Resource Allocation in Multi-cell OFDMA-based Relay Networks

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Abstract— Cooperative relay networks combined with Orthogonal Frequency Division Multiplexing Access (OFDMA) technology has been widely recognized as a promising candidate for future cellular infrastructure due to the performance enhancement by flexible resource allocation schemes. The majority of the existing schemes aim to optimize single cell performance gain. However, the higher frequency reuse factor and smaller cell size requirement lead to severe inter-cell interference problem. Therefore, the multi-cell resource allocation of subcarrier, time scheduling and power should be jointly considered to alleviate the severe inter-cell interference problem. In this paper, the joint resource allocation problem is formulated. Considering the high complexity of the optimal solution, a two-stage resource allocation scheme is proposed. In the first stage, all of the users in each cell are selected sequentially and the joint subcarrier allocation and scheduling is conducted for the selected users without considering the interference. In the second stage, the optimal power control is performed by geometric programming method. Simulation results show that the proposed interference-aware resource allocation scheme improves the system capacity compared with existing schemes. Especially, the edge users achieve more benefit.

I. INTRODUCTION

Due to the attractive features of high throughput, low power consumption and extended coverage, the cooperative relay network architecture has the trend to replace the traditional point-to-multi-point network architecture. Meanwhile, OFDMA technology is becoming a popular choice since the frequency selective fading problem in broadband system can be alleviated by dividing the whole bandwidth into multiple parallel subcarriers. The incorporation of OFDMA technology and the relay network structure provides a promising platform, which offers nice flexibility in terms of resource allocation, such as subcarrier allocation, scheduling and power control to achieve the multi-dimensional diversity gain. Therefore the emerging 4G wireless system such as Long Term Evolution-Advanced (LTE-A) [1] and WiMax [2] will adopt such a promising OFDMA-based relay network infrastructure.

The resource management is crucial to guarantee the system performance of a wireless system. In OFDMA-based relay networks, most of existing works concentrated on the single cell scenario and share the basic idea as allocating resources to maximize the local performance gain [4][5][12][13]. However, in future wireless networks, smaller cell size and higher frequency reuse factor is imperative to meet the growing capacity requirement, which induces severe inter-cell interference problem. The interaction among adjacent cells results in the fact that the maximization of local performance gain may not achieve the global optimal performance.

Take the scenario in Fig.1 as a motivating example. Two relay links in two adjacent cells are considered. The links between base stations (BSs) and relay stations (RSs) are defined as backbone links and denoted by solid arrows. The links between RSs and mobile stations (MSs) are defined as access links and denoted by hollow arrows. Two available subcarriers are represented by two colors, where the red channel has higher channel gain in all of the links. We name Scheme 1 as the one that tries to maximize the local performance gain, i.e., both of the two relay links select the red channel. However, the links suffer strong mutual interference and probably Scheme 1 cannot achieve optimal sum throughput. Since another blue channel is available, although the channel gain is lower than that of the red channel, allocating orthogonal channels to neighboring links can effectively reduce the interference, such as Scheme 2. The analysis above reveals that the key issue of optimal resource allocation is to achieve the tradeoff between local performance gain and the impact of interference.

To jointly consider the two factors, the subcarrier allocation, scheduling and power control should be jointly considered.
First, subcarrier allocation and scheduling should be jointly considered. When the same subcarrier is allocated to the links in neighboring cells, if the scheduling is not jointly considered, interference from neighboring BSs may degrades the throughput more severely since BSs have higher transmission power than RSs. On the other hand, due to the two-hop nature of relay links, appropriate scheduling order may avoid the dominant interference from BSs. For the example shown in Fig.1, we can have Scheme 3, which swaps the scheduling orders of access links and backbone links of the two cells so that the dominant interference from BS (e.g., $B_1$) to the neighboring RS ($R_2$) is substituted by the much weaker interference to the neighboring MS ($U_2$).

What is more, the power control scheme should be also coupled with subcarrier allocation and scheduling, because both the subcarrier and time slot allocation determine which links interfere with each other and how much power should be allocated to alleviate the interference. Once the subcarrier allocation and scheduling is fixed, the power allocation of BSs and RSs can be used to alleviate the interference, such as Scheme 4 of Fig.1. Reversely, if links are too close to each other and the interference can hardly be alleviated by power control, orthogonal resources in either frequency (Scheme 2) or time domain (Scheme 3) should be allocated to avoid the interference. In this case, the interference is avoided at the cost of local performance degradation. Therefore, the joint resource allocation scheme is imperative to achieve the optimal tradeoff between the two factors.

The joint resource allocation problem can be formulated as a mixed integer programming (MIP) problem [7], which is NP hard. The main contribution of the paper is that a low-complexity joint subcarrier allocation, scheduling and power control scheme is proposed. The scheme is divided into two stages to reduce the complexity. In the first stage, one MS is selected in each cell in each round based on the channel state information (CSI). Then the subcarrier allocation and scheduling scheme is operated for the selected MS. This operation iterate until all of the subcarriers have been allocated. In the second stage, the power control is conducted to optimize the throughput for all of the allocated subcarriers. The very nice observation we have is that when the Amplify-and-Forward (AF) relay technology is adopted, the multi-cell power control problem can be optimally solved by geometric programming method in the high Signal to Interference Ratio (SIR) region. Simulation results demonstrate that the proposed resource allocation scheme significantly enhances system capacity, especially for the edge users.

The rest of this paper is organized as follows. In Section II, the related work is summarized. Then a joint resource allocation problem is formulated in Section III. After that an iterative resource allocation scheme is proposed in Section IV. Section V shows the simulation results. Finally, Section VI concludes the paper.

II. RELATED WORK

Numerous previous work investigated resource allocation schemes in OFDMA-based relay networks [4][5][11][12][13][17]. The subcarrier allocation and the scheduling scheme were adopted to achieve frequency and time diversity gain. However, most of the previous work focused on single cell scenario and overlook the interference among adjacent cells, which is the system capacity bottleneck in future cellular networks. What is more, the power control scheme was not addressed, which plays an important role for inter-cell interference alleviation.

Some power control schemes have been exploited for interference mitigation in relay networks [6][10]. These work considered that several relay links transmit simultaneously and all of the links use the same frequency. However, as we have mentioned in Section I, power control should not be separated from the subcarrier allocation and scheduling. In [10], the point-to-multi-point scenario was discussed and a multi-user power control problem was solved. All of the links in the cell used orthogonal resources and the inter-cell interference problem was not addressed.

There have also been some work on the joint subcarrier and power allocations schemes of OFDMA-based relay networks under multi-cell scenario[7][8]. [7] proposed a distributed subcarrier and power allocation scheme. Each cell individually decides the resource allocation within its cell according to the measurement of interference from neighboring cells. However, the cooperative data is relayed by the adjacent BSs. In that case, the relay transmissions occupy the spectrum resource of the relaying BSs, therefore the system spectrum efficiency is lower than that with specific RSs. What is more, due to the distributed property of the resource allocation scheme, the interference was assumed constant, which is not practical when the transmission powers of the interfering cells are adjusted. In [8], a joint resource allocation problem in multi-cell scenario was also conducted. However, the per-user power constraint in each cell was assumed, which is not practical.

In [15], the geometric programming (GP) method is utilized to solve the power control problem in traditional cellular networks. Motivated by this work, we proved in this paper that when the AF relay technology is adopted, in the high SIR region the simplified power allocation problem can be optimally solved by the GP method and the optimality of the proposed resource allocation scheme can be guaranteed.

To summarize, the severe inter-cell interference problem brings new challenges to resource allocation of future OFDMA-based relay networks. The joint allocation of subcarrier allocation, scheduling and power control should be proposed to achieve the global optimal performance.

III. JOINT RESOURCE ALLOCATION PROBLEM

A. System Model

Consider a multi-cell wireless networks with several dedicated relay stations in each cell. There are totally $N$ BSs. For each BS $B_n \ (n \in [1, N])$, there are $R(n)$ RSs and $M(n)$ MSs belonging to the cell. Since BSs can cooperate with each other more easily by signalling transmitted via wired core networks, we focus on downlink relay transmission. The MSs with poor direct link channel state are first selected for
relay transmission by some rough criterions, which will be addressed in the next subsection. Then the resource can be divided into two portions for direct and relay transmissions respectively. We only focus on resource allocation for the selected MSs which have determined their transmission modes (direct mode or relay mode). The fixed AF relaying strategy without receiver combination is used [18]. Each fixed AF cooperative transmission is divided into two slots. The duration of the two slots are identical. In the first slot, only BS transmits and RS receives. In the second slot, only RS transmits and MS receives. We assume that the transmission among different BSs are also synchronized, i.e., the intra-frame interference is not considered. Such synchronization can be achieved by adopting Global Position System (GPS) as used in TDD-LTE system [1].

All of the MSs are assumed fixed and the channel gain is constant during each frame. For practical implementation, each MS is allowed to communicate with at most one RS to reduce the complexity of synchronization with multiple RSs at the physical layer. We assume that the relay selection is done before the resource allocation scheme according to long term CSI, such as [16]. Because without such assumption the online resource allocation for the relay nodes cannot be realized. Also we regulate that the signals from BS and RS cannot be combined due to synchronization difficulty.

Since we have fixed the relay selection for each MS, smart resource allocation scheme can be adopted to minimize the interference among the system. There are three resources that can be allocated for interference mitigation. The first is the transmission power. We assume that each single BS has the maximum overall transmission power $P_{\text{max}}$ constraint of all the subcarriers allocated to the BS. Each single RS has the maximum overall transmission power $P_{\text{max}}$ constraint of all the subcarriers allocated to the RS. The transmission power of $B_n$ to the jth RS $R_j(n)$ on subcarrier $k$ is denoted by $P_{jk}$ and the transmission power of $R_j(n)$ to the i th MS $M_i(n)$ in the cell on subcarrier $k$ is denoted by $P_{ijk}$.

The second resource is the subcarrier. We can dynamically decide which of the subcarriers are allocated to which access/backbone links according to the instantaneous CSI. We assume there are totally $K$ subcarriers available in each cell. Each subcarrier is allowed to be used only once in all of the access links and only once in all of the backbone links of one cell respectively. Although some references showed the potential performance gain by allocating the same subcarrier to different access links [3], we prohibit this allocation in our scheme. Further we assume that the data transmitted via one subcarrier in the backbone link to any RS can be only forwarded to one MS with one subcarrier, i.e., each subcarrier cannot be shared by more than one data stream. We denote $a_{ijk}$ as the index of allocating the subcarrier $k$ to the access link from $R_j(n)$ to $M_i(n)$ and $r_{ik}$ as the index of allocating the subcarrier $k$ to the backbone link from $B_n$ to $R_j(n)$.

The last resource is the scheduling order of the two-hop relay links. Since some data should be transmitted via two hops to the MSs using the relay mode, each stream belonging to any particular MS can decide whether the access link is scheduled in the first slot or the backbone link in the first slot. As we have demonstrated in Section I, the appropriate scheduling order can effectively avoid the inter-cell interference. We use $x_{ik}(n)$ to indicate the scheduling index of the access link to the $i$th MS in the cell $n$. $y_{ik}(n)$ indicates the scheduling index of the backbone link to the $j$th RS in $B_n$. All of the scheduling indexes are $\{0,1\}$ value, where 1 represents scheduling the corresponding link in the first slot and 0 represents the second slot.

B. Problem description and Formulation

The joint subcarrier allocation, scheduling and power control problem is formulated in this subsection. Since the problem is combinatorial, a low-complexity two-stage solution is proposed in the next section.

We first concentrate on the MS $M_i(n)$ in the cell $B_n$ and its associated RS $R_j(n)$. To evaluate the interference the two-hop link suffers, we first assume that the subcarrier $k$ and $k'$ has been allocated to the access link and backbone link of $M_i(n)$ respectively. The channel gain from any BS $B_n$ to $R_j(n)$ and $M_i(n)$ at channel $k$ are denoted as $G_{sd}(n)(ik)$ and $G_{rb}(n)(ik)$. The channel gain from RS $R_j(n)$ to $R_j(n)$ and $M_i(n)$ at channel $k'$ is denoted by $C_{rr}(n)(jj'k')$ and $C_{rd}(n)(ij'k')$ respectively. Then the received SIR of the direct link $\beta_{ik}$, backbone link $\beta_{ik}$ and access link $\gamma_{ik}$ can be expressed by Eq. (1), (2), and (3) respectively. $B$ is the bandwidth of each subcarrier and $N_0$ is the white noise power. The subscript $k$ represents that the access link adopts the subcarrier $k$ and the matched subcarrier $k'$ in the backbone link is omitted.

Before the joint resource allocation scheme is operated, each MS should first decide whether the direct mode or the relay mode should be selected for transmission. Since the transmission mode decision should be simple to reduce the complexity of the scheme, in this paper, we simply use the instantaneous SIR for the mode decision as follows:

$$i \in \begin{cases} D(n), & \max_{k,K} \alpha_{ik}(n) > \max_{k,K} \frac{\beta_{ik}(n) \gamma_{ik}(n)}{\beta_{ik}(n) \gamma_{ik}(n) + 1} \\ P(n), & \text{else} \end{cases}$$

(4)

where $D(n)$ is denoted as the set of MSs using the direct link and $P(n)$ as the set of MSs using the relay link in the $n$th cell, respectively.

Since the fixed AF relay technology without receiver combination is adopted, the receiving SIR of $M_i(n)$ at subcarrier $k$ is:

$$\text{SIR}_{ik}(n) = \begin{cases} \frac{\beta_{ik}(n) \gamma_{ik}(n)}{\beta_{ik}(n) \gamma_{ik}(n) + 1}, & i \in R(n) \\ \alpha_{ik}(n), & i \in D(n) \end{cases}$$

(5)
and the data rate achieved by $M_i^{(n)}$ is:

$$R^{(n)}_i = \log_2(1 + SIR^{(n)}_{ik}).$$

Then, our optimization goal of the joint resource allocation problem is to maximize the overall throughput of the system:

$$\max \sum_{n=1}^{N} \sum_{i=1}^{M} R^{(n)}_i$$

The first constraint of the optimization problem is that each subcarrier $k$ can be used by only one of the backbone links or one of the access links in each cell, i.e.:

$$\sum_{i=1}^{M} a_{ijk}^{(n)} \leq 1, \forall n, \forall j, \forall k$$

$$\sum_{j=1}^{M} r^{(n)}_{jk} \leq 1, \forall n, \forall j, \forall k$$

$$\alpha_{ijk}^{(n)} + r^{(n)}_{jk} \leq 1, \forall n, \forall i, j, \forall k$$

Also, there are maximum transmission power constraints for each BS and RS, i.e.:

$$\sum_{j=1}^{K} \sum_{k=1}^{P} r^{(n)}_{jk} \leq P_{\text{max}}, \forall n$$

$$\sum_{i=1}^{M} \sum_{k=1}^{R} P^{(n)}_j \leq P^{(n)}_{\text{max}}, \forall n, \forall j$$

Last, the scheduling indexes should be $\{0, 1\}$ variable, and each pair of subcarriers allocated for one relay link cannot be scheduled simultaneously, i.e.:

$$x_i^{(n)} + r_j^{(n)} = 1, \forall n, \forall i, j : M_i^{(n)} \in R_j^{(n)}$$

$$x_i^{(n)}, y_j^{(n)} \in \{0, 1\} \forall n, \forall i, \forall j$$

IV. IARA: An Distributed Subcarrier Allocation, Scheduling and Power Control Scheme

In Section III, the optimal resource allocation in multi-cell relay-based OFDM networks is formulated. However, the solution of the optimization problem of Eq.(7) with constraints Eq.(8), (9) and (10) is NP hard. It has been proved by Theorem 3 in [4] that, the joint subcarrier allocation and scheduling problem in the single cell relay network is NP hard. The computation complexity of our problem is at least $N$ times that of the single cell problem even without the power control. Therefore, the total computation complexity of the optimization problem is NP hard as well.

Since the computation complexity is extremely high, a low-complexity suboptimal resource allocation scheme is proposed in this section. The resource allocation scheme is divided into two stages to reduce the complexity. In the first stage, a subcarrier and scheduling scheme is proposed. In the first stage, one pair of subcarriers is allocated in each cell and their scheduling order is decided. This process iterates until all the subcarriers have been allocated. By such operation, all of the integer variables are fixed. In the second stage, a power control scheme is constructed to optimize the continuous power variables for all of the allocated subcarriers. An geometric programming (GP) method is used to derive the optimal power allocation result.

To further reduce the computation complexity, the dual decomposition method can be adopted in the power allocation stage such that the primal problem can be decomposed into $N$ subproblems, each of which is solved by one BS and only requires local CSI. The computation complexity of subcarrier and scheduling strategy is delectable compared with power allocation. The computation complexity of original power allocation problem is $O(K(N + RN))$. By decoupling the problem into separate dual problems, the complexity is $O(K)$, which is reduced by one order of magnitude compared with the primal problem.

A. Subcarrier Allocation and Scheduling Strategy

The joint scheme starts with the iterative subcarrier allocation and scheduling decision. In each round, based on
the current interference level, each cell greedily selects one particular MS and allocates one pair of subcarriers and the scheduling order to maximize the throughput of the selected MS, where the maximum transmission powers of the BS and RSs of the selected MS are assumed. For each pair of subcarrier allocation, the two different scheduling orders are both tried. Finally, the greedy subcarrier allocation and scheduling decision is made as follows:

\[(k, k') = \arg\max_{i \in M^{(n)}, x,y} R^{(n)}_{ik}, \quad \forall n, k \in c^{(n)}_a, k' \in c^{(n)}_b (11)\]

where \(C^{(n)}_a\) and \(C^{(n)}_b\) are the set of subcarriers that have not been allocated for the access links and backbone links in cell \(B_n\) respectively. After allocating subcarrier \(k\) and \(k'\), this pair of subcarriers can be removed from \(C^{(n)}_a\) and \(C^{(n)}_b\) respectively. By operating the same procedure for all of the \(N\) cells, \(N\) MSs with \(N\) subcarrier pairs with their scheduling order have been allocated. After \(K\) rounds of allocation, all the \(C^{(n)}_a\) and \(C^{(n)}_b\) become empty and the iteration terminates. Notice that all the \(N\) subcarrier allocations are selected in parallel without considering their mutual interference. After deciding the allocated subcarriers and their scheduling order, the optimal power control is operated as the next subsection describes.

\[B.\quad \text{Power Control: A Geometric Programming Method}\]

As we have mentioned in Section I, the multi-cell power allocation scheme can be solved with the geometric optimization method after all of the discrete variables in Problem (7) are fixed. To further reduce the computation complexity, the dual decomposition method is also used to divide the original problem into \(N\) subproblems.

After the first stage of subcarrier allocation and scheduling, the set of subcarriers allocated to the access and backbone links, namely \(c^{(n)}_a\) and \(c^{(n)}_b\), are fixed for each cell \(B_n\) and their corresponding scheduling indexes \(x^{(n)}\) and \(y^{(n)}\) are also determined. Then the power control problem is transformed as Eq.(12) shows.

\[
\begin{align*}
\text{maximize} & \quad \sum_{n=1}^{N} \sum_{i=1}^{M^{(n)}} \sum_{k \in S_a^{(n)}} R_{ik}^{(n)} \\
\text{s.t.} & \quad \sum_{k \in S_a^{(n)}} P_{ijk}^{(n)} R_{ijk}^{(n)} \leq P_{\text{max}}, \forall n, \forall j \\
& \quad \sum_{i=1}^{M^{(n)}} \sum_{k \in S_b^{(n)}} P_{ijk}^{(n)} R_{ijk}^{(n)} \leq P_{\text{max}}, \forall n \\
& \quad P_{ijk}^{(n)} \geq 0, \forall n, \forall i, \forall j, \forall k.
\end{align*}
\]

It is observed from Eq.(13) that, no matter which transmission mode is used, if the receiving SIR is large enough, the “1” in the log of Eq.(13) can be omitted. Also, the “1” in the denominator of SIR expression of the relay link can be omitted. Then the reverse of the expression in the log of Eq.(13) is a posynomial with respect to transmission powers. Therefore, the optimization goal of Eq.(12) can be reformulated to the minimization of products of a series of posynomials, which is still a posynomial as Eq.(14) shows. Consequently, the power control subproblem can be solved by GP method.

\[
\begin{align*}
\text{minimize} & \quad \prod_{n=1}^{N} \prod_{k=1}^{K} \left( \prod_{j \in D(n)} \frac{1}{\alpha_{i,k}} \prod_{j' \in R(n)} \frac{\beta_{i,k}^{(n)} + \gamma_{i,k}^{(n)}}{\alpha_{j'rk}^{(n)} \alpha_{j'rk}^{(n)}} \right) \\
& \quad \prod_{n=1}^{N} \prod_{k=1}^{K} \left( \prod_{j \in D(n)} \frac{1}{\alpha_{i,k}} \prod_{j' \in R(n)} \frac{\beta_{i,k}^{(n)} + \gamma_{i,k}^{(n)}}{\alpha_{j'rk}^{(n)} \alpha_{j'rk}^{(n)}} \right) \\
\end{align*}
\]

Finally, since the centralized power control problem is time consuming, the dual decomposition method can be utilized for the GP method. As described by Section V of [15], the auxiliary power \(P_{ijk}\) is introduced, where index \(i\) represents the interfered BS and \(j\) represents the interfering BS, \(k\) represents the particular subcarrier. The dual of the original problem is as Eq.(15), where \(S^{(n)} = S_a^{(n)} \cup S_b^{(n)}\). Obviously, the dual problem can be divided into subproblems for each subcarrier and the computation complexity can be significantly reduced.

The subproblem of \(BS_i\) can be formulated as Eq.(16). Notice that the solution of each dual problem only requires the local CSI, i.e., the CSI of interfering links to itself and the intra-cell CSI, which can be received by neighboring cell signalings.

\[
\min L_i = \sup_{\mathcal{P}_i} \sum_{j=1}^{M^{(i)}} \sum_{k \in S_a^{(i)}} \frac{\hat{P}_{ijk} G_{mk} + N_0}{C_{jk}^{(i)} P_{jk}^{(i)}}
\]

After each iteration, the dual costs of the auxiliary power items are updated to solve the primal problem. The process iterates until the power allocation result converge to the stable point. Since the objective function is differentiable and feasible solutions exist, the subgradient projection method can be utilized [19] to obtain the optimal primal problem solution. The dual cost can be updated as follows:
The Procedure of IARA

1: Initialize: \( S_b^{(n)} \) and \( S_b^{(n)} \) is set the total number of subcarriers for each cell
2: Each of MS individually decide whether to use direct link or relay link based on Eq.(4)
3: for \( n = 1; n \leq N; n = n + 1 \) do
4: Select one pair of subcarriers \((k, k')\) for one MS in cell \( B_n\) following Eq.(11)
5: \( \hat{S}_a^{(n)} = S_a^{(n)} / k, S_b^{(n)} = S_b^{(n)} / k' \)
6: end for
7: if \( S_a^{(n)} = \emptyset\), \( \forall n \in [1, N] \) then
8: Go to 3
9: end if
10: Do power control for all the allocated subcarriers as Section IV-B describes
11: Exits

\[ R_{ik}^{(n)} \approx \log_2 \alpha_{ik}^{(n)} = \log_2 \frac{G_{bs}^{(nn)}(ik)P_{ik}^{(n)}}{\sum_{m \in T_{ik}^{(n)}} P_m G_{mik} + N_0}, \forall i \in D^{(n)}, \forall k \]

\[ R_{ik}^{(n)} \approx \log_2 \frac{\beta_{ik}^{(n)} \gamma_{ik}^{(n)}}{\beta_{ik}^{(n)} + \gamma_{ik}^{(n)}} = \log_2 \frac{G_{br}^{(nn)}(ik)P_{ik}^{(n)} G_{rs}^{(nn)}(ik)P_{ijk}^{(n)}}{N_0(\sum_{m \in T_{ik}^{(n)}} P_m G_{mik} G_{br}^{(nn)}(ik)P_{ik}^{(n)} + N_0(\sum_{s \in I_{ijk}^{(n)}} P_{sjk} G_{sjk} G_{rs}^{(nn)}(ik)P_{ijk}^{(n)}), \forall i \in R^{(n)}, \forall k \]

\[ \min L = \sup_{P} \sum_{n=1}^{N} \sum_{i=1}^{M^{(n)}} \sum_{k \in S^{(n)}} R_{ik}^{(n)} - \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{N} S^{(i)}_i \alpha_{ijk} [\hat{P}_{ijk} - F_k^{(j)}] \] \hspace{1cm} (15)

D. Implementation Issues

In this section some key implementation issues of IARA are discussed. Since IARA should be operated for each OFDM frame, the transmission process during each frame period is described here and the implementation issues will be introduced as the order of the transmission process.

Before the cooperative transmission, the following two operations should be done: the CSI measurement and the relay selection. For the CSI measurement, BSs acquire the CSI of both access links and backbone links among the system for joint resource allocation. BS first broadcasts the pilot packets for channel estimation. After receiving the packets, the RSs/MSs perform channel estimation using the OFDM pilot symbols in the packet header. For each frame (also the resource allocation period) being considered, each of the MSs within the cell returns the measurement result by dedicate uplink channel and finally \( M^{(n)} \) MSs are scheduled for cooperative transmission in this OFDM frame. The MS scheduling scheme can refer to any literature about multi-user scheduling of OFDM system, such as [13].

The time granularity of the relay selection scheme should be much larger compared with the resource allocation scheme because the large time scale resource allocation should be done based on the selection result before we exploit the opportunistic gain of reducing interference in small time scale. Relay selection method adopted in this paper refers to [7]. Each MS compares the average channel gain to all of the RSs and select the highest one as its RS. Also each MS can decide whether to use direct link or relay link according to the local CSI.

The subcarrier and scheduling allocation stage does not require any inter-cell CSIs. In the power allocation stage, the dual decomposition is utilized such that only local CSI information is required for power computation, which guarantees the scalability of the scheme. For each BS, the CSI of the cells with interference powers above some threshold \( P_{th} \) are
recorded and made input for the power allocation. All of
the dual costs are given any positive initial values. Then the
decomposed problem of Eq.(15) is solved by each BS. After
that the calculated optimal power is disseminated to all of
the BSs which have strong enough interference powers for
the dual cost update by Eq.(17). After some iterations of dual
cost update, the optimal power allocation can be achieved.

After all the of the resource allocation have been done, the
OFDM frame can be transmitted. In cooperative transmission
phase the receiver may experiences a time offset between
the signals received from the its own cell and out of the
cell. Therefore the key implementation difficulty is the the
multi-cell frame level synchronization. The OFDM frame
synchronization can be solved by the scheme in [9], where
the cyclic prefix (CP) of the OFDM frames can be used to
synchronize the time offset of different frames. We should
regulate all of the BSs in the system to adopt the same
synchronization pattern such that the MS can synchronize the
frames from other cells.

V. PERFORMANCE EVALUATION

In this section we adopt discrete time event simulator to
verify the convergence of the iterative power control scheme
and the effectiveness of the proposed IARA joint resource
allocation scheme.

A. System Setup

Our simulation is based on the following topology: two-
tier cells are considered where the cell radius of each cell is
700m. Three RSs are evenly located in each cell, as Fig.2
shows. Equal number of MSs are randomly distributed in
each cell. Each selected MS has saturated traffic demand.
The Okumura-Hata path loss model is adopted [14]: $l(d) =
137.74 + 35.22 \log(d)$ in dB (where the unit of d is Km).
The simulation parameters are listed in Table.I. The i.i.d
block Rayleigh fading channel model is utilized. The channel
conditions keep constant during each OFDM frame and vary
in different frames. The frame duration $T$ is 10 milliseconds.
The default value of path loss $\alpha$ is 4 and shadow standard
deviation $\delta$ is 7 dB, which are the typical values for outdoor
fading environment [7].

We should first validate the convergence of the proposed
distributed scheme to guarantee the scalability. Specifically, the
convergence speed of the dual GP power control is analyzed.
Then the accuracy of the proposed power control scheme is
validated. After that, the throughput performance variation
with different network densities is given to observe the perfor-
mane gain of IARA in different wireless environments. The
most related work in [7] is compared. Since the original work
of [7] adopts the multi-BS cooperation, for the purpose of
comparison, the scheme in [7] is adapted into the topologies
with specific RSs. The performance of IARA is also compared
with the optimal result, which is obtained by exhaustive search.
Finally, the performance gain of the edge MSs are discussed
specifically to show the advantage of the relay architecture.

Fig. 2: Simulation topology.

TABLE I: Simulation Parameters

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<td>dB</td>
</tr>
<tr>
<td>$P_{bmax}$</td>
<td>20</td>
<td>W</td>
</tr>
<tr>
<td>$P_{smax}$</td>
<td>3</td>
<td>W</td>
</tr>
<tr>
<td>$N_0$</td>
<td>-105</td>
<td>dBmW</td>
</tr>
<tr>
<td>$T$</td>
<td>10</td>
<td>ms</td>
</tr>
</tbody>
</table>

Notice that although the dual decomposition is used to re-
duce the computation complexity by one order, the complexity
is still too high to be acceptable for real time algorithm. The
rest of the results shows that by introducing the interference-
aware resource allocation schemes, the OFDMA-based relay
networks can endure more interference and achieve higher
cooperative gain.

B. Simulation Results

We first verify the convergence of the proposed power
control algorithm. A 2-BS topology (cell 1 and 2 in Fig.2)
is adopted. For simplicity we concentrate on the allocated
powers of BS and the three RSs in cell 1. We run the dual
decomposition method of Eq.(15) for each BS and RS and
update the dual cost as Eq.(17) describes. It is clearly shown
from Fig.4 that the proposed distributed power control scheme
can quickly converge to the final power allocation result
without much fluctuation. Therefore the solution process can
be operated distributively to guarantee the scheme scalability.

Since the high SIR assumptions and dual decomposition
are utilized for the solution of power control which leads to
suboptimal power allocation result, the throughput loss of the
simplifications are investigated here. Also the two-cell scenario
is adopted and the throughput of one particular user in cell 1 is
observed. The throughput obtained by IARA is compared with
the actual optimal result (obtained by exhaustive power search) in Fig.5. The average SIR of the varies from 0dB to 50dB and the performance gaps with different SIR are observed. We regulate the channel fading of all of the links satisfy the Poisson distribution with the mean value as the given SIR. We can notice from the results in Fig.5 that the performance gap increases slightly as the mean SIR decreases. That is mainly because the omission of the "1" item in the left side of the rate expression is accurate only at the high SIR region. But the gap is always acceptable with different SIR regions. What is more, in the scenario IARA has overlook the interference that is lower than $P_{th}$. It is observed from Fig.5 that such simplification, which guarantees the power optimization to be done locally, does not lead to much performance degradation.

After that, the impact of network density on the aggregate throughput of IARA is compared with the scheme in [7] as well as the greedy method, which only aims to optimize the local throughput. We concentrate on the 19-cell scenario. The cell radius ranges from 400 to 1900m. The per-user throughput is represented in Fig.6. It is illustrated from the figure that both IARA and the scheme in [7] significantly outperform the greedy scheme. That is because the multi-cell resource allocation is conducted to alleviate the interference. Results also show that, as the cell density increases, the throughput gain of IARA goes up. When the radius is 400m, the performance gain is over 1.3Mbps per MS compared with the scheme in [7], while the gain is less than 0.5Mbps per MS when the radius increases to 1900m. That is mainly because the scheme in [7] considers the interference as constant. Actually, as network density increases, the variation of the interference becomes more severe. Our scheme can capture such fluctuation while the scheme in [7] cannot. It is also observed that, the system performance growing speed increases as the network density raises. That is because the RS deployment introduces more cooperative gain as the network density increases, which alleviates the advantages of relay transmission.

Since the specific RSs are utilized in the network, the performance gain of edge MSs, which is the system performance bottleneck, is investigated to show the advantages of the dedicated RS deployment. In this scenario, the last 5 users in Fig.7, which are nearer to the BS, adopt the direct mode; The MSs which are at the edge of the BS adopt the relay mode, i.e., the first 3 users in Fig.7. It is clearly observed from Fig.7 that the average throughput of edge MSs which adopt the relay mode are enhanced more significantly than that of nearer MSs. That is generally due to the signaling amplification by the RSs as well as intelligent interference alleviation.

VI. CONCLUSION

In this paper a low-complexity joint subcarrier allocation, scheduling and power control scheme was proposed for OFDMA-based relay networks by considering the potential
interference among multiple neighboring cells. Since the original joint resource allocation problem is NP hard, in our scheme the allocation process was decoupled into two stages to reduce the complexity. In the first stage, the subcarrier and scheduling was conducted by local search. In the second stage, power allocation was operated for all of the allocated subcarriers. By leveraging geometric programming, we prove that optimal power control can be achieved under high SIR region. Simulation results show that by utilizing the proposed joint resource allocation scheme, the aggregated throughput of OFDMA-based relay networks can be improved by over 15% compared with the previous peer work while the complexity of the scheme is much lower than the centralized schemes.

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