A Joint Uplink/Downlink Resource Allocation Scheme in Wireless OFDMA Networks

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Abstract- With the increasing demand for interactive services, it is important to investigate joint uplink/downlink resource allocation scheme in wireless networks, because the performance of the interactive service is determined by uplink and downlink jointly. In this paper, we propose a joint uplink/downlink resource allocation (RA) scheme in wireless orthogonal frequency division multiple access (OFDMA) networks with interactive service. The proposed RA scheme consists of a data interaction mechanism and a joint uplink/downlink RA algorithm. In the data interaction mechanism for interactive service, the base station encodes the received data from the interactive users over individual uplink channels using network coding technique, and multicasts the processed information over the same downlink channels. In the proposed RA algorithm, the uplink and downlink resources are allocated jointly for the interactive service. Simulation results show that the proposed joint uplink/downlink RA scheme allocates the resources efficiently in wireless OFDMA networks.

Keywords: Joint uplink/downlink resource allocation; network coding; wireless OFDMA networks

1 INTRODUCTION

Along with the development of mobile service, interactive services with coupled quality requirements between the uplink and downlink, such as video conference, mobile gaming, and so on, have being become more and more popular.

For interactive service, the overall end user satisfaction depends on good quality in both directions of uplink and downlink. Hence, only improving the transmission quality of one direction is not enough. For example, when a user makes a call, the overall user satisfaction is low if the quality of service (QoS) of downlink session is good, while the QoS of uplink session is bad [1]. For interactive communication between two users via the base station (BS) in wireless networks, the close interaction between the uplink and downlink exists such that improving the QoS of uplink or downlink solely is meaningless [2]. Therefore, it is important to address the joint uplink/downlink communication scheme to improve the overall end user satisfaction in wireless networks.

The joint uplink/downlink resource allocation issue in wireless networks has been concerned in some literatures. In [1], based on the states of uplink and downlink, the concept of the overall user satisfaction is introduced. The resource allocation is formulated as an optimization problem, which is solved using the Lagrangian dual approach. However, the analysis is quite simple, and the wireless channel features are not considered. A joint uplink/downlink resource allocation scheme based on the link quality and delay is proposed in [2]. By jointly considering the time varying channel conditions in the uplink and downlink, the proposed algorithm prevents the resource from wasting. In [3], the joint uplink/downlink resource allocation is formulated as an optimization problem with the coupled constraint on the requirements of uplink and downlink rates. The proposed algorithm maximizes the system throughput, as well as minimizes the gap between the allocated uplink and downlink rates. Based on the work in [3], a resource allocation scheme modeled as a two-sided stable matching game is proposed in [4]. Authors in [5] proposed a joint uplink/downlink resource allocation algorithm, where the scheduling process in one direction is controlled by the delay information of the other direction. This algorithm achieves an constrained delay behavior of BS.

On the other hand, Ahlswede, *et al.*, first proposed the concept of network coding in [6], and proved theoretically that the routers mixed information in different messages to achieve multicast capacity. Owing to the broadcast feature of the medium, the network coding technique in wireless networks has broad application prospects and has been received wide attention in recent years. The coded bi-directional relaying is first proposed in [7]. By analyzing the channel capacity, authors proposed a resource allocation scheme, and proved that the proposed scheme can improve the system performance significantly. The resource allocation scheme with network coding for downlink two-user orthogonal frequency division multiple access (OFDMA) system was proposed in [8]. It is concluded that the network coding mechanism can reduce power consumption effectively.

In order to exert the advantage of joint uplink/downlink resource allocation and network coding, we propose a joint uplink/downlink resource allocation scheme in wireless OFDMA networks with the interactive service. In this scheme, the network coding technique is used to improve the downlink resource utilization for the interactive service. Considering interactive users within a cell exchanging data via BS, a bi-directional data interaction model based on network coding is set up. The joint uplink/downlink resource allocation is formulated as an optimization problem with the objective to maximize the system throughput. The formulated problem is solved by the dual decomposition method. Finally, we evaluate the performance of the proposed joint uplink/downlink resource allocation scheme by simulations.

The remainder of the paper is organized as follows. Section 2 introduces the system model and formulates the problem we aim to resolve. Section 3 presents the proposed solution for the problem formulated in section 2. The performance of the proposed scheme is evaluated and analyzed in section 4. Finally, we conclude the paper in section 5.

2 SYSTEM MODEL AND PROBLEM FORMULATION

2.1 System Model

We consider one cell in wireless FDD-OFDMA network, as shown in Fig. 1. There are M^{U} users using uplink, M^{D} users using downlink, where $2M$ users using both uplink and downlink form M pairs of interactive users via interactive links. If a user communicates over both a uplink and downlink with a uncoupling mode, we assume that one user only uses the uplink and another only uses the downlink in the system model. In other words, there are three types of users in the network, namely the users using uplink only, the users using downlink only and the interactive users using both uplink and downlink.

K^{U} and K^{D} subcarriers are allocated among users in the uplink with bandwidth B^{U} and the downlink with bandwidth B^{D}, respectively. The bandwidth of a subcarrier, $B^{\mathrm{U}}/K^{\mathrm{U}}$ or $B^{\mathrm{D}}/K^{\mathrm{D}}$, is small enough so that each subcarrier is assumed to experience flat-fading [9].

Furthermore, it is assumed that the BS has perfect knowledge of the channel state information (CSI) between BS and users, which enables BS to allocate available resources dynamically according to the service requirements and channel conditions. In literatures, the resource allocation schemes in the wireless OFDMA network can be classified into two categories, one is based on full CSI and another is based on partial CSI. In the resource allocation algorithms with full CSI, researchers focus on the resource allocation mechanisms and the theoretical performance. And in the resource allocation algorithms with partial CSI, researchers pay attention to the performance of these algorithms in the actual networks. In our work, we focus on the mechanism of the joint uplink/downlink resource allocation scheme in the wireless OFDMA network with interactive service. Hence, we assume that the BS has perfect knowledge of CSI and the difficulty of obtaining the CSI is not considered [10].

It is assumed that the noise is additive white Gaussian noise (AWGN) with the power spectral density N_0. Moreover, the impact of bit error rate (BER) and modulation coded scheme in the physical layer is assumed to be ignored.

2.2 Wireless OFDMA Channel Model

In the uplink, for user m and uplink subcarrier k, the channel gain is denoted as $h^{\mathrm{U}}_{m,k}$. The channel-to-noise ratio (CNR) of user m in uplink subcarrier k is $H^{\mathrm{U}}_{m,k}=\left|h^{\mathrm{U}}_{m,k}\right|^2\Big/\left(N_0B^{\mathrm{U}}/K^{\mathrm{U}}\right)$.

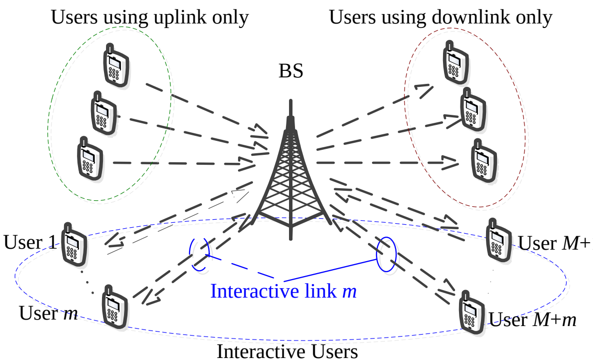


Figure 1: The structure diagram of a wireless network.

Let $\alpha^{\mathrm{U}}_{m,k}$ be the subcarrier allocation factor of user m in uplink subcarrier k. If uplink subcarrier k is allocated to user m, $\alpha^{\mathrm{U}}_{m,k}=1$; otherwise, $\alpha^{\mathrm{U}}_{m,k}=0$.

Let $p^{\mathrm{U}}_{m,k}$ be the power allocated to uplink subcarrier k by user m. Since $p^{\mathrm{U}}_{m,k}$ and $\alpha^{\mathrm{U}}_{m,k}$ are coupled, a new variable, $s^{\mathrm{U}}_{m,k}$ is introduced, and $s^{\mathrm{U}}_{m,k}=\alpha^{\mathrm{U}}_{m,k}p^{\mathrm{U}}_{m,k}$. Thereby, $s^{\mathrm{U}}_{m,k}$ and $\alpha^{\mathrm{U}}_{m,k}$ are decoupled [11].

The allocated rate is defined as the maximum achieved rate using the resource allocated by system. The allocated rate of user m in uplink subcarrier k, $C^{\mathrm{U}}_{m,k}$, is

$$C^{\mathrm{U}}_{m,k}=\frac{B^{\mathrm{U}}}{K^{\mathrm{U}}}\log_2\left(1+\frac{s^{\mathrm{U}}_{m,k}H^{\mathrm{U}}_{m,k}}{\alpha^{\mathrm{U}}_{m,k}}\right), m=1,2,...,M^{\mathrm{U}}, k=1,2,...,K^{\mathrm{U}}. \quad (1)$$

And the allocated uplink rate of user m, C^{U}_{m}, is

$$C^{\mathrm{U}}_{m}=\sum_{k=1}^{K^{\mathrm{U}}}\alpha^{\mathrm{U}}_{m,k}C^{\mathrm{U}}_{m,k}, m=1,2,...,M^{\mathrm{U}}. \quad (2)$$

In the downlink, for user m and downlink subcarrier k, the channel gain is denoted as $h^{\mathrm{D}}_{m,k}$. The CNR for user m in downlink subcarrier k is $H^{\mathrm{D}}_{m,k}=\left|h^{\mathrm{D}}_{m,k}\right|^2\Big/\left(N_0B^{\mathrm{D}}/K^{\mathrm{D}}\right)$.

Let $\alpha^{\mathrm{D}}_{m,k}$ be the subcarrier allocation factor of user m in downlink subcarrier k. If downlink subcarrier k is allocated to user m, $\alpha^{\mathrm{D}}_{m,k}=1$; otherwise, $\alpha^{\mathrm{D}}_{m,k}=0$.

Let $p^{\mathrm{D}}_{m,k}$ be the power allocated to user m in downlink subcarrier k by BS. Similarly, we introduce a new variable, and $s^{\mathrm{D}}_{m,k}=\alpha^{\mathrm{D}}_{m,k}p^{\mathrm{D}}_{m,k}$.

The allocated rate of user m in downlink subcarrier k, $C^{\mathrm{D}}_{m,k}$, is

$$C^{\mathrm{D}}_{m,k}=\frac{B^{\mathrm{D}}}{K^{\mathrm{D}}}\log_2\left(1+\frac{s^{\mathrm{D}}_{m,k}H^{\mathrm{D}}_{m,k}}{\alpha^{\mathrm{D}}_{m,k}}\right), m=1,2,...,M^{\mathrm{D}}, k=1,2,...,K^{\mathrm{D}}. \quad (3)$$

And the allocated downlink rate of user *m*, C_m^{D} , is

$$C_m^{\mathrm{D}} = \sum_{k=1}^{K^{\mathrm{D}}} \alpha_{m,k}^{\mathrm{D}} C_{m,k}^{\mathrm{D}}, m = 1, 2, ..., M^{\mathrm{D}} . \quad (4)$$

2.3 Network-coding-based Bi-directional Data Interaction Model for Interactive Service

In network-coding-based bi-directional communication for interactive service, a pair of interactive users exchange data via BS when they locate within a cell.

The flow diagram of network-coding-based bi-directional data interaction between users A and B is shown in Fig. 2. The interactive data exchange process works as follows.

Step I: Two interactive users transmit data X and Y to the BS through the uplink channels separately.

Step II: Receiving X and Y, the BS encodes X and Y, e.g., with an XOR bitwise operation, X ⊕ Y.

Step III: The BS multicasts encoded data, X ⊕ Y, to interactive users. For decoding at user A, a bitwise XOR operation of X ⊕ Y and X is performed to obtain Y. Another user performs the corresponding operation to obtain X.

The design of the network-coding-based bi-directional communication is based on two key principles.

(1). The broadcast property of radio is exploited to implement a one-to-many multicast communication.

(2). Network coding makes it possible to implement multicast communication in the downlink for interactive service. That is, the data from two interactive users are mixed at the BS before forwarding them. Users decode the mixed data independently.

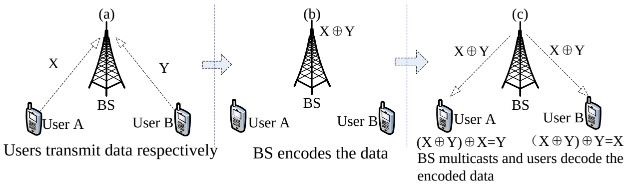
As shown in Fig. 1, user *m* and user *M*+*m* are a pair of interactive users of the interactive link *m*. That is, user *M*+*m* is the destination of user *m*, and vice versa. In this work, we only consider the interactive service with symmetric rate. However, the proposed approach here can be extended for generalized interactive service easily.

Due to the feature of symmetric interactive service, the maximum uplink rate of the interactive link *m*, R_m^{U} , is determined by the user with less allocated uplink rate. That is,

$$R_m^{\mathrm{U}} = \min\left\{C_m^{\mathrm{U}}, C_{M+m}^{\mathrm{U}}\right\}, m = 1, 2, ..., M . \quad (5)$$

In the downlink, the BS transmits encoded data to the pair of users of each interactive link by multicast. The downlink rate of interactive link *m* in downlink subcarrier *k* is determined by the user with less allocated downlink rate in this subcarrier. Hence, the maximum downlink rate of the interactive link *m*, R_m^{D} , is

$$R_m^{\mathrm{D}} = \sum_{k=1}^{K^{\mathrm{D}}} \min\left\{C_{m,k}^{\mathrm{D}}, C_{M+m,k}^{\mathrm{D}}\right\}, m = 1, 2, ..., M . \quad (6)$$



Users transmit data respectively

BS encodes the data

BS multicasts and users decode the encoded data

Figure 2: Network-coding-based bi-directional communication between interactive users.

When the BS encodes the data from two interactive users, massage padding of the shorter data packet is needed if two uplink data packets are unequal length. The length of encoded data packet equals to the length of longer data packet [12].

In addition, we assume that all users continue to send to or receive data and the data flows are continuous as similar as in [12]. In other words, data always exist in the cache of users and BS waiting for sending. And the impact of the flow dynamics on the resource allocation is not considered. To ensure the interactive users receiving and decoding data, the uplink allocated rate of interactive users should be less than the maximum downlink rate. Therefore, the interactive rate of the interactive link *m*, R_m, is determined by the minimum of the maximum uplink and downlink rate. That is,

$$R_m = \min\left\{R_m^{\mathrm{U}}, R_m^{\mathrm{D}}\right\} = \min\left\{C_m^{\mathrm{U}}, C_{M+m}^{\mathrm{U}}, R_m^{\mathrm{D}}\right\}, m = 1, 2, ..., M \ .(7)$$

For interactive users, the actual uplink and downlink rates equal to the interactive rate of interactive link. If the uplink and downlink allocated rates exceed to the interactive rate, resources will be wasted.

For non-interactive users, the actual uplink and downlink rates equal to the uplink and downlink allocated rates, respectively.

2.4 Problem Formulation

Each uplink subcarrier is exclusively allocated to no more than one user. Hence,

$$\sum_{m=1}^{M^{\mathrm{U}}} \alpha_{m,k}^{\mathrm{U}} \le 1,\ \alpha_{m,k}^{\mathrm{U}} \in \{0, 1\},\ k = 1, 2, ..., K^{\mathrm{U}} . \quad (8)$$

Let P_m be the maximum power budget of user *m*. We have

$$\sum_{k=1}^{K^{\mathrm{U}}} s_{m,k}^{\mathrm{U}} \le P_m,\ m\text{=}1,2,...,M^{\mathrm{U}} . \quad (9)$$

For interactive service, BS transmits the encoded data to interactive users by multicast. Therefore, the downlink subcarriers allocated to the users of each interactive link are identical. That is,

$$\alpha_{m,k}^{\mathrm{D}} = \alpha_{M+m,k}^{\mathrm{D}},\ m\text{=}1,2,...,M,\ k = 1, 2, ..., K^{\mathrm{D}} . \quad (10)$$

In the downlink of traditional wireless OFDMA networks, each downlink subcarrier is exclusively allocated to no more than one user. However, in our proposed scheme, the downlink subcarriers can be are allocated to the two users of one interactive link simultaneously. Hence,

$$\sum_{m=M+1}^{M^{\mathrm{D}}} \alpha_{m,k}^{\mathrm{D}} \le 1,\ \alpha_{m,k}^{\mathrm{D}} \in \{0,1\},\ k = 1,2,\ldots,K^{\mathrm{D}}\ . \tag{11}$$

Let P_{BS} be the maximum power of BS. We have

$$\sum_{m=M+1}^{M^{\mathrm{D}}} \sum_{k=1}^{K^{\mathrm{D}}} s_{m,k}^{\mathrm{D}} \le P_{\mathrm{BS}}\ . \tag{12}$$

Define the system throughput be the sum of allocated uplink and downlink rates of all users. Considering the interactive service, the uplink and downlink resources should be allocated jointly to maximize the system throughput.

Therefore, the joint uplink/downlink resource allocation problem in the wireless OFDMA network with the interactive service can be formulated as

$$\begin{aligned} &\max_{\{s_{m,k}^{\mathrm{U}}, s_{m,k}^{\mathrm{D}}, \alpha_{m,k}^{\mathrm{U}}, \alpha_{m,k}^{\mathrm{D}}\}} \left(4\sum_{m=1}^{M} R_m + \sum_{m=2M+1}^{M^{\mathrm{U}}} C_m^{\mathrm{U}} + \sum_{m=2M+1}^{M^{\mathrm{D}}} C_m^{\mathrm{D}} \right) \\ &\text{s.t. C1: } \sum_{m=1}^{M^{\mathrm{U}}} \alpha_{m,k}^{\mathrm{U}} \le 1,\ \alpha_{m,k}^{\mathrm{U}} \in \{0,1\},\ k = 1,2,\ldots,K^{\mathrm{U}} \\ &\quad \text{C2: } \sum_{k=1}^{K^{\mathrm{U}}} s_{m,k}^{\mathrm{U}} \le P_m,\ m=1,2,\ldots,M^{\mathrm{U}} \qquad , \\ &\quad \text{C3: } \sum_{m=M+1}^{M^{\mathrm{D}}} \alpha_{m,k}^{\mathrm{D}} \le 1,\ \alpha_{m,k}^{\mathrm{D}} \in \{0,1\},\ k = 1,2,\ldots,K^{\mathrm{D}} \\ &\quad \text{C4: } \alpha_{m,k}^{\mathrm{D}} = \alpha_{M+m,k}^{\mathrm{D}},\ m=1,2,\ldots,M,\ k = 1,2,\ldots,K^{\mathrm{D}} \\ &\quad \text{C5: } \sum_{m=M+1}^{M^{\mathrm{D}}} \sum_{k=1}^{K^{\mathrm{D}}} s_{m,k}^{\mathrm{D}} \le P_{\mathrm{BS}} \end{aligned} \tag{13}$$

where C1 and C2 are the subcarriers and power allocation constraints of the uplink, respectively. C3 and C5 are the subcarriers and power constraints of the downlink, respectively. And C4 is the subcarriers allocation constraint of downlink for the interactive users.

3 PROBLEM SOLUTION

Obviously, the problem formulated in (13) is a mixed integer nonlinear programming problem. By introducing new variables, the problem can be formulated into a convex optimization problem [13]. That is

$$\begin{aligned} &\max_{\{s_{m,k}^{\mathrm{U}}, s_{m,k}^{\mathrm{D}}, \alpha_{m,k}^{\mathrm{U}}, \alpha_{m,k}^{\mathrm{D}}\}} \left(4\sum_{m=1}^{M} t_m + \sum_{m=2M+1}^{M^{\mathrm{U}}} C_m^{\mathrm{U}} + \sum_{m=2M+1}^{M^{\mathrm{D}}} C_m^{\mathrm{D}} \right) \\ &\text{s.t. C1\textasciitilde C5 in eq. (13)} \\ &\quad \text{C6: } t_m \le C_m^{\mathrm{U}},\ m = 1,2,\ldots,M \qquad . \\ &\quad \text{C7: } t_m \le C_{M+m}^{\mathrm{U}},\ m = 1,2,\ldots,M \\ &\quad \text{C8: } t_m \le R_m^{\mathrm{D}},\ m = 1,2,\ldots,M \end{aligned} \tag{14}$$

It is shown in [14] that the dual gap of resource allocation problem in multicarrier system is nearly zero if the number of subcarriers is sufficiently large. And the dual problem is convex regardless of the convexity of the primal problem, and it can be solved easily [15]. Therefore, the problem formulated in (14) can be solved by the dual decomposition method.

The Lagrange function of the problem is given as

$$\begin{aligned} L = &\sum_{m=1}^{M} t_m \left(4 - \lambda_m^{\mathrm{U}} - \lambda_{M+m}^{\mathrm{U}} - \lambda_m^{\mathrm{D}}\right) + \sum_{m=1}^{M^{\mathrm{U}}} \sum_{k=1}^{K^{\mathrm{U}}} \alpha_{m,k}^{\mathrm{U}} f^{\mathrm{U}}\left(s_{m,k}^{\mathrm{U}}\right) \\ &+ \sum_{m=M+1}^{M^{\mathrm{D}}} \alpha_{m,k}^{\mathrm{D}} f^{\mathrm{D}}\left(s_{m,k}^{\mathrm{D}}\right) + \sum_{m=1}^{M^{\mathrm{U}}} \mu_m^{\mathrm{U}} P_m + \mu^{\mathrm{D}} P_{\mathrm{BS}} \end{aligned} ,\tag{15}$$

where λ_m^{U} , λ_m^{D} , μ_m^{U} , μ^{D} are the Lagrange multipliers. And

$$f^{\mathrm{U}}\left(s_{m,k}^{\mathrm{U}}\right) = \begin{cases} \lambda_m^{\mathrm{U}} C_{m,k}^{\mathrm{U}} - \mu_m^{\mathrm{U}} \dfrac{s_{m,k}^{\mathrm{U}}}{\alpha_{m,k}^{\mathrm{U}}}, m = 1,2,\ldots,2M \\ C_{m,k}^{\mathrm{U}} - \mu_m^{\mathrm{U}} \dfrac{s_{m,k}^{\mathrm{U}}}{\alpha_{m,k}^{\mathrm{U}}}, m = 2M+1,\ldots,M^{\mathrm{U}} \end{cases} , \tag{16}$$

and

$$f^{\mathrm{D}}\left(s_{m,k}^{\mathrm{D}}\right) = \begin{cases} \lambda_{m-M}^{\mathrm{D}} \min\left\{C_{m,k}^{\mathrm{D}}, C_{m-M,k}^{\mathrm{D}}\right\} - \mu^{\mathrm{D}} \dfrac{s_{m-M,k}^{\mathrm{D}}}{\alpha_{m-M,k}^{\mathrm{D}}}, m = M+1,\ldots,2M \\ C_{m,k}^{\mathrm{D}} - \mu^{\mathrm{D}} \dfrac{s_{m,k}^{\mathrm{D}}}{\alpha_{m,k}^{\mathrm{D}}}, m = 2M+1,\ldots,M^{\mathrm{D}} \end{cases} .\tag{17}$$

The dual problem of (14) is given by

$$\min_{\left\{\lambda_m^{\mathrm{U}}, \lambda_m^{\mathrm{D}}, \mu_m^{\mathrm{U}}, \mu^{\mathrm{D}}\right\}} D , \tag{18}$$

where is D the Lagrange dual function as

$$D = \max_{\left\{s_{m,k}^{\mathrm{U}}, s_{m,k}^{\mathrm{D}}, \alpha_{m,k}^{\mathrm{U}}, \alpha_{m,k}^{\mathrm{D}}, t_m\right\}} L\ . \tag{19}$$

Taking the derivative of L with respect to t_m and setting it to be zero yields

$$4 - \lambda_m^{\mathrm{U}} - \lambda_{M+m}^{\mathrm{U}} - \lambda_m^{\mathrm{D}} = 0,\ m = 1,2,\ldots,M\ . \tag{20}$$

Hence, the Lagrange dual function, D, is equivalent to

$$D = \max_{\left\{s_{m,k}^{\mathrm{U}}, \alpha_{m,k}^{\mathrm{U}}\right\}} \sum_{m=1}^{M^{\mathrm{U}}} \sum_{k=1}^{K^{\mathrm{U}}} \alpha_{m,k}^{\mathrm{U}} f^{\mathrm{U}}\left(s_{m,k}^{\mathrm{U}}\right) + \max_{\left\{s_{m,k}^{\mathrm{D}}, \alpha_{m,k}^{\mathrm{D}}\right\}} \sum_{m=M+1}^{M^{\mathrm{D}}} \sum_{k=1}^{K^{\mathrm{D}}} \alpha_{m,k}^{\mathrm{D}} f^{\mathrm{D}}\left(s_{m,k}^{\mathrm{D}}\right) . \tag{21}$$

The problem (21) can be decomposed into the uplink sub-problem and the downlink sub-problem. As $\alpha_{m,k}^{\mathrm{U}}$ and $s_{m,k}^{\mathrm{U}}$ are decoupled, the uplink sub-problem can be formulated as

$$\max_{\left\{s_{m,k}^{\mathrm{U}}, \alpha_{m,k}^{\mathrm{U}}\right\}} \sum_{m=1}^{M^{\mathrm{U}}} \sum_{k=1}^{K^{\mathrm{U}}} \alpha_{m,k}^{\mathrm{U}} f^{\mathrm{U}}\left(s_{m,k}^{\mathrm{U}}\right) = \max_{\left\{\alpha_{m,k}^{\mathrm{U}}\right\}} \sum_{m=1}^{M^{\mathrm{U}}} \sum_{k=1}^{K^{\mathrm{U}}} \max_{\left\{s_{m,k}^{\mathrm{U}}\right\}} \alpha_{m,k}^{\mathrm{U}} f^{\mathrm{U}}\left(s_{m,k}^{\mathrm{U}}\right) . \tag{22}$$

The inner maximization of (22) is over the set of allocated power. Hence, we obtain the optimal value as

$$p^{*\mathrm{U}}_{m,k} = \max_{\left\{s^{\mathrm{U}}_{m,k} \ge 0\right\}} \alpha^{\mathrm{U}}_{m,k} f^{\mathrm{U}}\left(s^{\mathrm{U}}_{m,k}\right). \tag{23}$$

Taking the derivative of $f^{\mathrm{U}}\left(s^{\mathrm{U}}_{m,k}\right)$ with respect to $s^{\mathrm{U}}_{m,k}$, and setting them to be zero yields

$$p^{*\mathrm{U}}_{m,k} = \frac{s^{*\mathrm{U}}_{m,k}}{\alpha^{\mathrm{U}}_{m,k}} = \begin{cases} \left[\dfrac{\lambda^{\mathrm{U}}_m}{\mu^{\mathrm{U}}_m \ln 2} - \dfrac{1}{H^{\mathrm{U}}_{m,k}}\right]^+, m = 1,2,\ldots,2M \\ \left[\dfrac{1}{\mu^{\mathrm{U}}_m \ln 2} - \dfrac{1}{H^{\mathrm{U}}_{m,k}}\right]^+, m = 2M+1,\ldots,M^{\mathrm{U}} \end{cases} ,(24)$$

where $[x]^+ = \max\{0, x\}$.

The subcarrier allocation solution is obtained by considering the outer maximization of (22). That is,

$$\alpha^{*\mathrm{U}}_{m,k} = \max_{\left\{\alpha^{\mathrm{U}}_{m,k}\right\}} \sum_{m=1}^{M^{\mathrm{U}}} \sum_{k=1}^{K^{\mathrm{U}}} \alpha^{\mathrm{U}}_{m,k} f^{\mathrm{U}}\left(s^{*\mathrm{U}}_{m,k}\right). \tag{25}$$

Note that each uplink subcarrier is exclusively allocated to no more than one user anytime. Hence,

$$\sum_{m=1}^{M^{\mathrm{U}}} \sum_{k=1}^{K^{\mathrm{U}}} \alpha^{\mathrm{U}}_{m,k} f^{\mathrm{U}}\left(s^{*\mathrm{U}}_{m,k}\right) \le \sum_{k=1}^{K^{\mathrm{U}}} \arg\max_{m} f^{\mathrm{U}}\left(s^{*\mathrm{U}}_{m,k}\right). \tag{26}$$

Therefore, $\alpha^{\mathrm{U}}_{m,k}$ is obtained for each subcarrier k by finding the user m to maximize $f^{\mathrm{U}}\left(s^{*\mathrm{U}}_{m,k}\right)$. That is,

$$\alpha^{*\mathrm{U}}_{m,k} = \begin{cases} 1\text{ , if } k = \arg\max\limits_{m} f^{\mathrm{U}}\left(s^{*\mathrm{U}}_{m,k}\right) \\ 0\text{ , otherwise} \end{cases}. \tag{27}$$

Similarly, the optimal power and subcarriers allocation in the downlink are obtained as

$$p^{*\mathrm{D}}_{m,k} = \begin{cases} \left[\dfrac{\lambda^{\mathrm{D}}_{m-M}}{\mu^{\mathrm{D}} \ln 2} - \dfrac{1}{\min\left\{H^{\mathrm{D}}_{m,k}, H^{\mathrm{D}}_{m-M,k}\right\}}\right]^+, m = M+1,\ldots,2M \\ \left[\dfrac{1}{\mu^{\mathrm{D}} \ln 2} - \dfrac{1}{H^{\mathrm{D}}_{m,k}}\right]^+, m = 2M+1,\ldots,M^{\mathrm{D}} \end{cases} ,(28)$$

and

$$\alpha^{*\mathrm{D}}_{m,k} = \begin{cases} 1\text{ , if } k = \arg\max\limits_{m} f^{\mathrm{D}}\left(s^{*\mathrm{D}}_{m,k}\right) \\ 0\text{ , otherwise} \end{cases}. \tag{29}$$

Substituting (24), (27), (28) and (29) into (18), we obtain the dual problem of (14) is

$$\begin{aligned} \min_{\left\{\lambda^{\mathrm{U}}_m, \lambda^{\mathrm{D}}_m, \mu^{\mathrm{U}}_m, \mu^{\mathrm{D}}\right\}} & \left[\sum_{m=1}^{M^{\mathrm{U}}} \sum_{k=1}^{K^{\mathrm{U}}} \alpha^{*\mathrm{U}}_{m,k} f^{\mathrm{U}}\left(s^{*\mathrm{U}}_{m,k}\right) + \sum_{m=M+1}^{M^{\mathrm{D}}} \sum_{k=1}^{K^{\mathrm{D}}} \alpha^{*\mathrm{D}}_{m,k} f^{\mathrm{D}}\left(s^{*\mathrm{D}}_{m,k}\right) \right. \\ & \left. + \sum_{m=1}^{M^{\mathrm{U}}} \mu^{\mathrm{U}}_m P_m + \mu^{\mathrm{D}} P_{\mathrm{BS}} \right] \qquad .(30) \\ \text{s.t.} \quad & \lambda^{\mathrm{U}}_m + \lambda^{\mathrm{U}}_{M+m} + \lambda^{\mathrm{D}}_m = 4,\ m=1,2,\ldots,M \\ & \lambda^{\mathrm{U}}_m, \lambda^{\mathrm{D}}_m, \mu^{\mathrm{U}}_m, \mu^{\mathrm{D}} \ge 0,\ m=1,2,\ldots,M \end{aligned}$$

The problem formulated in (30) can be solved by sub-gradient algorithm by updating the Lagrange multipliers simultaneously along the sub-gradients of them. Because the problem is convex, the sub-gradient update algorithm is convergent.

The sub-gradients of the Lagrange multipliers are

$$\begin{aligned} \Delta\lambda^{\mathrm{U}}_m &= C^{\mathrm{U}}_m(\alpha^{*\mathrm{U}}_{m,k}, s^{*\mathrm{U}}_{m,k}) - R^{\mathrm{D}}_m(\alpha^{*\mathrm{D}}_{m,k}, s^{*\mathrm{D}}_{m,k}),\ m=1,2,\ldots,M \\ \Delta\lambda^{\mathrm{U}}_{M+m} &= C^{\mathrm{U}}_{M+m}(\alpha^{*\mathrm{U}}_{M+m,k}, s^{*\mathrm{U}}_{M+m,k}) - R^{\mathrm{D}}_m(\alpha^{*\mathrm{D}}_{m,k}, s^{*\mathrm{D}}_{m,k}),\ m=1,2,\ldots,M \\ \Delta\mu^{\mathrm{U}}_m &= P_m - \sum_{k=1}^{K^{\mathrm{U}}} s^{*\mathrm{U}}_{m,k},\ m = 1,2,\ldots,M^{\mathrm{U}} \\ \Delta\mu^{\mathrm{D}} &= P_{\mathrm{BS}} - \sum_{m=M+1}^{M^{\mathrm{D}}} \sum_{k=1}^{K^{\mathrm{D}}} s^{*\mathrm{D}}_{m,k} \end{aligned} ,(31)$$

where $C^{\mathrm{U}}_m(\alpha^{*\mathrm{U}}_{m,k}, s^{*\mathrm{U}}_{m,k})$, $C^{\mathrm{U}}_m(\alpha^{*\mathrm{U}}_{M+m,k}, s^{*\mathrm{U}}_{M+m,k})$ and $R^{\mathrm{D}}_m(\alpha^{*\mathrm{D}}_{m,k}, s^{*\mathrm{D}}_{m,k})$ are obtained by substituting (24), (27), (28) and (29) into (2), (4) and (6), respectively. And the Lagrange multipliers are updated as

$$\begin{aligned} \lambda^{\mathrm{U}(l+1)}_m &= \left[\lambda^{\mathrm{U}(l)}_m - \varsigma^{(l)}_1 \Delta\lambda^{\mathrm{U}(l)}_m\right]^+,\ m=1,2,\ldots,M \\ \lambda^{\mathrm{U}(l+1)}_{M+m} &= \left[\lambda^{\mathrm{U}(l)}_{M+m} - \varsigma^{(l)}_2 \Delta\lambda^{\mathrm{U}(l)}_{M+m}\right]^+,\ m=1,2,\ldots,M \\ \mu^{\mathrm{U}(l+1)}_m &= \left[\mu^{\mathrm{U}(l)}_m - \varsigma^{(l)}_3 \Delta\mu^{\mathrm{U}(l)}_m\right]^+,\ m = 1,2,\ldots,M^{\mathrm{U}} \\ \mu^{\mathrm{D}(l+1)} &= \left[\mu^{\mathrm{D}(l)} - \varsigma^{(l)}_4 \Delta\mu^{\mathrm{D}(l)}\right]^+ \end{aligned} , \tag{32}$$

where, l is the iteration number, $\varsigma^{(l)}_1$, $\varsigma^{(l)}_2$, $\varsigma^{(l)}_3$ and $\varsigma^{(l)}_4$ are the step size in the lth iteration.

Substituting the obtained optimal solution of Lagrange multipliers to (24), (27) and (28), we solve the optimal subcarriers and power allocation of original problem.

By decomposing at each iteration, we can decouple the design in uplink and downlink. In the uplink, there are K^{U} subcarriers to be allocated M^{U} users, and the computational complexity is O($K^{\mathrm{U}}M^{\mathrm{U}}$) per iteration. In the downlink, there are K^{D} subcarriers to be allocated to M pairs of interactive users and (M^{D}-2M) users, and the computational complexity is O(K^{D}(M^{D}-M)) per iteration. Hence, the total computational complex at each iteration is O($K^{\mathrm{U}}M^{\mathrm{U}}$+($M^{\mathrm{D}}$-$M$)$K^{\mathrm{D}}$). Therefore, the computational complexity of the proposed scheme is comparatively low.

4 SIMULATION RESULTS AND DISCUSSIONS

In this section, we will evaluate the proposed joint uplink/downlink resource allocation scheme with Monte Carlo simulations.

Table 1. Simulation Parameters

Parameters	**value**
Bandwidth of uplink/downlink, B^U/B^D	1 MHz
Number of uplink/downlink subcarriers, K^U/K^D	128
Power spectral density of AWGN, N_0	-174 dBm/Hz
Maximum power of users, P_m	0.125 W
Maximum power of BS, P_{BS}	2 W

It is assumed that the channel fading of each subcarrier follows an independent Rayleigh distribution. The channel gain is exponentially distributed, and the propagation loss is represented as $\kappa d_m^{-\chi}$ [16], where κ is a constant chosen to be −128.1dB, χ is the path loss exponent set to be 3.76, and d_m is the distance between user m to the BS. The other simulation parameters are listed in Table 1.

For comparison, the performances of the following three algorithms are given.

(1). The resource allocation algorithm is to maximize the throughput in the uplink and downlink directions independently, proposed in [10] and [17]. It is denoted as ‘Independent RA algorithm’.

(2). The resource allocation algorithm is to maximize the throughput in the uplink and downlink directions jointly. It is denoted as ‘Joint RA algorithm’.

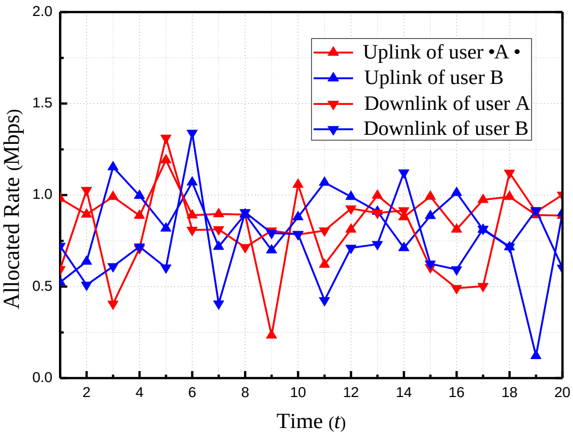
(3). The proposed resource allocation scheme is to maximize the throughput in the uplink and downlink directions jointly, where the network coding (NC) is used in the downlink multicast transmission for interactive service. It is denoted as ‘Joint RA algorithm with NC’.

From Fig. 3 to Fig. 6, it is assumed that 24 users are distributed in a circular cell. The first 8 users in uplink and downlink form 4 pairs of interactive users via 4 interactive links. And other 16 users are 8 users using uplink only and 8 users using downlink only, respectively.

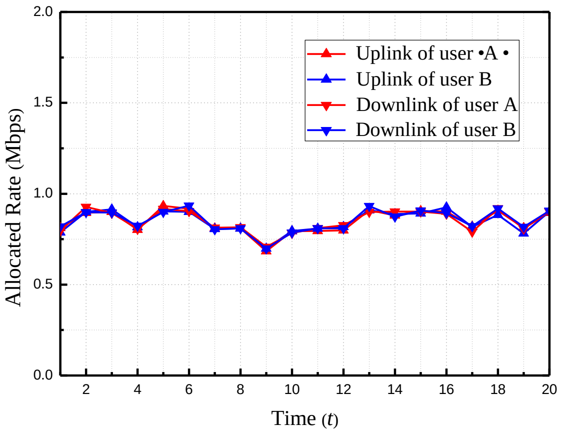
Figure 3 shows the comparison of the allocated uplink and downlink rates of a selected pair of interactive users using three resource allocation algorithms. The distances of all users to BS are 0.4 km, and the selected interactive users are denoted as user A and user B, respectively.

From Fig. 3(a), we observe that the allocated uplink and downlink rates of interactive users are independent each other. The system allocates resources according to the channel conditions for maximizing the uplink and downlink throughput. From Fig. 3(b) and 3(c), we observe that the allocated uplink and downlink rates of interactive users are fully coupled. The reason for this phenomenon is that Joint RA algorithm and Joint RA algorithm with NC minimize the gap between the uplink and downlink allocated rates of interactive users to save resources.

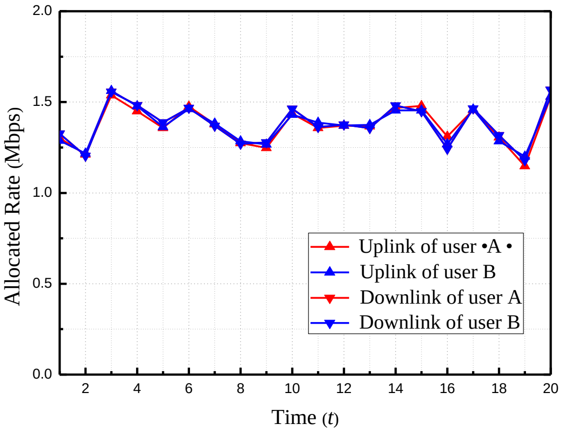
Moreover, comparing the results in Fig. 3(b) and 3(c), we observe that the allocated uplink and downlink rates of Joint RA algorithm with NC outperform Joint RA algorithm. The reason for this phenomenon is that Joint RA algorithm with NC improves the resource efficiency of downlink by network coding technique.



(a) Independent RA algorithm



(b) Joint RA algorithm



(c) Joint RA algorithm with NC

Figure 3: The comparison of the allocated uplink and downlink rates of a selected pair of interactive users.

Figure 4 shows the comparison of system throughput for three different algorithms, where the cell radius varies from 0.2 to 1.2 km, and all users are distributed uniformly.

From Fig. 4, we observe that, as the cell radius increases, the average channel condition of all users will deteriorate, and then the system throughput of three algorithms decreases. Moreover, due to fully coupling of the allocated uplink and downlink rates of each pair of interactive users, Joint RA algorithm and Joint RA algorithm with NC reduce the waste of the resource, and their system throughput

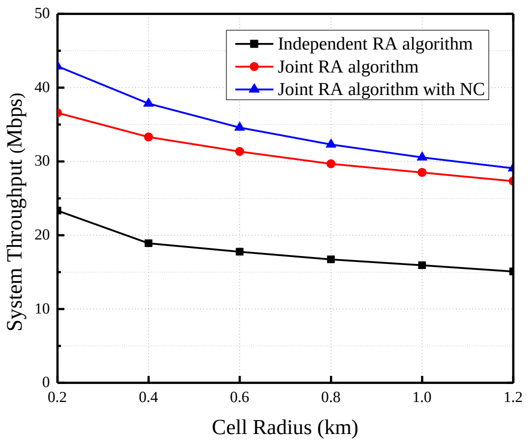


Figure 4: The comparison of the system throughput with different cell radius.

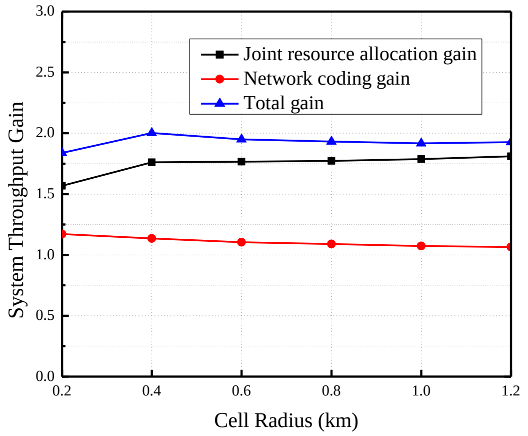


Figure 5: The comparison of the system throughput gain with different cell radius.

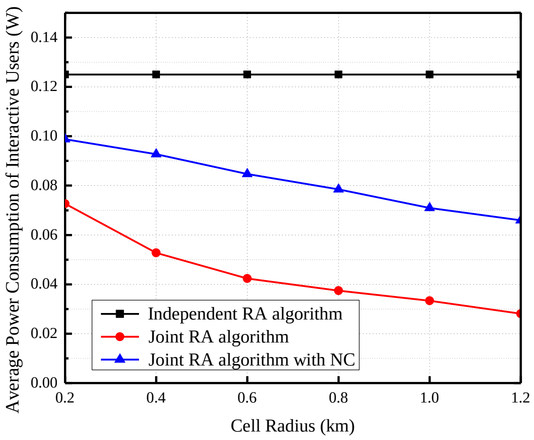


Figure 6: The comparison of average power consumption of interactive users.

outperforms that of Independent RA algorithm. However, owing to the network coding processing at BS, Joint RA algorithm with NC makes the resource utilization be more efficient, and achieves the largest system throughput among three RA algorithms.

In order to analyze the system throughput gain, Fig. 5 shows the comparison of the system throughput gain for three different algorithms, where the cell radius varies from 0.2 to 1.2 km.

The joint resource allocation gain is defined as the system throughput gain of Joint RA algorithm over Independent RA algorithm. The network coding gain is defined as the system throughput gain of Joint RA algorithm with NC over Joint RA algorithm. The total gain, which is the combined effect of both joint resource allocation gain and network coding gain, is defined as the system throughput gain of Joint RA algorithm with NC over Independent RA algorithm.

From Fig. 5, we observe that the joint resource allocation gain gradually increases as the cell radius increases. The reason for this phenomenon is that, as the cell radius increases, the average gap of channel conditions of each pair of interactive users will gradually increase and thereby, the advantage of joint uplink/downlink resource allocation schemes increases. To exploit the network coding advantage, it is preferable to encode the downlinks of each pair of interactive users with similar channel gains. For this reason, as the cell radius increases, the coding gain will gradually decreases, as shown in Fig. 5. Obviously, a tradeoff, between the joint resource allocation gain and network coding gain, is achieved. Hence, the total gain first increases, and then decreases along with the increase of cell radius, as shown in Fig. 5.

The average power consumption of interactive users is defined as the mean value of power consumption of all interactive users.

Figure 6 shows the comparison of the average power consumption of interactive users for three different RA algorithms, where the cell radius varies from 0.2 to 1.2 km.

From Fig. 6, we observe that, the average power consumption of interactive users of Joint RA algorithm and Joint RA algorithm with NC is lower than that of Independent RA algorithm. The reason for this phenomenon is that as the allocated uplink and downlink rates of each pair of interactive users are coupled in Joint RA algorithm and Joint RA algorithm with NC, the interactive users need not to allocate all power budget to subcarriers when the gap of the uplink and downlink channel conditions of each pair of interactive users are big enough.

Moreover, we also observe that the average power consumption of interactive users for Joint RA algorithm and Joint RA algorithm with NC decreases gradually as the cell radius increases. The reason for this phenomenon is that the system has more chance to save the power of interactive users since the average gap of channel conditions of each pair of interactive users gradually increases along with the increase of the cell radius.

In addition, due to the uplink rate of interactive users for Joint RA algorithm with NC outperforms that of Joint RA algorithm as shown in Fig. 3, the average power consumption of interactive users for Joint RA algorithm with NC also outperforms that of Joint RA algorithm, as shown in Fig. 6.

Figure 7 shows the comparison of the system throughput for three different RA algorithms as the number of interactive links, *M*, varies from 0 to 7, where the cell radius

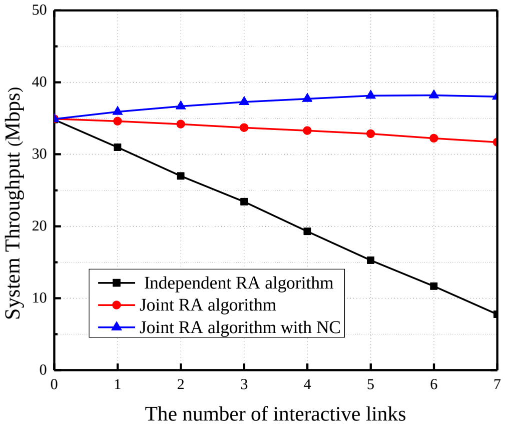


Figure 7: The comparison of the system throughput with different number of interactive links.

is 0.4 km. As the number of interactive links increases from 0 to 7, the number of users using uplink or downlink only decreases from 16 to 2.

As the number of interactive links increases, more and more users are influenced by the coupling constraint of the allocated uplink and downlink rates of each pair of interactive users. Hence, the system throughput of Independent RA algorithm and Joint RA algorithm decreases simultaneously. However, owing to the network coding processing at BS and the advantage of multicast in the downlink for the interactive users, the system throughput of Joint RA algorithm with NC gradually increases.

5 CONCLUSIONS

In this paper, we propose a joint uplink/downlink resource allocation scheme in wireless OFDMA networks with the interactive service. The proposed scheme consists of a bi-directional data interaction mechanism and a joint uplink/downlink resource allocation algorithm. In the data interaction mechanism, BS encodes the received data packets from two interactive users in individual uplink using the network coding technique, and multicasts the encoded data packet in the same downlink. In the proposed resource allocation algorithm for the interactive service, the uplink and downlink resources are allocated jointly to improve the system throughput, as well as considering the characteristic of interactive service.

Simulation results show that the performance of the proposed joint uplink/downlink resource allocation scheme, in terms of the system throughput and the power consumption of interactive users, outperforms other two resource allocation schemes.

In the future, we will investigate the joint uplink/downlink resource allocation problem for delay-sensitive interactive service in wireless networks.

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