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Path Selection Strategy for Network-Coded Cooperation with Decode-and-Forward Relay

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Abstract. Network coded cooperation (NCC) scheme combines both network coding (NC) and cooperative communication (CC) and has recently gained interest in multi-sources cooperative systems due to its ability to improve spectral efficiency and to increase the network throughput. In this paper, we consider a wireless communication system composed of two users, a single decode and forward (DF) relay, and a single destination. We propose a scheme that combines both the NCC scheme and path selection (PS) strategy and denoted by network coded cooperation path selection (NCCPS) scheme. To quantify the proposed NCCPS performance, both the outage probability and the mean spectral efficiency (MSE) of the NCCPS are investigated over Nakagami-$m$ fading channels. Simulation results show that our proposed NCCPS strategy outperforms NCC and achieves better coding gain and better MSE for symmetric channels. For asymmetric channels, when the direct channels are stronger than the source-relay-destination, our proposed strategy also achieves better outage probability and MSE. For the case when the source-relay-destination channels are stronger, our proposed scheme achieves the same performance as NCC since they will be the same scheme. Furthermore, when we compare it with NCC with two relays and use relay selection, NCCPS achieves better performance at low SNR values.

Keywords: Cooperative Communication, Network Coding, Path Selection, Decode and Forward Relay.

1 Introduction

Network Coding (NC) is a promising technique in both wired and wireless networks. By allowing intermediate network nodes to combine packets of multiple users and forward them in a single transmission, NC provides more efficient usage of network resources and improves throughput \cite{1,10}.

Cooperative communications (CC) exploits the broadcast nature of the wireless channels and improves the error performance by increasing the diversity order (DO) compared to conventional point-to-point wireless communications \cite{9,14}. In CC systems a user communicates with a destination with the help of a single or multiple relay nodes in two-time slots. In the first time slot, the
source broadcasts its transmitted signal to both the relay and the destination. In the second time slot, the relay forwards the packet to the destination. At the relay, the received information is first processed and then forwarded to the destination node using relaying protocols such as Amplify-and-Forward (AF) \[3\], or Decode-and-Forward (DF) \[4\]. Recently, the combination of multiple-input multiple-output (MIMO) and CC has gained greater significance in wireless communication systems due to its ability to enhance the data rates and the reliability \[19, 13\]. However, this gain comes at the expense of an increase in the system hardware complexity. Antenna selection (AS), is a suboptimal strategy that enjoys a great deal of MIMO advantages with less complexity \[3, 12\].

To alleviate the spectral inefficiency of multi-user CC systems, researchers combine both NC and CC to form Network Coded Cooperation (NCC) \[5, 7, 16\]. In NCC with $N$ users, instead of using $N$ transmissions rounds so that the relay forwards the $N$ packets to the destination and due to NC advantage, the relay first computes a weighted sum of the $N$ users’ packets and then it forwards it to the destination in a single time-slot. Therefore with NCC, the spectral efficiency is significantly increased \[7\]. Recently, NCC has drawn much attention, in which several papers have investigated the benefits of NC for relay networks. For multiple relays, in \[15\] a network consists of $N$ sources, $M$ relays and one destination node is considered. The exact successful decoding probability expression for random NCC (RNCC) is derived over Rayleigh fading channels. For a single relay selection, the impact of outdated channel state information (CSI) on the performance of NCC with relay selection is investigated in \[7\] over Rayleigh fading channels. In \[2,7\], the outage probability is examined in the presence of frequency-selective Rayleigh fading channels. For Multiple relay selection, in \[6,8\] a MIMO-NCC system with multiple relays is considered. Both a single relay selection and multiple relay selection strategies are considered and the exact outage probability expressions are derived. In addition, a new relay strategy is developed in \[8\].

In CC, the source communicates with the destination through two paths, the direct path (source-destination) and the cooperative path (source-relay-destination). Joint antenna and path selection (JAPS) is a strategy proposed for MIMO-CC systems. The proposed JAPS strategy achieves full DO. In \[18\], the analysis was carried out from an ergodic capacity perspective using orthogonal space-time block coding (OSTBC). In \[11\] for antenna selection, both ergodic capacity and symbol error rate (SER) were analyzed. In \[17\] an asymptotic bound for SER is derived for any arbitrary transmission schemes and fading channels. To the best of our knowledge, the use of NCC and PS has not yet been reported in the literature. The main objective of this paper is to improve the performance of NCC by incorporating path selection. Specifically, we consider an NCC system consisting of two sources, one relay and a single destination. The relay uses DF protocol and adopts maximum distance separable (MDS) codes as their encoding vectors. We quantify the performance of the proposed NCCPS scheme by investigating both the outage probability and the mean spectral efficiency (MSE). For Symmetric channels, we show that the proposed NCCPS scheme
can improve the performance of the NCC scheme in terms of the OP and the MSE. Furthermore, when we compare the NCC scheme with two relays and use relay selection, our proposed NCCPS scheme gives better performance at low SNR values. For asymmetric channels, when the source relay destination links are better than the source-destination links, we can see that both NCC and NCCPS give the same performance since our scheme will be the same as NCC, which validates the performance of our proposed scheme. The remainder of the paper is organized as follows. In Section II we present the system model. In Section III we describe the proposed strategy. Simulations and results are given and discussed in Section IV. We conclude this work in Section V.

Notations:
Let \( x \in \mathbb{GF}(q) \) denotes a symbol of a Galois field (GF) of size \( q \). Let \( + \) and \( \otimes \) denote addition and multiplication operations in a GF. We use \( S_1, S_2, R \) and \( D \) to denote the first user, the second user, the relay and the destination, respectively. The total transmit power is \( P \). Let \( h_{XY} \) and \( n_{XY} \) be the channel coefficient and the noise respectively, between the \( X \) and \( Y \). All \( h_{XY} \) between \( X \) and \( Y \) are identical independent and modeled as Nakagami-\( m \) (integer \( m \)) random variables. Let \( n_{XY} \) be the noise which is a complex additive white Gaussian noise (AWGN) with zero mean and variance \( N_0 \). Let \( \gamma_{XY} = \frac{P|h_{XY}|^2}{N_0} \) be the instantaneous SNR at \( Y \), in the hop \( XY \), which follows gamma distribution with parameters \( \beta_{XY} = \frac{N}{(P_X\delta^2_{XY})} \) and \( m \). The probability density function (PDF) and the cumulative distribution function (CDF) of \( \gamma_{XY} \) are given by

\[
\begin{align*}
    f_{\gamma_{XY}}(x) &= \frac{(m_{XY})^{m_{XY}}(\beta_{XY})^{m_{XY}}x^{m_{XY}-1}e^{-m_{XY}\beta_{XY}x}}{\Gamma(m_{XY})} \\
    F_{\gamma_{XY}}(x) &= \frac{\gamma(m_{XY}, m_{XY}\beta_{XY}x)}{\Gamma(m_{XY})}.
\end{align*}
\]

2 System Model

We consider a NCC system consisting of two users \( S_t, t \in \{1, 2\} \), a single relay \( R \) and one destination \( D \) as shown in Fig. 1. All terminals i.e, both sources, the relay and the destination operate in half-duplex mode and are equipped with a single antenna. Let \( P_{S_1}, P_{S_2} \) and \( P_R \) be the transmit powers corresponding to \( S_1, S_2 \) and \( R \), respectively. The total power budget for the NCC wireless system is constrained as \( P = P_{S_1} + P_{S_2} + P_{RD} \). For NCC, two orthogonal transmission phases are used for the transmission the broadcast phase and the relaying phase. In the broadcast phase, both sources transmit in two orthogonal time-slots. The broadcast phase lasts 2 time-slots. The received signals at the destination and the relay in the broadcast phase for user \( S_t \) are given respectively, as:

\[
\begin{align*}
    y_{S_t, D} &= \sqrt{P_{S_t}}h_{S_t,D}x_{S_t} + n_{S,D}, \\
    y_{S_t, R} &= \sqrt{P_{S_t}}h_{S_t,R}x_{S_t} + n_{S,R}
\end{align*}
\]
where $x_S$ is the modulated symbol of the transmitted data symbol $b_S$ of user $S$, $h_{XY}$ is the fading coefficient from node $X$ to node $Y$ and $n_{XY}$ is the complex AWGN. The instantaneous SNR in the link $S \rightarrow D$ and $S \rightarrow R$ are $\gamma_{S,D} = \frac{P_{S,D}|h_{S,D}|^2}{N_0}$ and $\gamma_{S,R} = \frac{P_{S,R}|h_{S,R}|^2}{N_0}$, respectively. The relay detects $x_S$ by using $y_{S,D}$. Let $\hat{x}_S$ be the detected version of the modulated symbol $x_S$. Similarly, let $\hat{b}_S$ be the detected version of transmitted data symbol $b_S$. In the relaying phase, the relay generates the network-coded transmitted data symbol as follows:

$$b_R = \sum_{t=1}^{2} \oplus \left( a_t \oplus \hat{b}_S \right)$$

where $a_t$ is the coding coefficient which is selected from a finite field, $GF(q)$. The received signals at the destination in the relay phase are given as:

$$y_{RD} = \sqrt{P_R|h_{RD}|^2}x_R + n_{RD}$$

where $x_R$ is the modulated symbol of the transmitted data symbol $\hat{b}_R$. The instantaneous SNR in the link $R \rightarrow D$ is $\gamma_{RD} = \frac{P_{RD}|h_{RD}|^2}{N_0}$.

3 Proposed NNC Path Selection Strategy

In the proposed path selection strategy, each source $S_t$ has two paths to the destination, the direct path and the cooperative path through the relay node. The performance of the relay link i.e., source-to-relay-to-destination, is dominated by the weakest signal to noise ratio (SNR) link of all links that are connected.
to the relay node. The equivalent SNR of the source-relay-destination link is denoted by $\gamma_{REq}$ and given by

$$\gamma_{REq} = \min\{\gamma_{S1R}, \gamma_{S2R}, \gamma_{RD}\}$$

(7)

We propose that when the minimum of both the direct links SNRs i.e $\gamma_{S1D}$ and $\gamma_{S2D}$ is greater than the relay link SNR $\gamma_{REq}$, the total power is equally shared only between the sources, the relay does not participate and we do not use NCC. Otherwise, we use NCC and the total power is equally shared between both sources and relay. The steps of the proposed NCC path selection strategy are given as follows:

- If $\min\{\gamma_{S1D}, \gamma_{S2D}\} \geq \gamma_{REq}$
  - We do not use NCC strategy.
  - The total power budget is split between the two users i.e, $P_{S} = \frac{P}{2}$.
- If $\min\{\gamma_{S1D}, \gamma_{S2D}\} < \gamma_{REq}$
  - We use NCC strategy.
  - The total power budget is split between the two users and the relay i.e, $P_{S} = P_{R} = \frac{P}{3}$.

4 Performance Analysis

4.1 Outage Probability

In wireless communication, outage probability (OP) is a meaningful metric to measure the quality of a transmission. The OP $P(\mathcal{R})$ of the link $XY$ can be determined as:

$$P(\mathcal{R}) = \mathbb{P}\{\log(1 + \gamma_{XY}) < \mathcal{R}\}$$

(8)

$$= \mathbb{P}\{\gamma_{XY} < \gamma_{th}\}$$

(9)

where $\mathcal{R}$ targets the transmission rate and $\gamma_{th} = 2^\mathcal{R} - 1$. Let $\phi = \{\min\{\gamma_{S1D}, \gamma_{S2D}\} \geq \gamma_{REq}\}$ be the event of choosing the direct paths without using NCC and $\bar{\phi} = \{\min\{\gamma_{S1D}, \gamma_{S2D}\} < \gamma_{REq}\}$ be the event of using NCC. From [6], the OP of NCC scheme is given by $P_{NCC}(\mathcal{R}) = 1 - \bar{P}_{NCC}(\mathcal{R})$, where $\bar{P}_{NCC}(\mathcal{R})$ is the probability that the system is not in outage, given by

$$\bar{P}_{NCC}(\mathcal{R}) = \mathbb{P}\{\gamma_{S1D} > \gamma_{th} \land \gamma_{S2D} > \gamma_{th}\}$$

$$+ \mathbb{P}\{\gamma_{RD} > \gamma_{th}\} \times (\mathbb{P}\{\gamma_{S1D} < \gamma_{th} \land \gamma_{S2D} > \gamma_{th}\}$$

$$+ \mathbb{P}\{\gamma_{S1D} > \gamma_{th} \land \gamma_{S2D} < \gamma_{th}\}).$$

(10)

When we use only the direct links i.e, without NCC, the OP is denoted by $P_{D}(\mathcal{R})$ and is given by the probability that both the direct links are in an outage, and is given by

$$P_{D}(\mathcal{R}) = \mathbb{P}\{\gamma_{S1D} < \gamma_{th} \land \gamma_{S2D} < \gamma_{th}\}. $$

(11)
Finally, the OP of the proposed strategy NCCPS denoted by \( P_{NCCPS}(R) \) is given by \( 12 \).

\[
P_{NCCPS}(R) = \begin{cases} 
P_d(R) \text{ given that } \{\min\{\gamma_{S_1D}, \gamma_{S_2D}\} \geq \gamma_{R_{eq}}\} \\
P_{NCC}(R) \text{ given that } \{\min\{\gamma_{S_1D}, \gamma_{S_2D}\} < \gamma_{R_{eq}}\}
\end{cases}
\]

(12)

4.2 Spectral Efficiency

In the NCC scheme, the transmission of two packets is accomplished in three-time slots. Therefore, since two packets of rate \( R \) are transmitted in three-time slots, the mean spectral efficiency (MSE) of the NCC denoted by \( \bar{R} \) is

\[
\bar{R} = \frac{2R}{3}\text{.}
\]

(13)

In contrast, in the NCCPS scheme, the transmission process is accomplished in two or three-time slots, depending on whether we use only the direct links i.e, does not use NCC or use NCC, respectively. If we use only the direct links, then the spectral efficiency equals \( R \); otherwise, if we use NCC then the spectral efficiency equals \( \frac{2R}{3} \).

Therefore, the MSE \( \bar{R} \) is

\[
\bar{R} = R\mathbb{P}\{\min\{\gamma_{S_1D}, \gamma_{S_2D}\} \geq \gamma_{R_{eq}}\} + \frac{2R}{3}\mathbb{P}\{\min\{\gamma_{S_1D}, \gamma_{S_2D}\} < \gamma_{R_{eq}}\}
\]

(14)

\[
= \frac{R}{3} \left( 2 + \mathbb{P}\{\min\{\gamma_{S_1D}, \gamma_{S_2D}\} \geq \gamma_{R_{eq}}\} \right)
\]

(15)

it is clear that it lies in the interval \( [\frac{2R}{3}, R] \) when \( P = 0 \) is \( \frac{2R}{3} \) and when \( P = 1 \) is \( R \).

5 Simulations and Results

In this section, we present the simulation results of the aforementioned proposed strategy i.e NCCPS and we compare it to the traditional NCC scheme. Nakagami-\( m \) fading channel types are considered in the simulations. For user \( t \) where \( t \in \{1, 2\} \), we use \( m_{S,D} = m_{S,R} = m_{R,D} = m_{SRD} \) and \( \delta_{S,D}^2 = \delta_{S,R}^2 = \delta_{SD}^2 \). For NCCPS, if the direct path is used i.e the event \( \phi \) occurs, here the total power is shared equally between both sources \( (P_{S_t} = \frac{P}{2}) \). If the event \( \phi \) occurs, here the total power is shared equally between both sources and relay \( (P_{S_t} = P_{RD} = \frac{P}{3}) \). In Fig. 2 we plot the OP vs. SNR for both NCCPS and NCC schemes for different values of \( R \) First for symmetric channels, with a single relay, we can see for both cases \( R = 2 \) and \( R = 1 \) that our NCCPS outperforms
5. SIMULATIONS AND RESULTS

![Graph showing outage probability vs. SNR for different values of R.](image)

Fig. 2: The outage probability vs. SNR for both NCCPS and NCC scheme for different values of R. Here for both R = 2 and R = 1 we have $m_{SD} = m_{SRD} = 1$, $m_{SRD} = m_{RD} = 1$, $\delta_{SD}^2 = \delta_{SRD}^2 = 1$ and $\delta_{RD}^2 = \delta_{SRD}^2 = 1$ otherwise is specified in the Figure for $R = 0.5$

and performs better than the NCC scheme and achieves better performance. Furthermore, it is clear that our proposed scheme achieves the same DO of the NCC scheme which equals two [20] since the curves of NCCPS and NCC have the same slope. However, NCCPS achieves better coding gain over NCC (the NCCPS curve is shifted to the left i.e., lower OP). Table 1 summarizes the SNR gain of NCCPS compared to NCC for some OP values.

<table>
<thead>
<tr>
<th>(OP value, R)</th>
<th>NCCPS SNR gain [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(10^{-3}, 1)$</td>
<td>1.8217</td>
</tr>
<tr>
<td>$(10^{-2}, 2)$</td>
<td>1.9924</td>
</tr>
</tbody>
</table>

Table 1: The SNR gain of NCCPS over NCC obtained from Fig. 2
In Fig. 2, we also compare our proposed NCCPS with the NCC system composed of two relays and use relay selection (See Appendix 7.1). For this case, we can see that our NCCPS achieves better performance at low SNR even that NCC with two relays has more advantages (use two relays). This is because, in this region, the relays found difficulties to decode the source packet at a low SNR region, and the sources broadcast with less power compared to NCCPS. However, when SNR increases, it is clear that NCC with two relays achieves better performance from both NCC with a single relay [20], and NCCPS with a single relay.

For asymmetric channels, it is clear that for the scenario when the direct path is better than the source-relay destination path, NCCPS performs better than the NCC scheme since in NCCPS the direct links are stronger than the source-relay-destination link and in NCCPS the power allocated to the sources is more than that in NCC. For the scenarios when the cooperative path is better than the direct paths, we can see that both NCCPS and NCC achieve the same performance which is logical since in this case, we have \( P\{\gamma_{R_{eq}} > \min\{\gamma_{S_1D}, \gamma_{S_2D}\}\} \approx 1 \) and therefore NCCPS will be the same as NCC and therefore the same performance. In Fig. 3, we compare the impact of the source-destination parameters \((m_{S,D} and \delta^2_{SD})\) on the MSE. For that, we plot the MSE vs. \(\delta^2_{SD}\) with \(R = 3\). We can see that the MSE of NCC is \(2R/3\) since we always use three transmissions for two symbols. For NCCPS we can see that the MSE lies in the interval \([2R/3, R]\).

- When \(\delta^2_{SD}\) is small i.e the direct links are weak we observe that the MSE rapidly decreases to \(2R/3\) since \(P\{\min\{\gamma_{S_1D}, \gamma_{S_2D} > \gamma_{R_{eq}}\}\}\) is close to zero, therefore NCC scheme is most frequently used which means three transmissions.
- When \(\delta^2_{SD}\) increases, the MSE rapidly increases to \(R\) since \(P\{\min\{\gamma_{S_1D}, \gamma_{S_2D} < \gamma_{R_{eq}}\}\}\) increases as long as \(\delta^2_{SD}\) increases, therefore the direct links are frequently used which means two transmissions.
- When, the source-relay and the relay-destination channels get stronger, the MSE decreases (See Table 2).

Table 2 summarizes the MSE values achieved by both NCCPS and NCC for different channels parameters.

<table>
<thead>
<tr>
<th>((m_{SD}, \delta^2_{SD})), ((m_{SRD}, \delta^2_{SRD}))</th>
<th>NCC</th>
<th>NCCPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>((5, 5), (3, 3))</td>
<td>2</td>
<td>2.9694</td>
</tr>
<tr>
<td>((5, 5), (5, 5))</td>
<td>2</td>
<td>2.8310</td>
</tr>
<tr>
<td>((5, 5), (5, 10))</td>
<td>2</td>
<td>2.4749</td>
</tr>
</tbody>
</table>
6. Conclusion

In this paper, a new path selection strategy, namely NCCPS, is proposed for NCC denoted by NCCPS composed of two users, a single DF relay and a single destination. Both OP and MSE are investigated for the proposed NCCPS over Nakagami-m fading channels. Simulation results show that our proposed NCCPS strategy outperforms NCC and achieves better coding gain and better MSE. Furthermore, when we compare it with the NCC scheme composed of two relays and using relay selection, NCCPS achieves better performance at low SNR values.
Bibliography


7 Appendices

7.1 Appendix 1

NCC with two relays using relay selection strategy For a NCC system composed of two sources $S_1$ and $S_2$, two relays $R_1$ and $R_2$ and a destination node, let $\gamma_{S_1R_1}, \gamma_{S_2R_1}$ and $\gamma_{R_1D}$ be the instantaneous SNR of links $S_1$ to $R_1$, $S_2$ to $R_1$ and $R_1$ to $D$, respectively. Similarly to $R_2$, let $\gamma_{S_1R_2}, \gamma_{S_2R_2}$ and $\gamma_{R_2D}$ be the instantaneous SNR of links $S_1$ to $R_2$, $S_2$ to $R_2$ and $R_2$ to $D$, respectively. For relay $i$, the equivalent SNR of the source-relay$_i$-destination is $\gamma_{R_i,Eq}$

$$\gamma_{R_i,Eq} = \min\{\gamma_{S_1R_i}, \gamma_{S_2R_i}, \gamma_{R_iD}\}. \quad (16)$$

In a single relay selection, the relay with the maximum equivalent SNR $\gamma_{R_i,Eq}$ is selected for the transmission. The SNR of the selected relay denoted by $\gamma_{max}$ can be formulated as follows:

$$\gamma_{max} = \max\{\gamma_{R_1,Eq}, \gamma_{R_2,Eq}\}. \quad (17)$$