Efficient Interference Mitigating Strategies for Two-Way Relay Channels

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Abstract—Dual-hop hierarchical wireless networks have the potential to provide the needed capacity to a large number of mobile stations (MSs). According to this system architecture, the MSs are served by a dense network of fixed relay nodes (RNs) fed by a small number of large hub base stations (HBSs). In such deployment, high spectral efficiencies can be achieved if the RNs act as two-way relays; however this gives rise to co-channel interference (CCI) which needs to be mitigated. In order to gain insights on the impact of CCI to this scenario we consider an HBS with two highly directional antennas communicating with two MSs via two interfering two-way RNs. We investigate the average maximum sum-rate of a cooperative strategy based on Decode-and-Forward (DF) with network coding and a strategy based on Amplify-and-Forward (AF) with Network MIMO. Furthermore we devise some cooperative protocols that utilise two, three or four time slots. It is shown that the 2-slot schemes perform generally better and that the DF strategy achieves superior performance when CCI is low while AF with Network MIMO is superior when CCI is high.

Index Terms—Two-way relaying, hierarchical networks, decode-and-forward (DF), amplify-and-forward (AF).

I. INTRODUCTION

The use of relay nodes (RNs) in wireless networks has been recognized as a very promising avenue towards future wireless communications [1]. RN-enabled communications are seen as cost-effective means to improve connectivity, transmission reliability and quality-of-service without requiring a large number of antenna elements per network node [1], [2]. RNs can be inexpensive fixed wireless nodes or even user terminals that relay signals intended for other users [3], [4]. Recently it has been identified that RN-enabled networks apart from achieving the aforementioned gains, they can also greatly increase the achievable capacity density of the network, measured in bits/sec/km² [5], [6].

A promising hierarchical architecture for future wireless systems entails that mobile stations (MSs) are served in a two-hop fashion via a dense grid of fixed RNs deployed at the street level. The RNs are fed by a small number of hub base stations (HBSs) deployed above rooftops [5], [6]. The spectral efficiency of such system can be improved with the use of full-duplex RNs, i.e., RNs that can transmit and receive at the same time and frequency. However this type of RNs is hard to implement [7]. Alternatively, spectral efficiency can be enhanced using two-way relaying with half-duplex RNs [7]–[12]. Although such technique is promising, the dense RN deployment of hierarchical networks results in high co-channel interference (CCI) which limits system performance. In the literature the issue of CCI has been identified for two-way relaying systems [11]–[13], however its effects have not been investigated for the hierarchical system architecture of interest.

In this paper we investigate how CCI impacts on hierarchical networks and how its effects can be mitigated. We study the average maximum sum rate (AMSR) performance of a simple hierarchical network consisting of an HBS with two highly directional antennas, two interfering two-way RNs and two MSs. We propose two general cooperative strategies; the first is based on Decode-and-Forward (DF) with the aid of network coding and the second is based on Amplify-and-Forward (AF) with Network MIMO processing at the HBS. Furthermore we devise some communication protocols requiring two, three or four time slots that are combined with our proposed strategies. We show that for the considered system scenario the 2-slot protocols perform best. The DF-based strategy performs better in the low CCI regime while the AF-based strategy exploits CCI in the uplink and greatly outperforms DF when CCI is dominant.

The remainder of this paper is structured as follows. In Section II the signal and system model is presented. In Sections III and IV the proposed schemes based on DF relaying combined with network coding and AF relaying coupled with Network MIMO are presented and discussed. In Section V simulation results are shown and in Section VI the paper is concluded.

Notations: Vectors and matrices are denoted by boldface lowercase letters and boldface capital letters respectively. A [i, j] represents the i,j-th element of a matrix. The transpose, transpose conjugate, the inverse and the pseudo-inverse of a matrix A are denoted by $A^T$, $A^H$, $A^{-1}$ and $A^\dagger$ respectively. The XOR operation is denoted by $\oplus$. Furthermore $E[\cdot]$ denotes expectation and $C(x) \triangleq \log_2 (1 + x)$.

II. SIGNAL AND SYSTEM MODEL

We consider a hierarchical system consisting of two single-antenna MSs (nodes 1 and 2), two half-duplex single-antenna RNs (nodes 5 and 6), and an HBS with two directional antennas which are assumed to create two non-interfering channels (designated as nodes 3 and 4) as shown in Fig. 1. The MS and RN antennas are assumed to be omni-directional. The HBS and the MS nodes want to exchange messages via
the RN nodes; node 1 with node 3 and node 2 with node 4. Nodes 1 and 2 receive/cause interference from/to nodes 6 and 5 respectively. The wireless links between the HBS antennas and the RNs are defined as the backhaul network, while the links between the RNs and the MSs are defined as the access network. The wireless channels between any pair of nodes are assumed to experience flat fading. The channel coefficient between nodes $k$ and $n$ is

$$h_{k,n} = \Gamma_{k,n} \sqrt{\gamma_{k,n}}$$

where $\Gamma_{k,n}$ denotes the normalized fading coefficient and $\gamma_{k,n}$ denotes the average signal-to-noise ratio (SNR) of the link. Transmission is corrupted by unit variance zero-mean circularly symmetric additive white Gaussian noise (AWGN).

The MS and HBS nodes are assumed to be transmitting unit variance symbols grouped in vector $\mathbf{x} = [x_1, x_2, x_3, x_4]^T$. The RN nodes receive the signal vector $\mathbf{y}_R = [y_5, y_6]^T$. It should be noted that the elements of vectors $\mathbf{x}$ and $\mathbf{y}_R$ can be transmitted and received in different time slots depending on the employed cooperative protocol.

### III. DF with Network Coding

In this section we present a cooperative strategy and some communication protocols based on DF. The RNs decode the wanted signals treating the received interference as noise. The decoded symbols are combined with the use of the bitwise XOR operation and forwarded to the destination nodes. Communication can take place in two, three or four time slots. As the number of time slots grows, the impact of CCI on the attained performance becomes less significant. However increasing the number of slots incurs a pre-log penalty that limits the achievable capacity.

#### A. 2-slot DF-XOR

In the first time slot the HBS transmits the symbol vector $\mathbf{x}_B = [x_3, x_4]^T$ and the MSs transmit the symbol vector $\mathbf{x}_U = [x_1, x_2]^T$. Node 5 decodes symbols $x_1, x_3$ treating $h_{5,2}x_2$ as noise and node 6 decodes $x_2, x_4$ treating $h_{6,1}x_1$ as noise. In the second time slot nodes 5 and 6 transmit $x_5 = x_1 \oplus x_3$ and $x_6 = x_2 \oplus x_4$ respectively. Nodes 1 and 3 decode $x_5$ and retrieve the symbol $x_3$ and $x_1$ respectively. Similarly, nodes 2 and 4 decode $x_6$ and retrieve $x_4$ and $x_2$ respectively.

We define some rate expressions for the multiple access (MAC) phase of the first time slot in the following, which will be used as rate constraints later. $C_{15} = \frac{1}{2} C \left( \frac{|h_{5,1}|^2}{|h_{5,1}|^2 + 1} \right)$, $C_{35} = \frac{1}{2} C \left( \frac{|h_{5,2}|^2}{|h_{5,2}|^2 + 1} \right)$, $C_{M5} = \frac{1}{2} C \left( \frac{1}{|h_{5,1}|^2 + 1} \right)$, $C_{26} = \frac{1}{2} C \left( \frac{|h_{6,2}|^2}{|h_{6,2}|^2 + 1} \right)$, $C_{46} = \frac{1}{2} C \left( \frac{|h_{6,4}|^2}{|h_{6,4}|^2 + 1} \right)$ and $C_{M6} = \frac{1}{2} C \left( \frac{|h_{6,2}|^2 + |h_{6,4}|^2}{|h_{6,2}|^2 + |h_{6,4}|^2 + 1} \right)$. The rate expressions for the broadcast (BC) phase of the second time slot are defined as: $C_{53} = \frac{1}{2} C \left( |h_{3,5}|^2 \right)$, $C_{51} = \frac{1}{2} C \left( |h_{1,5}|^2 \right)$, $C_{62} = \frac{1}{2} C \left( |h_{6,2}|^2 \right)$ and $C_{64} = \frac{1}{2} C \left( |h_{4,6}|^2 \right)$.

#### B. 3-slot DF-XOR

According to this protocol, in the first time slot nodes 1 and 3 transmit symbols $x_1$ and $x_3$ respectively and RN 5 decodes them in the absence of CCI. In the second time slot nodes 2 and 4 transmit symbols $x_2$ and $x_4$ respectively and RN 6 decodes them also in the absence of CCI. In the third time slot nodes 5 and 6 transmit $x_5 = x_1 \oplus x_3$ and $x_6 = x_2 \oplus x_4$ respectively. Furthermore, nodes 1 and 3 decode $x_5$ and retrieve the symbol $x_3$ and $x_1$ respectively. Similarly, nodes 2 and 4 decode $x_6$ and retrieve $x_4$ and $x_2$ respectively. It should be noted that nodes 1 and 2 treat $h_{1,6}x_6$ and $h_{2,5}x_5$ as noise while decoding $x_3$ and $x_4$.

The rate expressions for the MAC phase of the 3-slot protocol are the following: $C_{15} = \frac{1}{2} C \left( |h_{5,1}|^2 \right)$, $C_{35} = \frac{1}{2} C \left( |h_{5,2}|^2 \right)$, $C_{M5} = \frac{1}{2} C \left( |h_{5,1}|^2 + |h_{5,2}|^2 \right)$, $C_{26} = \frac{1}{2} C \left( |h_{6,2}|^2 \right)$, $C_{46} = \frac{1}{2} C \left( |h_{6,4}|^2 \right)$ and $C_{M6} = \frac{1}{2} C \left( |h_{6,2}|^2 + |h_{6,4}|^2 \right)$. The rate expressions for the BC phase are defined as: $C_{53} = \frac{1}{2} C \left( |h_{3,5}|^2 \right)$, $C_{51} = \frac{1}{2} C \left( |h_{1,5}|^2 \right)$, $C_{62} = \frac{1}{2} C \left( |h_{6,2}|^2 \right)$ and $C_{64} = \frac{1}{2} C \left( |h_{4,6}|^2 \right)$.

#### C. 4-slot DF-XOR

The 4-slot protocol frees the system from CCI and serves as a performance benchmark. In the first time slot nodes 1 and 3 transmit symbols $x_1$ and $x_3$ respectively and RN 5 decodes them. In the second time slot node 5 transmits $x_5 = x_1 \oplus x_3$ and nodes 1 and 3 decode $x_5$ and retrieve symbols $x_3$ and $x_1$ respectively. Similarly, in the third time slot nodes 2 and 4 transmit symbols $x_2$ and $x_4$ respectively and RN 6 decodes them. In the fourth time slot node 6 transmits $x_6 = x_2 \oplus x_4$ and nodes 2 and 4 decode $x_6$ and retrieve symbols $x_2$ and $x_4$ respectively.

The rate expressions for the MAC phase of the 4-slot protocol are the following: $C_{15} = \frac{1}{2} C \left( |h_{5,1}|^2 \right)$, $C_{35} = \frac{1}{2} C \left( |h_{5,2}|^2 \right)$, $C_{M5} = \frac{1}{2} C \left( |h_{5,1}|^2 + |h_{5,2}|^2 \right)$.
Let $r = [R_1, R_3, R_2, R_4]^T$ be the vector containing the transmit rates of HBS and MS nodes. Let $b_1 = [C_51, C_35, C_3M, C_26, C_46, C_M6]^T$, $b_2 = [C_51, C_51, C_64, C_66]^T$ be the vectors containing the rate constraints of the MAC and BC phases respectively. The maximum sum-rate can be expressed as

$$ R_{DF} = \max_{k=1}^{4} R_k \quad \text{s.t.} \quad \begin{bmatrix} A & \mathbf{I} \end{bmatrix} \begin{bmatrix} r \end{bmatrix} \leq \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} $$

where $I$ is the identity matrix and

$$ A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix}. $$

### IV. AF with Network MIMO

In the present section it is proposed that AF relaying can be applied combined with Network MIMO in order to mitigate the effects of CCI. The proposed strategy can utilise two or three time slots.

#### A. 2-Slot AF

In the first slot MS and HBS nodes transmit their symbols, grouped in vector $x$, and the RNs receive the following signal vector

$$ y_R = H_R x + n_R $$

where $n_R$ is a vector of AWGN coefficients, $\mathbb{E} [n_R n_R^H] = I$, and

$$ H_R = \begin{bmatrix} h_{51} & h_{52} & h_{53} & 0 \\ h_{61} & h_{62} & 0 & h_{64} \end{bmatrix}. $$

Note that the zero elements in $H_R$ reflect the fact that the HBS antennas (nodes 5 and 6) are assumed not to interfere. In the second time slot both RNs transmit an amplified version of their received signal and the amplification factors take the following values for RN nodes 5 and 6

$$ \alpha_5 = \left( |h_{51}|^2 + |h_{52}|^2 + |h_{53}|^2 + 1 \right)^{-1/2}, $$

$$ \alpha_6 = \left( |h_{61}|^2 + |h_{62}|^2 + |h_{64}|^2 + 1 \right)^{-1/2}. $$

The MS and the HBS antennas receive the signal vectors $y_U = [y_1, y_2]^T$ and $\tilde{y}_B = [\tilde{y}_1, \tilde{y}_2]^T$ respectively, which can be expressed as

$$ y_U = H_U x + n_U $$

$$ \tilde{y}_B = H_B \tilde{x}_U + n_B $$

where $H_U = H_U x + n_U$, $n_B = H_B n_R + n_B$, and

$$ H_U = \begin{bmatrix} \alpha_5 h_{51} & \alpha_6 h_{51} \\ \alpha_5 h_{52} & \alpha_6 h_{52} \end{bmatrix}, $$

$$ H_B = \begin{bmatrix} \alpha_5 h_{53} & 0 \\ 0 & \alpha_6 h_{64} \end{bmatrix}. $$

The noise covariances are

$$ R_{n_U} = \text{diag} \left\{ \sum_{n=1}^{2} |H_U [1, n]|^2 + 1, \sum_{n=1}^{2} |H_U [2, n]|^2 + 1 \right\}, $$

$$ R_{n_B} = \text{diag} \left\{ |H_B [1, 1]|^2 + 1, |H_B [2, 2]|^2 + 1 \right\}. $$

As MS nodes are remote they can only process signals individually. Node 1 decodes the message of node 3 and node 2 that of node 4. For the 2-slot protocol the achievable rates for the transmission of nodes 3 and 4 are

$$ R_3 = \frac{1}{2} C \left( \frac{|H_U [1, 3]|^2}{|H_U [1, 3]|^2 + |H_U [2, 1]|^2 + |R_{n_U} [1, 1]|} \right), $$

$$ R_4 = \frac{1}{2} C \left( \frac{|H_U [2, 4]|^2}{|H_U [2, 4]|^2 + |H_U [1, 2]|^2 + |R_{n_U} [2, 2]|} \right). $$

Note that nodes 1 and 2 subtract self-interference $\tilde{H}_U [1, 1] x_1$ and $H_U [2, 4] x_2$ respectively. The HBS receives two signals from nodes 3 and 4 containing both $x_1$ and $x_2$, which are jointly processed. Let $H_B = [H_{B1} H_{B2}]$ where

$$ H_{B1} = \begin{bmatrix} \alpha_5 h_{53} h_{51} & \alpha_5 h_{53} h_{52} \\ \alpha_6 h_{53} h_{61} & \alpha_6 h_{53} h_{62} \end{bmatrix}, $$

$$ H_{B2} = \begin{bmatrix} \alpha_5 h_{53} h_{53} & 0 \\ 0 & \alpha_6 h_{64} h_{64} \end{bmatrix}. $$

The sub-matrix $H_{B2}$ represents self-interference for nodes 3 and 4 and therefore its effects can be cancelled. In consequence only $H_{B1}$ affects the achievable rate of nodes 1 and 2 whose signals are jointly decoded by nodes 3 and 4. We assume that $H_{B1}$ is fully known by the HBS. In the case of linear detection a beamforming matrix $W = [w_1, w_2]$, which is a function of $H_{B1}$ representing the global channel state information (CSI), is designed by the HBS and applied to the received signals. $w_1, w_2 \in \mathbb{C}^{2 \times 1}$ denote the beamforming vectors corresponding to the signals transmitted by nodes 1 and 2 respectively. The finally extracted signal can be expressed in vector form as

$$ y_B = W \tilde{y}_B = W H_{B1} x_U + W n_B $$

where $x_U = [x_1, x_2]^T$. Let $\tilde{H}_{B1} = [h_1, h_2]$ where $h_k$ corresponds to node $k$. The achievable rate for nodes $k = 1, 2$ is
The composite channel \( \tilde{H} \) is obtained through zero-forcing (ZF) or the Minimum Mean Square Error (MMSE) beamforming matrix. The corresponding factors \( \tilde{H}_k \) are given by (6). The composite channel \( \tilde{H} \) is as follows

\[
\tilde{H} = \begin{bmatrix} h_1, h_2 \end{bmatrix}
\]

and \( W_k \) is the first row of matrix \( W_k \). The beamforming vector \( W_k \) corresponds to nodes \( k \). The achievable sum-rate is

\[
R_{AF} = \sum_{k=1}^{4} R_k.
\]  

**B. 3-slot AF**

According to this protocol, in the first time slot MS and HBS nodes transmit their signals and the received signal by the RNs is given by (4). In the second time slot RN 5 transmits with the amplification factor \( \alpha_5 \) and RN 6 remains silent. The third time slot RN 6 transmits with the amplification factor \( \alpha_6 \) and RN 5 remains silent. The employed amplification factors are given by (6).

The received signals by the MSs and the HBS antennas (vectors \( \mathbf{y}_U \) and \( \mathbf{y}_B \) respectively), accumulated in the second and third time slot, are as in (7). It should be noted that \( H_k, H_U \) are in (5) and (8) respectively, where \( H_U \) is as follows

\[
H_U = \begin{bmatrix} \alpha_5 h_{1,5} & 0 \\ 0 & \alpha_6 h_{2,6} \end{bmatrix}.
\]

The achievable rates for the transmission of nodes 3 and 4 are

\[
R_3 = \frac{1}{3} C \left( \frac{\left| [H_U[1,3]] \right|^2}{\left| [H_U[1,2]]^T + [R_u]_{[1,1]} \right|^2} \right)
\]

\[
R_4 = \frac{1}{3} C \left( \frac{\left| [H_U[2,4]] \right|^2}{\left| [H_U[2,1]]^T + [R_u]_{[2,2]} \right|^2} \right).
\]

**V. Numerical Results**

For simplicity, we assume a symmetric interfering two-way relay channel: the wireless links of the access network, the backhaul network and the interfering links experience the same average SNR. When CCI becomes stronger, the performance of all schemes improves when the quality of backhaul links is improved further if it is performed in a successive manner. However, the detected symbols are subtracted from the remaining received signal. This frees the signal from some interference components and can enhance the achievable capacity. The composite channel \( \tilde{H} \) is ordered so that \( \| h_1 \| \leq \| h_2 \| \). The beamforming vector \( W_k \) corresponding to node \( k \) is the first row of matrix \( W_k \) for ZF and \( W_k = (\tilde{H}_k^H \tilde{H}_k + R_k)^{-1} \tilde{H}_k^H \) for MMSE, where \( \tilde{H}_k = [h_k, h_{k+1}]^T \). With successive interference cancellation (SIC), each node experiences only interference from nodes with higher index. This results in improved performance compared with linear detection. The achievable sum-rate is

\[
R_{AF} = \sum_{k=1}^{4} R_k.
\]
considered two general cooperative strategies, one based on DF with network coding and another based on AF with Network MIMO. We devised a number of cooperative pro-

tocols based on 2, 3 or 4 time slots and compared their performance as a function of the interference strength. It was shown that the 2-slot protocols perform generally better than the 3-slot and 4-slot ones. The DF-XOR scheme achieves superior performance when CCI is weak while the AF with Network MIMO performs better in the high CCI regime by turning CCI into an advantage. This is due to the fact that Network MIMO essentially exploits interference at the cost of requiring accurate CSI at the HBS.

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REFERENCES


