On the Capacity of the Interference Channel with a Relay

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Abstract*—Capacity gains due to relaying in wireless networks with multiple source-destination pairs are analyzed. A two-source, two-receiver network with the relay is considered. The focus is on the scenario in which, due to channel conditions, the relay can observe the signal from *only one* source. The relay can thus help the intended receiver of this message, via message forwarding, to decode it. In addition, the relay can simultaneously help the unintended receiver subtract the interference associated with this message. We call the latter strategy *interference forwarding*. An achievable rate region employing decode-and-forward (that simultaneously does message and interference forwarding) at the relay is derived and analyzed. This strategy is shown to achieve the capacity region under certain conditions. Our results demonstrate that the relay can help both receivers, despite the fact that it forwards only the message intended for one of them. This applies in general to communications in the presence of an interferer transmitting at any arbitrary rate. Interference forwarding improves reception of interfering signals at the receivers. This facilitates decoding of the unwanted messages and eliminating the resulting interference. Therefore, in networks with multiple source-destination pairs, in addition to relaying messages, interference forwarding may also be employed to help in combating interference.

I. Introduction

The interference channel (IC) [1], [2] is the smallest wireless network capturing a multiple source-destination pair scenario. A key question in such settings is how to cope with the interference created by simultaneous transmissions. Depending on the level of interference at the receivers, different regimes can be distinguished. The capacity region is known when the interference is "strong" [3]. In this regime, the received interfering signal component carrying the unwanted message is strong enough so that a receiver can also decode the unwanted message. The interference channel then behaves as two multiaccess channels, one to each receiver.

In general, interference is not strong enough at both receivers to allow for decoding of the unwanted messages. In this case, *rate-splitting* [2] can be used at the encoders to allow receivers to decode *part* of the unwanted message. Rate-splitting achieves the best rates known today for the interference channel [4]. In this encoding scheme, each encoder splits its message into two messages and encodes them separately. A receiver decodes one message of the other user and cancels a part of the interference. This will increase the rate for his communication, but will lower the rate for the other communicating pair due to the additional decoding requirement. Hence, there is a tradeoff between the rate of sending a message only to the desired receiver and enabling interference cancellation at the other receiver.

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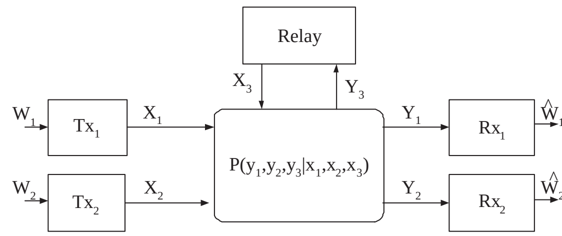

Fig. 1. Interference channel with a relay.

There are various ways in which relays, when present in networks, can help communication. For a discrete memoryless channel with a single source and destination, the two basic relaying strategies are decode-and forward (DF) and compress-and-forward (CF) [5]. Both DF and CF forward the *desired message* to the *intended destination*. Intriguingly, relaying strategies for networks with multiple source-destination pairs have received less attention. The DF and CF approach can be generalized for such settings [6]. Furthermore, as decoding of interfering messages helps in the presence of multiple transmitters, it is plausible to imagine that forwarding an *unwanted* message by a relay may allow receivers to decode it (or a part of it). They can then eliminate interference and improve their own rate.

Consider the smallest two-source, two-destination scenario with relaying as shown in Fig. 1. We refer to this network as the *interference channel with a relay (ICR)*. The ICR has elements of interference, multiaccess, relay and broadcast channels. The encoders, as well as the relay, can employ rate-splitting. Since the relay is broadcasting information to two receivers, it can employ a broadcast code [7]. The relay can adopt either the DF or CF relaying to forward messages. Using DF, it can decode and transmit messages to their intended receivers. Alternatively, adopting CF, the relay can quantize the observed signal that contains channel inputs from both sources and forward it. Some of these approaches have recently been analyzed in [8], [9].

Among the variety of possibilities, we focus on simple forwarding of one of the messages using the DF encoding scheme. Specifically, we are interested in evaluating gains from forwarding unwanted messages, strategy we refer to as *interference forwarding*. Therefore, we consider a scenario in which, due to channel conditions, the relay can observe only the signal sent by one of the sources, say Tx_2 (see Fig. 2). The relay can therefore only decode message W_2 sent by that source. Forwarding message W_2 increases the rate to Rx_2, but also increases the interference at Rx_1. In Sec. III, we derive the achievable rate region. We show that, under certain conditions, our derived rates are the capacity region. Based on the obtained results, in Sec. III-B we analyze the ways in which the relay helps not only Rx_2, but also Rx_1, despite the fact that it cannot relay any information about Rx_1's desired message. Although relaying of the unwanted message W_2 is only interference forwarding from the perspective of Rx_1, it can *improve* reception of W_2 at Rx_1. The relay can effectively place Rx_1 in the "strong interference" regime, which allows Rx_1 to decode W_2 and subtract interference. Because the relay is changing the quality of received signals, the opposite can happen as well: the relay can "push" Rx_1 out of the strong interference regime by significantly improving the rate to Rx_2.

To avoid causing interference at Rx_1, the relay may choose not to convey the message. The channel then acts as the interference channel. In Sec. III-C, we compare interference forwarding to the case when the relay does not help and rate-splitting is used at the encoders. We determine conditions under which the rates with interference forwarding outperform rate-splitting. The numerical results for the Gaussian case are given in Sec. IV. We first introduced interference forwarding in [10], where we considered a special case of the scenario analyzed in this paper.

II. Channel Model

The discrete interference channel with a relay (ICR) consists of three finite input alphabets $\mathcal{X}_1, \mathcal{X}_2, \mathcal{X}_3$, three finite output alphabets $\mathcal{Y}_1, \mathcal{Y}_2, \mathcal{Y}_3$, and a probability distribution $p(y_1, y_2, y_3|x_1, x_2, x_3)$. Each encoder t, $t = 1, 2$, wishes to send a message $W_t \in \mathcal{W}_t$ to decoder t (see Fig. 1). The channel is memoryless and time-invariant in the sense that

$$\begin{aligned} &p(y_{1,i}, y_{2,i}, y_{3,i}|x_1^i, x_2^i, x_3^i, y_1^{i-1}, y_2^{i-1}, y_3^{i-1}, w_1, w_2) \\ &\quad = p_{Y_1,Y_2,Y_3|X_1,X_2,X_3}(y_{1,i}, y_{2,i}, y_{3,i}|x_{1,i}, x_{2,i}, x_{3,1}) \end{aligned} \tag{1}$$

We will follow the convention of dropping subscripts of probability distributions if the arguments of the distributions are lower case versions of the corresponding random variables.

An (R_1, R_2, n) code for the ICR consists of two message sets $\mathcal{W}_1 = \{1, \dots, 2^{nR_1}\}$, $\mathcal{W}_2 = \{1, \dots, 2^{nR_2}\}$, two encoding functions at the encoders, $X_1^n = f_1(W_1)$, $X_2^n = f_2(W_2)$, an encoding function at the relay $X_{i,3} = f_{3,i}(Y_3^{i-1})$, and two decoding functions $\hat{W}_t = g_t(Y_t^n)$. The average error probability of the code is given by $P_e = P\left[\hat{W}_1 \neq W_1 \cup \hat{W}_2 \neq W_2\right]$. A rate pair (R_1, R_2) is achievable if, for any $\epsilon > 0$, there exists, for a sufficiently large n, a code (R_1, R_2, n) such that $P_e \leq \epsilon$. The capacity region is the closure of the set of all achievable pairs (R_1, R_2).

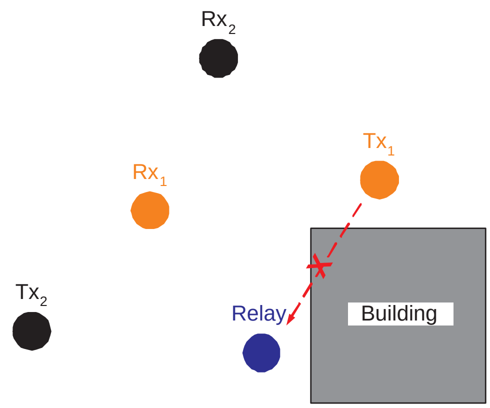

Fig. 2. Interference channel with a relay. Scenario in which the relay cannot receive signal from Tx_1.

Assumption

Our goal in this paper is to propose relaying strategies for networks with multiple source-destination pairs like the ICR. We want to demonstrate that there are scenarios in which the relay can improve a rate, for example, R_1 *without* forwarding useful information about W_1. We will therefore consider a scenario in which the relay cannot observe X_1. Consequently, the relay can forward no information about W_1. In particular, the following is assumed:

A_1: The relay observation Y_3 is independent of channel input X_1, given X_2, X_3:

$$p(y_3|x_3, x_2, x_1) = p(y_3|x_3, x_2) \tag{2}$$

i.e. we have a Markov chain $X_1 \rightarrow (X_2, X_3) \rightarrow Y_3$. This can happen in the wireless channel if, for example, due to heavy shadowing the channel input X_1 is not observed at the relay. In the Gaussian channel model, this condition corresponds to having the channel gain from the encoder 1 to the relay be zero (see Fig. 2).

III. Achievable Rates and a Capacity Result

A. Main Results

In this section we present our main results: the achievable rates for the ICR and conditions under which these rates are the capacity region.

Theorem 1: Any rate pair (R_1, R_2) that satisfies

$$R_1 \leq I(X_1; Y_1|X_2, X_3, Q) \tag{3}$$
$$R_2 \leq I(X_2, X_3; Y_2|X_1, Q) \tag{4}$$
$$R_1 + R_2 \leq I(X_1, X_2, X_3; Y_1, Q) \tag{5}$$
$$R_1 + R_2 \leq I(X_1, X_2, X_3; Y_2|Q) \tag{6}$$
$$R_2 \leq I(X_2; Y_3|X_3, Q) \tag{7}$$

for some joint distribution that factors as

$$p(q)p(x_1|q)p(x_2, x_3|q)p(y_1, y_2, y_3|x_1, x_2, x_3) \tag{8}$$

is achievable in the ICR. Q is a time-sharing random variable.

Proof: (outline). Tx_1 employs a codebook $x_1^n(w_1)$ generated according to $p_{X_1}(\cdot)$. Tx_2 and the relay employ block-Markov regular encoding with codebooks (x_2^n, x_3^n) of same size generated according to $p_{X_2X_3}(\cdot,\cdot)$. Decoders use backward decoding [11, Sect. 7]. Alternatively, block-Markov irregular encoding can be used [5]. ■

We denote by $\mathcal{R}_{ICR}$ the rate region given by (3)-(7). The time-sharing variable is not considered in the rest of the paper.

Consider next the conditions:

$$I(X_1;Y_1|X_2,X_3) \le I(X_1;Y_2|X_2,X_3) \tag{9}$$
$$I(X_2,X_3;Y_2|X_1) \le I(X_2,X_3;Y_1|X_1) \tag{10}$$

that hold for every distribution (8).

Remark 1: Conditions (9)-(10) can be viewed as the *strong interference conditions* for the ICR channel in the sense that under these conditions, the received interfering signals are strong so that the receivers can decode both messages.

A_2: Also assume that the following *degradedness* condition holds:

$$p(y_2|y_3,x_3,x_2) = p(y_2|y_3,x_3) \tag{11}$$

i.e., the Markov chain $X_2 \to (X_3,Y_3) \to Y_2$ holds.

To prove that the rates of Thm. 1 constitute the capacity region of ICR under conditions (9)-(10), we need the following.

Lemma 1: If (9)-(10) are satisfied for any distribution given by (8), then

$$I(X_1^n;Y_1^n|X_2^n,X_3^n) \le I(X_1^n;Y_2^n|X_2^n,X_3^n) \tag{12}$$
$$I(X_2^n,X_3^n;Y_2^n|X_1^n) \le I(X_2^n,X_3^n;Y_1^n|X_1^n) \tag{13}$$

Proof: Proof follows the same steps as in [12, Lemma 5]. ■

We have the following capacity result.

Theorem 2: Under conditions (9)-(11), the rates of Thm. 1 are the capacity region of the ICR channel.

Proof: The achievability follows from Thm. 1. We next prove the converse. We first prove that the bound (5) is tight. Following Fano's inequality we have

$$\begin{aligned}
n(R_1+R_2) &\le I(W_1;Y_1^n) + I(W_2;Y_2^n) \\
&\le I(W_1;Y_1^n) + I(W_2;Y_2^n|W_1) && (14)\\
&= I(X_1^n;Y_1^n) + I(W_2;Y_2^n|X_1^n) && (15)\\
&\le I(X_1^n;Y_1^n) + I(W_2,X_2^n,X_3^n;Y_2^n|X_1^n) && (16)\\
&= I(X_1^n;Y_1^n) + I(X_2^n,X_3^n;Y_2^n|X_1^n) && (17)\\
&\le I(X_1^n;Y_1^n) + I(X_2^n,X_3^n;Y_1^n|X_1^n) && (18)\\
&= I(X_1^n,X_2^n,X_3^n;Y_1^n) \\
&\le \sum_{i=1}^{n} I(X_{1,i},X_{2,i},X_{3,i};Y_{1,i}) && (19)
\end{aligned}$$

where (14) follows by independence of (W_1,W_2) and (18) follows by (10) and Lemma 1.

Using a similar approach it can be shown that the bound (6) is tight. Bounds (3) and (4) can be shown by standard methods utilizing Fano's inequality.

Finally, we can show (7) starting again from Fano's inequality. Or, we can observe directly from the cut-set bound that

$$\begin{aligned}
R_2 &\le I(X_2;Y_2,Y_3|X_1,X_3) \\
&= I(X_2;Y_3|X_1,X_3) && (20)\\
&= I(X_2;Y_3|X_3) && (21)
\end{aligned}$$

where (20) follows by (11), and (21) by (2). ■

Remark 2: If the relay is not present, the ICR reduces to the interference channel. To see what happens in that case we can assume that the relay channel input X_3 is independent of (X_1,X_2) and is known to the receivers. The decoding requirement at the relay (7) is not needed. The region (3)-(6) reduces to the IC capacity region in strong interference [3]. Conditions (9)-(11) reduce to the strong interference conditions for the IC [3]

$$I(X_1;Y_1|X_2,X_3) \le I(X_1;Y_2|X_2,X_3) \tag{22}$$
$$I(X_2;Y_2|X_1,X_3) \le I(X_2;Y_1|X_1,X_3) \tag{23}$$

for any $p(x_1)p(x_2)p(x_3)p(y_1,y_2|x_1,x_2,x_3)$.

Remark 3: Under the condition that the relay cannot help receiver 2 in the sense that

$$X_3 \to (X_1,X_2) \to Y_2, \tag{24}$$

the above region reduces to the one of [10, Thm. 2].

B. Benefits of Interference Forwarding

Note that, due to condition (2), the relay is forwarding only information desired at Rx_2. Hence, from the perspective of Rx_1, the relay is only performing interference forwarding. We next discuss how such relaying can help $\text{Tx}_1 - \text{Rx}_1$ pair. To illustrate the point, we compare it to the situation in which the relay is not present i.e., the interference channel. As remarked in the previous section, the IC region [3] can be obtained from (3)-(6) by assuming X_3 is known at the receivers and is independent from the other inputs.

For the Gaussian case described by (30) the IC region is shown in Fig. 3. The region is given by the intersection of two MAC regions denoted as MAC_1 and MAC_2. The case in which (5) is tighter than (6), i.e., $I(X_1,X_2;Y_1|X_3) \le I(X_1,X_2;Y_2|X_3)$, is shown. Observe that the maximum rate R_1 can be achieved for $R_2 < I(X_2;Y_1|X_3)$ (point B: $(R_1,R_2) = (I(X_1;Y_1|X_2,X_3), I(X_2;Y_1|X_3))$). As R_2 increases above $I(X_2;Y_1|X_3)$, the sum-rate bound (5) becomes active, Rx_1 cannot decode W_2, and thus it cannot achieve $I(X_1;Y_1|X_2,X_3)$.

In the presence of the relay, the region $\mathcal{R}_{ICR}$ is in the intersection of the two MAC regions, denoted as MAC_3 and MAC_4 in Fig. 3, that are determined by (3)-(6), and for which constraint (7) at the relay is satisfied. We observe that the maximum R_1 is achievable for higher values of R_2 than in the previous case. As long as $R_2 < I(X_2,X_3;Y_1)$, (point A: $(R_1,R_2) = (I(X_1;Y_1|X_2,X_3), I(X_2,X_3;Y_1))$) Rx_1 can decode W_2. In effect, the relay increases the "strong interference" regime for Rx_1. This enables user 1 to achieve its maximum interference-free rate for larger range of values

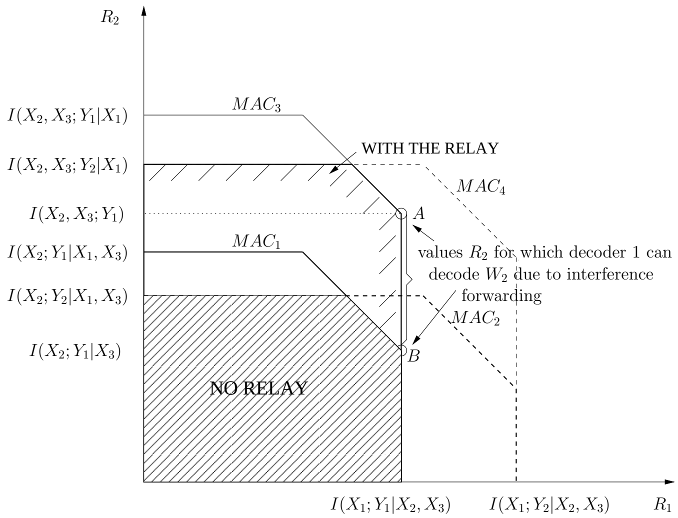

Fig. 3. Capacity region of a Gaussian channel with a relay, in strong interference. In this scenario $I(X_1, X_2; Y_1|X_3) < I(X_1, X_2; Y_2|X_3)$ and $I(X_1, X_2, X_3; Y_1) < I(X_1, X_2, X_3; Y_2)$.

R_2 than in the IC without the relay. This conclusion is true even in the more limiting case when the relay cannot "help" receiver Rx_2, i.e., under the assumption (24), as shown in [10].

Remark 4: If there is a constraint to preserve the maximum interference-free rate for Rx_1 in the presence of an interferer, i.e. Rx_2, then R_2 is bounded by $R_2 < I(X_2, X_3; Y_1)$.

Remark 5: The presence of the relay changes the strong interference conditions. Let us compare (10) with the IC strong interference condition at Rx_1 given by (23) and satisfied for every $p(x_1)p(x_2)p(x_3)$. We observe that the strong interference regime at receiver 1 changes with the help of the relay. Specifically, suppose that (23) is satisfied. By writing the mutual information for $t = 1, 2$ in (10) as

$$I(X_2, X_3; Y_t|X_1) = I(X_3; Y_t|X_1) + I(X_2; Y_t|X_1, X_3)$$

we observe that when

$$\begin{aligned} &I(X_3; Y_2|X_1) - I(X_3; Y_1|X_1) \\ &\geq I(X_2; Y_2|X_1, X_3) - I(X_2; Y_2|X_1, X_3), \end{aligned} \tag{25}$$

the strong interference condition (10) is not satisfied, i.e., Rx_1 cannot decode W_2 without reducing R_2. The relay "pushes" Rx_1 out of strong interference. Similarly, the opposite can happen: one can show that when (23) does not hold, (10) holds if

$$\begin{aligned} &I(X_3; Y_1|X_1) - I(X_3; Y_2|X_1) \\ &\geq I(X_2; Y_2|X_1, X_3) - I(X_2; Y_1|X_1, X_3). \end{aligned} \tag{26}$$

Rx_1 moves from weak to strong interference due to interference forwarding and decoding W_2 becomes optimal.

C. Comparison with Rate-Splitting

We next consider a case in which, when the relay does not help, the strong interference condition [3] given by (23) is not satisfied at Rx_1. Hence, receiver 1 cannot decode W_2 without decreasing the maximum achievable rate R_2. Receiver 2 is subject to strong interference, i.e., (22) holds.

When an IC that is not in strong interference, the highest known achievable rates are obtained by rate-splitting [4]. To evaluate gains due to the relay, we compare the rates of Thm. 1 with rate-splitting rates. Because receiver 2 is in strong interference, no rate-splitting is required at encoder 1. Achievable rates can be obtained from [4], [13] and are stated in the following lemma.

Lemma 2: Any rate pair (R_1, R_2) that satisfies

$$\begin{aligned} R_1 &\leq I(X_1; Y_1|U_2, X_3) \\ R_2 &\leq I(X_2; Y_2|X_1, X_3) \\ R_1 + R_2 &\leq I(X_1, U_2; Y_1|X_3) + I(X_2; Y_2|X_1, U_2, X_3) \\ R_1 + R_2 &\leq I(X_1, X_2; Y_2|X_3) \\ 2R_1 + R_2 &\leq I(X_1, U_2; Y_1|X_3) + I(X_1, X_2; Y_2|U_2, X_3) \end{aligned} \tag{27}$$

for some joint probability distribution that factors as $p(x_1)p(u_2, x_2)p(y_1, y_2, y_3|x_1, x_2, x_3)$ is achievable.

Proof: The encoding and decoding procedure are as described in [13]. The rates can also be obtained directly from [13, Lemma 3] by choosing $U_1 = X_1$, noticing that the constraint (39) can be omitted in this case, and applying Fourier-Motzkin elimination. ∎

We denote by $\mathcal{R}_{RS}$ the convex hull of rates that satisfy (27).

Consider the following two conditions satisfied for all $p(x_1)p(x_2, x_3)$:

$$I(X_2; Y_2|X_1) < I(X_3; Y_1) \tag{28}$$

$$I(X_2; Y_2|X_1) < I(X_2; Y_3|X_3). \tag{29}$$

We have the following Proposition as in [10].

Proposition 1: Under conditions (28)-(29), we have

$$\mathcal{R}_{RS} \subset \mathcal{R}_{ICR}.$$

We next evaluate the obtained rates for Gaussian channels.

IV. Gaussian Channel

The channel is given as:

$$\begin{aligned} Y_1 &= X_1 + h_{12}X_2 + h_{13}X_3 + Z_1 \\ Y_2 &= h_{21}X_1 + X_2 + h_{23}X_3 + Z_2 \\ Y_3 &= h_{31}X_1 + h_{32}X_2 + Z_3 \end{aligned} \tag{30}$$

The region of Thm. 1 becomes

$$\begin{aligned} R_1 &\leq C(P_1) \\ R_2 &\leq C(P_2 + h_{23}^2 P_3 + 2h_{23}\rho\sqrt{P_2 P_3}) \\ R_1 + R_2 &\leq C(P_1 + h_{12}^2 P_2 + h_{13}^2 P_3 + 2h_{12}h_{13}\rho\sqrt{P_2 P_3}) \\ R_1 + R_2 &\leq C(h_{21}^2 P_1 + P_2 + h_{23}^2 P_3 + 2h_{23}\rho\sqrt{P_2 P_3}) \\ R_2 &\leq C(h_{32}^2(1 - \rho^2)P_2) \end{aligned} \tag{31}$$

where $Z_t \sim \mathcal{N}[0, 1]$, $E[X_t^2] \leq P_t$, $0 \leq \rho \leq 1$ is the correlation coefficient between X_2 and X_3 and $C(x) = 0.5\log(1 + x)$.

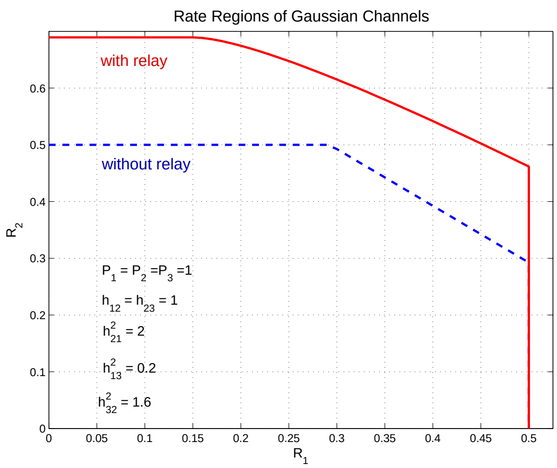

Fig. 4. Rate region of the Gaussian channel without the relay (solid line) and with the relay (dashed line).

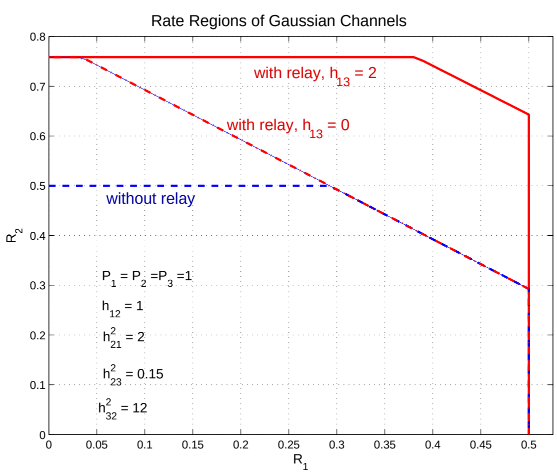

Fig. 5. Rate region of the Gaussian channel without the relay (solid) and with the relay (dashed). The dot-dashed region shows the rates for $h_{13} = 0$, i.e., when the relay does not perform interference relaying. The difference between two regions with the relay illustrates the gains of interference forwarding.

The conditions (9)-(10) become

$$h_{21} \geq 1 \tag{32}$$

$$\begin{aligned} h_{12}^2 P_2 + h_{13}^2 P_3 + 2\rho h_{12} h_{13} \sqrt{P_2 P_3} \\ \geq P_2 + h_{23}^2 P_3 + 2\rho h_{23} \sqrt{P_2 P_3} \end{aligned} \tag{33}$$

for any $0 \leq \rho \leq 1$. The region (31) is shown by the solid line in Fig. 4 and 5 for two different sets of channel gains. Also shown are rates for the IC without the relay, by the dashed line. Without the relay, the strong interference conditions [3] hold and hence the latter region is the IC capacity region. With the help of the relay, R_2 increases, and new strong interference conditions (9)-(10) are not satisfied. The relay helps Rx_1 to achieve a single-user rate, $R_1 = C(P_1)$, for a larger range of values R_2 than with no relay. To emphasize gains from interference forwarding, Fig. 5 shows rates (dot-dashed) for $h_{13} = 0$ when interference forwarding is not possible.

V. Conclusion

We consider relaying in networks with multiple source-destination pairs. In such settings, a variety of relaying strategies are available. Encoders and the relay can use rate splitting to facilitate partial decoding of unwanted messages. The relay can use either DF and CF for message and interference forwarding, and a broadcast code to transmit to multiple receivers. The relay can use interference forwarding to improve the reception of the unwanted message and facilitate its decoding, or otherwise remain silent. The best strategy or combination of strategies will depend on network conditions.

In this paper, we focus on the scenario in which the relay observes a signal from only one source. The relay can then forward only messages intended for one of the receivers. An achievable rate region is derived. It is shown that this region constitutes the ICR capacity region under certain channel conditions. From the perspective of the unintended receiver, the relay is only performing interference forwarding. Our results demonstrate that this relaying strategy can, in fact, help both receivers. These conclusions apply in general to communications in the presence of an interferer transmitting at any arbitrary rate. Interference forwarding improves reception of interfering signals at the receivers. This facilitates decoding of the unwanted messages and eliminating the resulting interference. Therefore, in networks with multiple source-destination pairs, in addition to relaying messages, interference forwarding may also be employed to help in combating interference.

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