On the Maximum Achievable Sum-Rate of Interfering Two-Way Relay Channels

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***Abstract*—Hierarchical networks can provide very high data rates to multiple mobile stations (MSs) through a dense network of fixed relay nodes (RNs) fed by few hub base stations (HBSs). In order to achieve high spectral efficiencies RNs can act as two-way RNs. However the dense RN deployment gives rise to high co-channel interference (CCI) that limits sum-rate performance. In this letter we consider a simple hierarchical network consisting of an HBS with two highly directional antennas communicating with two MSs via two interfering two-way RNs. To mitigate CCI and boost sum-rates we propose a two-way relaying strategy based on AF combined with Network MIMO processing which is applied over the concatenation of the backhaul and access network channels. We compare our proposed strategy with a baseline DF approach and we show that it performs significantly better when CCI is dominant.**

***Index Terms*—Two-way relay channels (2WRCs), amplify-and-forward (AF), network coding (NC), Network MIMO, CoMP.**

I. Introduction

THE use of relay nodes (RNs) can admittedly bring significant gains to wireless networks [1], [2]. More specifically, RNs can be efficiently exploited under a hierarchical dual-hop system architecture, entailing that mobile stations (MSs) are served indirectly by a hub base station (HBS) via a dense network of fixed RNs [3]–[6]. High spectral efficiencies in such hierarchical network can be attained by full-duplex RNs which are hard to implement [7], or alternatively by half-duplex RNs that exploit the properties of two-way relay channels (2WRCs), a technique that has recently attracted a lot of attention [8]–[15]. This structure can effectively be considered in terms of a series of interfering two-way RNs.

The dense RN deployment of hierarchical networks results in high co-channel interference (CCI) which limits system performance. Therefore CCI needs to be efficiently addressed to make such systems practical. In [4] two-way RNs were introduced in the system level and their performance was optimized through resource allocation. In [5] an approach based on time sharing and amplify-and-forward (AF) relaying has been proposed for a dual-hop architecture with multiple MSs and RNs. The achievable performance of this approach is limited by the time-sharing constraint. In [12] a combined bi-directional relaying approach with interference alignment is presented for the case of a single multi-antenna BS and RN. The authors in [13] present linear precoding designs in a cellular two-way network assisted by a single multi-antenna RN. However the issue of maximizing sum-rate in a hierarchical two-way network with multiple single-antenna RNs and multiple MSs has not been addressed.

In this work we consider a simple hierarchical network consisting of an HBS with two highly directional antennas, two interfering two-way RNs and two MSs. Our aim is to maximize the average maximum sum rate (AMSR). To this end, we propose a cooperation scheme based on AF combined with Network MIMO processing. Network MIMO techniques, also known as coordinated multipoint (CoMP), are conventionally applied on the access network [16], [17]. In this letter we propose that Network MIMO techniques are applied over the concatenation of the access and backhaul network channels. We compare our proposed approach with a baseline scheme based on decode-and-forward (DF) relaying and network coding (NC) for which we formulate the capacity expressions under the presence of CCI. We show that our proposed AF scheme with Network MIMO greatly outperforms DF when CCI is dominant, although DF performs better when CCI is low.

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

II. Signal and System Model

We consider a system with 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 not to interfere[1] (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*

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[1] Any remanent interference may be removed by linear precoding/processing at the HBS.

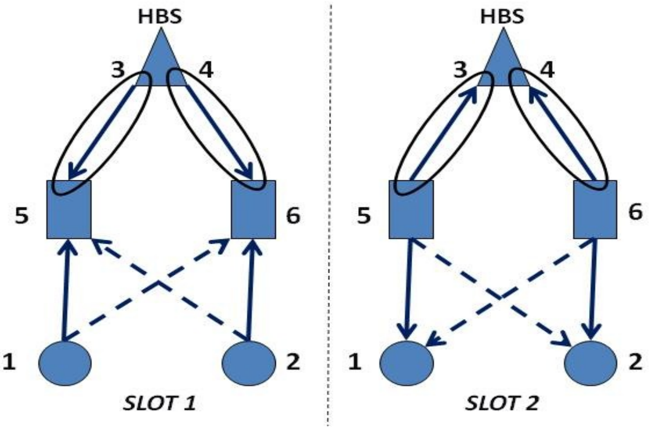

Fig. 1. The considered system scenario: an HBS with two directional antennas (nodes 3, 4), two MSs (nodes 1, 2), and two RNs (nodes 5, 6).

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. Let $h_{k,n} = \Gamma_{k,n}\sqrt{\bar{\gamma}_{k,n}}$ be the channel coefficient between nodes k and n, where $\Gamma_{k,n}$ denotes the normalized fading coefficient and $\bar{\gamma}_{k,n}$ 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).

Communication takes place in two time slots and it is assumed that there is no direct link between HBS and MSs; in the first slot the MS and HBS nodes transmit a vector of unit variance symbols $\mathbf{x} = [x_1, x_2, x_3, x_4]^T$ and the RN nodes receive the signal vector $\mathbf{y}_R = [y_5, y_6]^T$. In the second slot RNs either amplify the received signal or decode it, process it and forward it depending on the employed cooperative scheme.

III. COOPERATIVE SCHEMES FOR INTERFERING 2WRCS

In this section we introduce two cooperative schemes for the considered interfering 2WRCs. The first one is based on DF and network coding and is treated as a baseline approach. The second one is based on AF together with Network MIMO. The system maximum sum-rate for each of the cooperative schemes is derived.

A. DF with Network Coding

According to this baseline approach, during the first time slot the HBS and MS nodes transmit the symbol vectors $\mathbf{x}_B = [x_3, x_4]^T$ and $\mathbf{x}_U = [x_1, x_2]^T$ respectively. Node 5 decodes x_1, x_3 treating x_2 as noise and node 6 decodes x_2, x_4 treating 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. For this scheme we assume that the capacity-approaching binary forward error correction (FEC) codes are used according to the layered strategy described in [18].

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

Let $\mathbf{r} = [R_1, R_3, R_2, R_4]^T$ be the vector containing the transmit rates of HBS and MS nodes. Let $\mathbf{b}_1 = [C_{15}, C_{35}, C_{M5}, C_{26}, C_{46}, C_{M6}]^T$, $\mathbf{b}_2 = [C_{53}, C_{51}, C_{64}, C_{62}]^T$ be the vectors containing the rate constraints of the MAC and BC phases respectively. The maximum sum-rate with adaptive rate control can be expressed as

$$\begin{aligned} R_{DF} &= \max_{\mathbf{r}} \sum_{k=1}^{4} R_k \\ \text{s.t.} \quad & \mathbf{A}\,\mathbf{r} \le \mathbf{b}_1 \\ & \mathbf{I}\,\mathbf{r} \le \mathbf{b}_2 \end{aligned} \tag{1}$$

where $\mathbf{I}$ is the identity matrix and

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix}. \tag{2}$$

Problem (1) is a constrained linear optimization and thus R_{DF} can be obtained numerically using linear programming. The AMSR of this approach is $\mathbb{E}\left[R_{DF}\right]$, where expectation is taken over the channel realizations.

B. AF with Network MIMO

In order to maximize AMSR we propose an AF relaying scheme. We find below that this can be effectively combined with Network MIMO that is applied over the concatenation of the backhaul and access network channels. In the first slot the RNs receive the following signal vector

$$\mathbf{y}_R = \mathbf{H}_R\,\mathbf{x} + \mathbf{n}_R \tag{3}$$

where $\mathbf{n}_R$ is a vector of AWGN coefficients, $\mathbb{E}\left[\mathbf{n}_R\mathbf{n}_R^H\right] = \mathbf{I}$ and

$$\mathbf{H}_R = \begin{bmatrix} h_{5,1} & h_{5,2} & h_{5,3} & 0 \\ h_{6,1} & h_{6,2} & 0 & h_{6,4} \end{bmatrix}. \tag{4}$$

Note that the zero elements in $\mathbf{H}_R$ reflect the fact that the HBS antennas (nodes 3 and 4) are assumed not to interfere. In the second time slot the RNs transmit an amplified version of their received signal and the amplification factors take the following values for RN nodes 5 and 6, in order to guarantee that the power constraints of the RNs are met

$$\alpha_5 = \left[|h_{5,1}|^2 + |h_{5,2}|^2 + |h_{5,3}|^2 + 1\right]^{-1/2} \tag{5a}$$

$$\alpha_6 = \left[|h_{6,1}|^2 + |h_{6,2}|^2 + |h_{6,4}|^2 + 1\right]^{-1/2}. \tag{5b}$$

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

$$\mathbf{y}_U = \mathbf{H}_U\,\mathbf{H}_R\,\mathbf{x} + \mathbf{H}_U\,\mathbf{n}_R + \mathbf{n}_U = \tilde{\mathbf{H}}_U\,\mathbf{x} + \tilde{\mathbf{n}}_U \tag{6a}$$

$$\tilde{\mathbf{y}}_B = \mathbf{H}_B\,\mathbf{H}_R\,\mathbf{x} + \mathbf{H}_B\,\mathbf{n}_R + \mathbf{n}_B = \tilde{\mathbf{H}}_B\,\mathbf{x} + \tilde{\mathbf{n}}_B \tag{6b}$$

where $\tilde{\mathbf{H}}_U = \mathbf{H}_U\,\mathbf{H}_R$, $\tilde{\mathbf{H}}_B = \mathbf{H}_B\,\mathbf{H}_R$, $\tilde{\mathbf{n}}_U = \mathbf{H}_U\,\mathbf{n}_R + \mathbf{n}_U$, $\tilde{\mathbf{n}}_B = \mathbf{H}_B\,\mathbf{n}_R + \mathbf{n}_B$ and

$$\mathbf{H}_U = \begin{bmatrix} \alpha_5\,h_{1,5} & \alpha_6\,h_{1,6} \\ \alpha_5\,h_{2,5} & \alpha_6\,h_{2,6} \end{bmatrix} \tag{7a}$$

$$\mathbf{H}_B = \begin{bmatrix} \alpha_5\,h_{3,5} & 0 \\ 0 & \alpha_6\,h_{4,6} \end{bmatrix}. \tag{7b}$$

The noise covariance for the MS and the HBS nodes is

$$\mathbf{R}_{\tilde{n}_U} = \operatorname{diag}\left\{\sum_{n=1}^{2} |\mathbf{H}_U[1,n]|^2 + 1, \sum_{n=1}^{2} |\mathbf{H}_U[2,n]|^2 + 1\right\} \tag{8a}$$

$$\mathbf{R}_{\tilde{n}_B} = \operatorname{diag}\left\{|\mathbf{H}_B[1,1]|^2 + 1,\ |\mathbf{H}_B[2,2]|^2 + 1\right\}. \tag{8b}$$

As MSs are remote they can only process signals individually. Node 1 decodes the message of node 3 and node 2 that of node 4. Any capacity achieving modulation and coding schemes could be employed. The achievable rates for the transmission of nodes 3 and 4 are

$$R_3 = \frac{1}{2}C\left(\frac{\left|\tilde{\mathbf{H}}_U[1,3]\right|^2}{\left|\tilde{\mathbf{H}}_U[1,2]\right|^2 + \left|\tilde{\mathbf{H}}_U[1,4]\right|^2 + \mathbf{R}_{\tilde{n}_U}[1,1]}\right) \tag{9a}$$

$$R_4 = \frac{1}{2}C\left(\frac{\left|\tilde{\mathbf{H}}_U[2,4]\right|^2}{\left|\tilde{\mathbf{H}}_U[2,1]\right|^2 + \left|\tilde{\mathbf{H}}_U[2,3]\right|^2 + \mathbf{R}_{\tilde{n}_U}[2,2]}\right). \tag{9b}$$

Note that nodes 1 and 2 subtract self-interference $\tilde{\mathbf{H}}_U[1,1]\,x_1$ and $\tilde{\mathbf{H}}_U[2,4]\,x_2$ respectively.

HBS receives two signals from nodes 3 and 4 containing both x_1 and x_2, which are jointly processed. Let $\tilde{\mathbf{H}}_B = \left[\tilde{\mathbf{H}}_{B1}\,\tilde{\mathbf{H}}_{B2}\right]$ where

$$\tilde{\mathbf{H}}_{B1} = \begin{bmatrix} \alpha_5\,h_{3,5}\,h_{5,1} & \alpha_5\,h_{3,5}\,h_{5,2} \\ \alpha_6\,h_{4,6}\,h_{6,1} & \alpha_6\,h_{4,6}\,h_{6,2} \end{bmatrix} \tag{10a}$$

$$\tilde{\mathbf{H}}_{B2} = \begin{bmatrix} \alpha_5\,h_{3,5}\,h_{5,3} & 0 \\ 0 & \alpha_6\,h_{4,6}\,h_{6,4} \end{bmatrix}. \tag{10b}$$

The sub-matrix $\tilde{\mathbf{H}}_{B2}$ represents self-interference for nodes 3 and 4 and its effects are cancelled. In consequence only $\tilde{\mathbf{H}}_{B1}$ affects the achievable rate of nodes 1 and 2 whose signals are jointly decoded by nodes 3 and 4. We assume that $\tilde{\mathbf{H}}_{B1}$, representing the concatenation of the access and backhaul channels, is fully known by the HBS[2]. In the case of linear detection a beamforming matrix $\mathbf{W} = [\mathbf{w}_1, \mathbf{w}_2]$, which is a function of $\tilde{\mathbf{H}}_{B1}$, is designed by the HBS and applied to the received signals. $\mathbf{w}_1, \mathbf{w}_2 \in \mathbb{C}^{2\times 1}$ 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

$$\mathbf{y}_B = \mathbf{W}\,\tilde{\mathbf{y}}_B = \mathbf{W}\,\tilde{\mathbf{H}}_{B1}\,\mathbf{x}_U + \mathbf{W}\,\tilde{\mathbf{n}}_B \tag{11}$$

where $\mathbf{x}_U = [x_1, x_2]^T$. Let $\tilde{\mathbf{H}}_{B1} = [\mathbf{h}_1, \mathbf{h}_2]$ where $\mathbf{h}_k$ corresponds to node k. The achievable rate for nodes $k = 1, 2$ is

$$R_k = \frac{1}{2}C\left(\frac{\left|\mathbf{w}_k^T\,\mathbf{h}_k\right|^2}{\left|\mathbf{w}_k^T\,\mathbf{h}_{n,n\neq k}\right|^2 + \left\|\mathbf{w}_k^T\right\|^2 \mathbf{R}_{\tilde{n}_B}[k,k]}\right) \tag{12}$$

where factors $\left|\mathbf{w}_k^T\,\mathbf{h}_{n,n\neq k}\right|^2$ and $\left\|\mathbf{w}_k^T\right\|^2 \mathbf{R}_{\tilde{n}_B}[k,k]$ correspond to inter-node interference and noise enhancement respectively, which both have a detrimental effect.

We assume that the HBS obtains perfect concatenated backhaul and access CSI (matrix $\tilde{\mathbf{H}}_{B1}$) and acts as a Network MIMO central unit. The beamforming matrix can be based on Zero-Forcing (ZF), where $\mathbf{W} = \tilde{\mathbf{H}}_{B1}^{\dagger}$, maximal ratio combining (MRC), where $\mathbf{W} = \tilde{\mathbf{H}}_{B1}^{H}$ or Minimum Mean Square Error (MMSE), where $\mathbf{W} = \left(\tilde{\mathbf{H}}_{B1}^{H}\tilde{\mathbf{H}}_{B1} + \mathbf{R}_B\right)^{-1}\tilde{\mathbf{H}}_{B1}$. Detection can be improved further if it is performed successively, i.e., the detected symbols are subtracted from the remaining received signal. This frees the signal from some interference components and enhances the achieved capacity. The composite channel $\tilde{\mathbf{H}}_{B1} = [\mathbf{h}_1, \mathbf{h}_2]$ is ordered so that $\|\mathbf{h}_1\| \leq \|\mathbf{h}_2\|$. The beamforming vector $\mathbf{w}_k$ corresponding to node k is the first row of matrix $\mathbf{W}_k = \hat{\mathbf{H}}_k^{\dagger}$ for ZF, $\mathbf{W}_k = \hat{\mathbf{H}}_k^{H}$ for MRC and $\mathbf{W}_k = \left(\hat{\mathbf{H}}_k^{H}\,\hat{\mathbf{H}}_k + \mathbf{R}_B\right)^{-1}\hat{\mathbf{H}}_k^{H}$ for MMSE, where

$$\hat{\mathbf{H}}_k = [\mathbf{h}_k, \mathbf{h}_{k+1}]^T. \tag{13}$$

With successive interference cancellation (SIC), each node expreriences only interference from nodes with higher index. The achievable sum-rate is

$$R_{AF} = \sum_{k=1}^{4} R_k. \tag{14}$$

The AMSR of this approach is $\mathbb{E}[R_{AF}]$, where expectation is taken over the channel realizations.

IV. NUMERICAL RESULTS AND DISCUSSION

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, i.e., $\bar{\gamma}_{1,5} = \bar{\gamma}_{5,1} = \bar{\gamma}_{2,6} = \bar{\gamma}_{6,2} = \bar{\gamma}_{AC}$, $\bar{\gamma}_{5,3} = \bar{\gamma}_{3,5} = \bar{\gamma}_{4,6} = \bar{\gamma}_{6,4} = \bar{\gamma}_{BH}$, and $\bar{\gamma}_{5,2} = \bar{\gamma}_{2,5} = \bar{\gamma}_{1,6} = \bar{\gamma}_{6,1} = \bar{\gamma}_{I}$.

Fig. 2 plots the total AMSR versus the average SNR $\bar{\gamma}_I$ for the considered schemes when backhaul and access networks experience identical average SNR $\bar{\gamma}_{BH} = \bar{\gamma}_{AC} = 10\,\mathrm{dB}$ and Rayleigh fading. It is shown that in the low CCI regime ($\bar{\gamma}_I < 0\,\mathrm{dB}$) the baseline DF-NC approach performs better. When

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[2] This concatenated channel can be estimated end-to-end using pilot symbols transmitted by the MS.

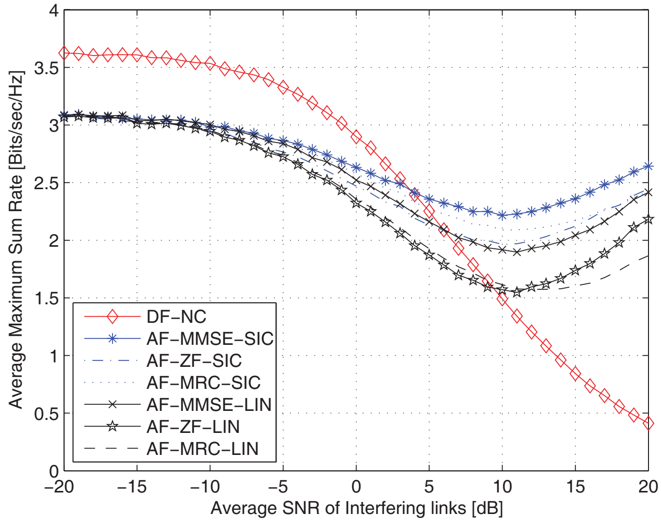

Fig. 2. The AMSR versus $\bar{\gamma}_I$ when $\bar{\gamma}_{BH} = \bar{\gamma}_{AC} = 10\,\mathrm{dB}$.

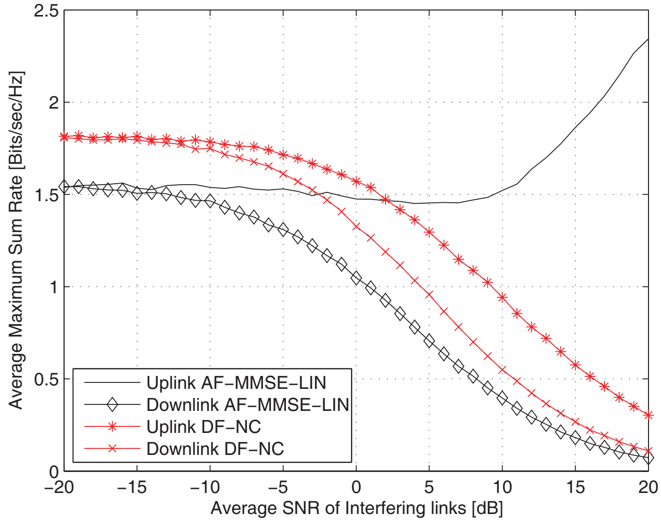

Fig. 3. The AMSR of the uplink and downlink of DF-XOR and AF-MMSE-LIN versus $\bar{\gamma}_I$ when $\bar{\gamma}_{BH} = \bar{\gamma}_{AC} = 10\,\mathrm{dB}$.

CCI becomes dominant, our proposed AF schemes perform better as they effectively exploit CCI through Network MIMO processing applied over the concatenation of the backhaul and access network channels. Amongst the proposed AF schemes, those based on SIC are superior. The best performance is achieved by the scheme based on MMSE, as expected.

Fig. 3 plots the AMSR for the downlink and uplink separately, for the DF-NC and the proposed AF-MMSE-LIN. Uplink rate is generally higher as the directional HBS antennas eliminate CCI in the second time slot. The AMSR deteriorates when CCI becomes stronger for all cases apart from the uplink of the AF scheme. The AMSR for the uplink of AF improves as $\bar{\gamma}_I$ increases because the HBS jointly processes the received signals by nodes 3 and 4 using Network MIMO techniques.

V. CONCLUSIONS

In this letter we addressed the issue of CCI in a promising dual-hop hierarchical network architecture employing two-way RNs. We proposed an AF scheme combined with Network MIMO processing applied over the concatenation of the access and backhaul network channels. We compared our proposed approach with a baseline scheme based on DF relaying and network coding, for which we formulated the capacity expressions under the presence of CCI. We showed that the proposed AF scheme combined with Network MIMO greatly outperforms DF when CCI is dominant, although DF performs better when CCI is low.

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