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Thai, Chan T.D.; Popovski, Petar

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# Coordinated Direct and Relay Transmission with Interference Cancellation in Wireless Systems

Chan Dai Truyen Thai and Petar Popovski

**Abstract**—Two-way relaying schemes in wireless systems obtain throughput gain by utilizing two features (1) jointly serve two communication flows, thus implementing network coding and (2) use of information that is *a priori* known to cancel interference and obtain the desired signal. Based on these principles, we propose other schemes that bring throughput gains in wireless cellular systems, where relayed and direct transmissions are carried out in coordinated way. The results show that the coordinated transmission exhibit throughput improvement similar to the two-way relaying schemes.

**Index Terms**—Cooperative communications, relaying, analog network coding, interference cancellation.

## I. INTRODUCTION

RECENTLY there have been extensive studies on cooperative, relay-based transmission schemes for extending cellular coverage or increasing diversity. Several basic relaying transmission techniques have been introduced, such as amplify-and-forward (AF) [3], [4], decode-and-forward (DF) [5], [6] and compress-and-forward (CF) [7]. These transmission techniques have been applied in one-, two- or multi-way relaying scenarios.

In particular, two-way relaying scenarios [1], [2], [8] have attracted a lot of attention, since it has been demonstrated that in these scenarios one can apply techniques based on network coding in order to obtain a significant throughput gain. There are two basic principles used in designing throughput-efficient schemes with wireless network coding:

- 1) *Aggregation of communication flows*: instead of transmitting each flow independently, the principle of network coding is used in which flows are sent/processed jointly, which is in the spirit of network coding;
- 2) *Intentional cancellable interference*: the flows are allowed to interfere, either through the multiple access channel or through the digital operation at the relay, knowing *a priori* that the interference can be cancelled by the destination.

In this work we introduce other scenarios, different from two-way relaying, in which these principles can be utilized to offer throughput gains. The scenarios are related to wireless cellular systems that feature direct and relayed transmissions in uplink/downlink. We propose two schemes for coordinating the direct and the relay transmissions such that the cellular Base Station (BS) can use information known *a priori* in order to cancel interference. We term such a scheme *coordinated direct/relay (CDR)* transmission scheme. Transmission schemes

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The authors are with the Department of Electronic Systems, Aalborg University, Denmark (e-mail: {ttc, petarp}@es.aau.dk).

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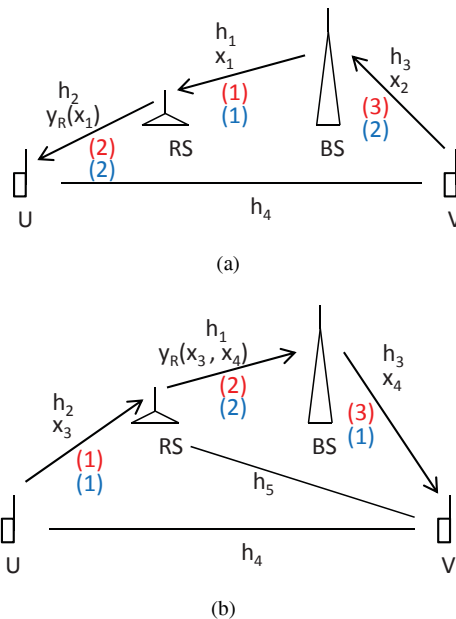


Fig. 1. Network model with channel coefficients and time slots used for the reference (upper labels) and proposed (lower labels) scheme 1 (a) and 2 (b).

that are somewhat related to the schemes proposed in this paper have appeared before [10], [11], or to relayed users [9], nevertheless the schemes introduced here are, to the best of our knowledge, original. An added value with respect to the two-way relaying scenario can be seen as follows: the gain from analog network coding requires symmetric traffic patterns for the two end nodes, while coordinated transmission in cellular networks can exhibit gains with much restricted symmetry requirements, since the traffic from different nodes is combined.

The paper is organized as follows. Section II describes the system model and transmission schemes. Section III analyzes the reference and proposed schemes in terms of sum-rate and sum-throughput. Numerical results are presented in Section IV. Section V concludes the paper.

## II. SYSTEM MODEL AND TRANSMISSION SCHEMES

The basic setup for a CDR scheme is the scenario with one base station (BS), one relay (RS), and two users U and V, see Fig. 1(a). All transmissions have a unit power and normalized bandwidth of 1 Hz. Each of the complex channels  $h_i$ ,  $i \in \{1, 2, 3, 4, 5\}$ , is reciprocal, known at the receiver and Rayleigh-faded such that  $E[|h_i|^2] = 1$ . We use  $x_i$  may denote a packet or a single symbol, and it will be clear from the context. In scheme 1, the packet that BS wants to send to U is denoted by  $x_1$ ; but if we want to express the signal received, then we use expressions of type  $y = hx_1 + z$ , where all

variables denote symbols (received, sent, or noise). Similarly, V wants to send packet  $x_2$  to the BS. In scheme 2 (Fig. 1(b)), U has packet  $x_3$  for BS and BS has packet  $x_4$  for V.

The basic time unit is one time slot, which corresponds to a transmission of a single packet. A direct transmission takes one slot while a transmission through the relay takes two slots: in the downlink, one for the BS–RS transmission and one for the RS–U transmission. The uplink transmission is similar. Relaying with amplify-and-forward (AF) is used, and therefore the transmission BS–RS has the same duration with the transmission RS–U (and vice versa in the uplink). The received signal and Additive White Gaussian Noise (AWGN) at BS, RS, U and V in time slot  $j$  is denoted by  $y_{ij}$  and  $z_{ij} \sim \mathcal{CN}(0, N)$ ,  $i = \{B, R, U, V\}$ ,  $j = \{1, 2, 3\}$ . The instantaneous Signal-to-Noise Ratio (SNR) for the  $i$ -th channel is  $\gamma_i = |h_i|^2/n$  and its capacity is denoted as  $C(\gamma_i) = \log_2(1 + \gamma_i)$ . The direct channel BS–U is assumed weak and U relies only on the amplified/forwarded signal from RS in order to decode the signal from BS. At RS, the received signal is scaled to comply with the transmit constraint.

In the reference scheme 1, first, BS sends  $x_1$  to RS, second, RS receives and then amplifies/forwards the received symbols to U, third, V sends  $x_2$  to BS. The order of time slots is shown in red (upper) labels in Fig. 1(a). In the reference scheme 2, first, U sends  $x_3$  to RS, second RS forwards the symbol received to BS, third, BS sends  $x_4$  to V (red (upper) labels in Fig. 1(b)).

In the proposed schemes, network throughput is increased as less slots are used to send the data, similar to wireless network coding. The transmission order for the proposed schemes is shown in blue labels in the figures. For scheme 1, in the first slot, BS sends  $x_1$  to RS. In the second slot, RS amplifies and forwards the symbol received to U, while V sends  $x_2$  to BS. The reception of  $x_2$  at BS is interfered by the transmission of amplified  $x_1$  from RS, but BS knows this signal *a priori* and can cancel it to detect  $x_2$ . In the first slot of scheme 2, U sends  $x_3$  to RS and BS sends  $x_4$  to V. RS receives interference between  $x_3$  and  $x_4$ , which it amplifies and forwards in the second slot. BS knows  $x_4$  *a priori*, cancels it and detects  $x_3$ . V combines the signals received in the two slots to decode  $x_4$ . In the sequel we present analysis of these transmission schemes.

### III. ANALYSIS OF THE PROPOSED SCHEMES

#### A. Calculation of the Sum-Rate

For each scheme we calculate the sum-rate of the downlink and the uplink traffic assuming that all transmitters know the instantaneous SNR at the respective receiver.

1) *Scheme 1*: RS, U and BS receive respectively  $y_{R1} = h_1x_1 + z_{R1}$ ,  $y_{U2} = h_2\sqrt{g_1}y_{R1} + z_{U2}$ ,  $y_{B3} = h_3x_2 + z_{B3}$ , with  $g_1 = 1/(|h_1|^2 + N)$ . The sum-rate for the reference scheme is:

$$C_{E1} = \frac{1}{3}[C(\gamma_{E1U}) + C(\gamma_3)] \quad (1)$$

where  $\gamma_{E1U} = \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+1}$ .

In the proposed scheme 1 the transmissions 2 and 3 are in the same time slot, such that U and BS receive, respectively  $y_{U2} = h_2\sqrt{g_1}y_{R1} + h_4x_2 + z_{U2}$ ,  $y_{B2} = h_1\sqrt{g_1}y_{R1} + h_3x_2 +$

$z_{B2}$ . BS knows  $x_1$  *a priori* and cancels it in  $y_B$  to get  $\tilde{y}_{B2} = h_1\sqrt{g_1}z_{R1} + h_3x_2 + z_{B2}$ , resulting in sum-rate:

$$C_{P1} = \frac{1}{2}[C(\gamma_{P1U}) + C(\gamma_{P1V})] \quad (2)$$

where  $\gamma_{P1U} = \frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2+\gamma_4+\gamma_1\gamma_4+1}$  and  $\gamma_{P1V} = \frac{\gamma_3(\gamma_1+1)}{2\gamma_1+1}$ .

2) *Scheme 2*: RS, BS and V receive respectively  $y_{R1} = h_2x_3 + z_{R1}$ ,  $y_{B2} = h_1\sqrt{g_2}y_{R1} + z_{B2}$ ,  $y_{V3} = h_3x_4 + z_{V3}$ , with  $g_2 = 1/(|h_2|^2 + N)$ . The sum-rate for reference scheme 2 is the same as for scheme 1,  $C_{E2} = C_{E1}$  since it has the same role for  $\gamma_1$  and  $\gamma_2$ .

In the first slot RS and V receive, respectively:

$$y_{R1} = h_2x_3 + h_1x_4 + z_{R1} \quad y_{V1} = h_4x_3 + h_3x_4 + z_{V1}$$

In the second slot, V and BS receive, respectively:

$$y_{V2} = h_5\sqrt{g_3}y_{R1} + z_{V2}, \quad y_{B2} = h_1\sqrt{g_3}y_{R1} + z_{B2}$$

with  $g_3 = 1/(|h_1|^2 + |h_2|^2 + N)$ . Since  $x_4$  is available at BS, it can be cancelled to obtain  $\tilde{y}_{B2} = h_1\sqrt{g_3}(h_2x_3 + z_{R1}) + z_{B2}$ . Using zero forcing to decode  $x_3$ ,  $x_4$  from  $y_{V1}$  and  $y_{V2}$  at V, the sum-rate is

$$C_{P2} = \frac{1}{2}[C(\gamma_{P2U}) + C(\gamma_{P2V})] \quad (3)$$

with  $\gamma_{P2U} = \frac{\gamma_1\gamma_2}{2\gamma_1+\gamma_2+1}$ ,  $\gamma = \frac{|h_2h_3+h_1h_4|^2}{N^2}$  and  $\gamma_{P2V} = \frac{\gamma_5\gamma}{\gamma_4\gamma_5+\gamma_2\gamma_5+\gamma_4(\gamma_1+\gamma_2+1)}$ .

If the channel between U and V has a negligible SNR, then V receives only  $x_4$  from BS in slot 1. In that case  $C_{E2}$  does not change, while  $C_{P2} = \frac{1}{2}[C(\gamma_{P2U}) + C(\gamma_3)]$ .

If the link BS–RS is ideal ( $\gamma_1 \rightarrow \infty$ ), the capacity of the relayed transmission of  $x_3$  from U to BS depends only on  $h_2$  and V can extract  $x_4$  from  $y_{V1}$  (SINR =  $\frac{\gamma_3}{\gamma_4+1}$ ) or  $y_{V2}$  (SINR =  $\gamma_5$ ), such that:

$$C_{E2} = \frac{1}{3}[C(\gamma_2) + C(\gamma_3)] \quad (4)$$

$$C_{P2} = \frac{1}{2} \left[ C(\gamma_2) + C \left( \max \left( \frac{\gamma_3}{\gamma_4+1}, \gamma_5 \right) \right) \right] \quad (5)$$

Note that the link capacity in the second slot does not depend on the channel  $h_4$  between the two users.

#### B. Outage Probability and Sum-Throughput

In this section we assume that the SNR at the receiver is not known at the transmitter, such that each transmitter sends at rate  $R$ . The link throughput is calculated as  $R(1 - P_{\text{out}})$ , where  $P_{\text{out}}$  is the outage probability. The sum-throughput is calculated as  $\frac{R}{2}(2 - P_{\text{out}1} - P_{\text{out}2})$ , where  $P_{\text{out}1}$ ,  $P_{\text{out}2}$  are outage probabilities at the two receivers.

Outage probability for the transmission to U in the reference scheme 1 is

$$P_{E1U} = \mathbb{P}[C(\gamma_{E1U}) < R] \quad (6)$$

$$= N^2 \int_a^\infty e^{-N\gamma_2} \int_0^{\frac{a(\gamma_2+1)}{\gamma_2-a}} e^{-N\gamma_1} d\gamma_1 d\gamma_2 + \int_0^a N e^{-N\gamma_2} d\gamma_2$$

with  $a = 2^R - 1$ . When  $\gamma_1 \rightarrow \infty$ ,  $P_{E1U} = \int_0^a N e^{-N\gamma_2} d\gamma_2 = 1 - e^{-aN}$ . Similarly, outage probability for the transmission from V is  $P_{E1V} = 1 - e^{-aN}$  and the sum-throughput is  $T_{E1} = \frac{2R}{3}e^{N(1-2^R)}$ . The reference scheme 2 has the same sum-throughput  $T_{E2} = T_{E1}$ .

Outage probability for transmission to U in the proposed scheme 1:

$$P_{P1U} = P[C(\gamma_{P1U}) < R] = P_{E1U} + (1 - P_{E1U})N^3 \int_a^\infty e^{-N\gamma_2} \int_{\frac{a(\gamma_2+1)}{\gamma_2-a}}^\infty e^{-N\gamma_1} \int_b^\infty e^{-N\gamma_4} d\gamma_1 d\gamma_2 d\gamma_4 \quad (7)$$

with  $b = \frac{\gamma_1\gamma_2 - a(\gamma_1 + \gamma_2 + 1)}{a(\gamma_1 + 1)}$ . When  $\gamma_1 \rightarrow \infty$  (ideal BS-RS), BS can completely cancel the interference:

$$P_{P1U} = P\left[\log_2\left(1 + \frac{\gamma_2}{\gamma_4 + 1}\right) < R\right] = 1 - \frac{e^{N(1-2^R)}}{2^R}. \quad (8)$$

$$P_{P1V} = P[\log_2(1 + \gamma_3) < R] = 1 - e^{N(1-2^R)}. \quad (9)$$

The sum-throughput for the proposed scheme is:

$$T_{P1} = \frac{R}{2} \left[ \frac{e^{N(1-2^R)}}{2^R} + e^{N(1-2^R)} \right]. \quad (10)$$

When  $\gamma_1 \rightarrow \infty$ , outage probability for the downlink transmission is  $P_{P2V} = P\left[\max\left(\frac{\gamma_3}{\gamma_4 + 1}, \gamma_5\right) < a\right]$ , resulting in sum-throughput:

$$T_{P2} = \frac{R}{2} e^{2(1-2^R)} \left[ 2 + \frac{1}{2^R} - \frac{e^{N(1-2^R)}}{2^R} \right]. \quad (11)$$

#### IV. NUMERICAL RESULTS

Computer simulation with network scenarios and parameters as presented in part II is conducted to illustrate sum-rate and sum-throughput for the reference and proposed schemes. Rayleigh channels are considered with average SNR of 13 dB for  $\gamma_i, i \in \{1, 2, 3\}$ . The sum-rate/throughput of the reference schemes is the same due to the symmetry  $\gamma_1$  and  $\gamma_2$ .

Fig. 2 depicts the average instantaneous sum-rate of the reference and the proposed schemes as functions of the average  $\gamma_4$ . When the interference between U and V is weak (low  $\gamma_4$ ), the sum-rate of the proposed schemes is higher than the reference schemes. Furthermore, the sum-rate of the proposed scheme 2 improves as the link RS-V becomes better (higher  $\gamma_5$ ). The proposed schemes are not always better than the reference ones — for example, when the interference from V to U, the sum-rate of the proposed scheme 1 drops rapidly. Fig. 3 shows the average sum-throughput with different values of R rates when the users are isolated ( $\gamma_4 = 0$ ). The saving in transmission slots for the proposed schemes 1 and 2 is best reflected by the higher maximal values of the sum-throughput compared to the reference scheme.

#### V. CONCLUSION

In this paper, we propose two schemes for coordinated relay and direct transmissions in wireless cellular network. The schemes are utilizing the fact that the interfering signals can be known *a priori* and thus can be cancelled in order to detect the desired signal. We have analyzed the capacity and outage features of the proposed schemes. The transmission techniques introduce here can be utilized to propose advanced scheduling algorithms in cellular systems that include both relayed users and users that are served directly by the base stations.

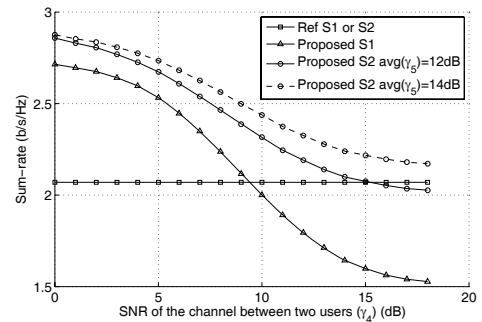


Fig. 2. Average capacities as functions of the average SNR  $\gamma_4$  between the two mobile stations.

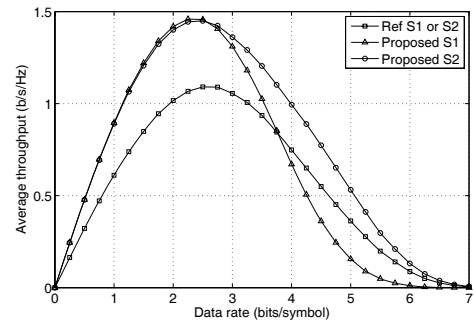


Fig. 3. Average throughput with different data rates (R) when the users are isolated ( $\gamma_4 = 0$ ).

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