Two-Way Multiple Relays Channel: Achievable Rate Region and Optimal Resources

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Abstract. *This paper considers a communication model containing two users that exchange their information with the help of multiple parallel relay nodes. To avoid interference at these common nodes, two users are required to transmit over the different frequency bands. Based on this scenario, the achievable rate region is initially derived. Next, an optimization scheme is described to choose the best relays that can be used by each user. Then, two power allocation optimization schemes are investigated to allocate the proper average power value to each node. Finally, comparisons between these two optimization schemes are carried out through some numerical examples.*

Keywords

Channel capacity, decode and forward, power allocation, two-way relay channel.
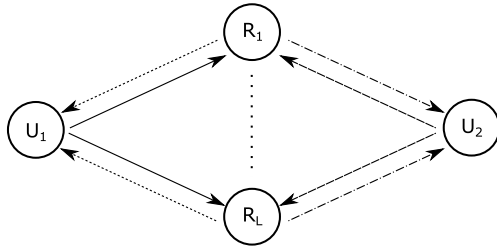
1. Introduction

Relaying has a major role in extending and/or improving the performance of wireless networks. In its simplest form, the relay channel, which is mainly composed of a source transmitting to its destination with assistance of a relay node, was initially proposed by van der Meulen in his seminal work [1]. Since then, this channel model has been received an extensive investigation in both theory and practice. From an information theory perspective, the achievable rate of the physically degraded relay channel was studied in [2]. Further, based on the channel's gain from the source and the relay to the destination, various encoding techniques have been studied. These encoding schemes include Decode-and-Forward (DF) [2] and [3], Partial Decode-and-Forward (PDF) [4] and Amplify-and-Forward (AF) scheme [5] and [6]. For practical purposes, a relay channel with orthogonal channel components was studied in [7], [8] and [9]. The motivation beyond this scheme is that a relay cannot simultaneously receive and transmit over the same frequency band.

Recent studies show that a bidirectional relay node may be used to increase the spectrum efficiency. In this channel model, a relay node can be used to help two users in exchanging their information. This Two-Way Relay Channel (TWRC) was extensively addressed in many different scenarios [10], [11], [12], [13], [14], and [15]. For instance, the achievable rate region was considered in [10], [11] and [12], an efficient compute and forward scheme was investigated in [15], and an AF encoding scheme was examined in [5]. Further, performance of this TWRC was studied in [13] and [16] for the case that Orthogonal Frequency Division Multiplexing (OFDM) is employed by both of the users. In addition, TWRC with multiple parallel relays has been investigated from various aspects like beamforming [17], and diversity analysis [18] and [19].

This paper considers the TWRC with multiple parallel relays and orthogonal channel components, as shown in Fig. 1. This channel model consists of two users want to exchange their information via the help of multiple parallel relays. This communication scenario may model two users want to communicate with the help of common node(s) such as access point(s). In order to avoid interference between the two users' signals at each relay, the users are required to transmit over channels with different frequency bands. First, the achievable rate region is derived using full DF at all relays. Next, an optimization scheme is described to

select the best two relays to forward the two users' signals to their destination. Then, based on whether these relays can cooperate to form a Multiple Input Single Output (MISO) channel with each destination or not, two power allocation schemes are distinguished and investigated. These power allocation schemes are used to allocate the optimal power values at both source nodes and the selected relays such as the sum rate is maximized under the fairness constraint. Afterwards, some numerical examples are discussed to show the importance of our theoretical work.

Fig. 1: TWRC with multiple relays. Different link formats are given to represent channels with different frequency bands.

The rest of this paper is organized as follows. The communication model that we study in this paper is introduced in Section 2. Next, the achievable rate region of the TWRC with multiple relays and orthogonal channel components is characterized in Section 3. Then, for a given user, the best relay to use and the optimum power allocation that maximize the sum rate are investigated in Section 4. Numerical results are presented in Section 5. Finally, we conclude the paper in Section 6.

2. TWRC: Channel Model

In this Section, the communication model, as shown in Fig. 1. is presented. This model consists of two users, which want to exchange their information, and multiple parallel relay nodes. In order to avoid interference between the two user's signals at each relay, the relays are assumed to operate over multiple frequency bands with multi-standards. These relays can decode and then forward the two users' signals to their destinations. Also, in this case, the relays are assumed to forward the signals over channels with different frequency bands. This selection can simplify the transmissions and also optimize the available power between the two users. In addition, data transferring is performed over $2n$ of the channel uses, In particular, n uses of the channel are consumed in the broadcast phase, and another n uses of the channel are employed in the multiple access phase. In the first step, each user broadcasts (BC) its signal X_i, $i \in \{1, 2\}$, over channels

with different frequency bands, to all the relays. Thus, for a given relay, the received signal, Y_{iR_j}, is given by

$$Y_{iR_j} = \sum_{j=1}^{L} h_{iR_j} X_i + Z_{iR_j}, \qquad (1)$$

where h_{iR_j} is the channel gain from user U_i, $i \in \{1, 2\}$, to relay R_j, $j \in [1, L]$, and L is the number of used relays. Further, the noise signal Z_{iR_j} is assumed to be Gaussian noise with 0 mean and variance normalized to 1. Indeed, the average transmit power, P_i, at each source is limited by

$$\frac{1}{n} \sum_{k=1}^{n} X_{i,k}^2 \leq P_i. \qquad (2)$$

In the second step, each relay forward the two users' signals to their destinations. Since multiple relays can forward each user's signal, thus, a multiple access channel (MAC) is formed. Therefore, the received signal Y_i, $i \in \{1, 2\}$, at each destination is expressed as

$$Y_i = \sum_{j=1}^{L} h_{R_j i} X_{R_j i} + Z_i, \qquad (3)$$

where $h_{R_j i}$ is the channel gain from a relay R_j to destination U_i. In addition, for instance, $X_{R_j 2}$, $j \in [1, L]$, is the signal forwarded to the destination U_2 and it is a function of X_1, i.e. $X_{R_j 2} = f(X_1)$, and with average power $P_{R_j 2}$ given by

$$\frac{1}{n} \sum_{k=1}^{n} X_{R_j 2,k}^2 \leq P_{R_j 2}. \qquad (4)$$

Moreover, the noise signal Z_i is assumed to be Gaussian noise with 0 mean and variance normalized to 1. Since the BC term is performed over n uses of the channel, and the MAC term is also performed over another n uses of the channel, the transmission from a given source to its destination is performed over $2n$ uses of the channel.

3. Achievable Rate Region

In this Section, the achievable rate region of the TWRC, which is augmented by multiple parallel relays, is derived. The transmission is composed of two phases. In the first phase, the users broadcast to the relays. Then, in the second phase, the relays forward the decoded messages to their destinations. The achievable rates and the transmission phase are introduced in the following Thm. 1.

Theorem 1. *The achievable rate region of the TWRC with multiple parallel relay nodes is given by*

$$R_1 = \frac{1}{2} \max \min \left(\sum_{j=1}^{L} C\left(|h_{1R_j}|^2 P_1\right), C(A_1) \right), \quad (5)$$

$$R_2 = \frac{1}{2} \max \min \left(\sum_{j=1}^{L} C\left(|h_{2R_j}|^2 P_2\right), C(A_2) \right), \quad (6)$$

where

$$
\begin{aligned}
A_1 &= \left(\sum_{j=1}^{L} |h_{R_j 2}| \sqrt{P_{R_j 2}} \right)^2 \\
&= \sum_{j=1}^{L} |h_{R_j 2}|^2 P_{R_j 2} \quad (7) \\
&\quad + \sum_{j=1}^{L} \sum_{v=j+1}^{L} 2\rho_{jv} |h_{R_j 2}||h_{R_v 2}| \sqrt{P_{R_j 2} P_{R_v 2}}, \\
A_2 &= \left(\sum_{j=1}^{L} |h_{R_j 1}| \sqrt{P_{R_j 1}} \right)^2 \\
&= \sum_{j=1}^{L} |h_{R_j 1}|^2 P_{R_j 1} \quad (8) \\
&\quad + \sum_{j=1}^{L} \sum_{v=j+1}^{L} 2\rho_{jv} |h_{R_j 1}||h_{R_v 1}| \sqrt{P_{R_j 1} P_{R_v 1}},
\end{aligned}
$$

$$E\left[X_{R_j i} X_{R_v i} \right] = \rho_{jv} |h_{R_j i}||h_{R_v i}| \sqrt{P_{R_j i} P_{R_v i}}, \quad (9)$$

$$C(x) = \frac{1}{2} \log_2 (1 + x), \quad (10)$$

and ρ_{jv} is the cross-correlation between the signals forwarded by the relays j and v, respectively. In addition, $E[.]$ denotes the expectation.

Proof. The transmission from a given source to its destination consists of two phases, the BC phase, and the MAC phase. In the BC phase, as seen in Fig. 2, a source broadcasts its signal into multiple parallel relays. This transmission is equivalent to that over parallel Gaussian channel [20]. Thus, the achievable rate, for user U_1, in the BC phase, can be expressed by:

$$
\begin{aligned}
R_{BC,1} &= I\left(X_1; Y_{1R_1}, \cdots, Y_{1R_L}\right) \\
&= h\left(Y_{1R_1}, \cdots, Y_{1R_L}\right) - h\left(Y_{1R_1}, \cdots, Y_{1R_L} | X_1\right) \\
&= h\left(Y_{1R_1}, \cdots, Y_{1R_L}\right) - h\left(Z_{1R_1}, \cdots, Z_{1R_L}\right) \\
&= h\left(Y_{1R_1}, \cdots, Y_{1R_L}\right) - \sum_{j=1}^{L} h(Z_{1R_j}) \quad (11) \\
&\leq \sum_{j=1}^{L} h(Y_{1R_j}) - h(Z_{1R_j}) \\
&\leq \sum_{j=1}^{L} \frac{1}{2} \log_2 \left(1 + |h_{1R_j}|^2 P_1\right),
\end{aligned}
$$

where $I(.)$ is the mutual information, and $h(.)$ is the differential entropy. Remember that the noise variance over all channels is normalized to 1. Also the second user's signal is received by all the relays. We remind that the relays can receive signals over different frequency bands. Thus, in the BC phase, the achievable rate for user U_2 can be expressed by

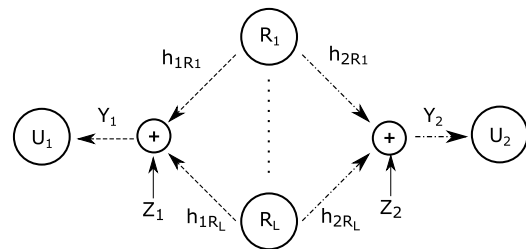$$R_{BC,2} \leq \sum_{j=1}^{L} \frac{1}{2} \log_2 \left(1 + |h_{2R_j}|^2 P_2\right). \quad (12)$$
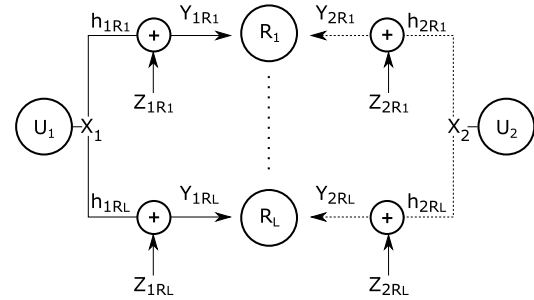
Fig. 2: Broadcast Phase. Different frequency bands are used to transmit to the relays.

At the end of this phase, the relays can decode the users' signals. Then, in the second phase, the relays can forward each signal to its destination. Thus, the transmission from all relays to a given destination forms a MAC channel, as depicted in Fig. 3. For instance, the achievable rate of DF X_1 to its destination U_2, in the MAC phase, can be expressed as:

$$
\begin{aligned}
R_{MAC,1} &= I\left(Y_2; X_{R_1 2}, \cdots, X_{R_j 2}\right) \\
&= h(Y_2) - h\left(Y_2 | X_{R_1 2}, \cdots, X_{R_j 2}\right) \\
&= h(Y_2) - h(Z_2) \quad (13) \\
&= \frac{1}{2} \log_2 (1 + A_1),
\end{aligned}
$$

where A_1 is the total signal-to-noise ratio from all relays to the destination U_2, in the MAC phase, and is already defined in the previous theorem. Moreover, similar results can be obtained from decode and then forward X_2 to its destination U_1.

Fig. 3: Multiple Access Phase. Different frequency bands are used to transmit to the destinations.

$\square$

4.   Optimal Power Allocation

In this Section, power allocation techniques, which are used to distribute the available total power among the two sources and the relays, are studied. In particular, the power is allocated such that the two users have the same data rate. To understand how this power should be distributed, the transmission phases should be analyzed. For a given user, in the MAC term, the authors in [21] showed that the total available power is given to the node that has the best channel gain with the destination. This means that in decoding and forwarding X_1 to its destination, U_2, the relay which has the highest channel gain with U_2 is selected. This scenario is also used to select the relay to contact with U_1 in DF X_2. Generally, the selected relay to extend the transmission to U_1, may not be the same one that has to contact with U_2. For instance, in the MAC phase, assume R_g and R_h are the selected relays to forward the signals to U_1 and U_2, respectively. Since the BC phase and the MAC phase are done over orthogonal time periods, we can easily assume that the channel gain for a given link does not change over $2n$ uses of the channel i.e., $|h_{1R_g}| = |h_{R_g1}|$. Then, for instance, the selected relay to forward to U_1 can be chosen to receive from U_1 in the BC phase. Since each user can be in touch with only the selected relay over a given frequency band, the two relays may be used to receive from the two sources in the BC phase and then to DF the signals in the MAC phase, as depicted in Fig. 4.
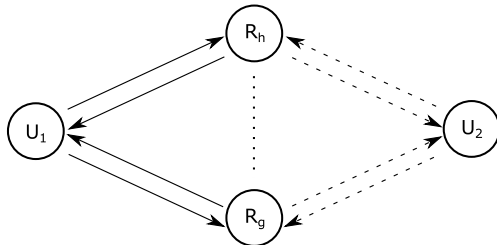
Fig. 4: TWRC in which the relays that have the best channel gains to the destinations are selected. R_g has the best channel gain with U_1, R_h has the best channel with U_2. The two sources use different frequencies to communicate with the relays.

Thus, the power allocation among the two users and the selected two relays has an important role of maximizing each user's rate and also the sum rate. Therefore, the problem of maximizing the sum rate under the fairness constraint is considered. Hence, this optimization problem can be formulated as:

$$\begin{aligned} \text{maximize} \quad & R_T = R_1 + R_2 \\ \text{s.t.} \quad & R_1 = R_2 \\ & P_T = P_1 + P_2 + P_{R_h} + P_{R_g} \\ & 0 < P_1, P_2, P_{R_h}, P_{R_g} < P_T. \end{aligned} \quad (14)$$

Now based on the ability of the relays to cooperate, two transmission schemes are developed. In the case of cooperation, these relays can form a sender with two transmit antennas. Hence, Multiple Input Single Output (MISO) channel with two transmit antennas and one receive antenna is formed. When there is no cooperation, the relays are considered as two separate users transmitting to a given receiver to form a MAC channel. Based on these two cases, the achievable sum rate is studied in the next two Subsections.

4.1.   Power Optimization in MISO Channel

In this Subsection, the achievable sum rate is maximized in the case that the two relays and their destination forms a MISO channel. We start solving this optimization problem by noting that the maximum achievable rate, over a relay channel, is obtained in the case of $R_{BC} = R_{MISO}$. Thus, for the user, U_1, we may write

$$R_{BC_1} = R_{MISO_1}, \quad (15)$$

where

$$R_{BC_1} = C\left(|h_{1R_g}|^2 P_1\right) + C\left(|h_{1R_h}|^2 P_1\right) = \quad (16)$$
$$= C\left(|h_{1R_g}|^2 P_1 + |h_{1R_h}|^2 P_1 + |h_{1R_g}|^2|h_{1R_h}|^2 P_1^2\right),$$

$$R_{MISO_1} = C\left(\frac{P_3(|h_{R_g2}|^2 + |h_{R_h2}|^2)}{2}\right), \quad (17)$$

where P_3 is the part of each relay's power allocated to transmit X_{R_g2} and X_{R_h2}. Noting that, in the case of cooperative relays, the transmission from the two relays to any destination forms a MISO channel. For example, the capacity of the MISO channel, with two transmit antennas and one receive antenna, from the relays to U_2, is given by [22]:

$$C_{MISO_1} = C\left(\frac{P_3(|h_{R_g2}|^2 + |h_{R_h2}|^2)}{2}\right). \quad (18)$$

Hence, in Multiple Input Multiple Output (MIMO) channel, equal allocated power to all transmit antennas is commonly used. Further, similar result can be obtained for U_2. In this case, we may start by choosing

$$R_{BC_2} = R_{MISO_2}, \quad (19)$$

where

$$R_{BC_2} =$$
$$= C\left(|h_{2R_g}|^2 P_2 + |h_{2R_h}|^2 P_2 + |h_{2R_g}|^2|h_{2R_h}|^2 P_2\right) \quad (20)$$

$$R_{MISO_2} = C\left(\frac{P_4(|h_{R_g1}|^2 + |h_{R_h1}|^2)}{2}\right), \quad (21)$$

where $P_3 + P_4 = P_{R_g} = P_{R_h}$, P_4 is the part of each relay's power allocated to transmit X_{R_g1} and X_{R_h1} to

their destination U_1. From Eq. (15) and Eq. (19), it is clear that four unknowns P_1, P_2, P_3, and P_4 are available. Thus, two more equations should be obtained to solve this problem. The key to our solution is that $R_1 = R_2$, $R_{BC_1} = R_{MISO_1}$ and $R_{BC_2} = R_{MISO_2}$. Thus, we may have

$$R_{BC_1} = R_{BC_2}, \tag{22}$$

and

$$R_{MISO_1} = R_{MISO_2}, \tag{23}$$

Now by solving Eq. (23), the following is obtained,

$$P_3 = \frac{|h_{R_g1}|^2 + |h_{R_h1}|^2}{|h_{R_g2}|^2 + |h_{R_h2}|^2} P_4. \tag{24}$$

Then, by substituting the result from Eq. (24) in Eq. (15) and in Eq. (19), we get

$$P_1 = \frac{|h_{R_g2}|^2 + |h_{R_h2}|^2}{2} P_4, \tag{25}$$

and

$$P_2 = \frac{|h_{R_g2}|^2 + |h_{R_h2}|^2}{2} P_4, \tag{26}$$

respectively.

Finally, by replacing the results from Eq. (24), Eg. (25), and Eq. (26) in $P_T = P_1 + P_2 + P_{R_h} + P_{R_g}$, the total available power can be optimally distributed as

$$P_4 = \frac{2b}{2ab + 4a + 4b} P_T, \tag{27}$$

$$P_3 = \frac{2a}{2ab + 4a + 4b} P_T, \tag{28}$$

$$P_2 = \frac{ab}{2ab + 4a + 4b} P_T, \tag{29}$$

$$P_1 = \frac{ab}{2ab + 4a + 4b} P_T, \tag{30}$$

and

$$\begin{aligned} P_{R_h} &= P_{R_g} \\ &= P_3 + P_4 \\ &= \frac{a + b}{ab + 2a + 2b} P_T, \end{aligned} \tag{31}$$

where $a = (|h_{R_g1}|^2 + |h_{R_h1}|^2)$, and $b = (|h_{R_g2}|^2 + |h_{R_h2}|^2)$. In forwarding the signals to their destinations, this solution confirms that more power is allocated to the direction which has the lower channel gain. However, this is a suboptimal solution since more solutions can be obtained by solving $R_{BC_1} = R_{BC_2}$, $R_{BC_1} = R_{MISO_2}$, and $R_{BC_2} = R_{MISO_1}$.

In the next Subsection, instead of solving a set of equations again, an iterative algorithm is designed to solve the power allocation problem among all nodes.

4.2. Power Optimization in MAC Channel

In this Subsection, we consider the case that the selected relays do not cooperate to forward each user's signal into its destination. Thus, the channel from the relays to each destination form a MAC one. Thus, forwarding $U_1's$ signal to its destination, by the two relays, is given by:

$$\begin{aligned} R_{MAC_1} = C\left(|h_{R_g2}|^2 P_{R_g2} + |h_{R_h2}|^2 P_{R_h2} \right. \\ \left. + 2\rho_2 |h_{R_g2}||h_{R_h2}|\sqrt{P_{R_g2}P_{R_h2}}\right). \end{aligned} \tag{32}$$

Similarly, forwarding $U_2's$ signal to its destination is expressed as:

$$\begin{aligned} R_{MAC_2} = C\left(|h_{R_g1}|^2 P_{R_g1} + |h_{R_h1}|^2 P_{R_h1} \right. \\ \left. + 2\rho_1 |h_{R_g1}||h_{R_h1}|\sqrt{P_{R_g1}P_{R_h1}}\right). \end{aligned} \tag{33}$$

Further, we remind that the rates during the BC phase, as derived in the previous Subsection, do not change.

In this case, an iterative power allocation algorithm is characterized instead of solving a set of equations to get a suboptimal solution, as in the previous Subsection. Here, an algorithm is characterized to allocate the total power among all nodes such that the sum rate R_T is maximized under fairness constraint.

Algorithm 1 Iterative Power Optimizations.

1: Initializations: Based on the channel gains, select P_1 and P_2 such that $R_{BC_1} = R_{BC_2}$.
2: Select P_{Rg2} and P_{R_h2} such that $R_{BC_1} = R_{MAC_1}$.
3: Can we find P_{Rg1} and P_{Rh1} such that $R_{BC_2} = R_{MAC_2}$, $P_{R_g} = P_{R_g1} + P_{R_g2}$, and $P_{R_h} = P_{R_h1} + P_{R_h2}$,
    3.1: If yes, then go to step 4.
    3.2: If no, then go to step 1.
4: Save this solution as R_T^*. Can we find another set of values to get higher than R_T^*
    4.1: If yes, then go to step 1.
    4.2: If no, then go to step 5.
5: Save R_T^*
6: Stop

Remark 1. *The following points should be considered when Alg. 1 is implemented.*

- *In allocating P_1 and P_2, the user which has less channel gains with the relays is given more power such that $R_{BC_1} = R_{BC_2}$ is obtained.*

- *In allocating P_{Rg2} and P_{R_h2}, the relay which has higher channel gain with the desired destination is given more power than the other relay.*

5.   Numerical Results

This Section presents some numerical examples to show the importance of our theoretical part. Basically, two examples are presented (i) to show the relation between the achievable rate of a given user and number of relays, (ii) to compare between the two developed encoding schemes, and (iii) to compare between the two studied power allocation techniques.

Figure 5 shows the achievable rate of U_1 as a function of the number of used relays. In this numerical example, the following parameters $h_{1R_i} = 2$, $P_1 = 100$, and $P_{R_i} = \frac{100}{L}$, where $i \in [1, L]$ are used. It clearly shows that the achievable rate increases as the number of relays is so increased. In addition, as number of relays increases beyond a given value such as $L = 10$, the achievable rate marginally increases. Further, as the channel gain $h_{R_i 2}$ increases so does the achievable rate.
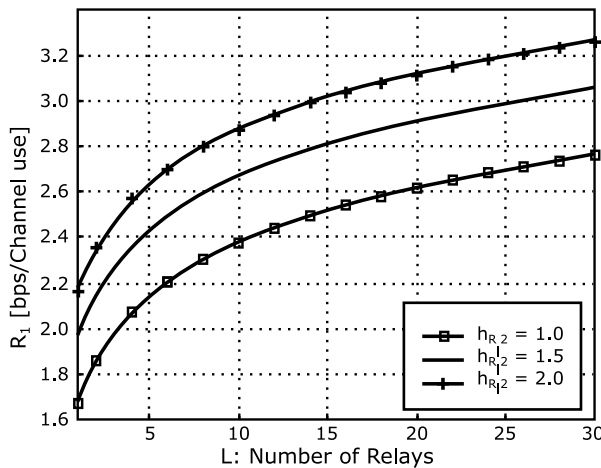

Fig. 5: Achievable rate of U_1 vs. number of used relays for different values of $h_{R_i 2}$.

Figure 6 shows the achievable rate region of the TWRC in three different cases. This is to compare between the considered (i) two optimization algorithms, and (ii) two forwarding encoding mechanisms. In these examples, $h_{1R_h} = h_{R_h 1} = 2$, $h_{1R_g} = h_{R_g 1} = 1.2$, $h_{2R_h} = h_{R_h 2} = 1.5$, $h_{2R_g} = h_{R_g 2} = 1.8$, and $P_T = 200$ are set. First, In MISO channel, this figure clearly demonstrates that the iterative algorithm has achievable rate higher than that obtained by employing the non-optimal analytical solution. This is mainly because the iterative solution gives more chance to select the right power for each node. Secondly, this figure also shows that when the two relays form a MAC channel has achievable region higher than that the MISO case.
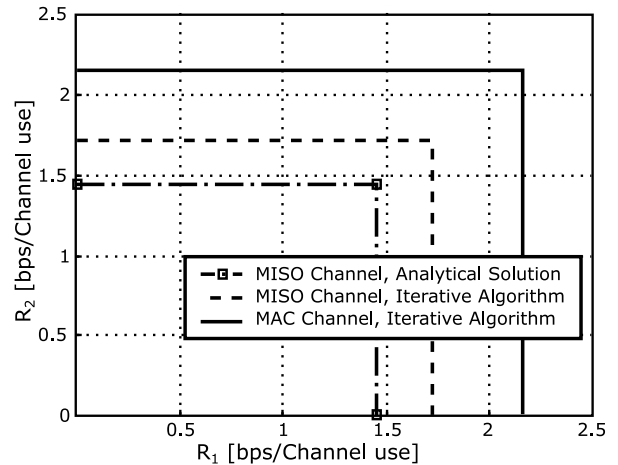

Fig. 6: Comparison between the two encoding schemes.

6.   Concluding Remarks

In this paper, the TWRC with multiple parallel relays has been considered. The achievable rate region has been derived in the case that the transmission is carried over channels with different frequency bands. In addition, the best relays, that can be used to forward the signals, have been selected. To allocate the right amount of power to every node, two optimization problems were considered. Finally, some numerical examples were drawn to show the importance of our theoretical work.

References

[1] MEULEN, V. D. Three-Terminal Communication Channels. *Advances in Applied Probability*. 1971, vol. 3, iss. 1, pp. 120–154. ISSN 0001-8678. DOI: 10.2307/1426331.

[2] COVER, T. and A. E. GAMAL. Capacity theorems for the relay channel. *IEEE Transactions on Information Theory*. 1979, vol. 25, iss. 5, pp. 572–584. ISSN 0018-9448. DOI: 10.1109/TIT.1979.1056084.

[3] KRAMER, G., M. GASTPAR and P. GUPTA. Cooperative Strategies and Capacity Theorems for Relay Networks. *IEEE Transactions on Information Theory*. 2005, vol. 51, iss. 9, pp. 3037–3063. ISSN 0018-9448. DOI: 10.1109/TIT.2005.853304.

[4] GHABELI, L. and M. R. AREF. Comprehensive partial decoding approach for two-level relay networks. *IET Communications*. 2009, vol. 3, iss. 4, pp. 585–596. ISSN 1751-8628. DOI: 10.1049/iet-com.2008.0141.

[5] HU, R., C. HU, J. JIANG, X. XIE and L. SONG. Full-Duplex Mode in Amplify-and-Forward Relay Channels: Outage Probability and Ergodic Capacity. *International Journal of Antennas and Propagation*. 2014, vol. 2014, iss. 1, pp. 1–8. ISSN 1687-5877. DOI: 10.1155/2014/347540.

[6] WEN, C. K., K. K. WONG and C. NG. On the Asymptotic Properties of Amplify-and-Forward MIMO Relay Channels. *IEEE Transactions on Communications*. 2011, vol. 59, iss. 2, pp. 590–602. ISSN 0090-6778. DOI: 10.1109/TCOMM.2011.111710.090516.

[7] EL GAMAL, A. and S. ZAHEDI. Capacity of a class of relay channels with orthogonal components. *IEEE Transactions on Information Theory Society*. 2005, vol. 51, iss. 5, pp. 1815–1817. ISSN 0018-9448. DOI: 10.1109/TIT.2005.846438.

[8] LIANG, Y. and V. V. VEERAVALLI. Gaussian Orthogonal Relay Channels: Optimal Resource Allocation and Capacity. *IEEE Transactions on Information Theory Society*. 2005, vol. 51, iss. 9, pp. 3284–3289. ISSN 0018-9448. DOI: 10.1109/TIT.2005.853305.

[9] SAHIN, O., O. SIMEONE and E. ERKIP. Interference Channel With an Out-of-Band Relay. *IEEE Transactions on Information Theory Society*. 2011, vol. 57, iss. 5, pp. 2746–2764. ISSN 0018-9448. DOI: 10.1109/TIT.2011.2119710.

[10] ZHANG, S., S. C. LIEW, H. WANG and X. LIN. Capacity of Two-Way Relay Channel. In: *4th International Conference, AccessNets 2009*. Hong Kong: Springer, 2010, pp. 219–231. ISBN 978-3-642-11664-3. DOI: 10.1007/978-3-642-11664-3.

[11] RANKOV, B. and A. WITTNEBEN. Achievable Rate Regions for the Two-way Relay Channel. In: *IEEE International Symposium on Information Theory*. Seattle, WA: IEEE, 2006, pp. 1668–1672. ISBN 1-4244-0504-1. DOI: 10.1109/ISIT.2006.261638.

[12] NAM, W., S. Y. CHUNG and Y. H. LEE. Capacity Bounds for Two-Way Relay Channels. In: *IEEE International Zurich Seminar on Communications*. Zurich: IEEE, 2008, pp. 144–147. ISBN 978-1-4244-1682-0. DOI: 10.1109/IZS.2008.4497296.

[13] HE, F., Y. SUN, L. XIAO and X. CHEN. Capacity Region Bounds and Resource Allocation for Two-Way OFDM Relay Channels. *IEEE Transactions on Wireless Communications*. 2013, vol. 12, iss. 6, pp. 2904–2917. ISSN 1536-1276. DOI: 10.1109/TWC.2013.042213.121205.

[14] CUI, T., T. HO and J. KLIEWER. Memoryless relay strategies for two-way relay channels. *IEEE Transactions on Communications*. 2009, vol. 57, iss. 10, pp. 3132–3143. ISSN 0090-6778. DOI: 10.1109/TCOMM.2009.10.080222.

[15] WEI, L and W. CHEN. Efficient Compute-and-Forward Network Codes Search for Two-Way Relay Channel. *IEEE Communications Letters*. 2012, vol. 16, iss. 8, pp. 1204–1207. ISSN 1089-7798. DOI: 10.1109/LCOMM.2012.052112.120469.

[16] RATAICZAK, K., K. BAKOWSKI and K. WESOLOWSKI. Two-way relaying for 5G systems: Comparison of network coding and MIMO techniques. In: *IEEE Wireless Communication and Networking Conference*. Istanbul: IEEE, 2014, pp. 376–381. ISBN 978-1-4799-3083-8. DOI: 10.1109/WCNC.2014.6952037.

[17] ZENG, M., R. ZHANG and S. CUI. On Design of Collaborative Beamforming for Two-Way Relay Networks. *IEEE Transactions on Signal Processing*. 2011, vol. 59, iss. 5, pp. 2284–2295. ISSN 1053-587X. DOI: 10.1109/TSP.2011.2107906.

[18] RAZMI, A., M. ATTARI, E. SOLEIMANI-NASAB and A. GHASEMI. Single and Dual Relay Selection in Two-Way Network-coded Relay Networks. *Wireless Personal Communications*. 2015, vol. 83, iss. 1, pp. 99–115. ISSN 0929-6212. DOI: 10.1007/s11277-015-2382-6.

[19] HGUYEN, H., H. NGUYEN and T. LE-NGOC. Diversity Analysis of Relay Selection Schemes for Two-Way Wireless Relay Networks. *Wireless Personal Communications*. 2011, vol. 59, iss. 2, pp. 173–189. ISSN 0929-6212. DOI: 10.1007/s11277-009-9911-0.

[20] COVER, T. M. and J. A. THOMAS. *Elements of Information Theory*. New York: Wiley, 2006. ISBN 978-0-471-24195-9.

[21] PARK, T., J. JANG, O. S. SHIN and K. B. LEE. Transmit power allocation for a downlink two-user interference channel. *IEEE Communication Letters*. 2005, vol. 9, iss. 1, pp. 13–15. ISSN 1089-7798. DOI: 10.1109/LCOMM.2005.01019.

[22] TELATAR, I. E. Capacity of multi-antenna Gaussian channels. *European Transactions on Telecommunications*. 1999, vol. 10, iss. 6, pp. 585–596. ISSN 2161-3915. DOI: 10.1002/ett.4460100604.

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