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Performance Analysis of Physical-layer Network Coding in Decode-and-forward Cooperative Communications

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Abstract: Physical-layer Network Coding (PNC) is an efficient approach that can improve the system spectrum efficiency by allowing two different nodes to transmit their information to a common node simultaneously which can save more time slot resource compared with Network Coding (NC). In this study, for the purpose of further improving the performance of cooperative networks, a new cooperative diversity scheme which combines Decode-and-forward (DF) protocol and physical-layer network coding, is proposed for a two-hop cooperative system with multiuser. In the proposed scheme, users broadcast their information using quadrature carriers simultaneously and the relay node employs decode-and-forward mode. To check its validity, the Bit Error Rate (BER) and throughput of the proposed scheme, under different propagation cases, are investigated and compared with that of traditional decode-and-forward. The simulation results reveal that the proposed scheme can effectively improve the system performances.

Key words: Network coding, relay protocol, multiuser cooperation, throughput

INTRODUCTION

Multiple-input Multiple-output (MIMO) (Wang *et al*., 2010; Hussain *et al*., 2011) is an attractive technology that can significantly improve the system performance and provide linear capacity growth using the inherent broadcast characteristic of wireless mediums, under the assumption that un-correlation between antennas is achieved. However, due to resource limitation, antennas configured at a same terminal can't be completely un-correlative which leads to severe degradation in the system performance. To tackle this problem, cooperative diversity (Sendonaris *et al*., 2003a, b) was proposed to form virtual MIMO through sharing the antenna resource among terminals to achieve spatial multiplexing and diversity gain. Two of the most common cooperative protocols, including Amplify-and-forward (AF) and Decode-and-forward (DF), were discussed by Laneman *et al*. (2004). A cooperative diversity scheme using both DF and AF was proposed by employing truncated stop-and-wait automatic repeat request for the error control in Nakagami-m fading channels (Wang *et al*., 2009). Tang and Wang (2013) introduced a non-combining incremental relaying protocol for a two-hop amplify-and-forward cooperative system. However, the existing traditional protocols of cooperative diversity achieve the diversity gain at the cost of a loss in spectrum efficiency. Moreover, one relay is allowed to help only one source to transmit information at a special time which leads to bandwidth inefficient due to employing orthogonal channels to forward the signals for different sources.

On the other hand, Network Coding (NC) (Ahlswede *et al*., 2000; Li *et al*., 2003) was proposed as a solution to enhance the system throughput for wireline networks through re-encoding information from different sources together before forwarding at the relay which means one relay can serve more sources simultaneously. Due to its high efficiency, it is widely applied to wireless relay networks (Chieochan and Hossain, 2013; Lin *et al*., 2013). Physical-layer Network Coding (PNC) was introduced by Zhang and Liew (2009) for two-way relay networks, where it can enhance the system performance allowing different sources to transmit their information simultaneously.

Due to the common feature between cooperative diversity and network coding, that the relays have ability to dispose the received signals, it is easy to combine them to further improve the wireless system performance. Zhou *et al*. (2010) developed a network coding aided iterative Multi-user Detection (MUD) scheme, where the relay employed exclusive or (XOR) operation and a multi-user soft network decoding algorithm was developed. A cooperative network coded scheme (Islam *et al*., 2012), employing Orthogonal Frequency Division Multiplexing (OFDM) and Bit-interleaved Coded

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Modulation (BICM), was discussed for a multiple-source cooperative network, where the relay used network coding over Galois fields (GFNC). Peng *et al*. (2010) investigated a cooperative network coded DF (CNC-DF) protocol for a two-hop relay network, in which Linear Network Coding (LNC) was employed at the relay and the ergodic capacity and outage probability of the scheme were explicitly derived.

In this study, a cooperative network coding scheme employing PNC and DF is proposed for a two-hop relay network which comprises two users, one relay and one destination. The two users broadcast orthogonal Binary Phase Shift Keying (BPSK) signals modulated with quadrature carriers to both the relay and the destination, simultaneously. The relay re-encodes the packets from different users to a new packet using Quadrature Phase Shift Keying (QPSK) modulation before transmitting. The Bit Error Rate (BER) and through put of the proposed scheme are investigated though computer simulation.

SYSTEM MODEL

This section considers a two-hop cooperative relay network with two users (U_1, U_2), one relay (R) and one destination (D). The system model is illustrated in Fig. 1. For simplicity, all nodes are equipped with one antenna.

The entire cooperative process includes two phases: broadcast and relay. In the first phase, user broadcasts its signal to both R and D. R transmits the received signal to D in the second phase. It is assumed that the wireless channel is flat fading, so, the channel fading coefficient can be taken as a constant during a time slot. All receivers can obtain corresponding perfect Channel State Information (CSI). Decode-and-forward relay protocol is employed in this study.

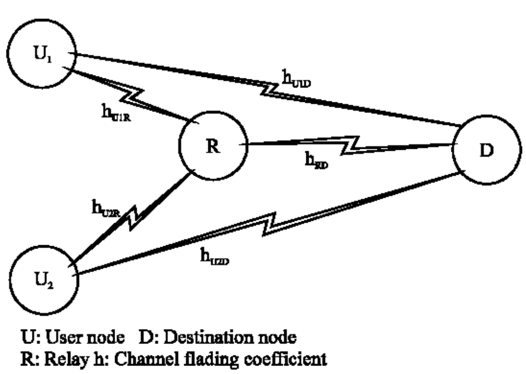

Fig. 1: System model for a cooperative network with two users, one relay and one destination

TRADITIONAL COOPERATIVE SCHEME AND THE PROPOSED COOPERATIVE SCHEME

Here, the details of the proposed cooperative network coding scheme and that of the traditional decode-and-forward cooperative scheme.

Traditional DF cooperative scheme: In a traditional cooperative relay network as shown in Fig. 1, two users (U_1, U_2) can't transmit signals simultaneously due to the interference between users. They can only use the Time-division Multiple-access (TDMA) method to transmit their information in order to avoid conflict. So, the relay can only serve one user at a given time.

Take U_1 for example. In the first time slot (broadcast phase), U_1 broadcasts information s_1 to both R and D. The received signals at R and D are:

$$\begin{aligned} y_{U1R} &= h_{U1R}s_1+n_{R1} \\ y_{U1D} &= h_{U1D}s_1+n_{D1} \end{aligned} \tag{1}$$

where, h_{U1R} and h_{U1D} are complex channel fading coefficients over U_1-R link and U_1-D link, respectively; n_{R1} and n_{D1} are complex Gaussian noise variables received at R and D in the first time slot, respectively.

In the second time slot (relay phase), R decodes the received signal y_{U1R} to get the estimate $\tilde{s}_1$ and then forwards it to D. The received signal at D is:

$$y_{RD} = h_{RD}\,\tilde{s}_1+n_{RD} \tag{2}$$

where, h_{RD} is complex channel fading coefficient over R-D link; n_{RD} is complex Gaussian noise variable received at D in the second time slot.

D decodes U_1's information according to the received signals from the first and second time slots and gets the estimate $\hat{s}_1$.

Analogously, D can decode U_2's information according to the received signals from the third and fourth time slots and gets the estimate $\hat{s}_2$.

Proposed PNC cooperative scheme: Due to the emergence of network coding, a relay can serve two or more sources simultaneously. In a cooperative network coding relay network described in Fig. 1, two users (U_1, U_2) transmit their information (s_1, s_2) to both R and D in the first time slot, simultaneously. Their signals are modulated with cosine and sine carriers, respectively. The transmitted signals from two users are:

$$x_1(t) = s_1 \cos(2\pi f_c t)$$
$$x_2(t) = s_2 \sin(2\pi f_c t) \quad (3)$$

where, f_c is carrier frequency. The received signals at R and D are expressed as:

$$y_{UR}(t) = h_{U1R}x_1(t)+h_{U2R}x_2(t)+n_{R1}(t)$$
$$y_{UD}(t) = h_{U1D}x_1(t)+h_{U2D}x_2(t)+n_{D1}(t) \quad (4)$$

where, h_{U2R} and h_{U2D} are complex channel fading coefficients over U_2-R link and U_2-D link, respectively. R and D put the received signal $y_{UR}(t)$ and $y_{UD}(t)$ through their correlation receivers, respectively. The correlator outputs of R and D are:

$$\begin{cases} y_{UR1} = h_{U1R}s_1 + n_{R1,c} \\ y_{UR2} = h_{U2R}s_2 + n_{R1,s} \end{cases} \quad (5)$$

$$\begin{cases} y_{UD1} = h_{U1D}s_1 + n_{D1,c} \\ y_{UD2} = h_{U2D}s_2 + n_{D1,s} \end{cases} \quad (6)$$

where, $n_{R1,c}$, $n_{R1,s}$ and $n_{D1,c}$, $n_{D1,s}$ are real Gaussian noise variables. R decodes two users' information using Eq. 5 and gets the estimates $\tilde{s}_1$ and $\tilde{s}_2$.

In the second time slot, R re-encodes two users' information using QPSK modulation before transmitting information to D. The transmitted information from R is:

$$s_R = \sqrt{0.5}\left(\tilde{s}_1 + j\tilde{s}_2\right) \quad (7)$$

Then, the received signal at D in the second time slot is expressed as:

$$y_{RD}(t) = h_{RD}s_R(t)+n_{RD}(t) \quad (8)$$

Through correlation receivers, D obtains another group of correlator outputs, written as:

$$\begin{cases} y_{RD1} = \sqrt{0.5}h_{RD}\tilde{s}_1 + n_{RD,c} \\ y_{RD2} = \sqrt{0.5}h_{RD}\tilde{s}_2 + n_{RD,s} \end{cases} \quad (9)$$

Finally, D retrieves two users' information using Eq. 6 and 9 and gets the estimates $\hat{s}_1$ and $\hat{s}_2$.

SIMULATION RESULTS AND ANALYSIS

Here, the BER and throughput performances of a two-hop cooperative relay network with traditional DF and proposed PNC cooperative schemes which are discussed above in this study, are evaluated using classic Monte Carlo method. It is assumed that Maximum Likelihood (ML) decoding and Log-Likelihood Ratio (LLR) decoding are employed in this study. The simulation contains the following three cases:

Case 1: All links have the same Signal to Noise Ratio (SNR)
Case 2: S-R link is better than S-D and R-D links
Case 3: R-D link is better than S-R and S-D links

The corresponding SNRs (SNR_{SR}, SNR_{SD}, SNR_{RD}) of the three cases are (SNR, SNR, SNR), (SNR+gap, SNR, SNR) and (SNR, SNR, SNR+gap), respectively. Here, gap = 20 and 5 dB. In the simulation results, DF and PNC denote traditional DF cooperative scheme and the proposed PNC cooperative scheme, respectively; ML and LLR denote maximum likelihood decoding and log-likelihood ratio decoding, respectively.

Figure 2 and 3 illustrate the BER and throughput performances of Case 1, respectively. It can be seen that

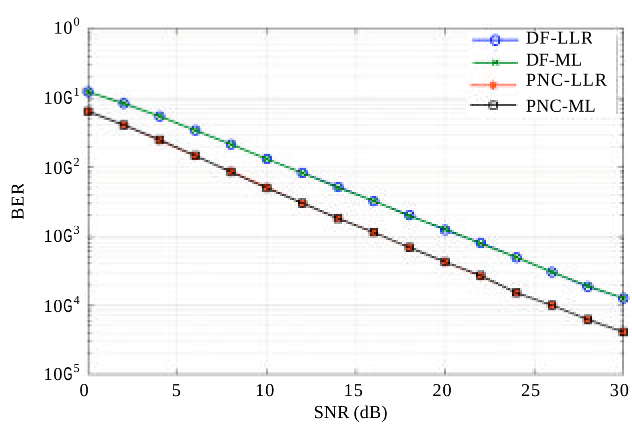

Fig. 2: BER performance of Case 1 ($SNR_{SR} = SNR_{SD} = SNR_{RD}$)

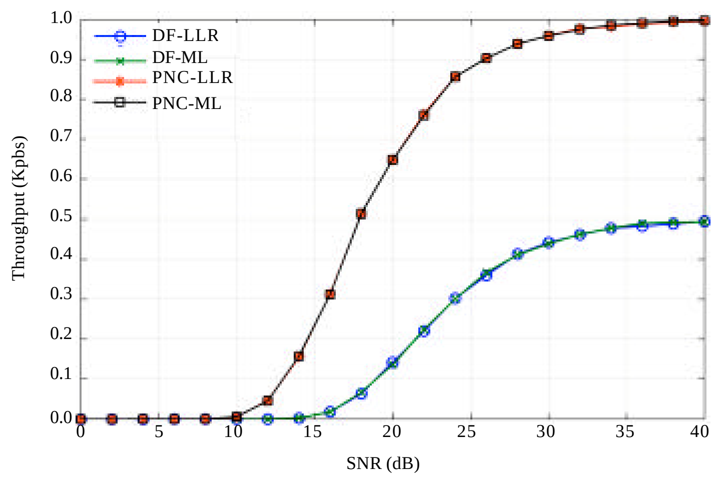

Fig. 3: Throughput performance of Case 1 (SNR_{SR} = SNR_{SD} = SNR_{RD})

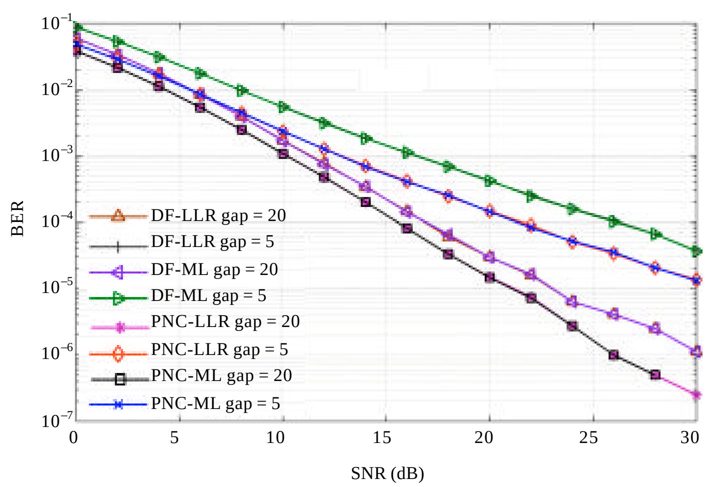

Fig. 4: BER performance of Case 2 (SNR_{SD} = SNR_{RD} = SNR, SNR_{SR} = SNR+gap dB)

the performance improves as the SNR increases and the proposed scheme outperforms traditional DF scheme. For instance, when BER is equal to 10^{-3}, the proposed scheme provides about a 4.5 dB gain compared with traditional DF cooperative scheme. In addition, ML decoding and LLR decoding have the same system performance for a particular scheme, when all links have the same SNR. Due to saving 2 time slots compared with traditional DF, the proposed scheme can significantly improve the system throughput and it can provide an up to 100% throughput gain.

The BER and throughput performances of Case 2 are shown in Fig. 4 and 5, respectively. It can be observed that the proposed scheme outperforms traditional DF and the performance improves with the increase of gap due to the increase of successful decoding probability at the relay. But, the performance gain provided by the proposed scheme decreases with the increase of gap. For example, when BER is equal to 10^{-4}, the proposed scheme provides about a 4.6 dB gain when gap is 5 dB while about a 1.5 dB gain when gap is 20 dB. In addition, ML decoding and LLR decoding still have the same performance for a particular scheme under this case.

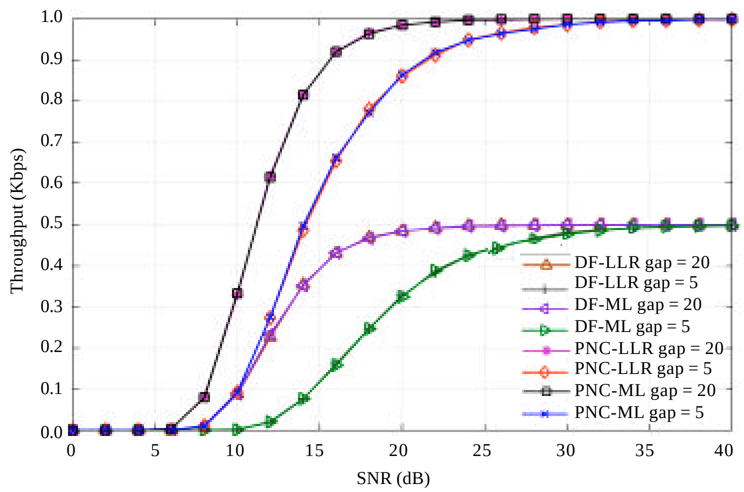

Fig. 5: Throughput performance of Case 2 (SNR_{SD} = SNR_{RD} = SNR, SNR_{SR} = SNR+gap dB)

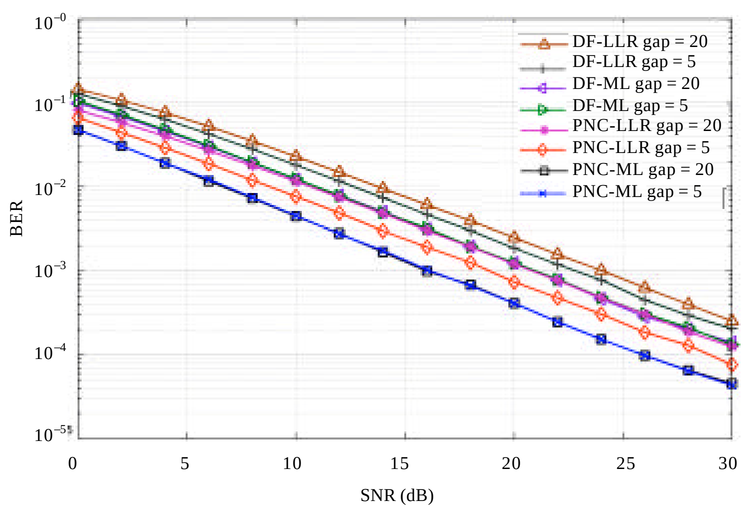

Fig. 6: BER performance of Case 3 (SNR_{SR} = SNR_{SD} = SNR, SNR_{RD} = SNR+gap dB)

The BER and throughput performances of Case 3 are illustrated in Fig. 6 and 7, respectively. It can be seen that the proposed scheme outperforms traditional DF and ML decoding outperforms LLR decoding for a particular scheme. It also can be observed the performance of LLR decoding decreases with the increase of gap while the performance of ML decoding almost doesn't vary with the increase of gap. The main difference between ML and LLR is that the signals from S-D and R-D links have the same weight in ML decoding while the weight of the signal from R-D link is bigger than that of S-D link in LLR decoding, when the SNR of R-D link is better than that of S-D link which corresponds to Case 3. The reason, that ML performs better than LLR, is that the relay doesn't check the correctness of decoding information.

From Fig. 6, it also can be seen that, at BER = 10^{-3}, the proposed scheme provides about a 5 dB gain for ML decoding; for LLR decoding, the proposed scheme provides about a 4 dB gain when gap = 5 dB while about a 3-dB gain when gap = 20 dB.

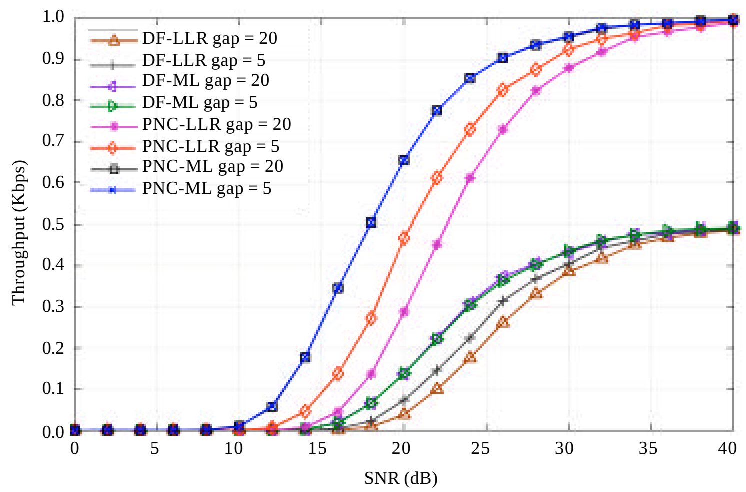

Fig. 7: Throughput performance of Case 3 ($SNR_{SR} = SNR_{SD} = SNR$, $SNR_{RD} = SNR+gap$ dB)

CONCLUSION

In this study, physical-layer network coding and cooperative diversity jointly work to further improve the performance for a DF-based relay network. The BER and throughput of the proposed PNC cooperative scheme are investigated using computer simulation. The simulation results reveal that, whatever the circumstances, the proposed PNC cooperative scheme can significantly enhance the system performance for a two-hop relay network which adopts DF relay protocol and consists of multiuser. Because it's a 2 time slots scheme, it can provide a 100% throughput gain compared with the traditional DF cooperative scheme, at the appropriate SNR. In addition, this study verifies the effect of different decoding methods on the performance of the proposed scheme. When R-D link and S-D link have the same SNR which corresponds to Case 1 and Case 2, ML and LLR have the same performance and the performance improves with the increase of gap; when R-D link is better than S-D link which corresponds to Case 3, ML outperforms LLR and the performance of LLR decreases with the increase of gap while that of ML almost doesn't vary.

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