

Radio Resource Management of CoMP System in HetNet under Power and Backhaul Constraints

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Received May 29, 2014; revised July 22, 2014; revised September 4, 2014; accepted October 1, 2014; published November 30, 2014

Abstract

Recently, Heterogeneous Network (HetNet) with Coordinated Multi-Point (CoMP) scheme is introduced into Long Term Evolution-Advanced (LTE-A) systems to improve digital services for User Equipments (UEs), especially for cell-edge UEs. However, Radio Resource Management (RRM), including Resource Block (RB) scheduling and Power Allocation (PA), in this scenario becomes challenging, due to the intercell cooperation. In this paper, we investigate the RRM problem for downlink transmission of HetNet system with Joint Processing (JP) CoMP (both joint transmission and dynamic cell selection schemes), aiming at maximizing weighted sum data rate under the constraints of both transmission power and backhaul capacity. First, joint RB scheduling and PA problem is formulated as a constrained Mixed Integer Programming (MIP) which is NP-hard. To simplify the formulation problem, we decompose it into two problems of RB scheduling and PA. For RB scheduling, we propose an algorithm with less computational complexity to achieve a suboptimal solution. Then, according to the obtained scheduling results, we present an iterative Karush-Kuhn-Tucker (KKT) method to solve the PA problem. Extensive simulations are conducted to verify the effectiveness and efficiency of the proposed algorithms. Two kinds of JP CoMP schemes are compared with a non-CoMP greedy scheme (max capacity scheme). Simulation results prove that the CoMP schemes with the proposed RRM algorithms dramatically enhance data rate of cell-edge UEs, thereby improving UEs' fairness of data rate. Also, it is shown that the proposed PA algorithms can decrease power consumption of transmission antennas without loss of transmission performance.

Keywords: Wireless cellular network, heterogeneous network (HetNet), coordinated multi-point (CoMP), joint processing (JP), radio resource management (RRM)

1. Introduction

To meet an ever-increasing number of demands for reliable and high rate transmission in cellular networks, 3rd Generation Partnership Project (3GPP) integrates several promising techniques into Long Term Evolution-Advanced (LTE-A) systems [1]. In addition to higher-order MIMO and carrier aggregation, Heterogeneous Network (HetNet) [2] is proposed as a new deployment strategy to eliminate coverage holes and improve data rate of macro cells. Different from traditional homogeneous network, the coverage area of a macro cell in HetNet is overlaid by multiple small cell sites (Pico, Femto, Remote Radio Head, etc.) distributed in multiple geographical locations. These small cell sites are physically or logically connected to a Control Unit (CU) that is usually embedded in an evolved Node B (eNB). Small cells perform wireless communications with User Equipments (UEs) instead of the eNB, which shortens the propagation distance, and thereby enables higher strengthen of signals. In an ideal scenario, this new deployment significantly improves the data rate of a macro cell. Unfortunately, the dense deployment of small cell sites may cause severe intercell interference, which degrades network performance in terms of transmission quality.

To combat with intercell interference, 3GPP introduces and standardizes Coordinated Multi-Point (CoMP) technique into LTE-A systems. The rationale behind CoMP is to make small cell sites cooperate with each other and work as a virtual MIMO system, such that signals are jointly processed with the help of the instantaneous Channel State Information (CSI). According to the methods dealing with interference, CoMP schemes are mainly grouped into two major categories [3]: Coordinated Scheduling/Coordinated Beamforming (CS/CB) and Joint Processing (JP). CS/CB scheme is dedicated to mitigating intercell interference via jointly scheduling and beamforming signals among small cells. One option of CS/CB scheme is well-known Dirty Paper Coding (DPC) [4] that is proved to be a capacity achieving strategy in MIMO broadcast channels [5]. However, it is complexity prohibitive to implement DPC in practice, because of its successive encodings and decodings at terminal antennas. By contrast, Zero-Forcing (ZF) [6], as a linear precoding method for joint signal processing, can significantly reduce the computational complexity. Nevertheless, in order to implement ZF precoding, the required number of receiver antennas should be no more than that of transmission antennas, which restricts available independent channels.

Different from CS/CB scheme, JP scheme intends to utilize dominating intercell interference to benefit desired transmissions. One way to do that is to allow a UE located in an overlapped area of several cells to select the cell with the best channel quality for transmission in each time slot. This method is named as Dynamic Cell Selection (DCS). Another typical JP scheme is referred to as Joint Transmission (JT) that enables multiple cells to simultaneously serve a specific UE. In this case, the UE can receive multiple versions of the desired signals from several spatially independent channels. With appropriate combining methods at UE end, the signal can be strengthened, so that transmission quality is improved in this way.

In addition to advanced transmission schemes of CoMP, Radio Resource Management (RRM), involving Resource Block (RB) scheduling and Power Allocation (PA), is also an effective method to alleviate intercell interference and improve network performance. RRM has been widely studied in single-cell scenario, where transmissions to different UEs are properly scheduled to improve system performance, and orthogonal channels are allocated to avoid intracell interference. Generally, RRM in single-cell scenario mainly focuses on achieving a local performance optimization, without consideration of intercell interference; in

HetNet, however, since multiple small cells are deployed densely, intercell interference is a non-negligible problem, which seriously affects system performance. Obviously, existing solutions to single-cell RRM are not efficacious any more.

Recently, RRM in multi-cell scenario has attracted much attention in the literature [7]-[9]. Compared with single-cell scenario, multi-cell scenario makes RRM more complicated in several aspects. First, although it is easy to be operated in practice, completely Orthogonal Frequency Division Multiplexing (OFDM) among cells is not suited in multi-cell scenario, due to the low frequency reuse factor. Thus, to reduce intercell interference, while maintaining high frequency spectrum efficiency, spectrum resources must be carefully scheduled. Second, joint resource management requests collecting and exchanging CSIs among small cell sites. The connections of small cells in HetNet are termed backhaul links, on which CSIs are collected and control information, as well as data packets, can be delivered by the CU. Many works assume that capacity of backhaul links is infinite, so that time delay on backhaul can be ignored [10][11]; however, backhaul capacity is actually limited and time delay severely affects the efficiency of RRM, which further leads to the decrease of the overall network performance [12]. Therefore, it is necessary to consider backhaul limitation, when discussing RRM in multi-cell scenario. In addition, RRM problem in multi-cell scenario is a Mixed Integer Programming (MIP), which is proved to be NP-hard. Thus, appropriate methods are necessary to be studied to simplify the problem and make it applicable in practice.

In this work, we focus on RRM in HetNet where JP CoMP (DCS or JT) is employed to improve network performance. For simplicity, all points equipped with transmission antennas in a single geographical location, including eNB and small cell sites, are referred to as Transmit Points (TPs) in the rest of this paper. Different from an ideal scenario, practical resource limitations are considered, involving transmission power at each TP and capacity of backhaul links connecting TPs, which makes the problem more complicated but practical. Since it is unrealistic to achieve globally optimal solution, we divide the formulated problem into an integer programming for RB scheduling and a continuous variable programming for PA. We solve the RB scheduling problem under the assumption of constant transmission power. Then, we substitute the obtained scheduling results into the PA problem, and solve the PA problem by an iterative Karush-Kuhn-Tucker (KKT) method. The final solution is suboptimal for the formulation, but it requests applicable computational effort and easy to be realized. Simulation results validate the effectiveness of the proposed algorithm. The major contributions of this paper are summarized as follows:

- We formulate RRM problem in HetNet with JP CoMP as an MIP problem. The formulation aims to maximize the overall weighted data rate, while taking into account constraints of both transmission power and backhaul capacity.
- To reduce computational complexity, we decompose the formulated problem into two parts: RB scheduling problem and PA problem.
- To solve RB scheduling problem, we propose an approach based on instantaneous CSI, under the assumption of constant power. DCS and JT schemes are considered separately.
- To solve PA problem, we propose an algorithm with the obtained RB scheduling solution. The proposed algorithm further divides the problem into independent sub-problems and solves each sub-problem by an iterative KKT method.

The rest of the paper is organized as follows. In Section 2, we describe the system model in detail. Then, mathematical formulation of the discussed problem is presented in Section 3. Section 4 and 5 propose approaches to the separated RB scheduling problem and PA problem,

respectively. We show simulation results in Section 6 and conclude our work in Section 7.

2. System Model

In this section, we introduce the considered a HetNet system, consisting of a CU located at the center and several TPs surrounding the CU, as shown in Fig.1. The system is assumed to be operated in Frequency Division Duplexing (FDD) mode, whereby uplink and downlink transmissions are conducted independently in different frequency bands. In this paper, we focus our discussions on downlink transmissions. All necessary CSIs are measured by UEs and sent back to the CU via dedicated uplink channels since FDD operation is considered.

Denote $\Pi = \{1, \dots, M\}$ as the set of all TPs. The CU is connected to TPs by backhaul links with limited capacity. All computation tasks about RRM is processed at the CU. After processing, control information, as well as data packets, will be sent from the CU to each TP before actual downlink transmissions. We assume that all TPs are perfectly synchronized in both time and phase thanks to the connections by backhaul links between CU and TPs.

There are totally K UEs in this macro cell located with the uniform distribution. In this paper, UEs are divided into two categories: cell-in UEs and cell-edge UEs, according to UEs' channel conditions. In LTE-A systems, the channel conditions are measured by reference signals (RSs) from TPs to UEs. For a cell-in UE, since it is most probably located near to a TP, the channel between them is outstanding quality, compared with the others. Therefore, there is an RS whose power level is much higher than RSs from any other TPs. As for a cell-edge UE, it receives several RSs with similar power levels. This situation indicates that the UE may suffer from interference caused by transmissions of neighboring TPs.

Before classifying cell-in UEs and cell-edge UEs formally, we need to introduce the concept of CoMP set. LTE-A systems allow UEs to decide a CoMP set, in which several TPs are selected as candidates to serve a specific UE. Denote Π_k as the CoMP set of UE k , and the rule of selecting Π_k is given as

$$\begin{cases} m \in \Pi_k & RS(\text{the strongest TP}) - RS(\text{TP } m) \leq \Delta_{\text{thres}} \\ m \notin \Pi_k & \text{otherwise} \end{cases}, \quad (1)$$

where RS indicates the strength of the reference signal, and Δ_{thres} is the threshold in dB, which can be changed to adjust the dimension of CoMP set. It is obvious that the smaller Δ_{thres} is, the more TPs will be added into CoMP set, which is beneficial for UEs to improve the transmission quality and data rate. However, overhead caused by cooperation among TPs in the set will increase consequently. Therefore, Δ_{thres} should be carefully decided as a system parameter. Although this is an interesting subject, it is out of the scope of our paper. Instead, we simply set the threshold to be 5 dB as suggested in [11].

Using the criterion described above, UE k measures all the received RSs and then decides the CoMP set $\Pi_k \in \Pi$. In specific, if $|\Pi_k|=1$, UE k is a cell-in UE, and Π_k includes its home TP only; whereas if $|\Pi_k| > 1$, UE k is a cell-edge UE.

According to the LTE-A standard, OFDM Access (OFDMA) is adopted in downlink systems, which splits the entire frequency bandwidth into several non-overlapping subcarriers. Twelve consecutive subcarriers for a duration of a Transmit Time Interval (TTI) consist of an RB. In this paper, we assume the total bandwidth is divided into N_{RB} RBs and is used at each TP with universal frequency reuse factor. The numbers of antennas at each TP and each UE

are denoted by N_T and N_R , respectively. In addition, we assume that the channel fading is quasi-static, so that channel fading remains constant during per TTI.

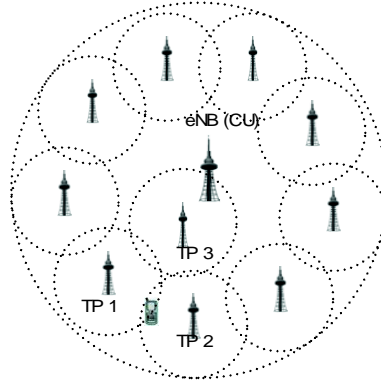


Fig. 1. System model

2.1 Non-CoMP Scenario

In multi-cell scenario, a downlink transmission is impacted by interference from the other signals transmitted simultaneously, especially when frequency is fully reused among cells. Since single user-MIMO (SU-MIMO) with OFDMA technology is considered in this paper, intracell interference is entirely removed. The signal received by UE k on the n th RB of TP m can be described as

$$\mathbf{y}_k^n = \mathbf{H}_{m,k}^n \mathbf{w}_m^n \sqrt{p_m^n} s_m^n + \sum_{m' \in \Pi \setminus \{m\}} \mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n \sqrt{p_{m'}^n} s_{m'}^n + \mathbf{n}_k^n \quad (2)$$

where $\mathbf{H}_{m,k}^n$ is an $N_R \times N_T$ channel matrix whose element $\mathbf{H}_{m,k}^n(i, j)$ denotes the channel coefficient between the j th antenna of TP m and the i th antenna of UE k on the n th RB; \mathbf{w}_m^n ($(\mathbf{w}_m^n)^H \mathbf{w}_m^n = 1$) is the $N_T \times 1$ dimension precoding vector which maps data stream s_m^n ($E[|s_m^n|] = 1$) onto the transmission antennas of TP m ; p_m^n is the power used by TP m for transmission on n th RB; $\mathbf{n}_k^n \sim CN(\mathbf{0}, \sigma^2 \mathbf{I}_{N_R})$ is the corresponding complex Gaussian noise vector; $\Pi \setminus \{m\}$ represents a subset of Π without the element m . The first term on the right of Eq. (2) denotes the intended signal arrived at the receiver, while the second term is the interference caused by simultaneous transmissions from other TPs.

The Signal-to-Interference-plus-Noise Ratio (SINR) of UE k on RB n is defined as follows,

$$\gamma_k^n = \frac{\|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 p_m^n}{\sum_{m' \in \Pi \setminus \{m\}} \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 p_{m'}^n + \sigma^2}. \quad (3)$$

According to the information theory, the data rate of UE k on RB n is

$$R_k^n = b \log(1 + \gamma_k^n), \quad (4)$$

where b is the bandwidth of each RB. In LTE-A systems, it is standardized to be 180kHz [13] [14].

As indicated in Eq. (3), the transmission quality of cell-edge UEs could be unfavorable, due to the low signal strength caused by long-distance propagation from the serving TP and severe intercell interference from neighboring TPs. JP CoMP schemes, as mentioned before, intend to

make use of the dominating interference to enhance the desired signal, which results in significant abatement of interference. Details will be discussed in the next subsection.

2.2 JP CoMP Scenario

As mentioned before, UEs select their own CoMP sets according to the strengthen of RSs under the rule given by Eq. (1), and then notify the results to the CU. The CoMP set Π_k is fixed once UE k enters the network. However, due to the variability of channels in time and frequency domains, it is not optimal to employ all TPs in CoMP sets for transmissions all the time. Therefore, we further define a transmission set for UEs on each RB, denoted by $\Omega_k^n, \forall k, n$, which is comprised of TPs selected to perform actual transmissions to UE k on the n th RB. Note that Ω_k^n is a subset of Π_k ($\Omega_k^n \subseteq \Pi_k$) and it varies on each RB.

2.2.1 DCS CoMP

When DCS scheme is employed, the TP in CoMP set Π_k with the best channel gain associated with UE k on RB n will be used for the data transmission, i.e., $|\Omega_k^n|=1$. The preferred TP varies on each RB due to time-variance of wireless channels. Compared with conventional cellular systems, the strength of signal arriving at UE k is potentially improved, thanks to the selection gain in DCS scheme. To decrease intercell interference on UE k , TPs in $\Pi_k \setminus \Omega_k^n$ ($\Pi_k \setminus \Omega_k^n$ denotes the relative complement of Ω_k^n with respect to Π_k) are not selected to transmit, but are forced to be silent on RB n . As a result, dominating interference is removed and transmission quality is improved. This scheme is known as DCS with muting [15].

Accordingly, signal received by UE k on the n th RB in DCS scheme can be written as

$$\mathbf{y}_k^n = \sum_{m \in \Omega_k^n} \beta_{m,k}^n \mathbf{H}_{m,k}^n \mathbf{w}_m^n \sqrt{p_m^n} s_m^n + \sum_{m' \in \Pi \setminus \Pi_k} \mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n \sqrt{p_{m'}^n} s_{m'}^n + \mathbf{n}_k^n, \quad (5)$$

and the corresponding SINR reads

$$\gamma_k^n = \frac{\sum_{m \in \Omega_k^n} \|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 p_m^n}{\sum_{m' \in \Pi \setminus \Pi_k} \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 p_{m'}^n + \sigma^2}. \quad (6)$$

Denote scheduling index set as $\{\beta_{m,k}^n\}$, where $\beta_{m,k}^n \in \{0,1\}, \forall m, k, n$. $\beta_{m,k}^n = 1$ indicates that TP m is chosen to transmit data signal to UE k on the n th RB in the current TTI. With scheduling indices, the transmission set can be denoted as $\Omega_k^n = \{m \mid \beta_{m,k}^n = 1, m \in \Pi_k\}, \forall k, n$ and the SINR in Eq. (6) can be further expressed as

$$\gamma_k^n = \frac{\sum_{m \in \Pi} \beta_{m,k}^n \|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 p_m^n}{\sum_{m' \in \Pi \setminus \Pi_k} (1 - \beta_{m',k}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 p_{m'}^n + \sigma^2}. \quad (7)$$

As expressed above, in DCS CoMP, UE k receives a single version of data signal from the selected TP, thus $\sum_{m \in \Pi_k} \beta_{m,k}^n = 1$. As shown in Eq. (7), interference in this scheme is only caused by TPs out of CoMP set Π_k (i.e., TPs in $\Pi \setminus \Pi_k$). Thus, the interference strength is not as significant as that in traditional systems without CoMP schemes.

2.2.2 JT CoMP

Different from DCS scheme, JT CoMP allows several TPs in a UE's CoMP set to simultaneously transmit the desired data signal. Due to spatial separation of transmission antennas, multiple versions of the desired signal will be received by the UE from independent channels, which generates extra spatial diversity gain. Thus, signal strength is further enhanced in this way. On the other hand, potential intercell interference can be mitigated, since partial interference sources are utilized to send data signals. As a consequence, transmission quality can be remarkably improved.

The original idea of JT CoMP scheme is to require all TPs in a CoMP set to transmit signals simultaneously, regardless of frequency selectivity of channels, i.e., $\Omega_k^n = \Pi_k, \forall k, n$. However, fixed transmission set restricts the performance of JT CoMP (This is proved by our simulation results shown in Section 6). In this paper, we adopt Dynamic JT (DJT) scheme, which selects a proper transmission set for a UE from its CoMP set, according to CSIs on each RB. Specifically, Ω_k^n is dynamically determined on each RB and $1 \leq |\Omega_k^n| \leq |\Pi_k|$.

Similarly, signal model of DJT CoMP transmission can be described as follows:

$$\mathbf{y}_k^n = \sum_{m \in \Omega_k^n} \mathbf{H}_{m,k}^n \mathbf{w}_m^n \sqrt{p_m^n} s_m^n + \sum_{m' \in \Pi \setminus \Omega_k^n} \mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n \sqrt{p_{m'}^n} s_{m'}^n + \mathbf{n}_k^n. \quad (8)$$

The expression of SINR corresponding to the transmission in Eq. (8) is

$$\gamma_k^n = \frac{\sum_{m \in \Omega_k^n} \|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 p_m^n}{\sum_{m' \in \Pi \setminus \Omega_k^n} \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 p_{m'}^n + \sigma^2} = \frac{\sum_{m \in \Pi} \beta_{m,k}^n \|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 p_m^n}{\sum_{m' \in \Pi} (1 - \beta_{m',k}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 p_{m'}^n + \sigma^2}. \quad (9)$$

Although some interference are potentially retained in DJT CoMP, compared with DCS muting method, UEs' SINRs can still be improved due to the enhanced signal strength caused by spatial diversity gain.

Summarily, both DCS and DJT methods intend to strengthen signal and mitigate intercell interference by mean of UEs CoMP sets. Eqs. (7) and (9) prove that UE's communication quality is improved by JP CoMP compared with traditional system.

3. Problem Formulation

In this section, we mathematically formulate the RRM problem in HetNet with JP CoMP. In order to improve system performance, it is necessary to properly allocate RBs and power to each transmission, as well as to select UEs' transmission set Ω_k^n . Generally, to maximize overall data rate, more resource should be allocated to UEs with better channel quality, while other UEs are ignored as the well-known greedy algorithm; however, this algorithm is unfair, and cell-edge UEs in bad conditions experience unsatisfactory transmission performance. To this end, we construct the objective function as the sum of weighted UEs' data rate, so that fairness among UEs can be maintained to a certain extent. In addition, from practical consideration, we also deliberate resource constraints of backhaul capacity and transmission power in the formulation.

3.1 Objective Function

The objective of the proposed formulation is to maximize the sum of UEs' utility functions. To

guarantee UEs' fairness, we weight R_k with the time average of data rate of UE k , and define the weighted data rate as utility function $f_k^n(\beta_{m,k}^n, p_m^n)$. The objective function is constructed as the sum of weighted data rates, which can be expressed as

$$\max \sum_{k=1}^K \sum_{n=1}^{N_{RB}} f_k^n(\beta_{m,k}^n, p_m^n) = \max \sum_{k=1}^K \sum_{n=1}^{N_{RB}} \frac{R_k^n}{\bar{R}_k} \quad (10)$$

In this expression, \bar{R}_k is defined as the time average of data rate of UE k

$$\bar{R}_k = \alpha \bar{R}_k^{\text{before}} + (1 - \alpha) R_k \quad (11)$$

where $\bar{R}_k^{\text{before}}$ denotes the average data rate of UE k before current TTI. It refers to a cumulative mean value of data rate of UE k ; R_k is the data rate in the current TTI, which can be obtained by $R_k = \sum_{n=1}^{N_{RB}} R_k^n$; α is a forgetting factor to balance the influence of weights between $\bar{R}_k^{\text{before}}$ and R_k . Weighting instantaneous data rate R_k^n by $1/\bar{R}_k$, we can improve the fairness among all UEs. The rationale is that the UE with lower \bar{R}_k in the past transmission will have more opportunities to assign RB n [19]. To measure fairness of UEs' data rates formally, we use fairness factor defined in [16]

$$F = \left(\sum_{k=1}^K R_k \right)^2 / K \sum_{k=1}^K R_k^2 \quad (12)$$

Obviously, F is in the range of $[0,1]$ and $F=1$ indicates an absolutely fair situation.

3.2 Power and Backhaul Constraints

To make the formulation more practical, several limitations are considered in this paper. The crucial one is backhaul limitation, which restricts the data rate of each TP. Delays of transmissions of control information and data packets via backhaul links should be tolerable to ensure the effectiveness of the system. In the considered system, the delay must be much less than a TTI. Due to the limited capacity, traffic load on backhaul links need to be restricted.

Since data packets are much more voluminous than control information, we just consider data traffic as backhaul load. Let Λ_m denotes the set of UEs served by TP m . The data packets transmitted by TP m are limited by backhaul capacity. Denote the capacity of backhaul link between the CU and TP m by C_m . The cooresponding constraint can be expressed as

$$\sum_{k \in \Lambda_m} R_k = \sum_{n=1}^{N_{RB}} \sum_{k \in \Lambda_m} \beta_{m,k}^n R_k^n \leq C_m \quad (13)$$

In addition to the constraint on backhaul capacity, limited transmission power at each TP is also considered. Let p_m^n be the transmission power used by TP m on RB n . We assume that p_m^n is bounded by zero and a given positive value S_m^n .

3.3 Formulation

By jointly considering the objective function and constraints above, we formulate the proposed RRM problem in HetNet system as follows:

$$\begin{aligned}
& \max_{\beta_{m,k}^n, p_m^n} && \sum_{k=1}^K \sum_{n=1}^{N_{\text{RB}}} \frac{R_k^n}{\bar{R}_k} \\
\text{s.t.} & \text{C1: } && \beta_{m,k}^n \in \{0,1\}, \text{ and } \sum_{k=1}^K \beta_{m,k}^n \leq 1, \quad \forall m,n,k \\
& \text{C2: } && 0 \leq p_m^n \leq S_m^n, \quad \forall m,n, \\
& \text{C3: } && \sum_{n=1}^{N_{\text{RB}}} \sum_{k \in \Lambda_m} \beta_{m,k}^n R_k^n \leq C_m, \quad \forall m.
\end{aligned} \tag{14}$$

The solutions to Eq. (14) is to approach optimal power allocation (p_m^n) and scheduling index set ($\beta_{m,k}^n$), which maximize the sum of weighted data rate under the constraints C1-C3.

C1 ensures each index $\beta_{m,k}^n$ to be a bit number, such that on each RB, each TP can serve no more than one UE; C2 and C3 demonstrate the constraints on transmission power and backhaul capacity, respectively.

The proposed formulation is an MIP, which is proved to be NP-hard and impossible to achieve the optimal solution in polynomial time. In this paper, we aim to find out an algorithm to obtain a suboptimal solution to Eq. (14) with low computational complexity. The principle of the proposed algorithm is to separate Eq. (14) into an RB scheduling problem with the assumption of constant transmission power, and a PA problem with the obtained scheduling indices. Details of the proposed algorithm are given in the following sections.

4. RB Scheduling Problem

As mentioned before, C2 in Eq. (14) imposes the power constraint on the resource allocation problem. To obtain a suboptimal solution $\beta_{m,k}^n, \forall m,k,n$ of the proposed formulation, i.e. the selection of transmission set Ω_k^n for each UE on each RB, we discuss the RB scheduling problem with fixed transmission power at the first place. It is reasonable to set all transmission power p_m^n to its maximum S_m^n . For simplicity, we assume that $S_m^n = S \geq 0, \forall m,n$. Therefore, the RB scheduling problem can be written as

$$\begin{aligned}
& \max_{\beta_{m,k}^n} && \sum_{k=1}^K \sum_{n=1}^{N_{\text{RB}}} \frac{R_k^n}{\bar{R}_k} \\
\text{s.t.} & \text{C4: } && \beta_{m,k}^n \in \{0,1\}, \text{ and } \sum_{k=1}^K \beta_{m,k}^n \leq 1, \quad \forall m,n,k \\
& && p_m^n = S, \quad \forall m,n \\
& \text{C5: } && \sum_{n=1}^{N_{\text{RB}}} \sum_{k \in \Lambda_m} \beta_{m,k}^n R_k^n \leq C_m, \quad \forall m.
\end{aligned} \tag{15}$$

The straightforward method is to test every possible solution of $\{\beta_{m,k}^n\}$, and find the optimal one to maximize the objective function, as well as meeting all the constraints. This search algorithm requests enormous effort of calculation. In this paper, we propose two search methods with lower computation complexity for DCS and DJT schemes, respectively. The detailed search processes are described in the rest of this section.

4.1 Searching Method for DCS Scheme

Step One: This step aims at deciding the scheduling index set that satisfies constraint C4 in Eq.

(15). Consider UE k in Λ_m , its estimated data rate on the n th RB is given as

$$\tilde{R}_k^{n(\text{DCS})} = b \log \left(1 + \frac{\|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 S}{\sum_{m' \in \Pi \setminus \Pi_k} \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S + \sigma^2} \right). \quad (16)$$

Then, the proposed algorithm searches Λ_m to find the UE with the largest utility function, i.e.

$$k' = \arg \max_{k \in \Lambda_m} \left(\tilde{R}_k^{n(\text{DCS})} / \bar{R}_k \right), \quad (17)$$

where \bar{R}_k is given in Eq. (11). After the searching, k' is determined, and as a result, $\beta_{m,k'}^n$ is set to 1, while $\beta_{m,k}^n (\forall k \neq k')$ are set to 0. Then, a coarse scheduling result can be obtained after accomplishing the search for each RB of all TPs.

Step Two: The result from *Step One* satisfies C4 of Eq. (15). The *Step Two* then, is aiming at restricting the data traffic of each TP to its backhaul constraint. If the total data traffic of a TP is larger than its capacity of backhaul link to the CU, partial traffic should be suspended in order to guarantee effectiveness of the system.

Consider the Signal-to-Leaking-plus-Noise Ratio (SLNR) of each transmission defined as

$$SLNR_{m,k}^n = \frac{\|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 S}{\sum_{k=1; k' \neq k}^K \|\mathbf{H}_{m,k'}^n \mathbf{w}_m^n\|^2 S + \sigma^2}. \quad (18)$$

The expression of SLNR implies the ratio of signal strength to interference caused by the transmission to other UEs. In the proposed algorithm, TP m shuts the transmission with the lowest SLNR, when the traffic on backhaul link is beyond its capacity. The two-step searching method for the DCS scheme is summarize in Algorithm 1.

Algorithm 1 DCS Scheduling Algorithm

Output: The scheduling index set.

% Step One

1: for $n=1: N_{\text{RB}}$ do

2: for $m=1: M$ do

3: Find $k^* = \arg \max_{k \in \Lambda_m} \left(\tilde{R}_k^{n(\text{DCS})} / \bar{R}_k \right)$, where $\tilde{R}_k^{n(\text{DCS})}$ and \bar{R}_k are defined as Eqs. (16) and (11).

4: $\beta_{m,k^*}^n \leftarrow 1$.

5: end for

6: end for

% Step Two

7: for $m=1: M$ do

8: Calculate $L_m = \sum_{k \in \Lambda_m} R_k$.

9: while $L_m > C_m$ do

10: Find $(k^*, n^*) = \arg \min_{\{(k,n) | \beta_{m,k}^n = 1\}} SLNR_{m,k}^n$, where $SLNR_{m,k}^n$ is defined as Eq. (18).

11: $\beta_{m,k^*}^n \leftarrow 0$, update L_m and $\tilde{R}_k^{n(\text{DCS})}$.

12: end while

13: end for

4.2 Searching Method for DJT Scheme

For the DJT scheme, transmission set Ω_k^n contains one or more elements ($|\Omega_k^n| \geq 1$). Therefore, the search method proposed in the previous subsection should be modified as follow.

Step One: Similar to the first step of DCS scheme, in *Step One* of searching for DJT scheme, the UE with the maximum utility function is selected on each RB. However, since TPs participating transmission to a specific UE is not fixed all the time, i.e., Ω_k^n is unsure at present, we can only have an approximated expression of SINR in this step, expressed as

$$\tilde{R}_k^{n(\text{DJT})} = b \log \left(1 + \frac{\sum_{m \in \Pi_k} \|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 S}{\sum_{m' \in \Pi \setminus \Pi_k} \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S + \sigma^2} \right) \quad (19)$$

Step Two: Result from *Step One* satisfies C4 of Eq. (15), but does not maximize the objective function. Therefore, an extra step is necessary.

Note that Eq. (19) is a coarse estimation that cannot describe the real data rate of UE k , when using DJT CoMP. In fact, there are $|\Pi_k|!$ options of Ω_k^n , which obviously increases the complexity of the exhaustive searching for an optimal solution. In the rest of this section, we propose a low complexity algorithm, which can reach a suboptimal solution to scheduling index set with rational requirement of computations on the basis of the result obtained from *Step One*.

Consider the n th RB of TP μ assigned to UE k' by the previous selection (i.e., $\beta_{\mu,k'}^n = 1$). On this RB, the proposed algorithm calculates the utility functions of other UEs in set Λ_μ to figure out whether there is a UE that could reach a higher weighted data rate, if it occupies the current RB instead of k' . If the algorithm finds a UE $k \in \Lambda_\mu$ ($k \neq k'$) who satisfies the condition, the scheduling index set should be reset, and R_k^n becomes

$$(R_k^n)^{+\mu} = b \log \left(1 + \frac{\sum_{m \in \Pi} \beta_{m,k}^n \|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2 S + \|\mathbf{H}_{\mu,k}^n \mathbf{w}_\mu^n\|^2 S}{\sum_{m' \in \Pi} (1 - \beta_{m',k}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S - \|\mathbf{H}_{\mu,k}^n \mathbf{w}_\mu^n\|^2 S + \sigma^2} \right). \quad (20)$$

As a result of adding TP μ into UE k 's transmission set on the n th RB Ω_m^n , R_k^n is increased by a variation expressed as

$$(R_k^n)^\Delta = (R_k^n)^{+\mu} - R_k^n = b \log \left(\frac{\sum_{m' \in \Pi} (1 - \beta_{m',k}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S + \sigma^2}{\sum_{m' \in \Pi} (1 - \beta_{m',k}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S - \|\mathbf{H}_{\mu,k}^n \mathbf{w}_\mu^n\|^2 S + \sigma^2} \right). \quad (21)$$

Correspondingly, the data rate of UE k' decreases because of losing the cooperation of TP μ . Similarly, we have the decreased data rate of UE k' as

$$(R_{k'}^n)^{-\mu} = b \log \left(1 + \frac{\sum_{m \in \Pi} \beta_{m,k'}^n \|\mathbf{H}_{m,k'}^n \mathbf{w}_m^n\|^2 S - \|\mathbf{H}_{\mu,k'}^n \mathbf{w}_\mu^n\|^2 S}{\sum_{m' \in \Pi} (1 - \beta_{m',k'}^n) \|\mathbf{H}_{m',k'}^n \mathbf{w}_{m'}^n\|^2 S + \|\mathbf{H}_{\mu,k'}^n \mathbf{w}_\mu^n\|^2 S + \sigma^2} \right), \quad (22)$$

and the corresponding data rate variation is

$$(R_{k'}^n)^\Delta = (R_{k'}^n)^{-\mu} - R_{k'}^n = b \log \left(\frac{\sum_{m' \in \Pi} (1 - \beta_{m',k'}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S + \sigma^2}{\sum_{m' \in \Pi} (1 - \beta_{m',k'}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S + \|\mathbf{H}_{\mu,k}^n \mathbf{w}_\mu^n\|^2 S + \sigma^2} \right). \quad (23)$$

Algorithm 2 DJT Scheduling Algorithm

Output: The scheduling index set.

% Step One

1: for $n=1:N_{\text{RB}}$ do

2: for $m=1:M$ do

3: Find $k^* = \arg \max_{k \in \Lambda_m} \tilde{R}_k^{n(\text{DJT})} / \bar{R}_k$ where $\tilde{R}_k^{n(\text{DJT})}$ and \bar{R}_k are defined as Eqs. (19) and (11).

4: $\beta_{m,k^*}^n \leftarrow 1$.

5: end for

6: end for

% Step Two

7: for $\mu=1:M$ do

8: for $n=1:N_{\text{RB}}$ do

9: Find k' which satisfies that $\beta_{\mu,k'}^n = 1$.

10: $k^* \leftarrow k', \Delta \leftarrow 0$.

11: Calculate $\gamma_k^n, R_k^n, (R_k^n)^{-\mu}$ and $(R_k^n)^\Delta$ according to Eqs. (9), (4), (22), (23).

12: for $k=1:K, k \neq k'$ do

13: Calculate $\gamma_k^n, R_k^n, (R_k^n)^{+\mu}$ and $(R_k^n)^\Delta$ according to Eqs. (9), (4), (20), (21).

14: Calculate $\Delta(k \rightarrow k')$ according to Eqs. (24) and (25).

15: if $\Delta(k \rightarrow k') > \Delta$ then

16: $\Delta \leftarrow \Delta(k \rightarrow k'), k^* \leftarrow k$.

17: end if

18: end for

19: if $k^* \neq k'$ then

20: $\beta_{\mu,k^*}^n \leftarrow 1, \beta_{\mu,k'}^n \leftarrow 0$.

21: end if

22: end for

23: end for

% Step Three

24: for $m = 1:M$ do

25: Calculate $L_m = \sum_{k \in \Lambda_m} R_k$.

26: while $L_m > C_m$ do

27: Find $(k^*, n^*) = \arg \min_{\{(k,n) | \beta_{m,k}^n = 1\}} SLNR_{m,k}^n$, where $SLNR_{m,k}^n$ is defined as Eq. (18).

28: $\beta_{m,k^*}^n \leftarrow 0$, update L_m and $\tilde{R}_k^{n(\text{DJT})}$.

29: end while

30: end for

The variation of the target utility function caused by this change can be written as

$$\Delta(k \rightarrow k') = \frac{(R_k^n)^\Delta}{\bar{R}_k} + \frac{(R_{k'}^n)^\Delta}{\bar{R}_{k'}}. \quad (24)$$

In fact, $(R_k^n)^\Delta / \bar{R}_k$ is constant on RB n of TP μ . We denote it as $\Phi(\mu, n, k')$ determined by instantaneous and time-averaged data rates of UE k' previously scheduled on RB n of TP μ . Rewrite the variation of utility function as

$$\Delta(k \rightarrow k') = \frac{b}{R_k} \log \left(\frac{\sum_{m' \in \Pi} (1 - \beta_{m',k}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S + \sigma^2}{\sum_{m' \in \Pi} (1 - \beta_{m',k}^n) \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 S - \|\mathbf{H}_{\mu,k}^n \mathbf{w}_\mu^n\|^2 S + \sigma^2} \right) + \Phi(\mu, n, k'), \quad (25)$$

where $\Delta(k \rightarrow k') > 0$ indicates that the gain of utility function is positive, if replacing k' by k on the n th RB of TP μ . In this case, the previous scheduling result is not appropriate, and it is necessary to be adjusted. Let $\Delta(k \rightarrow k) = 0$. The algorithm searches all UEs and find k^* that maximizes Eq. (24), i.e.,

$$k^* = \arg \max_{k \in \Lambda_\mu} \Delta(k \rightarrow k'). \quad (26)$$

Then, the scheduling indices will be reset as $\beta_{\mu,k^*}^n = 1$, and $\beta_{\mu,k'}^n = 0$. The solution can be obtained after repeating this comparison for each TP and RB.

Step Three: The constraint of backhaul capacity should be considered at the same time. According to the backhaul constraint in Eq. (13), if the total data rate of TP m is no less than the capacity limitation of backhaul, no more traffic should be assigned to it. Taking into account of backhaul constraint, scheduling algorithm for DJT scheme includes last step the same as in DCS scheme (*Step Two* in Algorithm 1).

The algorithm solves the scheduling problem in Eq. (15) and gives a suboptimal solution of scheduling index set. The proposed algorithm for DJT CoMP is summarized in Algorithm 2.

4.3 Analysis of computational complexity

An straightforward method to find the solution, that not only satisfies all the constraints, but also maximizes the objective function, is the exhaustive search; however, since $\beta_{m,k}^n$ is a bit number, there are totally $2^{MN_{\text{RB}}K}$ options of $\{\beta_{m,k}^n\}$, and the computational complexity of the exhaustive search is $O(2^{MN_{\text{RB}}K})$. This is complexity prohibitive when parameters M , N_{RB} , and K increase.

The first idea to reduce complexity is to utilize the predetermined CoMP sets of each UE. For UE k with CoMP set Π_k , the feasible space of the index set, i.e., set $\{\beta_{m,k}^n, \forall m, n\}$, is $2^{|\Pi_k|N_{\text{RB}}}$. Therefore, the total required search to solve the formulated problem are reduced to $2^{\sum_k |\Pi_k| N_{\text{RB}}}$, and the corresponding computation complexity is $O\left(2^{\sum_k |\Pi_k| N_{\text{RB}}}\right)$, where $K \leq \sum_k |\Pi_k| \leq KM$. $\sum_k |\Pi_k| = K$ indicates that each UE is served by only one TP, while $\sum_k |\Pi_k| = KM$ implies that the CoMP set for each UE is comprised of all TPs. With the help of CoMP sets, the complexity of exhaustive search can be reduced to some extent. However, it is still an exponential complexity algorithm with respects to M , N_{RB} , and K .

The proposed algorithm further reduces the computation complexity. With the predetermined CoMP sets, the proposed search method for DCS scheme calculates the

estimated data rate $\tilde{R}_k^{n(\text{DCS})}$ for each UE, and then accomplishes comparison operation expressed in Eq. (11) to obtain the solution. The computation complexity for calculating all the $\tilde{R}_k^{n(\text{DCS})}$ consists of multiplication operations $O(M-|\Pi_k|+1)$ and a logarithm operation $O(KN_{\text{RB}})$. In addition, the proposed searching method contains comparison operations $O(N_{\text{RB}}\sum_{m \in \Pi} |\Lambda_m|)$, where $\sum_{m \in \Pi} |\Lambda_m| \leq KM$ (the equation holds only if all TPs cooperatively work together).

Similarly, the proposed search method for DJT scheme contains multiplication operations $O(M)$ and a logarithm operation $O(KN_{\text{RB}})$ for calculating $\tilde{R}_k^{n(\text{DJT})}$ and comparison operations $O(N_{\text{RB}}\sum_{m \in \Pi} |\Lambda_m|)$. From the analysis above, it is observed that the proposed algorithms reduce the computational complexity with respects to M , N_{RB} , and K from exponential complexity to polynomial complexity, that is to say, the problem can be solved in polynomial time.

5. Power Allocation Algorithm

In this section, we propose an algorithm to solve the PA problem based on the obtained scheduling index set $\{\beta_{m,k}^n\}$. We first divide the PA problem into N_{RB} independent sub-problems, and then, solve each sub-problem by an iterative KKT-method.

The problem in terms of PA can be rewritten as

$$\max_{p_m^n} \sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \frac{R_k^n}{\bar{R}_k} \quad (27)$$

$$\text{s.t.} \quad 0 \leq p_m^n \leq S, \forall m, n$$

$$\sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n R_k^n \leq C_m, \forall m \quad (28)$$

The dual function of the problem with respect to the backhaul capacity constraint in Eq. (28) is

$$\max_{p_m^n} \sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \frac{R_k^n}{\bar{R}_k} - \sum_{m \in \Pi} \lambda_m \left(\sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n R_k^n - C_m \right) \quad (29)$$

$$\text{s.t.} \quad 0 \leq p_m^n \leq S, \forall m, n$$

where $\lambda_m, \forall m$ are the non-negative dual variables. There are MN_{RB} variables except the dual variables in the optimization problem. To make it easier to solve, we decompose the dual problem into N_{RB} independent sub-problems, each of which includes M variables, such that the computational complexity is reduced. Since $\sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n \neq 0$, we can rewrite C_m as

$$C_m = \sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n \frac{C_m}{\sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n} = \sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n \frac{C_m}{\beta_m} \quad (30)$$

where $\beta_m = \sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n$ is a constant when scheduling index set $\{\beta_{m,k}^n\}$ is determined.

Substituting Eq. (30) into Eq. (29), we have

$$\sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \frac{R_k^n}{\bar{R}_k} - \sum_{m \in \Pi} \lambda_m \left(\sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n R_k^n - \sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n \frac{C_m}{\beta_m} \right) = \sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \left(\frac{R_k^n}{\bar{R}_k} - \sum_{m \in \Pi} \lambda_m \beta_{m,k}^n \left(R_k^n - \frac{C_m}{\beta_m} \right) \right) \quad (31)$$

Therefore, the problem is decoupled into N_{RB} independent sub-problems as follows:

$$\begin{aligned} \max_{p_m^n} \quad & \sum_{k=1}^K \left(\frac{R_k^n}{R_k} - \sum_{m \in \Pi} \lambda_m \beta_{m,k}^n \left(R_k^n - \frac{C_m}{\beta_m} \right) \right) \\ \text{s.t.} \quad & 0 \leq p_m^n \leq S, \forall m \end{aligned} \quad (32)$$

The objective of Eq. (32) is a well-known non-convex function, for which finding the global optimum solution is believed to be difficult. In this work, we use an iterative method based on KKT condition to achieve a local optimum solution.

Taking the first derivative of the objective in Eq. (32) with respect to p_m^n , we have

$$\frac{\partial}{\partial p_m^n} \left(\sum_{k=1}^K \left(\frac{R_k^n}{R_k} - \sum_{m \in \Pi} \lambda_m \beta_{m,k}^n \left(R_k^n - \frac{C_m}{\beta_m} \right) \right) \right) = \sum_{k=1}^K \left(\frac{1}{R_k} - \sum_{m \in \Pi} \lambda_m \beta_{m,k}^n \right) \frac{\partial R_k^n}{\partial p_m^n} \quad (33)$$

It is easy to obtain the first derivative of R_k^n with respect to p_m^n as follows:

$$\frac{\partial R_{k^*}^n}{\partial p_m^n} = \frac{b \sum_{m \in \Pi} \beta_{m,k^*}^n \|\mathbf{H}_{m,k^*}^n \mathbf{w}_m^n\|^2}{\|\mathbf{H}_{m,k^*}^n \mathbf{w}_m^n\|^2 p_m^n + \sum_{m' \in \Pi \setminus \{m\}} \|\mathbf{H}_{m',k^*}^n \mathbf{w}_{m'}^n\|^2 p_{m'}^n + \sigma^2}, \quad \text{if } \beta_{m,k^*}^n = 1 \quad (34)$$

$$\frac{\partial R_k^n}{\partial p_m^n} = \frac{b(\gamma_k^n)^2 \|\mathbf{H}_{m,k}^n \mathbf{w}_m^n\|^2}{1 + \gamma_k^n \sum_{m' \in \Pi} \beta_{m',k}^n \|\mathbf{H}_{m',k}^n \mathbf{w}_{m'}^n\|^2 p_{m'}^n}, \quad \forall k \neq k^* \quad (35)$$

For ease of expression, we denote

$$T_m^n = \sum_{k=1, k \neq k^*}^K \left(\frac{1}{R_k} - \sum_{m \in \Pi} \lambda_m \beta_{m,k}^n \right) \frac{\partial R_k^n}{\partial p_m^n} \quad (36)$$

$$A_m^n = \sum_{m' \in \Pi \setminus \{m\}} \|\mathbf{H}_{m',k^*}^n \mathbf{w}_{m'}^n\|^2 p_{m'}^n + \sigma^2 \quad (37)$$

For simplicity, we use $\{p_m^n\}$ of the last iteration to calculate Eqs. (36) and (37), such that T_m^n and A_m^n can be calculated as constants when computing p_m^n . Substitute Eqs. (34) - (37) into Eq. (33), and let it be 0, we obtain the expression of \hat{p}_m^n :

$$\hat{p}_m^n = \frac{1}{\|\mathbf{H}_{m,k^*}^n \mathbf{w}_m^n\|^2} \times \left(\frac{b}{T_m^n} \left(\frac{1}{R_{k^*}} - \sum_{m \in \Pi} \lambda_m \beta_{m,k^*}^n \right) \left(\sum_{m' \in \Pi} \beta_{m',k^*}^n \|\mathbf{H}_{m',k^*}^n \mathbf{w}_{m'}^n\|^2 \right) - A_m^n \right) \quad (38)$$

Combining with power constraint $0 \leq p_m^n \leq S$, we have the solution to PA as:

$$p_m^n = \max \left\{ \min \left\{ \hat{p}_m^n, S \right\}, 0 \right\} \quad (39)$$

Since it is almost impossible to obtain closed-form solution of p_m^n , we employ a sub-gradient iteration approach to achieve the suboptimal solution. The multipliers λ_m can be updated using the sub-gradient method [17] in each step as

$$\lambda_m^{t+1} = \max \left\{ \lambda_m^t - \nu^t \left(\sum_{n=1}^{N_{\text{RB}}} \sum_{k=1}^K \beta_{m,k}^n R_k^n - C_m \right), 0 \right\} \quad (40)$$

where t refers to iteration times.

The proposed iterative KKT-method solves each sub-problem to obtain a set of $p_m^n, \forall m$. The final solution of PA can be achieved after solving the total N_{RB} sub-problems.

6. Simulation Results

To evaluate the performance of the proposed algorithms, we simulate the system described in Section 2. We use the Space Channel Model (SCM) [18] to create MIMO radio links in an urban environment, where obstacles like buildings and trees obstruct Line of Sight (LOS) of radio links. The suggested simulation parameters therein are listed in Table 1. Due to obstacles existing in radio environment, shadowing and penetration loss are considered in channel model. The coverage radiuses of TPs are set as 250 m, since we consider a densely-deployed HetNet system. The network topology in Fig. 2 simply illustrates the relative positions of TPs and UEs without details of channels. In this paper, we adopt a wrap-around simulation technology, which has been used to simulate large-scale cellular systems [20]. In our simulation, we have built a scenario containing 37 hexagon cells, where 19 TPs in the middle actually communicate with UEs, and the others 18 TPs wrapping them around produce interference with assumed strength.

Table 1. Simulation parameters

Parameter	Assumption
Layout of cells	37 hexagon cells; wrap-around used
Radius of cells	250m
Central frequency	2GHz
N_{RB} number of RBs	100
S_m	46dBm ($\approx 40w$)
$N_T \times N_R$	2×2
TTI	1ms
α	0.1
Channel model	SCM (PathLoss + Shadowing + MIMO fading)
Minimal distance (TP and UE)	35m
Height of transmit/receive antenna	35m/1.5m
Penetration loss	20dB
Traffic Model	Full Buffer
Speed of UE	10m/s

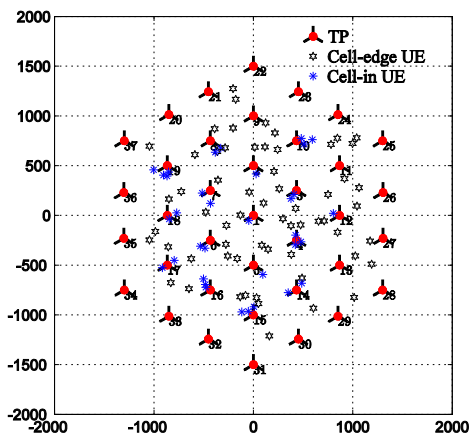


Fig. 2. Simulation topology

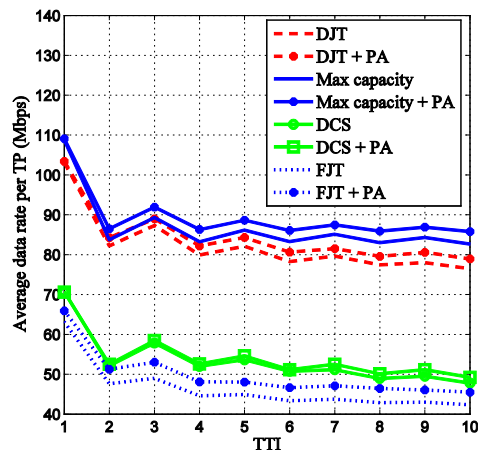


Fig. 3. Average data rate per TP

For comparisons, two more scheduling schemes are considered, besides the proposed DCS and DJT: max capacity and fixed JT (FJT). Max capacity is a non-CoMP greedy algorithm, in which each UE selects the TP with the highest SINR to communicate on each RB, without

consideration of UEs' fairness. In FJT scheme, all the TPs in UEs' CoMP set must transmit data signals simultaneously. Although the data rate of cell-edge UEs is improved in this way, the overall data rate cannot be maximized due to its inflexibility.

Fig. 3 shows average data rate of each TP without backhaul constraint. The results show that max capacity has the highest data rate, followed by the proposed DJT. Both of these two schemes can achieve higher than 80 Mbps average data rate per TP; however, data rate per TP goes lower than 60 Mbps in the proposed DCS and further decreases to 50 Mbps or lower in FJT, respectively. Additionally, it is also observed that the proposed PA method is effective to further improve data rate for all scheduling schemes.

Nevertheless, the fairness of max capacity is unfavorable, as shown in Fig. 4. The reason is that in max capacity scheme, RB and power resources are preferred to allocate to those UEs with better channel conditions (cell-in UEs). In contrast, since CoMP schemes are inclined to improve the data rate of cell-edge UEs, the corresponding fairness factor is higher than that of max capacity. In addition, the results in Fig. 3 and 4 show that the proposed DJT scheme performs excellently in terms of both data rate and UEs' fairness.

Fig. 5 compares average data rate of cell-in UEs with that of cell-edge UEs. This figure gives another way to explain the results in Figs. 3 and 4. It is obvious that the DJT scheme can provide better services for cell-edge UEs than the other three schemes.

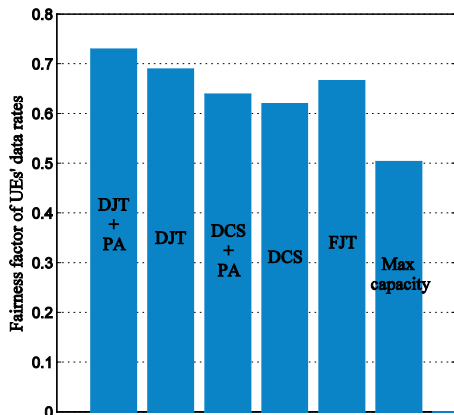


Fig. 4. Fairness factor

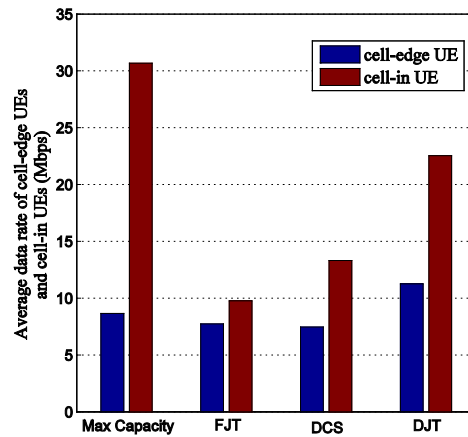


Fig. 5. Average data rate of UEs

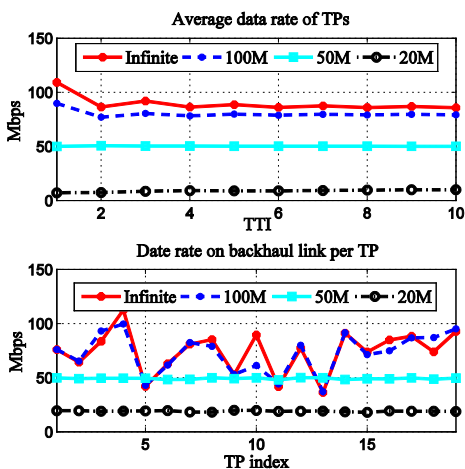


Fig. 6. Performance of max capacity scheme

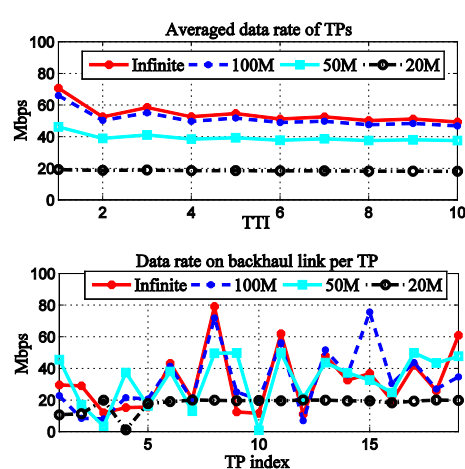


Fig. 7. Performance of DCS scheme

Figs. 6, 7 and **8** show average data rate and traffic on backhaul link of each TP in max capacity, DCS and DJT, respectively. Situations of infinite, 100M, 50M and 20M backhaul limitation are considered. From the simulation results, we can see that the backhaul limitation can be satisfied in all schemes, which verifies the effectiveness of the proposed RRM algorithms in terms of backhaul constraint. In addition, the results also show that average data rate is restricted by backhaul constraint. When backhaul capacity is restricted to 50M and 20M, the average data rate decreases dramatically. This result proves our motivation that it is a key problem to exploit efficient RRM algorithm, when capacity of backhaul link is limited.

Fig. 9 is the power consumptions of the proposed PA algorithm with DCS scheme and DJT scheme, respectively. As shown in **Fig. 9**, the proposed PA method can greatly save power than constant transmission power solution, without decreasing system performance. By using the proposed PA algorithm, TPs degrade their transmission power according to the instantaneous CSIs. As a result, the leaking interference is reduced and average data rate can be improved, as shown in **Fig. 3**. Power-saving, as a characteristic of the proposed PA algorithm, tightly meets the requirement of green cells for the environmental purpose.

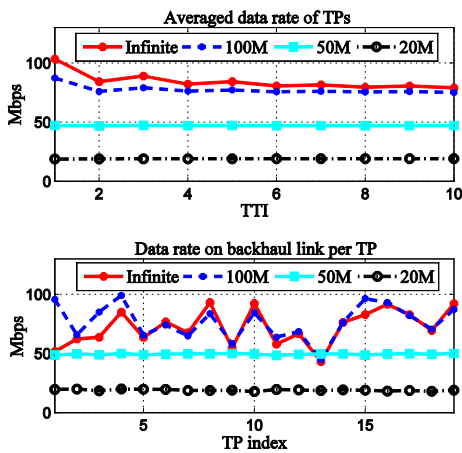


Fig. 8. Performance of DJT scheme

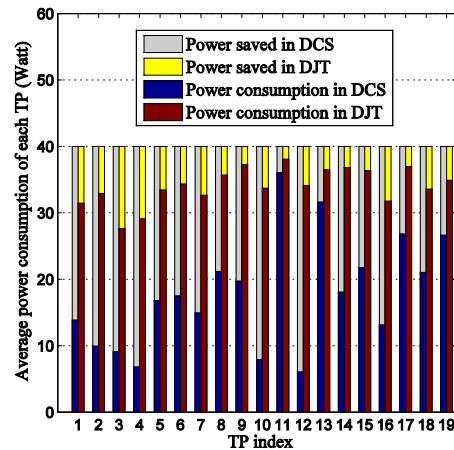


Fig. 9. Power consumption in DCS and DJT

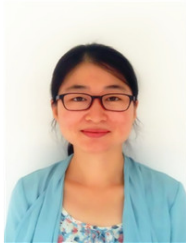
7. Conclusion

In this paper, we have studied RRM problem in LTE-A HetNet scenario, where JP CoMP is employed. The problem involves practical constraints on transmission power and backhaul capacity. Since the problem is too complicated to achieve the optimal solution, we propose a suboptimal algorithm with applicable computational complexity, which separates the MIP into two solvable problems: RB scheduling and Power Allocation. For RB scheduling, we have considered both DCS and DJT schemes with constant transmission power, and have proposed algorithms based on instantaneous CSIs to assign RBs to UEs. Then, we have substituted the results of RB scheduling into PA problem, and have solved it by an iterative KKT-method. Extensive simulations are conducted to verify the effectiveness of our proposed algorithms. According to the obtained simulation results, we have shown that JP CoMP benefits cell-edge UEs. In particular, the proposed DJT scheduling has outstanding performance in the aspects of both data rate and UEs' fairness. Additionally, the proposed PA method can not only further improve data rate, but also greatly save power consumption.

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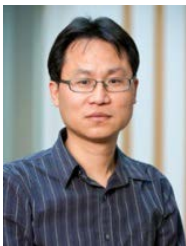
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