Fairness-aware Resource Allocation in Relay-enhanced TD-LTE-A Systems

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***Abstract*—Relay technique is introduced in the Long Term Evolution Advanced (LTE-Advanced) system to extend the network coverage, improve the performance of cell-edge user equipments (UEs) and increase the fairness among different UEs. The combination of multiple-input-multiple-output (MIMO) and relay can further increase frequency efficiency and improve system performance. In this paper, based on the architecture of MIMO relay-enhanced TD-LTE-Advanced system, a fairness -aware resource allocation algorithm is proposed, and the resource allocation is divided into 3 phases: a frequency resource partition scheme is firstly proposed to realize the tradeoff between fairness among UEs served by various relay nodes and system throughput; and secondly, a backhaul resource allocation algorithm is presented to match the eNB to relay transmission with the relay to UE transmission with reduced feedback overhead; finally, a resource allocation algorithm from eNB and relay to UEs is given to maximize the proportional fairness so that user fairness can be guaranteed. The property of the proposed resource allocation algorithm is investigated through system level simulation and the results show that both system throughput and user fairness can be improved with limited feedback overhead, compared with the existing algorithms.**

Keywords—TD-LTE-A; Relay; MIMO; Resource Allocation; Proportional Fairness Utility

I. INTRODUCTION

In TD-LTE-Advanced (TD-LTE-A) system, many enabling technologies have been introduced to further improve system performance, including relay, Coordinated Multiple Points Transmission (CoMP), multi-stream beamforming et al [1]. Relay is a cost-efficient technology to extend the network coverage and improve the receive performance of cell edge UEs. In 3GPP standard, two main relay types are considered, including Type 1 relay, which performs the role of a functional eNB to the UEs and Type 2 relay, which is part of the donor cell. Type 1 relay has been used in TD-LTE-A system since it can provide better coverage extension, with the features: (1) the backhaul link and the access link multiplexing the same frequency band; (2) operation in Time Division Multiplexing (TDM) mode to reduce interference; (3) independent resource management.

Since resource allocation among different links in relay-enhanced system is crucial to guarantee overall system performance, there has been a few literatures focusing on it. Based on OFDMA system, the authors in literature [2] propose throughput-optimal resource allocation algorithms for the scenarios of single relay node (RN) and multiple relay nodes. To improve user fairness, i.e. as far as possible to make each UE have an equal opportunity to be scheduled despite the UE channel condition, the authors in [3] propose a simplified algorithm to maximize the throughput of the worst UE in relay-enhanced LTE-A system. However, only the fairness of UEs with the worst performance is considered and the whole performance of fairness is poor. The fairness of all UEs is considered in [4], and, although all users behave selfishly, the equilibrium point of the game can realize the α-fairness efficiently. In order to achieve a good tradeoff between fairness and throughput, a total network proportional fairness utility is used as the objective function in [5] for OFDMA-based heterogeneous networks with relay nodes.

Although the performance of cell edge UEs can be improved using relay, the performance of the whole system can be further improved by the combination of relay and MIMO. In TD-LTE-A [6] relay-enhanced downlink, due to the property of channel reciprocity in TDD mode, the non-codebook based precoding can be used to reduce the interference among UEs and improve the sum capacity of the system at the same time. In [7], a resource allocation scheme with the combination of MIMO and Relay technology is introduced. The authors in [8] analyze the transmission model with fixed RN in cellular networks, and a precoding based relay strategy supporting multiuser transmission is proposed. However, only the single RN scenario is considered.

In order to improve the system throughput and user fairness in MIMO TD-LTE-A downlink with RNs, we propose an efficient and practical fairness-aware resource allocation algorithm based on proportional fairness utility, and the proposed algorithm can be divided into 3 phases: in the first phase, we propose a frequency resource partition scheme to balance system throughput and the fairness among UEs served by various relays. In the second phase, a backhaul resource allocation algorithm is given with limited feedback overhead to match the eNB-to-RN transmission with the RN-to-UE transmission. In the last phase, a resource allocation algorithm from eNB and RN to UEs is presented aiming at maximizing the proportional fairness utility. Simulation results show that the proposed algorithm can guarantee user fairness, and more than 75% signaling overhead can be reduced compared with existing algorithms with very limited loss of system throughput.

The rest of the paper is organized as follows. In section II, system model and the transmission procedure are described.

Then the proposed fairness-aware resource allocation algorithm is stated step by step in section III. Section IV provides the simulation results and analysis. Finally, section V concludes this paper.

II. SYSTEM MODEL AND TRANSMISSION ALGORITHMS

The downlink scenario of TD-LTE-A system with multi-antenna RNs is shown in Fig. 1: UEs can be divided into two groups: (1) D-UEs, which are near the eNB and experience better channel condition in the transmission with eNB so that direct communication can be realized; (2) R-UEs, which are far away from the eNB and they communicate through a RN. In this paper, whether a UE is D-UE or R-UE depends on its received power of pilot signal from eNB and RN.

In relay-enhanced TD-LTE-A system, wireless transmission links can be divided into three types: (1) the backhaul link L1, which is between the RN and the eNB; (2) access link L2, which connects the R-UEs and its serving RN; (3) direct link L3, which provides the connection between D-UEs and its eNB. Not only the frequency resources assigned between the direct links and access links are orthogonal, but also among the access links of different relays are orthogonal. It is essential to point out again that the backhaul link and the access link of relay transmission multiplexing the same frequency band. eNB and RNs are equipped with multiple antennas. The channel condition of backhaul link is usually good due to the careful selection of RN positions. Hence, we adopt transmission mode 4, i.e. spatial multiplexing, between eNB and RNs to increase system throughput. Due to reciprocity in TDD mode, non-codebook, zero-feedback precoding can be used: we use SVD (Singular Value Decomposition) precoding at eNB, by decomposing the spatial channel matrix between eNB and RN r is $\mathbf{H}_{s,r}$.

All UEs are equipped with only one receive antenna, and transmission mode 7, i.e. single-stream multi-user beamforming, is adopted in direct link and access link to reduce interference and improve system throughput. Signal-to-Leakage-and-Noise Ratio (SLNR) beamforming algorithm is used in this paper due to its good performance in terms of sum capacity and average BER performance with moderate complexity. The obtained SLNR of k^{th} UE can be expressed as:

$$SLNR_k = \frac{\|\mathbf{H}_k \mathbf{w}_k\|_F^2}{\sigma^2 + \sum_{i=1, i\neq k}^{K} \|\mathbf{H}_i \mathbf{w}_k\|_F^2}, \tag{1}$$

where, K is the total number of UEs, $\mathbf{H}_k$ is the matrix to show the channel gain from UE k to eNB or RN, $\mathbf{w}_k$ is the beamforming matrix for UE k, $\|\mathbf{A}\|_F$ represents Frobenius norm of matrix $\mathbf{A}$, and σ^2 refers to the variance of white Gaussian noise. The purpose of SLNR beamforming algorithm is to maximize the SLNR at the transmitter, so that the interference to other UEs can be minimized. Hence the optimal beamforming matrix with SLNR algorithm can be expressed as:

$$\mathbf{w}_k^{opt} = \arg\max_{\mathbf{w}_k} (SLNR_k), \tag{2}$$

The diagram of transmission procedure between eNB and R-UE is shown in Fig. 2. eNB is equipped with M transmit antennas, RN is equipped with M receive antennas and M transmit antennas. eNB decides which R-UEs' data will be scheduled according to RN's feedback. The SVD precoding matrix is obtained by channel information $\mathbf{H}_{s,r}$ of the backhaul link. RN receives data from eNB through SVD receiving. Then RN decodes the encoded data and re-encodes the bit stream according to the channel condition of the access link. Through a resource allocation algorithm, RN decides how to schedule R-UEs, and obtains a beamforming matrix according to the scheduling result and channel information of the access link. R-UE uses minimum-mean-square-error (MMSE) receiver to receive its own information transmitted from RN.

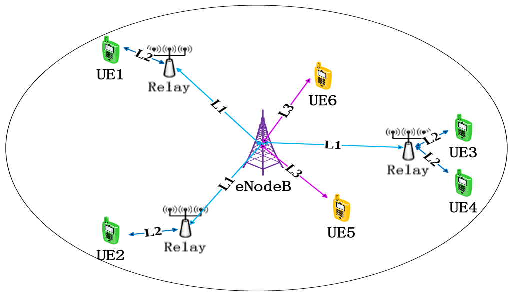

Fig. 1 Relay-enhanced TD-LTE-A system model

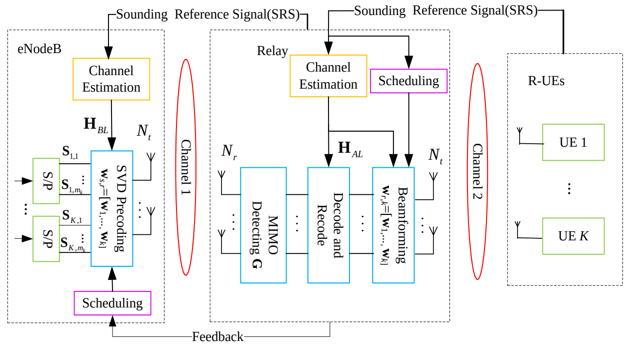

Fig. 2 The diagram of transmission procedure between eNB and R-UE

III. FAIRNESS-AWARE RESOURCE ALLOCATION SCHEME

A. Mathematical models for resource allocation problem

A seven-cell topology is considered in this paper and the performance of the central cell is analyzed. In the central cell, the signal-to-interference-plus-noise ratio (SINR) for various links can be described as follows (the number of RN is R).

The SINR of R-UE k in the backhaul link on physical resource block (PRB) n can be expressed as:

$$SINR_{s,r,k}^{(n)} = \frac{P_{s,r,k}^{(n)} \left\|\mathbf{G}_{s,r}^{(n)}\mathbf{H}_{s,r}^{(n)}\mathbf{w}_{s,r,k}^{(n)}\right\|_F^2}{\sigma_k^2 + \sum\limits_{i\in\Phi_s^{(n)}, i\neq k} P_{s,r,i}^{(n)} \left\|\mathbf{G}_{s,r}^{(n)}\mathbf{H}_{s,r}^{(n)}\mathbf{w}_{s,r,i}^{(n)}\right\|_F^2 + \sum\limits_{j'\neq j} P_{s_{j'}}^{(n)} \left|h_{s_{j'},r}^{(n)}\right|^2}, \tag{3}$$

where, $\mathbf{H}_{s,r}^{(n)} \in £^{M\times M}$ is the channel matrix between eNB and RN r on PRB n. $\mathbf{w}_{s,r}^{(n)} \in £^{M\times 1}$ is the precoding vector obtained from $\mathbf{V}$ and $\mathbf{G}_{s,r}^{(n)} \in £^{1\times M}$ is RN's receive vector. $P_{s,r,k}^{(n)}$ is the transmit power of eNB allocated for UE k, and since very limited performance gain can be obtained in TD-LTE-A downlink, average power allocation is considered in our work [9]. $\Phi_s^{(n)}$ is the selected UE set of eNB on PRB n. The second term in the denominator of (3) is the interference from other UEs on the same PRB n. The last term in the denominator is the interference from eNBs in adjacent cells where j represents the central cell and j' represents the neighbor cells.

The SINR of R-UE k in the access link on PRB n is:

$$SINR_{r,k}^{(n)} = \frac{P_{r,k}^{(n)} \left\| \mathbf{G}_{r,k}^{(n)} \mathbf{H}_{r,k}^{(n)} \mathbf{w}_{r,k}^{(n)} \right\|_F^2}{\sigma_k^2 + \sum_{i \in \Phi_r^{(n)}, i \neq k} P_{r,i}^{(n)} \left\| \mathbf{G}_{r,k}^{(n)} \mathbf{H}_{r,k}^{(n)} \mathbf{w}_{r,i}^{(n)} \right\|_F^2 + \sum_{j' \neq j} P_{r_{j'}}^{(n)} \left| h_{r_{j'},k}^{(n)} \right|^2}, \quad (4)$$

where, $\mathbf{H}_{r,k}^{(n)} \in £^{1 \times M}$ is channel matrix between RN r and R-UE k on PRB n. $\mathbf{w}_{r,k}^{(n)} \in £^{M \times 1}$ is RN's SLNR beamforming vector for R-UE k and $\mathbf{G}_{r,k}^{(n)}$ is UE k's receive vector. $P_{r,k}^{(n)}$ is the transmit power of RN r allocated for UE k, with average power allocation at RN. $\Phi_r^{(n)}$ is the set of UEs of RN r on PRB n.

Similarly, the SINR of D-UE k in the direct link on PRB n can be expressed as:

$$SINR_{s,k}^{(n)} = \frac{P_{s,k}^{(n)} \left\| \mathbf{G}_{s,k}^{(n)} \mathbf{H}_{s,k}^{(n)} \mathbf{w}_{s,k}^{(n)} \right\|_F^2}{\sigma_k^2 + \sum_{i \in \Phi_s^{(n)}, i \neq k} P_{s,i}^{(n)} \left\| \mathbf{G}_{s,k}^{(n)} \mathbf{H}_{s,k}^{(n)} \mathbf{w}_{s,i}^{(n)} \right\|_F^2 + \sum_{j' \neq j} P_{s_{j'}}^{(n)} \left| h_{s_{j'},k}^{(n)} \right|^2}, \quad (5)$$

As shown in [10], Channel Quality Indicator (CQI) according to the received reference signals can be obtained, and CQI decides Modulation and Coding Scheme (MCS) which decides how much data can be transmitted. Thus, we can obtain the data rate of various links $R_{s,r,k}^{(n)}$, $R_{r,k}^{(n)}$ and $R_{s,k}^{(n)}$ through relationships between SINR and data rate. And then, the rate of D-UE k can be obtained:

$$R_k = \sum\nolimits_n R_{s,k}^{(n)}, \; n \in N_{D-UE_k}, \quad (6)$$

where, N_{D-UE_k} is the set of physical resource blocks (PRBs) allocated to D-UE k.

R-UE k completes one data transmission during the downlink backhaul subframe and access subframe due to the half-duplex property, and hence, the data rate of R-UE k can be expressed as:

$$R_k = (1/2) \sum\nolimits_n \min\{R_{r,k}^{(n)}, R_{s,r,k}^{(n)}\}, \; n \in N_{R-UE_k}, \quad (7)$$

where, N_{R-UE_k} is the set of PRBs allocated to R-UE k.

In realistic mobile communication systems, we should consider both throughput and user fairness. In the traditional proportional fairness scheduling algorithm [11], the UE who has a maximum priority can be scheduled firstly. In our work, the maximization problem of proportional fairness utility is formulated as：

$$\text{(P1)} \quad \max \sum_{k \in K} \frac{R_k(t)}{\overline{R_k}(t-1)} = \sum_{k \in K_d} \frac{R_k(t)}{\overline{R_k}(t-1)} + \sum_r \sum_{k \in K_r} \frac{R_k(t)}{\overline{R_k}(t-1)}, \quad (8\text{-}1)$$

$$s.t. \quad \rho_{s,k}^{(n)}, \rho_{r,k}^{(n)}, \rho_{s,r,k}^{(n)} \in \{0,1\}, \quad \forall n, r, k \quad (8\text{-}2)$$

$$\sum_{k \in K_r} \rho_{r,k}^{(n)} \le M, \; \sum_{k \in K_d} \rho_{s,k}^{(n)} \le M, \quad \forall n \quad (8\text{-}3)$$

$$\sum_{k \in K_r} \rho_{s,r,k}^{(n)} = \sum_{k \in K_r} \rho_{r,k}^{(n)}, \quad \forall n \quad (8\text{-}4)$$

$$\begin{aligned} &(\sum_{k \in K_d} \rho_{s,k}^{(n)})(\sum_{k \in K_r} \rho_{r,k}^{(n)}) = 0 \;\; \forall r, n; \\ &(\sum_{k \in K_{r_1}} \rho_{r_1,k}^{(n)})(\sum_{k \in K_{r_2}} \rho_{r_2,k}^{(n)}) = 0, \;\; \forall_{r_1 \neq r_2} r_1, r_2 \in \{1,2,...,R\}, \forall n \end{aligned} \quad (8\text{-}5)$$

$$t_{BL} \sum_n \rho_{r,k}^{(n)} R_{r,k}^{(n)} \le Q_k^r(t), \quad \forall r, k \quad (8\text{-}6)$$

where, $R_k(t)$ is UE k's instantaneous transmission rate at t^{th} TTI, $\overline{R_k}(t)$ is the long-term average data rate during T Transmission Time Interval (TTI), and it can be defined as: $\overline{R_k}(t) = (1-1/T)\overline{R_k}(t-1) + R_k(t-1)/T$, K_d and K_r are the set of D-UEs and R-UEs served by eNB and RN r, respectively. Constraint (8-2) defines binary variables $\rho_{s,k}^{(n)}, \rho_{r,k}^{(n)}$ and $\rho_{s,r,k}^{(n)}$, where $\rho_{s,k}^{(n)} = 1$ indicates eNB schedules D-UE k on PRB n, $\rho_{r,k}^{(n)} = 1$ indicates RN r schedules R-UE k on PRB n, and $\rho_{s,r,k}^{(n)} = 1$ indicates eNB schedules R-UE k on PRB n in the backhaul link. Constraint (8-3) represents that at most M UEs can be served on PRB n at the same time due to MIMO constraints. Constraint (8-4) restricts the used frequency band of backhaul link and access link to be the same due to in-band relay. Constraint (8-5) restricts that one PRB cannot be used by both direct links and two-hop links to avoid mutual interference from eNB and each RN. Constraint (8-6) ensures that the volume of R-UE k's data transferred in the access link is not larger than its queue length at RN, where Q_k^r is UE k's buffered queue length at RN r. And Q_k^r can be updated according to $Q_k^r(t) = Q_k^r(t-1) + t_{\text{BL}} \sum \rho_{s,r,k}^{(n)} R_{s,r,k}^{(n)}, \forall r, k$, where t_{BL} is the transmission time of the backhaul link.

The problem (P1) is a multiple-choice knapsack problem, which has been proved to be a NP-hard problem. Thus it is impossible to find accurate results with low complexity. In order to solve the resource optimization problem (P1) in a feasible way we propose a suboptimal solution which divides the problem into 3 sub-problems. In the first sub-problem, we solve (8-5) so that eNB divides frequency resource for D-UEs and R-UEs served by different RNs. To match the transmission of the backhaul link with the access link for R-UEs and reduce signaling feedback overhead, backhaul scheduling is solved in the second sub-problem in which constraint (8-4) and (8-6) is satisfied. Based on the solution of the above two sub-problems, we solve the remaining problem including (8-1), (8-2), (8-3) and (8-6) in the third sub-problem.

B. Sub-problem 1: frequency resource partition

In this subsection, we divide all available PRBs in the system into several parts, and each part is assigned to the direct links or two-hop links of RNs independently. This method not only satisfies constraint (8-5), namely, on each arbitrary PRB, either the eNB schedules D-UEs or the RN r schedules corresponding R-UEs, but also ensures system performance and the fairness between D-UEs and R-UEs.

The number of PRBs assigned to D-UEs and R-UEs served by RN r can be calculated as：

$$Num_{\text{PRB}}(u) = \frac{priority(u)}{\sum_u priority(i)} Num_{\text{PRB\_total}}, \quad (9)$$

where, $u \in [1,2,...,R,R+1]$. Here, we regard all the D-UEs as a UE set which is represented by u=R+1 and u=1,…,R represents RN 1,…,R, respectively. And $priority(u)$, which is differently defined in various algorithms, is the indicator to measure how important is this kind of UE to obtain the limited resources to realize different performance index. In [12], the priority of different R-UEs and D-UEs is based on the number of R-UEs and D-UEs, i.e.,

$$priority(u) = \begin{cases} |K_r|, & for\ RN\ r \\ |K_d|, & for\ D-\text{UE}s \end{cases}, \tag{10}$$

where, K_r and K_d is the number of R-UEs served by RN r and the number of D-UEs, respectively.

The scheme in [12] allocates relatively equal resource to D-UEs and R-UEs, however, the R-UE's practical data rate shown in (7) is not considered. Hence, a novel scheme is proposed in this paper in order to enhance fairness between D-UEs and R-UEs. The average data rate in the previous scheduling cycle (2 TTIs) is considered in our proposed algorithm so that user fairness can be improved, and the priority is formulated as:

$$priority_1(u) = \begin{cases} priority(r) \cdot \dfrac{R_{system\_avg}}{R_{RUE\_avg}(r)}, & for\ RN\ r \\ priority(1+R) \cdot \dfrac{R_{system\_avg}}{R_{DUE\_avg}}, & for\ D-\text{UE}s \end{cases}, \tag{11}$$

where, R_{system_avg}, R_{DUE_avg} and $R_{RUE\_avg}(r)$ is the user average data rate of the whole system, the user average data rate of all the D-UEs, and the user average data rate of all the R-UEs in the previous scheduling cycle, respectively. And $priority(u)$ is defined in (10).

C. Sub-problem 2: resource allocation of the backhaul link

In the transmission from eNB to RN, if the access channel quality of R-UE k is poor, its data transmitted through the backhaul link is likely to be discarded due to the overflow of buffer at RN. However, if the access channel quality is much better than the backhaul channel quality for R-UE k, the buffer at RN for R-UE k is usually empty, and hence the requirement of R-UE k maybe cannot be satisfied. Hence, a backhaul resource allocation algorithm considering channel quality of both access link and backhaul link needs to be designed. A backhaul scheduling algorithm based on user queue (BSUQ) has been proposed in [13], and RN r feeds back the length of R-UE k's buffered data Q_k^r to eNB. eNB schedules UEs based on the priority which is shown as:

$$priority(UE_{r,k}) = \max(0, Q_k^{enb} - Q_k^r), \tag{12}$$

where, Q_k^{enb} is the length of R-UE k's buffered queue at eNB. However, the aforementioned algorithm would require much signaling feedback overhead. The feedback information Q_k^r requires 8 bits to quantize according to feedback format of UE Buffer State Report (BSR) in LTE-A system. It is assumed 5 bits are used to represent the UE identity. Hence the signaling overhead of RN's feedback is 13*K_r in total, where, K_r is the number of UEs served by RN r.

Algorithm1: Procedure for M-BSUQ

Input: the length of R-UE k's buffered data $Q_k^r, k=1,...,K_r$

Output: the result of backhaul resource allocation

1. $Q_{k\_\min}^r$ and $Q_{k\_\max}^r$ is set at RN r according to (13) and (14), respectively.
2. if $Q_k^r < Q_{k\_\min}^r$
3. $priority(k)$=1. $priority(k)$ is fed back to eNB with UE identity.
4. else if $Q_k^r > Q_{k\_\max}^r$
5. $priority(k)$=0. $priority(k)$ is fed back to eNB with UE identity.
6. end if
7. eNB schedules UEs with priority(k)=1. If not all PRBs have been used, other UEs will be scheduled.

To reduce feedback overhead, we propose a modified backhaul scheduling algorithm based on user queue (M-BSUQ). Firstly, RN sets upper and lower threshold value for R-UEs' buffer length and monitors buffered queues of R-UEs. Then, RN will set the UEs' priority according to Q_k^r. When Q_k^r is less than the lower threshold value, RN will set UE k's priority to 1; When Q_k^r is greater than the upper threshold value, RN will set UE k's priority to 0. Then, the priority and the corresponding UE identity are fed back to eNB. Finally, eNB schedules UEs whose priority is 1, and the UEs whose priority values are 0 will not be scheduled.

To avoid the underflow of buffer, Q_k^r should be greater than R-UE k's volume of data to be transmitted in the following access subframe, and hence, $Q_k^r / t_{\text{AL}} > R_{\text{AL}}(k)$ should be satisfied, where t_{AL} is the transmission time of the access link and $R_{\text{AL}}(k)$ is UE k's data rate of the access link. Since the following resource allocation result of the access link is unknown, the exact value of $R_{\text{AL}}(k)$ cannot be obtained, and we use the average rate R_{AL}/K_r to represent $R_{\text{AL}}(k)$, where R_{AL} is the sum rate of the access link in the previous scheduling cycle. Hence, $Q_k^r / t_{\text{AL}} > R_{\text{AL}} / K_r$ should be satisfied, and the lower threshold value can be set as:

$$Q_{k\_\min}^r = t_{\text{AL}} \cdot R_{\text{AL}} / K_r, \tag{13}$$

Through simulations, we set the upper threshold value as:

$$Q_{k\_\max}^r = \lambda Q_{k\_\min}^r, \tag{14}$$

where, λ =3 in this paper.

The proposed algorithm comprises the following phases as algorithm 1.

We use 5 bits to represent the UE identity and 1 bit to represent the priority value. Hence the signaling overhead of RN's feedback is 6*S_r in total, where, S_r is the number of UEs whose buffer length is over upper thresholds or under lower threshold.

D. Sub-problem 3: resource allocation at access/direct link

In this sub-problem, we aim at looking for the maximum priority (8-1) with constraints (8-2), (8-3) and (8-6). The optimization of resource allocation in direct link can be

Algorithm 2: Procedure for the proposed algorithm

Input: channel matrix $\mathbf{H}_k^{(n)}$

Output: the UE set allocated in PRB n S_n

Initialization: **set** the active UE set $A=\{1,2,\ldots,K\}$. $\boldsymbol{n}$**=1**

While ($n<(N+1)$ || $A \neq \varnothing$)

1. $U=A$. **Calculate** $priopritiy_{\mathrm{PF\_SISO}}(k), \forall k \in A$.
2. **Find** UE $q=\arg\max_{k\in A}(priopritiy_{\mathrm{PF\_SISO}}(k))$. $S_n=\{q\}$. $U=U-\{q\}$.
3. **Compute** $\eta_{f,v}^{(n)}$ by (16), $\forall v \in U, \forall f \in S_n$. And **calculate** the average spatial correlation $\overline{C_v}=\sum_{f\in S_n}\eta_{f,v}^{(n)}/|S_n|$.
4. **Find** E UEs with the lowest values of $\overline{C_v}$ from U, form candidate set F. $E=\min(M,|K|)$
5. **Calculate** $\sum_{k\in S_n\cup\{v\}} R_k^{(n)}/\overline{R_k}$.
6. If $\exists v \in F$, $\sum_{k\in S_n\cup\{v\}} R_k^{(n)}/\overline{R_k} \geq \sum_{k\in S_n} R_k^{(n)}/\overline{R_k}$

   find UE $i=\arg\max_{v\in F}\sum_{k\in S_n\cup\{v\}} R_k^{(n)}/\overline{R_k}$. $S_n=S_n\cup\{i\}$, $U=U-\{i\}$.

   Else

   terminate the allocation of PRB n and **jump** to step 8.

   End
7. **Repeat** step 3-7 until $|S_n|=M$.
8. $\boldsymbol{n}$**=**$\boldsymbol{n}$**+1**. **Update** Q_k^r for R-UE and Q_k^{enb} for D-UE, $\forall k \in S_n$. If $Q_k^r=0$ or $Q_k^{enb}=0$, $A=A-\{j\}$.

End

formulated as:

$$\max \sum_k (R_k(t)/\overline{\mathrm{R}_k}(t-1)), \tag{15-1}$$

$$\text{s.t.} \quad \sum_k \rho_{n,k} \leq M \tag{15-2}$$

$$\rho_{n,k} \in \{0,1\}, \quad \forall n \tag{15-3}$$

For the resource allocation of the access link, constraint (8-6) should be added. Although exhaustive search can obtain the optimal solution to the above problem, it is not suitable to be used in realistic systems due to huge realization complexity. A simple method is to extend conventional PF algorithm into MIMO scenario, i.e., the UEs who have the highest PF priorities calculated in SISO mode will be scheduled [14]. Since the extended PF algorithm does not consider the effect of beamforming, a suboptimal algorithm is proposed in this subsection. The proposed suboptimal algorithm uses spatial correlation to evaluate the interference and the spatial correlation between UE f and UE v on PRB n can be expressed as follows:

$$\eta_{f,v}^{(n)}=\left|\mathbf{H}_f^{(n)}(\mathbf{H}_v^{(n)})^H\right|/\left(\left\|\mathbf{H}_f^{(n)}\right\|_F\left\|\mathbf{H}_v^{(n)}\right\|_F\right), 0\leq\eta_{f,v}^{(n)}\leq 1 \tag{16}$$

A small $\eta_{f,v}^{(n)}$ indicates small interference between UEs, and thus high sum data rate can be achieved on PRB n.

In the proposed algorithm, the first UE is selected through

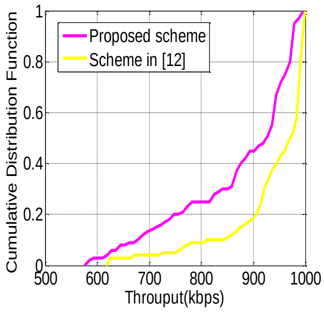

Fig. 3 Time-average throughput CDF of D-UEs

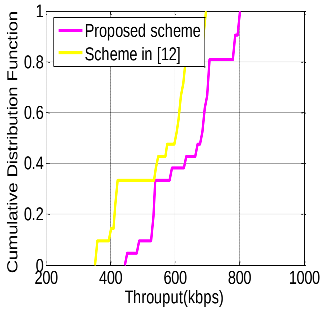

Fig. 4 Time-average throughput CDF of R-UEs

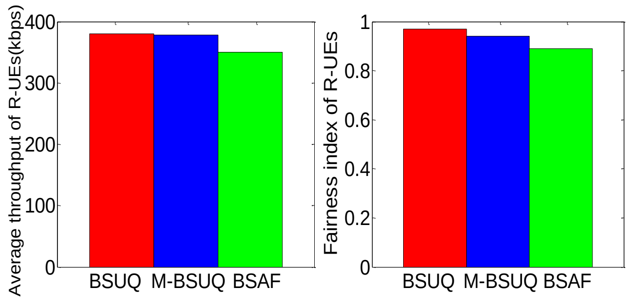

Fig. 5 Performance of R-UEs with three backhaul scheduling algorithms

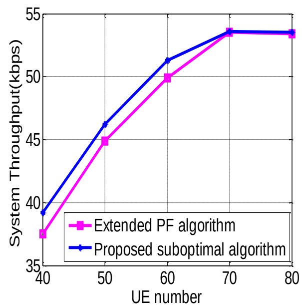

Fig. 6 System throughput vs UE number

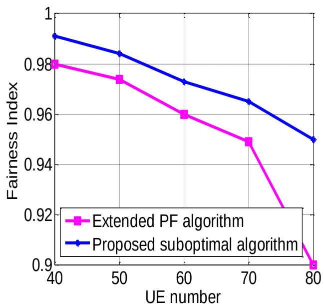

Fig. 7 Jain's fairness index value vs UE number

calculating each UE's PF priority on PRBs in SISO mode, and then PRBs are allocated to proper set of UEs by calculating the spatial correlation $\eta_{f,v}^{(n)}$. Finally, the PF utility function is calculated through SLNR beamforming based on the allocation result. The procedure of the proposed algorithm is summarized as algorithm 2.

IV. Simulation Results and Analysis

A system level simulation has been carried out in MATLAB to verify the property of the modified resource allocation scheme.

Our deployment scenario is seven three-sectored cells with one RN per sector. Configuration 1 of the TDD frame structure is adopted, i.e., subframe 1 and 5 are configured as access subframe, and subframe 4 and 9 as backhaul subframe. Thus the ratio of backhaul to access subframe is 1:1, and the simulation cycle is 2 TTIs. UEs are distributed randomly in the cell and nearly 30% UEs are connected with RNs, i.e., R-UEs. Other simulation parameters follow the parameter

TABLE I SIMULATION PARAMTERS

Parameters	Default
Carrier Frequency	2GHz
System Bandwidth	5MHz
PRBs number	25
Inter-site distance	500m
eNB Transmit Power	46dBm
RN Transmit Power	30dBm
Noise Figure	9dB
Channel Model	ITU-PedA
Transmission Mode	TM4、TM7
Antenna Configuration	4×4、4×1

settings listed in [1] for the 3GPP case 1 for urban scenario, and are summarized in Table I.To compare various algorithms of each sub-problem, the other two algorithms are fixed for the simulation of one sub-problem.

In Fig. 3 and 4, the performance of different algorithms in the first sub-problem is compared with 60 UEs per cell. From the time-average throughput Cumulative Distribution Function (CDF) of D-UEs and R-UEs, better throughput performance of R-UEs and worse throughput of D-UEs can be obtained by applying the proposed scheme due to the weighting factor in (11) compared with the scheme in [12]. For the overall system performance, the average user throughput of the scheme in [12] and the proposed scheme is 812kbps and 800kbps, respectively, and the fairness index is 0.91 and 0.96, respectively. Although system throughput is reduced slightly, user fairness is improved significantly. The reason is that in the proposed scheme, the user average data rate is considered to improve user fairness.

For sub-problem 2, Fig. 5 illustrates the performance of various backhaul scheduling algorithms in terms of throughput and fairness. Only the performance of R-UEs will be affected by the backhaul scheduling algorithm. The R-UEs' average throughput of the BSUQ algorithm, M-BSUQ algorithm and BSAF algorithm are 380kbps, 378kbps and 350kbps, respectively. And the Jain's indexes for R-UEs of three algorithms are 0.97, 0.94 and 0.89, respectively. The performance of M-BSUQ algorithm is slightly lower than BSUQ algorithm, however, the feedback overhead can be saved to 2532 bits compared with 10400 bits overhead of BSUQ during 40 TTIs. Hence, the proposed scheme can reduce by more than 75% feedback signaling overhead with a limited performance loss of system throughput and user fairness.

For sub-problem 3, the throughput and fairness of the proposed suboptimal algorithm and extended PF algorithm is given in Fig. 6 and Fig. 7, respectively. It can be seen from Fig. 6 that better throughput can be obtained by the proposed algorithm due to the reason that spatial correlation coefficient is used to reduce the interference among UEs on the same PRB for the proposed algorithm, and system throughput can thus be improved. From Fig. 7, the proposed algorithm can achieve better user fairness than extended PF algorithm, which means the proposed algorithm outperforms the extended PF algorithm both in throughput and user fairness.

V. CONCLUSION

In order to improve system throughput and user fairness, we propose a low feedback overhead fairness-aware resource allocation algorithm which is divided into 3 sub-problems to obtain a sub-optimal solution. In the first sub-problem, user fairness can be improved at the cost of slightly reduced system throughput. In the second sub-problem, more than 75% feedback overhead can be reduced with the proposed algorithm. Finally, based on the results of the above two sub-problems, the proportional fairness utility is maximized so that both system throughput and user fairness can be improved.

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References

[1] 3GPP TS 36.814, "Evolved Universal Terrestrial Radio Access (E-UTRA): Further advancements for E-UTRA physical layer aspects," V9.0.0, 2010.

[2] M. Kaneko, M. Kaneko, et al., "Throughput-Guaranteed Resource-Allocation Algorithms for Relay-Aided Cellular OFDMA System," IEEE Trans. Veh. Tech., 2009, vol. 58, no. 4, pp: 1951-1964.

[3] Z. Zhao, J. Wang, S. Redana, B. Raaf, "Downlink Resource Allocation for LTE-Advanced Networks with Type1 Relay Nodes," IEEE Vehicular Technology Conference (VTC Fall), 2012, pp: 1-5.

[4] Liang Zhou, Min Chen, Yi Qian, Hsiao-Hwa Chen, "Fairness Resource Allocation in Blind Wireless Multimedia Communications," IEEE Transactions on Multimedia, 2013, vol. 15, no. 4, pp: 946-956

[5] Q. Li, Q. Y. Hu, Y. Qian, G. Wu, "A proportional fair radio resource allocation for heterogeneous cellular networks with relays," IEEE GLOBECOM, 2012, pp: 5457-5463.

[6] 3GPP TS 36.212, "Evolved Universal Terrestrial Radio Access (E-UTRA): Multiplexing and Channel Coding," V10.5.0, 2012.

[7] T.S. Chang, KT Feng, JS. Lin, LC Wang, "Green Resource Allocation Schemes for Relay-Enhanced MIMO-OFDM Networks," IEEE Trans. on Veh. Tech., 2013, vol. 62, no. 9, pp: 4539-4554.

[8] C. Chae, T. Tang, R. W. Heath, S. Cho, "MIMO Relaying With Linear Processing for Multiuser Transmission in Fixed Relay Networks," IEEE Transactions on Signal Processing, 2008, vol. 56, no. 2, pp: 727-738.

[9] Mark S. K. Lau, Wuyi Yue, Li Ping, "Equal Power Allocation of IDMA systems: Feasibility, Optimality, and Throughput," IEEE Transactions on wireless communication, 2009, vol. 8, no. 2, pp: 746-756

[10] 3GPP TS 36.213, "Evolved Universal Terrestrial Radio Access (E-UTRA): Physical Layer Procedure," V9.2.0, 2010.

[11] X. Li, B. Li, B. Lan, M. Huang, G. Yu. "Adaptive PF Scheduling Algorithm in LTE Cellular System," Information and Communication Technology Convergence, 2010, pp: 501-504.

[12] G. Liebl, TM. de Moraes, A. Gonzalez, A. Soysal, E. Seidel. "Fair Resource Allocation for the Relay Backhaul Link in LTE-Advanced," Wireless Communications and Networking Conf., 2012, pp: 1196-1201.

[13] M. Salem, A. Adinoyi, H. Yanikomeroglu, D. Falconer. "Fair Resource Allocation Toward Ubiquitous Coverage in OFDMA-Based Cellular Relay Networks With Asymmetric Traffic," IEEE Transactions on Vehicular Technology, 2011, vol. 60, no. 5, pp: 2280-2292.

[14] J. Choi, Y. Kim, J. Lee, and etal., "User Throughput Estimation for the PF Scheduling Algorithm under MIMO Channel Environments", Wireless Communications Letters, 2012, vol. 1, no. 5, pp: 528-531.