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Coordinated Direct and Relay Transmission with Interference Cancelation 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 cancelation.**

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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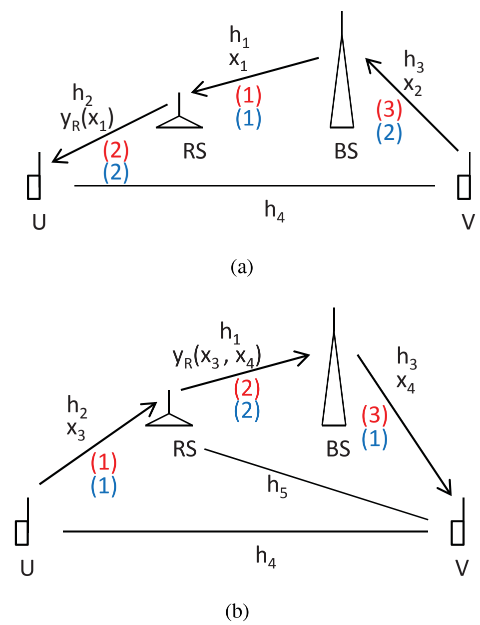

Fig. 1. Network model with channel coefficients and time slots used for the reference (upper labels) and proposed (lower labels) scheme 1 (a) and 2 (b).

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 $\mathrm{C}(\gamma_i) = \log_2(1 + \gamma_i)$. 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 $y_{R1} = h_1 x_1 + z_{R1},\ y_{U2} = h_2\sqrt{g_1} y_{R1} + z_{U2},\ y_{B3} = h_3 x_2 + z_{B3}$, with $g_1 = 1/(|h_1|^2 + N)$. The sum–rate for the reference scheme is:

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

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 $y_{U2} = h_2\sqrt{g_1} y_{R1} + h_4 x_2 + z_{U2},\ y_{B2} = h_1\sqrt{g_1} y_{R1} + h_3 x_2 + z_{B2}$. BS knows x_1 *a priori* and cancels it in y_B to get $\tilde{y}_{B2} = h_1\sqrt{g_1} z_{R1} + h_3 x_2 + z_{B2}$, resulting in sum–rate:

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

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 $y_{R1} = h_2 x_3 + z_{R1},\ y_{B2} = h_1\sqrt{g_2} y_{R1} + z_{B2},\ y_{V3} = h_3 x_4 + z_{V3}$, 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 γ_1 and γ_2.

In the first slot RS and V receive, respectively:

$$y_{R1} = h_2 x_3 + h_1 x_4 + z_{R1} \qquad y_{V1} = h_4 x_3 + h_3 x_4 + z_{V1}$$

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

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

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

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

with $\gamma_{P2U} = \frac{\gamma_1\gamma_2}{2\gamma_1+\gamma_2+1}$, $\gamma = \frac{|h_2 h_3 + h_1 h_4|^2}{N^2}$ 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 $C_{P2} = \frac{1}{2}\left[\mathrm{C}\left(\gamma_{P2U}\right) + \mathrm{C}(\gamma_3)\right]$.

If the link BS-RS is ideal ($\gamma_1 \to \infty$), 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:

$$C_{E2} = \frac{1}{3}\left[\mathrm{C}(\gamma_2) + \mathrm{C}(\gamma_3)\right] \tag{4}$$

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

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_{out} is the outage probability. The sum–throughput is calculated as $\frac{R}{2}(2 - P_{\text{out1}} - P_{\text{out2}})$, where $P_{\text{out1}},\ P_{\text{out2}}$ are outage probabilities at the two receivers.

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

$$\begin{aligned} P_{E1U} =& \mathrm{P}\left[\mathrm{C}(\gamma_{E1U}) < R\right] \\ =& N^2 \int_a^\infty e^{-N\gamma_2} \int_0^{\frac{a(\gamma_2+1)}{\gamma_2-a}} e^{-N\gamma_1}\, \mathrm{d}\gamma_1 \mathrm{d}\gamma_2 + \int_0^a N e^{-N\gamma_2}\, \mathrm{d}\gamma_2 \end{aligned} \tag{6}$$

with $a = 2^R - 1$. When $\gamma_1 \to \infty$, $P_{E1U} = \int_0^a N e^{-N\gamma_2}\, \mathrm{d}\gamma_2 = 1 - e^{-aN}$. 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:

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

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

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

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

The sum–throughput for the proposed scheme is:

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

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

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

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 γ_1 and γ_2.

Fig. 2 depicts the average instantaneous sum–rate of the reference and the proposed schemes as functions of the average γ_4. When the interference between U and V is weak (low γ_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 γ_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.

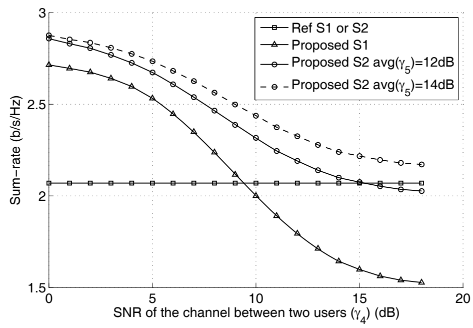

Fig. 2. Average capacities as functions of the average SNR γ_4 between the two mobile stations.

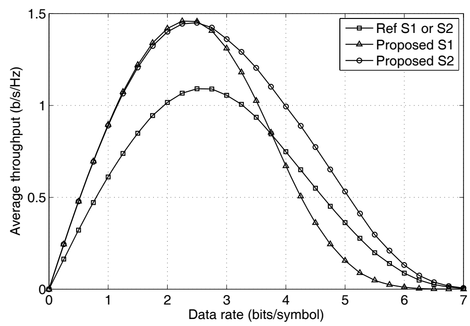

Fig. 3. Average throughput with different data rates (R) when the users are isolated ($\gamma_4 = 0$).

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