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Four-Way Relaying in Wireless Cellular Systems

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Abstract—Two-way relaying in wireless systems has initiated a large research effort during the past few years. Nevertheless, it represents only a specific traffic pattern and it is of interest to investigate other traffic patterns where such a simultaneous processing of information flows can bring performance advantage. In this paper we consider a four-way relaying scenario, where each of the two Mobile Stations (MSs) has a two-way connection to the same Base Station (BS), while each connection is through a dedicated Relay Station (RS). The RSs are placed in such a way that one RS and the terminals associated with it do not interfere with the other RS, and vice versa. We introduce and analyze a two-phase transmission scheme to serve the four-way traffic pattern defined in this scenario. Each phase consists of combined broadcast and multiple access. We analyze the achievable rate region of the new scheme for Decode-and-Forward (DF) operational model for the RS. We compare the performance with a state-of-the-art reference scheme, based on two-way relaying with DF. The results indicate that the achievable rate regions are significantly enlarged for the new scheme.

I. INTRODUCTION

One-way relaying suffers from a loss in spectral efficiency as a half-duplex relay cannot transmit and receive at the same time. Relays have received a fresh research potential with the introduction of two-way relaying based on wireless network coding (WNC) [1]–[3], as part of the spectral efficiency loss can be regained by simultaneously serving two or more data flows through the same relay. Various aspects of two-way relaying have been investigated, such as achievable rates [4] and optimal broadcasting strategies [5] when the relays operate in a Decode-and-Forward (DF) regime.

The benefits of WNC can reach beyond the usual two-way relaying scenario by observing the two underlying principles: (1) simultaneous service of multiple flows over the wireless medium and (2) cancellation of interference based on previously gathered information. We have utilized these principles to devise schemes to jointly serve a relayed and a BS. As AWGN before it is decoded. Fig. 2 illustrates the reference scheme based on time-division between two different two-way relaying instances. The first phase is the multiple access (MA) from U1 and BS to RS1. The second phase is the broadcast (BC) from RS1 to U1 and BS. The third and fourth phase are similar to the first and second phase respectively. Here we use random Gaussian codebooks, while in the companion paper [9] we have applied structured codes based on lattices.
III. ACHIEVABLE RATE REGIONS FOR TWO-PHASE FOUR-WAY RELAYING

The signals sent by U1 and U2 are denoted by \( x_1 \) and \( x_2 \), respectively. The BS uses superposition coding [10] and the broadcast signal is \( x_B = \sqrt{\alpha} x_{B1} + \sqrt{1-\alpha} x_{B2}, \alpha \in [0, 1] \), where \( x_{B1}(x_{B2}) \) is the signal intended for U1(U2) and \( E \{ |x_{B1}|^2 \} = E \{ |x_{B2}|^2 \} = \frac{1}{2} P_B \). Define \( R_i \) as the downlink (BS→RSi→U) data rate of U and define \( R_i^u \) as the uplink (U→RSi→BS) data rate of U. Note that, \( R_i^d \) and \( R_i^u \) are defined over the whole transmission time span. At the end of phase 1, RSi receives

\[
y_{Ri} = h_{i1} x_i + h_{i2} \sqrt{\alpha} x_{B1} + h_{i2} \sqrt{1-\alpha} x_{B2} + z_{Ri}.
\]

(1)

where \( (i, j) \in \{ (1, 2), (2, 1) \} \), \( \alpha_1 = \alpha, \alpha_2 = 1-\alpha \). The decoder in RSi decodes the signal \( x_i \) and \( x_{B1} \), then re-encodes the signals \( x_i \) and \( x_{B1} \) into \( x_{Ri} \). RSi does not need to decode \( x_{B2} \), as it is intended for Uj. In fact, \( x_{B2} \) should only be decoded if there is a benefit for decoding \( x_i \) and \( x_{B1} \); in such a case, successful decoding of \( x_{B1} \) imposes a rate limitation on \( R_i^d \). When \( x_{B2} \) is not decoded, it is treated as AWGN. At the end of phase 2, the received signals are

\[
y_i = h_{i1} x_{Ri} + z_i, \quad y_B = h_{12} x_{R1} + h_{22} x_{R2} + z_B.
\]

(2)

where \( y_i \) is received by U1 and \( y_B \) is received by the BS. Eq. (2) describes the combination of a BC and a MA channel, both with side information: the BC channel from RSi to U1 and BS and the MA channel at BS with signals from RS1 and RS2. Note that, a similar, but simpler, problem has been discussed in [11, Theorem 2], namely a BC channel with side information available at the terminals. In this paper, we apply the same codebook design method for \( x_{Ri} \) as [11, Theorem 2]. Based on the above re-encoding technique, we combine the successive decoding and time-sharing to achieve the optimal transmission performance from RSi to BS and U1 (details in Appendix A).

Here we interpret, rather informally, the achievable rate region for two-phase four-way relaying scheme. Let \( D^{(1)} \) and \( D^{(2)} \) denote the 4-dimensional rate regions achievable during the first and second phase, respectively. Then the achievable rate region is a convex closure of \( D = D^{(1)} \cap D^{(2)} \). The description of \( D^{(2)} \) is given in Appendix A. \( D^{(1)} \) can be found as the intersection \( D^{(1)} = D_{R1}^{(1)} \cap D_{R2}^{(1)} \), where \( D_{R1}^{(1)} \) is the achievable rate region with RS1 as a decoder during the first phase. Furthermore, \( D_{R1}^{(1)} \) is the union of \( M_{R1}^2 \) and \( M_{R1}^3 \). \( M_{R1}^2 \) is the rate region that is obtained when RS1 receives \( x_i \) and \( x_{B1} \), while treating \( x_{B2} \), \( i \neq j \), as a noise. The constraint for \( M_{R1}^2 \) is showed in (7) which is the constraint of two users MA channel [10]. \( M_{R1}^3 \) is the rate region when \( x_{B2} \) is decoded. This means RSi decodes \( x_i, x_{B1} \), and \( x_{B2} \) simultaneously which leads to the constraint of three users MA channel for \( M_{R1}^3 \) shown in (6), see [10]. \( M_{R1}^2, M_{R1}^3 \) and \( D^{(2)} \) are defined as follows. Note that \( M_{R1}^2 \) is a four-dimensional region in which no constraints are put on \( (R_j^u, R_j^d) \), \( j \neq i \), which means that they can have arbitrary non-negative values. Upper limits on \( (R_j^u, R_j^d) \) come from the alternative decoding option in RSi (\( M_{R1}^3 \)) and the decoding at RSj. A similar observation is valid when considering some points in \( D^{(1)} \) where the values of \( R_j^u \) or \( R_j^d \) can be arbitrarily large. Then we can determine the four-dimensional region \( D_{R1}^{(1)} = M_{R1}^2 \cup M_{R1}^3 \). The union operation may lead to a non-convex rate region for \( D \), so the final rate region of \( (R_1^u, R_1^d, R_2^u, R_2^d) \) needs the convex closure operation on \( D \) [10]. The projection of \( D_{R1}^{(1)} \) on the plane \( (R_1^u, R_1^d) \) defines all possible rate pairs that can be decoded at RSi. Clearly, some rate pairs are achievable when \( x_{B2} \) is decoded, others when it is treated as AWGN. Based on this, we can state the following proposition without proof:

**Proposition 1:** Let the superposition ratio be \( 0 \leq \alpha_i \leq 1 \) the duration of phase 1 and 2 be \( \tau \) and \( 1-\tau \), respectively, with \( 0 \leq \tau \leq 1 \). Then the achievable rate region of the two-phase four-way relaying scheme using DF is the convex closure of all 4-dimensional rate tuples satisfying \( (R_1^u, R_1^d, R_2^u, R_2^d) \in D \).
\begin{align}
R_1^u < (1 - \tau) C \left( |h_{11}|^2 P_{R1} \right) \quad (8a) \\
R_2^u < (1 - \tau) C \left( |h_{21}|^2 P_{R2} \right) \quad (8b) \\
R_1^d < (1 - \tau) C \left( |h_{12}|^2 P_{R1} \right) \quad (8c) \\
R_2^d < (1 - \tau) C \left( |h_{22}|^2 P_{R2} \right) \quad (8d) \\
R_1^d + R_2^d < (1 - \tau) C \left( |h_{12}|^2 P_{R1} + |h_{22}|^2 P_{R2} \right) \quad (8e)
\end{align}

where \((i, j) \in \{(1, 2), (2, 1)\}\).

### IV. Numerical Results

The achievable rate region for four-way relaying is 4-dimensional, as shown in (3), (4) and (5). In order to get a better, 2-dimensional insight, we can fix the downlink-uplink rate ratio to e.g. 1:1 (gaming and calls) or 5:1 (web browsing) \([12]\). We assume that, for the \(i\)-th user, the downlink rate demand \(R_i^d\) is related to the uplink rate demand \(R_i^u\), as \(R_i^d = \theta_i R_i^u\), see \([8]\). The time ratio \(\tau\) and superposition ratio \(\alpha\) are optimized jointly by sequential quadratic programming \([13]\). For simplicity, we plot the achievable rate regions of the rate pair \((R_i^u, R_i^d)\) and assume that each node has equal transmission power of \(P_k = 10, k \in \{1, R_1, B, R_2, 2\}\). The achievable rate regions of rate pair \((R_i^u, R_i^d)\) are shown on Fig. 4-5. S2 stands for the two-phase relaying scheme, S4 for cases 2 and 3 coincide. However, there is a data rate for both \(U_1\) and \(U_2\) when switching the downlink and uplink channel setting of 2 links in two-way relaying. So the curves of S4 for cases 2 and 3 coincide.

### V. Conclusion

We have described a new multi-way relay scenario of practical relevance, termed four-way relaying, in which each of the two MSs has a two-way connection to the same BS, while each connection is through a dedicated RS. One of the main assumptions is that the RSs are placed in such a way that one RS and the terminals associated with it do not interfere with the other RS. We have proposed novel communication schemes which leverage on the ideas of wireless network coding and compared the performance with a state-of-the-art reference scheme where time sharing is used between the two MSs, while each MS is served through a two-way relaying scheme. The results indicate that, when the RS operates in a DF mode, the achievable rate regions are significantly enlarged. An interesting issue for future work is to consider other types of operation for the relay, such as wireless network coding, use of lattices and noisy network coding.

### Appendix A

For each RS, phase 2 is a BC process with side information at the receivers, while simultaneous transmissions by RS1 and
RS2 define a MA channel at the BS. Hence, the achievable rates of the two BC transmissions are interrelated. We prove that the achievable rate region can be decomposed into two independent regions: 1) a MA region through channels $h_{12}$ and $h_{22}$ for rates $(R_1^u, R_2^u)$, independent from the links $h_{11}$ and $h_{21}$, and 2) two single-link rate regions $R_1^d$ and $R_2^d$ through $h_{11}$ and $h_{21}$, respectively.

Consider the MA rate region with $h_{12}$ and $h_{22}$ in Fig. 6. We define $A = (R_1^u(A), R_2^u(A))$ and $B = (R_1^u(B), R_2^u(B))$ as the corner points of the MA region, where $R_1^u(A) = C(|h_{11}|^2 P_{R1}/(|h_{12}|^2 P_{R2} + 1))$, $R_2^u(A) = C(|h_{22}|^2 P_{R2})$ and $R_2^u(B) = C(|h_{12}|^2 P_{R1})$, $R_2^u(B) = C(|h_{22}|^2 P_{R2}/(|h_{12}|^2 P_{R1} + 1))$. We now prove that point A can be achieved. Likewise, point B can be achieved. Time-sharing achieves the rates on the segment AB.

We recall that $x_{R1}$ is the re-encoded codeword at RS1. The BS receives both $x_{R1}$ and $x_{R2}$ though the channels $h_{12}$ and $h_{22}$. Let us consider a strategy where $x_{R2}$ is treated as AWGN in order to decode $x_{R1}$. Then, transmission from RS1 is a BC process with side information at the receivers U1 and BS. From [11, Theorem 2], the achievable upper bound on $R_1^u$ on link $h_{11}$ is the capacity $C(|h_{11}|^2 P_{R1})$ (denoted as $C_{11}$) while the achievable upper bound on $R_1^u$ on link $h_{21}$ is $R_1^d(A)$. After decoding $x_{R1}$, the BS cancels its contribution from the received signal. Then the transmission from RS2 is a BC process with side information at the receivers U1 and BS. From [11, Theorem 2], the achievable upper bound on $R_2^u$ on link $h_{22}$ is $R_2^u(A)$ while the achievable upper bound on $R_2^d$ on link $h_{21}$ is the capacity $C(|h_{21}|^2 P_{R2})$ (denoted as $C_{21}$). So far, we have proved that the MA region corner point A can be achieved as well as the capacity of the link $h_{11}$. The codewords used are denoted by $x_{R1}^A$. Similarly, we can prove that the rates corresponding to the corner point B can be achieved with the codewords denoted by $x_{R2}^B$. To summarize, an achievable upper bound on the rate tuple $(R_1^u, R_2^u, R_1^d, R_2^d)$ is $(R_1^u(A), R_2^u(A), C_{11}, C_{21})$ and is achieved by codewords $x_{R1}^A$. Another achievable upper bound is $(R_1^u(B), R_2^u(B), C_{11}, C_{21})$ is achieved by codewords $x_{R2}^B$.

The rates on the line AB in Fig. 6 are achieved by time-sharing between the codewords $x_{R1}^A$ and $x_{R2}^B$. Since U1, U2 and BS know the exact placement of $x_{R1}^A$ and $x_{R2}^B$ within the time-sharing, the decoding process during $t$ is to decode $x_{R1}^A$, the decoding process during $1-t$ is to decode $x_{R2}^B$. Therefore, $(tR_1^u(A) + tR_1^u(B), tR_2^u(A) + tR_2^u(B), C_{11}, C_{21})$ is achievable for every $t \in [0,1]$, $t = 1-t$. This proves that the line AB in Fig. 6, is achievable while the single-user capacity of the channel with $h_{11}$ can also be achieved. Note that the time-sharing does not affect the decoding at U1, since U1 knows the structure of the re-encoded codeword and it can apply the appropriate side information. Similarly, time-sharing achieves the rates on the lines CA and BD in Fig. 6. Then the whole MA region in Fig. 6 is achievable while the capacity of link $h_{11}$ is achievable. From these results, (8) follows.

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