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Maximizing Sum-Rate for Multi-User Two-Way Relaying Networks with ANC Protocol

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Abstract**—**In this paper we study the resource allocation problem for an OFDMA based cooperative two-way relaying (TWR) network. We focus on amplify and forward (AF) analog network coding (ANC) protocol. An optimization problem for two basic resources namely, sub-carrier and power is formulated for multi-user TWR networks. A joint optimal optimization problem is investigated and two-step low complexity sub-optimal resource allocation algorithm is proposed for multi-user TWR networks with ANC protocol. The proposed algorithm has been evaluated in term of total achievable system sum-rate and achievable individual sum-rate for each user-pair. The good tradeoff between system sum-rate and fairness is observed in the two-step proportional resource allocation scheme.

Keywords**—**Relay Network, Relay Protocols, Resource Allocation, Two –way relaying.

I. Introduction

THE cooperative or relay communication, generally refers toa system where the source transmits its signal to the destination with the cooperation of one or more relays to improve system performance. This idea of cooperative communication in wireless environment is more attractive due to the diverse quality of wireless channel and the limited number of usable resources. With this cooperation, users that experience a deep fade in their channel links can utilize better channels provided by relays to improve their quality of service. Due to the practical half-duplex nature of devices, there are two types of cooperative relaying proposed in the literature, namely one-way relaying (OWR)[1] and two-way relaying (TWR)[2]. Conventional cooperative networks are known as one-way relaying cooperative system. Due to half duplex operation of the relays in OWRnetwork, two separate phases of transmission are required for the mobile terminal (MT) and the base station (BS) to exchange information via cooperation. Hence a total of four time slots are required to complete the exchange of information between the MT and the BS. In this type of relaying, there is a loss of half of the spectral efficiency as compared to full duplex relaying. Full duplex relaying, in which a relay is able to transmit and receive on the same frequency at the same time, is practically more complex. Therefore, from a practical point of view, half duplex relaying is preferred over full duplex operation even with this loss of spectral efficiency [3].

To overcome the spectral loss in OWR; two types of TWR have been proposed in the literature. The first type assumes that no direct link is available between MT and BS and only a relay link is available for transmission. Therefore, two time slots are required to complete the exchange of information between the MT and BS.The second type takes into account the direct link, and requires three time slots in order to complete the exchange of information[4]. These two types of AF-based TWR are known as Analog Network Coding (ANC) protocol and Time Division Broadcast (TDBC) protocol, respectively [5]. But in this paper we will focus only on ANC protocol.

Orthogonal Frequency Division Multiplexing (OFDM) has already been employed in a number of communication standards including Digital Audio Broadcasting (DAB), Wireless LAN standards and IEEE 802.16 Broadband Wireless Access System. OFDM is also considered to employin next generation relaying wireless standards such as IEEE 802.16j, IEEE.802.16m and 3GPP LTE-A [6].

In recent years there has been an extensive amount of research undertaken and published in the area of cooperative networks. The initial work on cooperative networks was focused on OWR only but now TWR has been attracted a lot of interest by researchers due to its high spectral efficiency.

In [5] author has addressed the relay selection problem for both ANC and TDBC protocols. The closed form expression for outage probability is derived. Single-pair network is considered, therefore multi-user interference is not considered. Similar network configuration is used in [7] to address the relay selection problem in bidirectional relaying with unknown channel state information (CSI). The author in[4] has compared different protocols in half duplex TWR using decode and forward (DF) protocol. The research is focused on three node single carrier system. The problem of resource allocation in TWR has addressed in [8] for two terminal network with multiple relays. A fairness constraint is imposed on relays with maximum sum capacity as an objective function. In [9], authors have successfully analyzed the tradeoff between the communication reliability and transmission rate in amplify & forward (AF) TWR. They formulated the optimal rate allocation problem under sum-rate constraint and optimal power allocation with total power constrains for two terminal networks has also been investigated. Power allocation with data rate fairness is studied in [10] for AF and DF protocols.

The resource allocation problem for multi-user TWR is addressed in [11]. The optimum relay power allocation problem for TWR multi-user network is investigated in single carrier system with centralized approach. Therefore no sub-carrier allocation is considered here. In [12], a hierarchical protocol for OWR and TWR is proposed. The transmission mode of each MT as well as relay is already assigned, either

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direct or relaying. The joint resource allocation problem is formulated under total power constraints. The outage performance analysis for multi-user TWR is presented in [13]. In[14], we investigate the subcarrier allocation problem in AF protocol based OWR networks . Equal Power is allocated to source and relay and power optimization is not considered.

A. Motivation and Contribution

Most of the currently available resource allocation methods for TWR are constrained to single-pair scenarios and most of them do not consider a multi-user environment. But in practical scenarios, interference due to multiple users also plays a critical role in system performance degradation. In this paper, a joint optimization problem for two radio resources, sub-carriers and power is formulated with AF-based ANC protocol for multi-user TWR-networks. The objective function is to maximize overall sum-rate under the power and fairness constraints.A two-step low complexity sub-optimal resource allocation algorithm known as proportional fairness scheme is investigated for multi-user TWR networks with ANC protocol.Two conventional sub-carrier allocation techniques are also investigated and compared with proposed proportional scheme in multi-user TWR networks.

B. Organization

The rest of the paper is organized into four additional sections. Section II presents the system and propagation model. A brief description about protocols is also presented in this section. An analytical analysis is described in Section III. In Section IV resource allocation schemes and problem formulation is presented. Furthermore, numerical results with simulation are illustrated in Section V. Finally, conclusion is provided in Section VI.

II. System Model and Protocol Descriptions

A. System Model

Consider a TWR transmission in mobile cooperative network. The system model consists of a single BS, R number of relay terminals (RTs) and M number of mobile terminals (MTs). Each terminal is equipped with single antenna. Each MT makes a pair with BS for communication and we say that there is P number of pairs in this cell.

Time Division Duplex(TDD) is used to achieve separation between uplink and downlink transmission to and from relay respectively as all relays are working in half duplex mode and adopt AF protocol. In Long Term Evolution (LTE) system, a chunk, consists of twelve consecutive OFDM sub-carriers, known as of Resource Block (RB) is introduced. Therefore RB is the minimal unit that is allowed to be allocated to one user [15]. We assume that there are K numbers of RBs available in the cell.

B. Propagation Model

All the channel coefficients are modeled as Rayleigh flat fading, with zero mean and variance$h_o$and Additive White Gaussian Noise (AWGN) with zero mean and variance σ^2 .We consider that all channels remain constant for one complete transmission in both networks. For simplicity, it is assumed that Channel State Information (CSI) is known to all nodes.The CSI remains constant within one RB, but it is different for different RBs.

C. Protocol Descriptions

In TWR cellular cooperative communication, BS and MT communicate with each other in two time slots in ANC protocol.

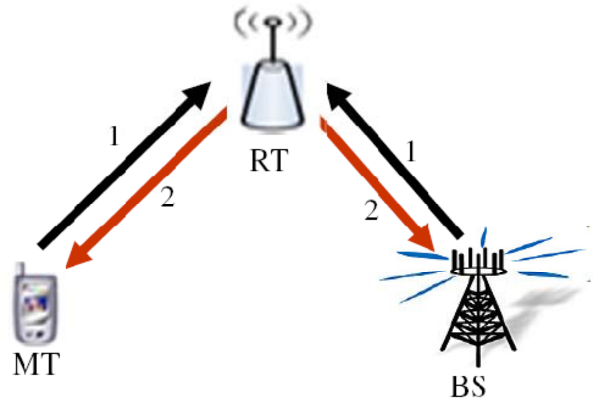

Fig. 1 TWR with ANC Protocol

In ANC protocol as shown in Fig. 1, both MT and BS transmit their signals to the RT during the first time slot. TheRT receives the combined signal of MT and BS due to broadcast nature of wireless channel. The RT amplifies this combined signal and then retransmits to both MT and BS in the second time slot. The received signal at MT and BS also consists of their own transmitted signal known as self-interference signal. With the knowledge of channel and its own signal, this self-interference signal can be subtracted from the received signal [2].

D. System Parameters

The system parameter and symbol notations are given in the Table I below.

TABLE I
System Model Parameters

Notation	Definition
P_x	Transmission Power of Node x
P_t	Total Transmission Power
H_{xy}	Channel Gains between node x and y
σ_x	Noise Variance of AWGN at node x
β_r^k	Amplification factor for r^{th} relay at k^{th} RB

III. Mathematical Analysis

For the mathematical analysis, first we define the instantaneous received Signal-to-Noise Ratios (SNRs) at each node. Let γ_{1m}^k and γ_{1b}^k represent the SNRs at MT and BS of p^{th}pair on k^{th} RB respectively and given by [2].

$$\gamma_{1m}^{k} = \frac{\left|\beta_r^k H_{br}^k H_{rm}^k\right|^2 P_b^k}{\left(\left|\beta_r^k H_{rm}^k \sigma_r\right|^2 + \sigma_m^2\right)} \quad (1)$$

$$\gamma_{1b}^{k} = \frac{\left|\beta_r^k H_{mr}^k H_{rb}^k\right|^2 P_m^k}{\left(\left|\beta_r^k H_{rb}^k \sigma_r\right|^2 + \sigma_b^2\right)} \quad (2)$$

β_r^k Is given as [2]:

$$\beta_r^k = \sqrt{\frac{P_r^k}{P_b^k\left|H_{br}^k\right|^2 + P_m^k\left|H_{mr}^k\right|^2 + \sigma_r^2}} \quad (3)$$

For simplicity of derivations we assume that the all noise variances are identical and respective channel gains are reciprocals (i.e. $H_{xy} = H_{yx}$ and $\sigma_b^2 = \sigma_m^2 = \sigma_r^2 = \sigma^2$). By substituting (3) in (1) and using the following substitutions,

$$\frac{\left|H_{br}^k\right|^2}{\sigma^2} = \frac{\left|H_{rb}^k\right|^2}{\sigma^2} = X, \frac{\left|H_{mr}^k\right|^2}{\sigma^2} = \frac{\left|H_{rm}^k\right|^2}{\sigma^2} = Y, \frac{\left|H_{bm}^k\right|^2}{\sigma^2} = \frac{\left|H_{mb}^k\right|^2}{\sigma^2} = Z$$

The received SNR γ_{1m}^k given in (1) can be written as:

$$\gamma_{1m}^{k} = \frac{P_b^k X\ P_r^k Y}{P_b^k X + (P_r^k + P_m^k)Y + 1} \quad (4)$$

and γ_{1b}^k given in (2) can be written as:

$$\gamma_{1b}^{k} = \frac{P_m^k Y\ P_r^k X}{(P_b^k + P_r^k)X + P_m^k Y + 1} \quad (5)$$

The achievable rates from BS to mobile *M* and from mobile *M* to BS are

$$R_{1,m}^k = \frac{1}{2}\log_2(1+\gamma_{1m}^k) \quad (6)$$

$$R_{1,b}^k = \frac{1}{2}\log_2(1+\gamma_{1b}^k) \quad (7)$$

The factor ½ appears here due to the half-duplex operation of relays. It means relays transmit and receive in two different time slots.

Therefore the instantaneous sum-rate of TWR-ANC protocol can be given as:

$$R_1^k = R_{1,m}^k + R_{1,b}^k$$

$$= \frac{1}{2}\log_2(1+\gamma_{1m}^k) + \frac{1}{2}\log_2(1+\gamma_{1b}^k) \quad (8)$$

IV. Resource Allocation

A. Joint optimal Resource Allocation

In this sub-section, we formulate a joint optimization problem for optimal allocation of power and resource blocks to all user pairs in TWR-ANC. The instantaneous sum-rate of TWR-ANC protocol is given in (6). Thetotal sum-rate achieved by ANC on all allocated RBs can be calculated as:

$$R_{sum} = \sum_{k=1}^{K} R_1^k \quad (9)$$

An optimization problem is formulated in this way that we maximizetheoverall sum-rate of the system with minimum sum-rate requirement for each MT-BS pair. Here we define a variable α_p^k, a RB allocation index.

$$\alpha_p^k = \begin{cases} 1 & \text{if RB k is alloocatedto Pair p} \\ 0 & \text{Otherwise} \end{cases}$$

The total achievable sum-rate of the system is given as

$$R_S = \sum_{p=1}^{P}\sum_{k=1}^{K} \alpha_p^k R_1^k \quad (10)$$

The optimization problem for optimal resource allocation can be formulated as

$$\max \sum_{p=1}^{P}\sum_{k=1}^{K} \alpha_p^k R_s^k \quad (11)$$

Subject to:

$$\alpha_p^k \in \{0,1\}, \ \forall\, k, p \quad (11a)$$

$$\sum_{p=1}^{P} \alpha_p^k = 1, \ \forall\, p \quad (11b)$$

$$\sum_{k=1}^{K} \alpha_p^k R_s^k \geq R_{\min} \ \forall \ p \quad (11c)$$

$$(P_b^k + P_r^k + P_m^k) \leq P_t^k \quad (11d)$$

$$(P_b^k, P_r^k, P_m^k) > 0 \quad (11e)$$

The first two constraints (11a) and (11b) in this optimization problem are that each RB can only be assigned to only one MT-BS pair to avoid multi-user interference. The constraint (11c) is the minimum sum-rate requirement of each pair and (11d, 11e) are the total and individual power constraints, respectively. Since this problem is combinatorial due to both discrete (RB allocation) and continuous (Power allocation) variable values and computational complexity is too high. To avoid this complexity, this paper focuses on the allocation of resourcesin two steps. In the first step only RBs are allocated at equal power allocation. In the second step, power optimization is applied to maximize the sum-rate of the system.

B. Two-Step Resource Allocation

1. RBs Allocation

The optimization problem as described in (11) is developed and RB allocation is made in three sub-steps.

a. Selection: In the first sub-step, priority of each pair is determined. The pair with highest received SNR among available pairs is first selected for the allocation of each RB. This selection ensures that best RB is used by available user who has best channel condition.

$$(m,k) = \arg \max \left(\gamma_m^k\right) \quad m \in MT, k \in RB;$$

b. Fairness: The second sub-step is the fairness step. RBs are allocated to different pairs to satisfy their minimum sum-rate ($R_{\min}$) requirement. The pair with highest priority is allowed to select the best RB from available RBs which maximize its sum-rate. This process continues till either all the pairs have achieved $R_{\min}$ or all the RBs are allocated to pairs. This step guarantees that pairs with higher sum-rate requirement or with good channel conditions are not allowed to use all the resources at the expense of others.

c. Maximization: This step aims to maximize the overall sum-rate of the system after achieving $R_{\min}$ for all pairs in the previous step. If RBs are still available, these are allocated to the pairs which maximize the system sum-rate.

In two-step Resource allocation scheme known as proportional fairness scheme (PFS), we optimize the overall system sum-rate by ensuring fairness among all pairs.The approach is depicted in Algorithm 1:

Algorithm 1 for RBs Allocation

Set
$MT = \{1,2,\ldots\ldots,M\}, \quad RT = \{1,2,\ldots\ldots,R\}$
$RB = \{1,2,\ldots\ldots,K\}$

Step:1

Selection

$(m,k) = \arg \max \left(\gamma_m^k\right) \quad m \in MT, k \in RB;$

Step: 2

Fairness

if $R_{sum} < R_{\min}$ *then*
$\alpha_m^k = 1, \; RB = K - \{k\};$

Update R_{sum}

elseif $R_{sum} \geq R_{\min}$ *and* $MT \neq \phi$

do

$MT = M - \{m\};$

Go to Step 1

end

Step: 3

Maximization

Update $MT = \{1,2,\ldots\ldots\ldots,M\},$

if $RB \neq \phi$
$(m,k) = \arg \max (R_S); \quad m \in M, k \in RB;$
$\alpha_m^k = 1, \; RB = K - \{k\};$

Update R_S, R_{sum}

end

2. Power Allocation

After the allocation of all RBs, the discrete variable has been fixed and the power is allocatedto each entity by optimizing the objective function:

$$\max \quad R_S \tag{12}$$

Subject to:

$$(P_b^k + P_r^k + P_m^k) \leq P_t \tag{12a}$$

$$(P_b^k, P_r^k, P_m^k) > 0 \tag{12b}$$

Now in this problem, only one variable in the form of power is present. This problem can be solved as simple convex optimization problem.

C. Conventional Schemes

In this sub-section we review two conventional RB allocation schemes and the proposed two-step approach will be compared with them.

1) Round Robin Scheme

In round robin scheme (RRS), the allocation of RBs is made in cyclic way to each MT-BS pair. In other words RBs are equally allocated to all pairs, regardless of the channel conditions.

2) Maximum SNR Scheme

In maximum *SNR* scheme (MSS), RBs are allocated to the MS-BS pairs which have maximum received SNRs. This scheme optimizes the overall system throughput but fairness between pairs is not considered. In this way, any pair which has worst received SNR due to poor channel conditions may not be allocated any RB.

V. Numerical Results

In this section, we present and compare numerical results of RB allocation schemes with help of computer simulations. For simplicity we choose only two MTs, hence two MT-BS pairs, and it is also assumed that only one RS is cooperating with each MT.No relay selection is discussed in this paper as we assume that relays are fixed or relay selection has already been made via relay selection techniques in [5]. Total of 96 subcarriers are used which construct eight RBs that are available for these two pairs. The proposed algorithm has been evaluated in term of total achievable system sum-rate and achievable individual sum-rate of each pair. The minimum sum-rate $R_{\min}$ = 2 Mb/Sec is set for each pairs.

Fig. 2 shows the overall achievable sum-rate for proportional fairness allocation scheme and it is compared with two conventional RB allocation schemes, described in section IV,with TWR-ANC protocol. At this stage equal power allocation is assumed in all schemes. The performance is observed at the average of different numbers of iterations at SNR = 20dB and it is clear that PFS always outperform RRS and it achieves overall system sum-rate very close to MSS.

In the case of individual sum-rate, PFS outperform both RRS and MSS as shown in Fig. 3. The fairness between all pairs is achieved in PFS, while MSS and RSS do not able to provide fairness in all iterations. For example, one of the pairs in RRS and MSS cannot get its minimum sum-rate requirement in iterations 30 and 60, respectively. The system performance against received SNR is shown in Fig. 4, which shows that PFS always achieves higher overall system throughput as compared to RRS and achieves almost same as in MSS.

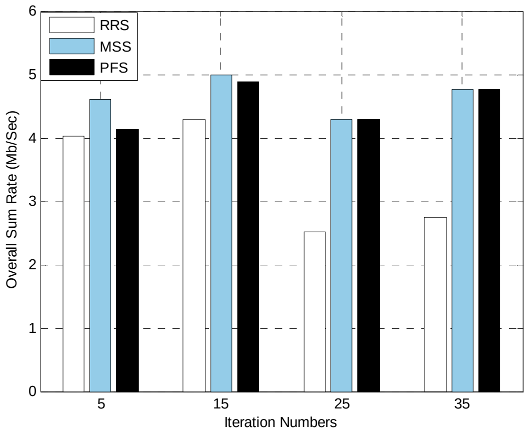

Fig. 2 Overall Sum-Rate

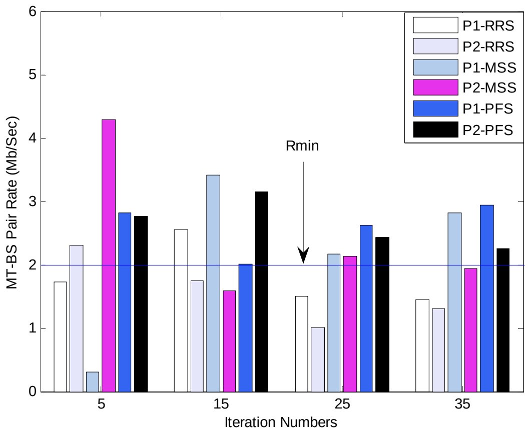

Fig. 3 Individual Sum-Rate

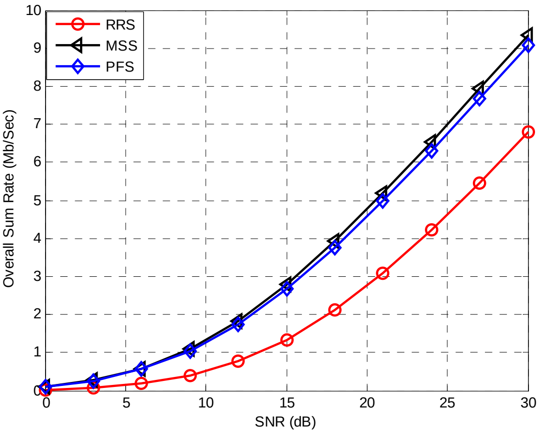

Fig. 4 Overall Sum-Rateversus SNR

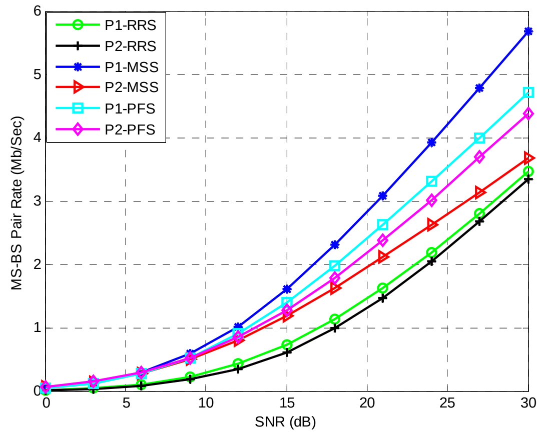

Fig. 5 Individual Sum-Rate versus SNR

The individual pair performance against SNR is sown Fig. 5. It is shown that in MSS, one of the pairs always gets much higher sum-rate as compared to others. While in PFS proportional fair sum-rate is ensuredfor both pairs. A good tradeoff between overall sum-rate and individual pair sum-rate is observed in PFS.

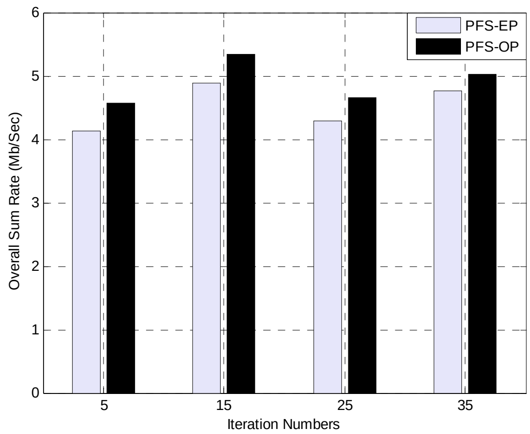

Fig. 6 Comparison of PFS-EP and PFS-OP

In Fig. 6, we present the comparison of PFS with equal power allocation (PFS-EP) and PFS with optimized power allocation (PFS-OP). To optimize the power, we apply MATLAB optimization toolbox command "*fmincon*" which is designed to find the minimum of agiven constrained nonlinear multivariable function.We observe that the PFS-OP achieves a significant sum-rate performance gain over the PFS-EP.

VI. Conclusion

The resource allocation problem in two-way relaying cooperative networks is investigated in this paper. An optimization problem is formulated to maximize the overall system sum-rate with minimum sum-rate guarantee to all user-pairs. By comparing the performance of different sub-carrier allocation schemes in two-way relaying, we conclude that proportional fairness scheme is a good choice for allocation of this resource with optimum power allocation because it not only enhancesthe system throughput but also ensure fairness between user pairs. Finally, we remark that, while this paper considers individual sum-rate of each pair, the consideration of individual rate of BS and MT in each pair remains interesting and to be discovered.

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