \\ &\sum_{i=1}^2 \sum_{j=j'_1}^N (x_{i,j}^* - x_{i,j}^*) \leq \beta x_{1,j'_1} + \\ &\left(\sum_{j=j'_1}^{j_0} (x_{1,j} - x'_{1,j}) - \beta x_{1,j'_1} \right) \gamma_{1,2}^{j'_1} + \sum_{j \in J_2^0} (x_{2,j} - x'_{2,j}) \end{aligned} \quad (18)$$

According to the sorting rule of UE, $\gamma_{1,2}^{j'_1-1} \geq \gamma_{1,2}^{j'_1}$. From (15) and (18), we have

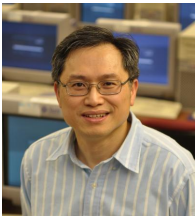
$$\sum_{i=1}^2 \sum_{j=1}^{j'_1-1} (x_{i,j}^* - x_{1,j}^*) \geq \sum_{i=1}^2 \sum_{j=j'_1}^N (x_{1,j}^* - x_{i,j}^*)$$

Consequently, the following result can be obtained which contradicts with the assumption that $\{x_{i,j}^*\}$ is the optimal solution.

$$\sum_{i=1}^2 \sum_{j=1}^N x_{i,j}^* \geq \sum_{i=1}^2 \sum_{j=1}^N x_{i,j}^*$$



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REFERENCES

- [1] Q. Cui, X. Huang, B. Luo, X. Tao, and J. Jiang. Capacity analysis and optimal power allocation for coordinated transmission in MIMO-OFDM systems. *Science China Information Sciences*, 55(6):1372–1387, 2012.
- [2] T. Han and N. Ansari. On greening cellular networks via multicell cooperation. *Wireless Communications, IEEE*, 20(1):82–89, 2013.
- [3] Xueqing Huang, Tao Han, and Nirwan Ansari. On green energy powered cognitive radio networks. *CoRR*, abs/1405.5747, 2014.
- [4] 3GPP. “C-RAN: The Road towards Green Radio Access Network,” white paper. <http://labs.chinamobile.com/cran/category/file-download/>. accessed on September 22, 2013.
- [5] L.E. Li, Z.M. Mao, and J. Rexford. Toward Software-Defined Cellular Networks. In *Software Defined Networking (EWSNDN), 2012 European Workshop on*, pages 7–12, 2012.
- [6] 3GPP. 3GPP TR 36.814 V0.4.1. Further Advancements for E-UTRA Physical Layer Aspects. <http://www.3gpp.org/ftp/Specs/html-info/36814.htm/>. accessed on September 22, 2013.
- [7] S-E Elayoubi, O. Ben Haddada, and B. Fourestie. Performance evaluation of frequency planning schemes in OFDMA-based networks. *Wireless Communications, IEEE Transactions on*, 7(5):1623–1633, 2008.
- [8] M. Qian, W. Hardjawana, Y. Li, B. Vucetic, J. Shi, and X. Yang. Inter-cell interference coordination through adaptive soft frequency reuse in LTE networks. In *Wireless Communications and Networking Conference (WCNC), 2012 IEEE*, pages 1618–1623, 2012.
- [9] D. Yang, X. Fang, and G. Xue. Game theory in cooperative communications. *Wireless Communications, IEEE*, 19(2):44–49, April 2012.
- [10] Q. Zhang, J. Jia, and J. Zhang. Cooperative relay to improve diversity in cognitive radio networks. *Communications Magazine, IEEE*, 47(2):111–117, 2009.
- [11] P. Li, S. Guo, Z. Cheng, and A.V. Vasilakos. Joint relay assignment and channel allocation for energy-efficient cooperative communications. In *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pages 626–630, 2013.
- [12] Z. Shen, J.G. Andrews, and B.L. Evans. Optimal power allocation in multiuser OFDM systems. In *Global Telecommunications Conference, 2003. GLOBECOM '03. IEEE*, volume 1, pages 337–341 Vol.1, 2003.
- [13] J. Jang and K.-B. Lee. Transmit power adaptation for multiuser OFDM systems. *Selected Areas in Communications, IEEE Journal on*, 21(2):171–178, 2003.
- [14] D. Kivanc, G. Li, and H. Liu. Computationally efficient bandwidth allocation and power control for OFDMA. *Wireless Communications, IEEE Transactions on*, 2(6):1150–1158, 2003.
- [15] X. Gong, S.A. Vorobyov, and C. Tellambura. Optimal bandwidth and power allocation for sum ergodic capacity under fading channels in cognitive radio networks. *Signal Processing, IEEE Transactions on*, 59(4):1814–1826, 2011.
- [16] C.-H. Chen and C.-L. Wang. Joint Subcarrier and Power Allocation in Multiuser OFDM-Based Cognitive Radio Systems. In *Communications (ICC), 2010 IEEE International Conference on*, pages 1–5, 2010.
- [17] F. Brah, A. Zaidi, J. Louveaux, and L. Vandendorpe. On the Lambert-W function for constrained resource allocation in cooperative networks. *EURASIP Journal on Wireless Communications and Networking*, 2011(1):19, 2011.
- [18] D.W.K. Ng, E.S. Lo, and R. Schober. Energy-Efficient Resource Allocation in OFDMA Systems with Hybrid Energy Harvesting Base Station. *Wireless Communications, IEEE Transactions on*, 12(7):3412–3427, 2013.
- [19] T. Han and N. Ansari. On optimizing green energy utilization for cellular networks with hybrid energy supplies. *Wireless Communications, IEEE Transactions on*, 12(8):3872–3882, 2013.
- [20] T. Han and N. Ansari. Ice: Intelligent cell breathing to optimize the utilization of green energy. *Communications Letters, IEEE*, 16(6):866–869, 2012.
- [21] Z. Mo, W. Su, S. Batalama, and J. Matyjas. Cooperative Communication Protocol Designs Based on Optimum Power and Time Allocation. *Wireless Communications, IEEE Transactions on*, PP(99):1–1, 2014.
- [22] X. Zhang, X.S. Shen, and L. Xie. Joint Subcarrier and Power Allocation for Cooperative Communications in LTE-Advanced Networks. *Wireless Communications, IEEE Transactions on*, 13(2):658–668, February 2014.

- [23] B. Luo, Q. Cui, H. Wang, and X. Tao. Optimal Joint Water-Filling for Coordinated Transmission over Frequency-Selective Fading Channels. *Communications Letters, IEEE*, 15(2):190–192, 2011.
- [24] H. Zhu and J. Wang. Radio Resource Allocation in Multiuser Distributed Antenna Systems. *Selected Areas in Communications, IEEE Journal on*, 31(10):2058–2066, October 2013.
- [25] A.K. Sadek, W. Su, and K.J.R. Liu. Multinode Cooperative Communications in Wireless Networks. *Signal Processing, IEEE Transactions on*, 55(1):341–355, Jan 2007.
- [26] Q. Cui, Bing Luo, X. Huang, A. Dowhuszko, and J. Jiang. Closed-form solution for minimizing power consumption in coordinated transmissions. *EURASIP Journal on Wireless Communications and Networking*, 2012(1):1–14, 2012.
- [27] J. Zhao, T.Q.S. Quek, and Z. Lei. Coordinated multipoint transmission with limited backhaul data transfer. *Wireless Communications, IEEE Transactions on*, 12(6):2762–2775, 2013.
- [28] V.S. Varma, S.E. Elayoubi, M. Debbah, and s. Lasaulce. On the energy efficiency of virtual mimo systems. In *Personal, Indoor and Mobile Radio Communications (PIMRC Workshops), 2013 IEEE 24th International Symposium on*, pages 11–15, Sept 2013.
- [29] 3GPP R1-050507 Soft frequency reuse scheme for UTRAN LTE. http://www.3gpp.org/ftp/tsg/_ran/wg1/_r1/TSGR1_41/Docs/. accessed on September 22, 2013.
- [30] E. Liu, Q. Zhang, and K.K. Leung. Relay-Assisted Transmission with Fairness Constraint for Cellular Networks. *Mobile Computing, IEEE Transactions on*, 11(2):230–239, Feb 2012.
- [31] D. Wang, X. Xu, X. Chen, and X. Tao. Joint scheduling and resource allocation based on genetic algorithm for coordinated multi-point transmission using adaptive modulation. In *Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on*, pages 220–225, Sept 2012.
- [32] G.Y. Li, Z. Xu, C. Xiong, C. Yang, S. Zhang, Y. Chen, and S. Xu. Energy-efficient wireless communications: tutorial, survey, and open issues. *Wireless Communications, IEEE*, 18(6):28–35, December 2011.
- [33] S. Cui, A.J. Goldsmith, and A. Bahai. Energy-constrained modulation optimization. *Wireless Communications, IEEE Transactions on*, 4(5):2349–2360, Sept 2005.
- [34] Stephen Boyd and Lieven Vandenberghe. *Convex Optimization*. Cambridge University Press, New York, NY, USA, 2004.
- [35] Xueqing Huang and Nirwan Ansari. Joint spectrum and power allocation for multi-node cooperative wireless systems. *CoRR*, abs/1405.5730, 2014.