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A novel user pairing scheme for functional decode-and-forward multi-way relay network

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A B S T R A C T

In this paper, we consider a functional decode and forward (FDF) multi-way relay network (MWRN) where a common user facilitates each user in the network to obtain messages from all other users. We propose a novel user pairing scheme, which is based on the principle of selecting a common user with the best average channel gain. This allows the user with the best channel conditions to contribute to the overall system performance. Assuming lattice code based transmissions, we derive upper bounds on the average common rate and the average sum rate with the proposed pairing scheme. Considering M-ary quadrature amplitude modulation with square constellation as a special case of lattice code transmission, we derive asymptotic average symbol error rate (SER) of the MWRN. We show that in terms of the achievable rates, the proposed pairing scheme outperforms the existing pairing schemes under a wide range of channel scenarios. The proposed pairing scheme also has lower average SER compared to existing schemes. We show that overall, the MWRN performance with the proposed pairing scheme is more robust, compared to existing pairing schemes, especially under worst case channel conditions when majority of users have poor average channel gains.

1. Introduction

Multi-way relay networks (MWRNs), where a single relay facilitates all users in the network to exchange information with every other user, have important potential applications in teleconferencing, data exchange in a sensor network or file sharing in a social network [1–12]. A MWRN is a generalization of two-way relay networks (TWRNs), which enable bidirectional information exchange between two users and are widely recognized in the literature for their improved spectral efficiency, compared to conventional relaying [13–19]. Note that multi-user TWRNs [20–25], where each user exchanges information with a pre-assigned user only, can be considered as a special case of MWRNs.

The users in a MWRN can adopt either pairwise transmission [1,5,9] or non-pairwise transmission [4,6,8,26] strategy for message exchange. Though non-pairwise transmission can offer larger spectral efficiency, its benefits come at the expense of additional signal processing complexity at the relay [6]. Hence, in this paper, we focus on pairwise transmission strategy. Recently, pairwise transmission based MWRNs have been studied for different relaying protocols, e.g., functional decode and forward (FDF) [1], decode and forward [4], amplify and forward [5] and compute and forward [7] protocols. It was shown in [1] that pairwise FDF with binary linear codes for MWRN, where the relay decodes a function of the users' messages rather than the individual messages from a user pair, is theoretically the optimal strategy since it achieves the common rate. Also it was shown in [2] that for a MWRN with lattice codes in an Additive White Gaussian Noise (AWGN) channel, the pairwise FDF achieves the common rate. Hence, in this paper, we consider FDF MWRN.

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In a pairwise transmission based FDF MWRN, user pair formation is a critical issue. In this regard, two different pairing schemes have been proposed in the literature. In the pairing scheme in [1], two consecutive users are paired with each other (i.e., user 1 with user 2, user 2 with user 3, user $L-1$ with user L, etc. where L is the number of users in the MWRN). Thus, in general, the ℓth and the $(\ell+1)$th users form a pair at the ℓth time slot, where $\ell \in [1, L-1]$. In the pairing scheme in [9], instead of consecutive users as in the pairing scheme in [1], two users in a pair are chosen from the two ends of a sequence such that the second user in one pair becomes the first user in the next pair (i.e., the pairs would be $(1, L)$, $(L, 2)$, $(2, L-1)$, etc.). Thus, in general, the ℓth and the $(L-\ell+1)$th user form a pair at the ℓth time slot when $1 \le \ell \le \lfloor L/2 \rfloor$ and the $(\ell+1)$th and $(L-\ell+1)$th user form a pair at the ℓth time slot when $\lfloor L/2 \rfloor < \ell \le L-1$, where $\lfloor \cdot \rfloor$ denotes the floor operation. The achievable rates for these two existing pairing schemes were analyzed in [1,2,9], while the average bit error rate (BER) for the first pairing scheme was analyzed in [27].

A major drawback of the pairing scheme in [1] is that they do not take the users' channel information into account when pairing the users. In [9], the authors have considered only one case of asymmetric channel conditions, which is $|h_{1,r}|^2 < |h_{2,r}|^2 < \cdots < |h_{L,r}|^2$. However, they have not utilized the channel gain information for intelligent choice of the user pairs. Rather, both in [1] and [9], the users with good and bad channel conditions transmit the same amount of time. The only difference between the pairing schemes in [1] and [9] is the ordering of the user pair. Thus, if the performance metrics of [1] and [9] are being averaged over a number of settings for average channel gain, [1] and [9] would give the same results. Though in [9], the authors have shown that their pairing scheme is optimal in terms of the common rate for DF protocol and the considered channel conditions, the pairing schemes in [1] and [9], are not optimal in terms of the sum rate and error performance. This is because both in [1] and [9], the users with good and bad channel conditions transmit the same amount of time and the overall throughput will be less than that if the user with good channel conditions are allowed to transmit more times. Moreover, in a MWRN, the decision about each user depends on the decisions about all other users transmitting before it. Thus, in the above pairing schemes, if any user experiences poor channel conditions, it can lead to incorrect detection of another user's message, which can adversely impact the system performance due to error propagation. We also note that a recent paper on opportunistic pairing [11] also suffers from the error propagation problem similar to [1].

In this paper, we propose a novel pairing scheme for user pair formation in a FDF MWRN. In this scheme, each user is paired with a common user, which is chosen by the relay as the user with the best average channel gain. This allows the user with the best channel conditions to contribute to improving the overall system performance by reducing the error propagation in the network. In our prior work in [28], we considered a pairing scheme to reduce error propagation in an amplify and forward (AF) MWRN. However, we considered simple binary phase shift keying (BPSK) modulation in [28], which is not suitable for practical high data rate systems. Also, our prior work in [28] reduces error propagation for a specific channel gain scenario but may not be optimal in terms of the common rate and sum rate. These major limitations of our prior work have motivated us to generalize and extend the prior work. The major contributions of this paper are as follows:

- Considering an L-user FDF MWRN employing sufficiently large dimension lattice codes, we derive upper bounds for the common rate and sum rate with the proposed pairing scheme (cf. Theorems 1–2).
- Considering an L-user FDF MWRN with M-ary quadrature amplitude modulation (QAM) based transmission, which is a special case of lattice code based transmission, we derive the asymptotic average SER with the proposed pairing scheme (cf. Theorem 3).
- We present important insights, obtained from a careful analysis of the results in Theorems 1–3, in the form of Propositions 1–9. Analyzing the results in Theorems 1–3, we compare the performance of the proposed pairing scheme with the existing pairing schemes and show that:
  - For the equal average channel gain scenario, the average common rate and the average sum rate are the same for the proposed and existing pairing schemes, but the average SER improves with the proposed pairing scheme (cf. Propositions 1, 4 and 7).
  - For the unequal average channel gain scenario, the average common rate, the average sum rate and the average SER all improve for the proposed pairing scheme (cf. Propositions 2, 5 and 8).
  - For the variable average channel gain scenario, the average common rate for the proposed pairing scheme is practically the same as the existing schemes, whereas, the average sum rate and the average SER improve for the proposed pairing scheme (cf. Propositions 3, 6 and 9).

The rest of the paper is organized as follows. The generalized system model is presented in Section 2. The proposed pairing scheme is discussed in Section 3 and the general lattice code based transmissions with the proposed pairing scheme are presented in Section 4. The common rate and the sum rate for a FDF MWRN with the proposed scheme is derived in Section 5. The average SER is derived in Section 6. The numerical and simulation results for verification of the analytical solutions are provided in Section 7. Finally, conclusions are provided in Section 8.

Throughout this paper, we use the following notations: $\hat{(\cdot)}$ denotes the estimate of a message, $\hat{\hat{(\cdot)}}$ denotes that the message is estimated for the second time, $|\cdot|$ denotes absolute value of a complex variable, $\|\cdot\|$ denotes Euclidean norm, $\arg(\cdot)$ denotes the argument, $\max(\cdot)$ denotes the maximum value, $\min(\cdot)$ denotes the minimum value, $E_H[\cdot]$ denotes the expected value with respect to random channel coefficients, $\lfloor \cdot \rfloor$ denotes the floor operation, $\log(\cdot)$ denotes logarithm to the base two and $Q(\cdot)$ is the Gaussian Q-function.