# A NOVEL PAIRING SCHEME TO REDUCE ERROR PROPAGATION IN AN AMPLIFY AND FORWARD MULTI-WAY RELAY NETWORK

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## ABSTRACT

In this paper, we propose a novel user pairing scheme to reduce the error propagation in an amplify and forward (AF) based multi-way relay network (MWRN). We consider a user pairing scheme, where, a common user is chosen based on its average channel gain to form pairs with every other user in the MWRN. We show that choosing the common user as the user with the minimum average channel gain reduces the contribution of the interference components from the common user's signal in the extracted signals of other users. This leads to better bit error rate (BER) performance for all other users. For the common user, the BER improves at high SNR but it degrades at low SNR. The results show that the proposed pairing scheme outperforms the existing pairing scheme in terms of average BER of different users at high SNR.

***Index Terms*—** multi-way relay network, amplify and forward (AF), error propagation, pairing scheme.

## 1. INTRODUCTION

Multi-way relay networks (MWRNs) are a generalization of two-way relay networks (TWRNs) [1, 2] which involve multiple users exchanging information with each other through a single relay [3, 4]. MWRNs allow the enhanced capacity and spectral efficiency benefits of TWRNs to be realized in a multi-user scenario. Potential applications of MWRNs include file sharing in a wireless network, exchange of local measurement in a sensor network or base station information exchange in a satellite network [3]. In a MWRN, the users take turns to transmit in pairs and the relay receives the sum of the signals. Prior studies on MWRNs include common rate capacity analysis through pair-wise DF (at the relay) for binary MWRN [4], as well as, maximization of sum rate by optimal user pairing scheme [5] for DF MWRNs and error performance analysis for synchronous and asynchronous MWRNs [6]. However, in this paper, we consider an AF MWRN for its simpler implementation.

For an AF MWRN, a pairing scheme has been introduced in [7, 8], which is similar to the pairing scheme for DF MWRN in [4]. In this scheme, at the $\ell^{th}$ time slot, the $\ell^{th}$ and the $(\ell+1)^{th}$ users transmit simultaneously, where, $\ell \in [1, L-1]$ and $L$ is the number of users in the MWRN. It has been shown that such pairwise data exchange in a MWRN leads to the error propagation problem [9]. This problem arises when a user wrongly decodes another user's message because it results in uncancelled interference components in the extracted signals, leading to error performance degradation.

To solve the above issue, we propose a novel pairing scheme, where the user pairs are chosen based on their average channel gain, rather than pairing the users without taking into account the channel conditions [4,5,7,8]. In our proposed scheme, it is possible to choose the user pairs in such a way that the non-cancellable interference components from the other user's signal in the extracted signal of the desired user, can be reduced. In this respect, we make the following contributions, which have not been addressed yet in the literature.

- We propose a novel pairing scheme for an AF MWRN, where the relay chooses a user based its average channel gain, which is then paired with every other user in the network. That is, the chosen user serves as a common user for all the user pairs.
- We show that choosing the user with the *minimum* average channel gain as the common user reduces error propagation at other users by lessening the influence of interference components from the common user's signal in the extracted signals of other users.
- We investigate the average BER at different users for the proposed pairing scheme and compare with existing pairing schemes. The proposed scheme is found to achieve better error performance than the existing pairing schemes.

The rest of the paper is organized in the following manner. The system model of an AF MWRN with the proposed pairing scheme is presented in Section 2. The error performance analysis is provided in Section 3. Section 4 compares the analytical solutions with the simulation results. Finally, conclusions are provided in Section 5.

## 2. SYSTEM MODEL

We consider an $L$-user AF MWRN, where the users exchange their information through a single relay as they have no direct path in between them. For complete information exchange among $L$ users, two phases are required− multiple access and broadcast phase, each comprising $L-1$ time slots. In the *multiple access phase*, the users transmit their data in a pairwise manner, whereas, in the *broadcast phase*, the relay broadcasts the amplified network coded message to all the users. The $2(L-1)$ time slots in these two phases constitute one time frame.

We choose the index for the time slot and the time frame as $t_s$ and $t_f$, respectively, where, $t_s \in [1, L-1]$ and $t_f \in [1, T_f]$. Also, we assume that in each time frame, each user transmits a message packet of length $T$ and the relay transmits $(L-1)$ message packets, each of length $T$, where, the message index is $t \in [1, T]$. During the $t_f^{th}$ time frame and the $t_s^{th}$ time slot, the channel from the $j^{th}$ user to the relay is denoted by $h_{j,r}^{t_s,t_f}$ and the channel from the relay to the $j^{th}$ user by $h_{r,j}^{t_s,t_f}$, where $j \in [1, L]$. We make the following assumptions regarding the channels:

1. The channels are assumed to be block Rayleigh fading channels which remain constant during one message packet transmission in a certain time slot in a certain multiple access or broadcast phase in each time frame. The channels between any user and the relay are considered reciprocal.

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2. The channel coefficients are zero mean complex-valued Gaussian random variables with variances given by $\sigma^2_{h_{j,r}} = \sigma^2_{h_{r,j}}$, The average channel gains for different users are considered unequal within a certain time frame and these average channel gains change every time frame.

3. The instantaneous channel state information (CSI) of all the users is available to the relay and all the other users. This perfect CSI assumption allows benchmark results to be obtained.

Next, we explain the transmission protocols for multiple access and broadcast phases in an AF MWRN.

### 2.1. Multiple Access Phase

In the multiple access phase, the users transmit in a pairwise manner. In this paper, we propose a new pairing scheme for the multiple access phase, based on the following set of assumptions:

- All the user pairs have a common user among them which is chosen and broadcast by the relay before each multiple access phase. In each time slot, the common user and one other user transmit simultaneously and the relay receives the sum of the signals.
- The common user is chosen to be the user that has the minimum average channel gain in the whole system. This allows the reduction of the interference from the common user in the extracted signal of any other user, which would be discussed in detail in the following section.
- After every time frame, the common user might change depending upon the changing channel conditions. Thus, fairness can be maintained because, on an average, every user gets the opportunity to become the common user.

In this analysis, we denote the $i^{th}$ user as the common user and the $\ell^{th}$ user as other users, where, $i, \ell \in [1, L]$ and $\ell \neq i$. For the remaining part of this paper, we consider message exchange within a certain time frame and choose to omit the superscript $t_f$ from the symbols for maintaining simplicity in the notations.

In a certain time frame, the message packet of the $\ell^{th}$ user is denoted by

$$\mathbf{W}_\ell^{t_s} = \begin{cases} \{W_\ell^{t_s,1}, W_\ell^{t_s,2}, ..., W_\ell^{t_s,T}\} & t_s = \ell - 1 \\ 0 & t_s \neq \ell - 1, \end{cases} \tag{1}$$

where, the elements $W_\ell^{t_s,t} \in \{0, 1\}$. Similarly, the message packet of the $i^{th}$ user is given by $\mathbf{W}_i = \{W_i^{t_s,1}, W_i^{t_s,2}, ..., W_i^{t_s,T}\}$ for $t_s \in [1, L-1]$.

In a certain time frame, in $t_s = (\ell-1)^{th}$ time slot, the messages of the $i^{th}$ and the $\ell^{th}$ user, i.e., $\mathbf{W}_i$ and $\mathbf{W}_\ell^{t_s}$ are BPSK modulated to $\mathbf{X}_i = \{X_i^{t_s,1}, ..., X_i^{t_s,T}\}$ and $\mathbf{X}_\ell^{t_s} = \{X_\ell^{t_s,1}, ..., X_\ell^{t_s,T}\}$, respectively, where $X_i^{t_s,t}\ X_\ell^{t_s,t} \in \{-1, 1\}$. The relay receives the signal $\mathbf{R}_{i,\ell}^{t_s} = \{r_{i,\ell}^{t_s,1}, ..., r_{i,\ell}^{t_s,T}\}$, where

$$r_{i,\ell}^{t_s,t} = h_{i,r}^{t_s} X_i^t + h_{\ell,r}^{t_s} X_\ell^{t_s,t} + n_1. \tag{2}$$

Here, $n_1$ is the zero mean complex AWGN at the relay with noise variance $\sigma^2_{n_1} = \frac{N_0}{2}$ per dimension, where, $N_0$ is the noise power. For this analysis, we assume equal and unity power at the users and the relay. Thus, the SNR per bit per user is $\frac{1}{N_0}$.

### 2.2. Broadcast Phase

The relay amplifies the received signal by an amplification factor, $\alpha = \frac{1}{\sqrt{|h_{i,r}|^2 + |h_{\ell,r}|^2 + N_0}}$ and broadcasts the resulting signal. The $j^{th}$ ($j \in [1, L]$) user receives $\mathbf{Y}_{i,\ell}^{t_s} = \{Y_{i,\ell}^{t_s,1}, ..., Y_{i,\ell}^{t_s,T}\}$, where

$$Y_{i,\ell}^{t_s,t} = \alpha h_{r,j}^{t_s} r_{i,\ell}^{t_s,t} + n_2. \tag{3}$$

Here, $n_2$ is the zero mean complex AWGN at the user with noise variance $\sigma^2_{n_2} = \sigma^2_{n_1}$ per dimension.

The common user ($i^{th}$ user), subtracts its own signal multiplied by $\alpha h_{r,j}^{t_s}$ and obtains

$$\hat{Y}_{i,\ell}^{t_s,t} = \alpha h_{\ell,r}^{t_s} h_{r,j}^{t_s} X_\ell^{t_s,t} + \alpha h_{r,j}^{t_s} n_1 + n_2. \tag{4}$$

Then it performs maximum likelihood (ML) detection [2] on the resulting signal and can estimate the message of all other users.

For other users, the process can be described as follows. At first, the $\ell^{th}$ user subtracts its own signal from the network coded signal received in the $(\ell - 1)^{th}$ time slot (i.e., $\mathbf{Y}_{i,\ell}^{t_s}$) and performs ML detection to estimate the message of the common user as $\hat{\mathbf{W}}_i$. After that, it BPSK modulates the extracted message of the $i^{th}$ user and subtracts it from the other network coded signals ($\mathbf{Y}_{i,m}^{t_s}$) ($m \in [1, L], m \neq i, \ell$) to obtain the message of the $m^{th}$ user.

Now, if the $\ell^{th}$ user incorrectly decodes the message of the $i^{th}$ user, then it cannot completely cancel out the interference component involving the $i^{th}$ user's signal from the other network coded signals. That is, if $\hat{\mathbf{X}}_i \neq \mathbf{X}_i$, then

$$\begin{aligned}\hat{Y}_{i,m}^{t_s,t} =& \alpha h_{m,r}^{t_s} h_{r,\ell}^{t_s} X_m^{t_s,t} + \alpha h_{r,\ell}^{t_s} h_{i,r}^{t_s} (X_i^{t_s,t} - \hat{X}_i^{t_s,t}) + \\ & \alpha h_{r,\ell}^{t_s} n_1 + n_2. \end{aligned} \tag{5}$$

Thus, the mean of the received signal is shifted and it can result into incorrect detection of the other users' messages, termed as error propagation problem [9].

**Remark 1** *From* (5)*, it can be noted that a careful choice for the channel gain of the $i^{th}$ user (common user) can reduce the contribution of the interference term and in effect, error propagation.*

## 3. ERROR PERFORMANCE ANALYSIS

In this section, we investigate the error performance of AF MWRN with the proposed pairing scheme. To simplify the notations, we omit the superscripts $t_s, t$ from the symbols defined in the previous section. In an $L$-user MWRN, each user has to decode $L - 1$ other users' messages. So we need to consider the SNR of all the users individually. The SNR of the $\ell^{th}$ user's signal, received at the $i^{th}$ user, can be obtained from (4) after substituting the value of $\alpha$ and straightforward manipulations, as

$$\gamma_{i,\ell} = \frac{|\ h_{\ell,r}\ |^2 |\ h_{r,i}\ |^2}{(2\ |\ h_{r,i}\ |^2 +\ |\ h_{\ell,r}\ |^2 + N_0) N_0}, \tag{6}$$

where, $|\ h_{\ell,r}\ |^2$ and $|\ h_{r,i}\ |^2$ represent the power of the channels $h_{\ell,r}$ and $h_{r,i}$, respectively. The SNR of the $i^{th}$ user, received at the $\ell^{th}$ user, can be obtained in a similar manner. When the $\ell^{th}$ user receives other users' messages, the SNR can be obtained from (5) by using $\alpha = \frac{1}{\sqrt{|h_{i,r}|^2 + |h_{m,r}|^2 + N_0}}$. Thus, the SNR of the $m^{th}$ user, received at the $\ell^{th}$ user, becomes

$$\gamma_{\ell,m} = \begin{cases} \frac{|h_{m,r}|^2 |h_{r,\ell}|^2}{4|h_{r,\ell}|^2 |h_{i,r}|^2 + (|h_{i,r}|^2 + |h_{r,\ell}|^2 + |h_{m,r}|^2 + N_0) N_0} & \hat{X}_i \neq X_i \\ \frac{|h_{m,r}|^2 |h_{r,\ell}|^2}{(|h_{i,r}|^2 + |h_{r,\ell}|^2 + |h_{m,r}|^2 + N_0) N_0} & \hat{X}_i = X_i. \end{cases} \tag{7}$$

**Remark 2** *In the pairing scheme in [7], at the $(m-1)^{th}$ time slot, the $(m-1)^{th}$ and the $m^{th}$ user transmit simultaneously. Thus, for scheme [7], the SNR expression in* (7) *can be modified by replacing $i$ with $m-1$, which is shown in* (8) *at the top of the next page.*

**Remark 3** *For AF MWRN, any uncancelled self-interference component in a particular signal received at the users acts as noise. For example, at the $(m-1)^{th}$ time slot, when the users decode the message of the $m^{th}$ user, the term $(4 \mid h_{r,\ell} \mid^2 \mid h_{i,r} \mid^2)$ in* (7) *and $(4 \mid h_{r,\ell} \mid^2 \mid h_{m-1,r} \mid^2)$ in* (8) *act as additional noise terms and decrease the SNR of the $m^{th}$ user. The only way to lessen the extra noise terms, is to reduce the effect of the interfering user through proper pairing selection based on average channel gains. Since, the $i^{th}$ user has the minimum average channel gain in the whole system, $E[\mid h_{m-1,r} \mid^2] \geq E[\mid h_{i,r} \mid^2]$. Then comparing* (7) *and* (8) *shows that when $E[\mid h_{m-1,r} \mid^2] \geq E[\mid h_{i,r} \mid^2]$, the SNR in scheme [7] is lower than that in the proposed scheme (after being averaged over a number of channel gains). For this reason, the error probabilities in scheme [7] would be much larger compared to the proposed scheme. Thus, choosing the user with the minimum average channel gain improves the BER performance of an AF MWRN.*

The expressions in (7) and (8) can be put to use to obtain the error probabilities at different users. Thus, the probability that the $i^{th}$ user incorrectly decodes the $\ell^{th}$ user's message, can be given by $P_{AF}(i,\ell) = Q(\sqrt{2\gamma_{i,\ell}})$. Similarly, the probability that the $\ell^{th}$ user incorrectly decodes the message of the $i^{th}$ user, is $P_{AF}(\ell,i) = Q(\sqrt{2\gamma_{\ell,i}})$. If the $\ell^{th}$ user correctly decodes the message of the $i^{th}$ user, the probability that it would incorrectly decode the $m^{th}$ user's message, is $P_{AF}(\ell,m) = Q(\sqrt{2\gamma_{\ell,m}})$. However, if $\hat{X}_i \neq X_i$, this error probability is denoted by $P'_{AF}(\ell,m)$.

In an $L$-user MWRN, each user needs to decode $(L-1)$ other users' messages and so, there are $(L-1)$ possible error events [9]. Here, the $k^{th}$ error event indicates that a user has incorrectly decoded exactly $k$ $(k \in [1, L-1])$ other users' messages. To have a complete view of the overall error performance of such a system, we take into account all these possible error events by performing average BER analysis. The average BER for the $j^{\text{th}}$ user in an $L$-user MWRN can be defined as [9]

$$P_{j,avg} = \frac{1}{L-1} \sum_{k=1}^{L-1} k P_j(k), \tag{9}$$

where $P_j(k)$, represents the probability of the $k^{th}$ error event at the $j^{th}$ user.

In an AF MWRN with the proposed pairing scheme, $k$ error events can occur in two cases:

- $A_k$: If the decoding user incorrectly extracts exactly $k$ users' messages except the $i^{th}$ user's message.
- $B_k$: If the decoding user incorrectly decodes exactly $k$ users' messages including the $i^{th}$ user's message.

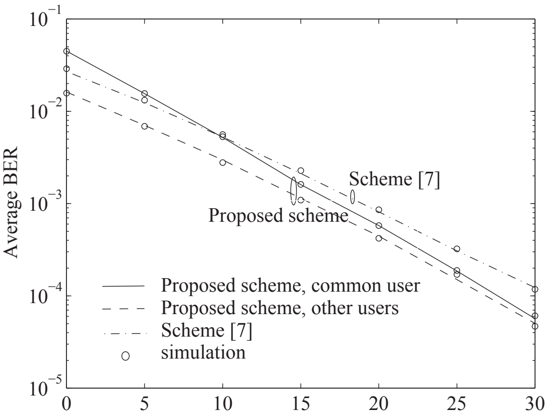

**Fig. 1**. Average BER for an $L = 10$ user AF MWRN with the proposed pairing scheme and scheme [7].

The probabilities of these error cases for the $i^{th}$ and the $\ell^{th}$ users can be expressed as shown in (10), (11) and (12) at the top of the next page. Thus, the probability of $k$ error events for the $i^{th}$ and the $\ell^{th}$ user can be expressed as:

$$\begin{aligned} P(i,k) &= P_{i,A_k} \\ P(\ell,k) &= P_{\ell,A_k} + P_{\ell,B_k}. \end{aligned} \tag{13}$$

Substituting the above expression in (9), we can get the exact result for the average BER of an $L$-user AF MWRN with the proposed pairing scheme. At high SNR, (i) the higher order error terms involving $P_{AF}^2$ and other higher powers can be neglected, (ii) the term $\{1 - P_{AF}(i, m_b)\}$, $\{1 - P_{AF}(\ell, m_b)\}$ in (10) and (11) can be approximated to be 1. Thus, $P_{i,A_k} \approx 0$ and $P_{\ell,A_k} \approx 0$ for $k > 1$ (see (10) and (11)). As a result, at high SNR, (13) can be approximated as:

$$\begin{aligned} P(i,k) &= \begin{cases} P_{i,A_1} & k = 1 \\ 0 & k \neq 1 \end{cases} \\ P(\ell,k) &= \begin{cases} P_{\ell,A_1} + P_{\ell,B_1} & k = 1 \\ P_{\ell,B_k} & k \neq 1 \end{cases}. \end{aligned} \tag{14}$$

Substituting the approximate expressions for probabilities of different error events from (14) into (9) gives an asymptotic bound on the average BER.

## 4. RESULTS

In this section, we provide numerical simulation results to verify the average BER analysis. We perform Monte Carlo simulation for $L = 10$ user MWRN, where each user transmits a packet of $T = 1000$ bits. Following [8], the average channel gain for each of the $j^{th}$ users is modeled by $\sigma^2_{h_{j,r}} = (1/(d_j/d_0))^{\nu}$, where $d_0$ is the reference distance, $d_j$ is the distance between the $j^{th}$ user and the relay which is assumed to be uniformly randomly distributed between 0 and $d_0$, and $\nu$ is the path loss exponent, which is assumed to be 3. Such a distance based channel model takes into account large scale path loss and has been widely considered in the literature [**?**, 10]. The SNR is assumed to be the SNR per bit per user (see after (2)). The simulation results are averaged over 100 time frames.

Fig. 1 shows the average BER for an AF MWRN with the proposed pairing scheme and scheme [7]. In this figure, the analytical results for the proposed pairing scheme (given by (9) and (14)) and the analytical results for average BER with scheme [7] (obtained by applying the BER analysis method of [9]) match with the simulation.

$$\gamma_{\ell,m}^{[7]} = \begin{cases} \frac{|h_{m,r}|^2|h_{r,\ell}|^2}{4|h_{r,\ell}|^2|h_{m-1,r}|^2+(|h_{m-1,r}|^2+|h_{r,\ell}|^2+|h_{m,r}|^2+N_0)N_0} & \hat{X}_{m-1} \neq X_{m-1} \\ \frac{|h_{m,r}|^2|h_{r,\ell}|^2}{(|h_{m-1,r}|^2+|h_{r,\ell}|^2+|h_{m,r}|^2+N_0)N_0} & \hat{X}_{m-1} = X_{m-1}. \end{cases} \tag{8}$$

$$P_{i,A_k} = \sum_{m_a=1, m_a \neq i}^{L} \prod_{a=1}^{k} P_{AF}(i, m_a) \prod_{m_b=1, m_b \neq m_a, i}^{L} \{1 - P_{AF}(i, m_b)\}. \tag{10}$$

$$P_{\ell,A_k} = \sum_{m_a=1, m_a \neq i, \ell}^{L} \prod_{a=1}^{k} P_{AF}(\ell, m_a) \prod_{m_b=1, m_b \neq \ell, m_a}^{L} \{1 - P_{AF}(\ell, m_b)\}. \tag{11}$$

$$P_{\ell,B_k} = \begin{cases} P_{AF}(\ell,i) \sum_{m_a=1,m_a\neq i,\ell}^{L} \prod_{a=1}^{k-1} P'_{AF}(\ell,m_a) \prod_{m_b=1,m_b\neq i,\ell,m_a}^{L} \{1 - P'_{AF}(\ell,m_b)\} & 1 < k < L-1 \\ P_{AF}(\ell,i) \prod_{m_b=1,m_b\neq i,\ell}^{L} \{1 - P'_{AF}(\ell,m_b)\} & k = 1 \\ P_{AF}(\ell,i) \sum_{m_a=1,m_a\neq i,\ell}^{L} \prod_{a=1}^{L-1} P'_{AF}(\ell,m_a) & k = L-1. \end{cases} \tag{12}$$

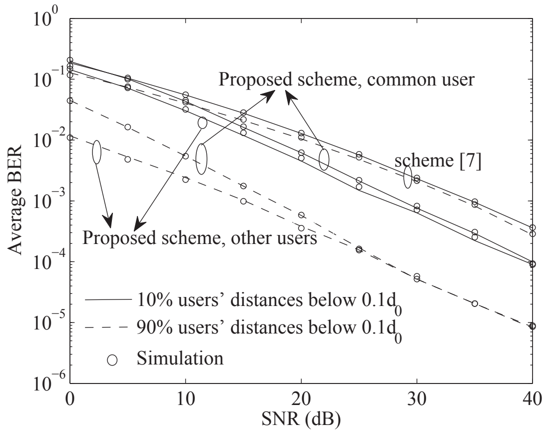

**Fig. 2**. Average BER for an $L = 10$ user AF MWRN when $10\%$ and $90\%$ users have distances below $0.1d_0$, corresponding to a small minority and a large majority, respectively, of users having good average channel gains.

The average BER at the common user is larger than the average BER for scheme [7] at low SNR. The reason is that the common user has the minimum average channel gain in the system. However, as the SNR increases, the average BER at the common user falls below that of scheme [7]. This is because at high SNR, the impact of individual channel gains is less than that of the overall SNR and the common user receives messages without any error propagation. The average BER at other users is better than that of the scheme in [7]. This is expected from the comparison between (7) and (8).

Fig. 2 shows the average BER for two sets of channel conditions (i) when $10\%$ users have distances from the relay below $0.1d_0$ (i.e., small number of users have good average channel gain) and (ii) when $90\%$ users have distances from the relay below $0.1d_0$ (i.e., most of the users have good average channel gain). From this figure, in scheme [7], when most of the users experience good channel conditions , the average BER does not improve due to error propagation problem. However, for the proposed pairing scheme, the average BER improves significantly.

## 5. CONCLUSION

In this paper, we have proposed a pairing scheme to reduce error propagation in an AF MWRN. We have compared the proposed scheme with existing pairing schemes in terms of average BER. We have shown that pairing each user with the minimum average channel gain common user improves the average BER at all the users except at the common user. For the common user with the minimum average channel gain, the average BER is larger than that for other users and scheme [7] at low SNR, which improves to the level of other users and falls below that in scheme [7] at high SNR. That is, to reduce error propagation problem in an AF MWRN, the best solution is to pair them with the minimum average channel gain user.

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