COMPRESS-AND-FORWARD COOPERATIVE RELAYING IN MIMO-OFDM SYSTEMS

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ABSTRACT

In this paper, we investigate the capacity of Compress-and-Forward (C&F) cooperative relaying scheme when the C&F relay operates in Time Division Duplex (TDD). In our evaluation we consider MIMO-OFDM transmission. An achievable rate was previously derived in [6] assuming scalar channel. We extend this Wyner-Ziv bound to MIMO-OFDM, by applying results from Bayesian vector estimation and rate-distortion coding theory. Then we derive the mutual information of a sub-optimum relaying scheme in which the relay applies Karhunen-Loeve transform to the signal received from the source before quantizing it and forwarding it to the destination as a new codeword. Finally, we illustrate by simulations (in an environment similar to IEEE802.16) the fact that for some scenarios, the C&F approach outperforms other known relaying techniques. This remains true even if the C&F sub-optimum scheme is considered.

1. INTRODUCTION

Recent wireless standardization efforts such as IEEE 802.16-2005 and 802.11n support a physical layer which combines the benefits of Coded Orthogonal Frequency Division Multiplexing (C-OFDM) and multiple antenna transmission. In these systems, the constellation, code rate and space-time coding technique (e.g. Space-Time Block Coding (STBC) or Spatial Division Multiplexing (SDM)), are dynamically selected in order to operate as close as possible to MIMO-OFDM channel capacity under QoS constraints [1]. In addition to physical layer features, several standardization groups like 802.11s and 802.16j work mainly on protocol aspects allowing multi-hop transmissions by introducing one or several relays between the source and destination. It is therefore of practical interest to investigate the capacity of MIMO-OFDM relaying schemes.

In conventional relaying, the signal goes through a single multi-hop path formed by relays between the source and destination. A distinction is commonly made between non-regenerative and regenerative relays. An example of the former is Amplify and Forward (A&F)[2], in which the relay amplifies the observed signal at its input before transmitting it to the destination. Regenerative relays decode the information before forwarding it to the destination, hence the name Decode and Forward (D&F).

Cooperative relaying, either regenerative or non-regenerative, is a promising approach for further increasing the capacity and range. In this scheme, the destination combines the signals received from the source and relay [3]. In the rest of this paper, we will always assume implicitly that relaying is cooperative, and will otherwise explicitly write "conventional relaying". This paper focusses on a non-regenerative type of relaying called Compress-and-Forward (C&F) (a.k.a. Quantize-and-Forward Q&F). This technique originates from Cover and El Gamal [4, theorem 6]. Roughly speaking, the principle is that the relay quantizes the signal it received from the source and encodes the samples into a new packet which is forwarded to the destination, so that the latter can combine the two observations. The relay and destination exploit the correlation between the observations at the relay and destination. More precisely, the relay employs source coding with side information at the destination (Wyner-Ziv coding [5]). Recent work ([6] and [7]) showed that the achievable rate of D&F is higher when the relay is close to the source, but C&F approaches the max-flow min-cut upper-bound on capacity as the relay gets closer to the destination.

In this paper we investigate how the capacity theorems provided in [6] and [7] can be applied to an OFDM physical layer with SDM, when the relay operates in TDD mode. After modeling the problem in section 2, we derive in section 3 an upper-bound on C&F mutual information when the relay employs Wyner-Ziv coding. The use of a practical implementation of the latter in C&F relaying has been addressed only very recently [14] for gaussian scalar channel using LDPC and nested scalar quantizer. It requires a careful selection of codes depending on the Channel State Information (CSI) on all links. As a sub-optimum alternative to Wyner-Ziv coding, we propose in section 4 a scheme in which the relay applies Karhunen-

Loeve transform to the input signal followed by a Lloyd-Max scalar quantization of each output. Finally, we illustrate the performance of this scheme in scenarios of practical interest, with typical 802.16-like assumptions, and compare it to the upper-bound of section 3 as well as to other well-known schemes.

2. MUTUAL INFORMATION OF TDD C&F RELAYING WITH MIMO-OFDM TRANSMISSION

In this paper, we consider a Source S, a Relay R and a destination D with respectively N_S, N_R, and N_D antennas, and we compute an upper-bound on the mutual information between S and D when OFDM combined with spatial multiplexing is the transmission technique, and the relay uses Wyner-Ziv coding or a sub-optimum source coding technique. The number of non-zero OFDM subcarriers is denoted by N_C. The FFT size is N_F and the bandwidth is approximately $B \approx N_C/(N_F T)$ where $1/T$ is the sampling rate. We neglect the overhead of the pilot symbols, but take into account the cyclic prefix of N_{CP} samples, leading to a total OFDM symbol duration $T_S = (N_{FFT} + N_{CP})T$.

We consider half-duplex (more precisely TDD) relay, because full-duplex operation presents some practical difficulties. A two-phase time-sharing protocol is assumed in which the source transmits during the first phase of duration t, with $0 \le t \le 1$ and the relay transmits during second phase of duration $1\text{-}t$. Note that this assumption differs from [6] which allows S to transmit during the second phase.

The frequency-domain OFDM symbols received at R and D during the first phase have the following expression:

$$\mathbf{y}_{S-R} = \mathbf{H}_{S-R}\mathbf{x}_S + \mathbf{n}_R \text{ and } \mathbf{y}_{S-D} = \mathbf{H}_{S-D}\mathbf{x}_S + \mathbf{n}_D \quad (1)$$

where $\mathbf{H}_{S-R}$ is the complex channel gain matrix of size $N_C N_R \times N_C N_S$. We assume circularly symmetric complex gaussian noise of covariance $\mathbf{R}_{n,R} = \sigma_{n,R}^2 \mathbf{I}_{N_C N_R}$. The channel is assumed constant over a codeword, i.e. non-ergodic, and perfectly estimated by the receiver. We also assume that S and R transmit covariance matrices are equal to $\mathbf{R}_{x_S} = (P_S / N_S)\mathbf{I}_{N_C N_S}$ and $\mathbf{R}_{x_R} = (P_R / N_R)\mathbf{I}_{N_C N_R}$ respectively. Clearly, isotropic transmission is not optimum. For instance, if R knows the second-hop channel, it can do bit and power loading per channel eigenmode to maximize mutual information on this link, ultimately increasing mutual information of the cooperative link. However, the joint optimization of transmit covariance at S and R is a non-trivial problem left for future study.

The mutual information of a single-hop link, for instance the R-D link, was computed by [8], writing $\mathbf{H}_{R-D}$ as a block-diagonal matrix of N_C blocks $\mathbf{H}_{R-D} = \text{diag}\{\mathbf{H}_{R-D}^k\}_{k=1}^{N_C}$ where $\mathbf{H}_{R-D}^k$ denotes the $N_D \times N_R$ MIMO channel matrix on the kth OFDM sub-carrier:

$$\text{I}(\mathbf{x}_R;\mathbf{y}_{R-D}) = \sum_{k=1}^{N_C} \log_2 \left| I_{N_D} + \frac{P_R}{N_R \sigma_{n,D}^2} \mathbf{H}_{R-D}^k \left(\mathbf{H}_{R-D}^k\right)^H \right| \quad (2)$$

The mutual information (in bit/s) equals:

$$I_{R\text{-}D} = \frac{1-t}{T_S}\text{I}(\mathbf{x}_R;\mathbf{y}_{R-D}) \quad (3)$$

The relay observes $\mathbf{y}_{S-R}$ and wants to transmit an estimate $\hat{\mathbf{y}}_{S-R}$ to the destination using at most $\text{M}(t) \triangleq (1\text{-}t)\text{I}(\mathbf{x}_R;\mathbf{y}_{R-D})$ error-free bits.

The squared distortion on the reconstructed signal at the destination is $d = \|\mathbf{y}_{S-R} - \hat{\mathbf{y}}_{S-R}\|^2$. Ultimately, we would like to maximize the mutual information between S and D:

$$I_{S-D} = \frac{t}{T_S}\text{I}(\mathbf{x}_S;\hat{\mathbf{y}}_{S-R},\mathbf{y}_{S-D}) \quad (4)$$

The latter can be obtained by stacking the two observations available to the destination at the end of the second phase, forming a virtual MIMO channel between N_S transmit antennas and N_R+N_D receive antennas:

$$\begin{bmatrix} \hat{\mathbf{y}}_{S-R} \\ \mathbf{y}_{S-D} \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{H}_{S-R} \\ \mathbf{H}_{S-D} \end{bmatrix}}_{\mathbf{H}_{coop}} \mathbf{x}_S + \underbrace{\begin{bmatrix} \boldsymbol{\eta}_{S-R} \\ \mathbf{n}_{S-D} \end{bmatrix}}_{\mathbf{n}_{coop}} \quad (5)$$

with $\boldsymbol{\eta}_{S-R}$ a noise plus distortion vector defined by the above equation.

From (3), (4) and (5), we see that the maximization of mutual information $I_{S\text{-}D}$ results from a trade-off between increasing t in order to exploit the virtual MIMO channel for a duration as long as possible, and reducing t to increase $I_{R\text{-}D}$ and M(t), thus enabling a reduction of the distortion in (5). In order to quantify this trade-off, we need to compute the covariance of the noise plus distortion vector $\boldsymbol{\eta}_{S-R}$ for a given value of M(t_0), which is the purpose of next section.

3. UPPER BOUND ON MUTUAL INFORMATION WITH WYNER-ZIV CODING

In this section, we assume that the relay can exploit the fact that the destination has already observed $\mathbf{y}_{S-D}$ during first phase, to reduce the number of bits M required for a given total squared distortion d. The source coding problem with side information at the decoder was addressed by Wyner in [5]. He computed the rate-distortion function when side information is available to both source and decoder. Clearly, for a given squared distortion d, the rate at which the source can be encoded is lower than with side information at the decoder only. However, Wyner showed that the rates are actually equal if source and side information are jointly gaussian. In that case, side information at the source does not allow a further rate reduction.

We proceed as in [5], lower-bounding M by the rate required when side information is available to both source and decoder. Here the source $\mathbf{y}_{S-R}$ is located in R and the decoder is in D. Assuming that side information $\mathbf{y}_{S-D}$ is also available at R is not realistic and not required by Wyner-Ziv coding, but it allows to lower-bound M as described below. Since M is proportional to the duration $1-t$ of the second phase, a lower-bound on M entails an upper-bound on t and eventually an upper bound on the mutual information I_{S-D}. First, assuming that vector $\mathbf{x}_S$ is circularly symmetric complex Gaussian of zero mean, as a result of lemma 3 and 4 of [9], $\mathbf{y}_{S-R}$ and $\mathbf{y}_{S-D}$ are also circularly symmetric complex Gaussian variables of zero-mean and respective covariance matrices:

$$\mathbf{R}_{\mathbf{y}_{S-R}} = \mathbf{H}_{S-R}\mathbf{R}_{\mathbf{x}_s}\mathbf{H}_{S-R}^H + \mathbf{R}_{\mathbf{n},S-R} \tag{6}$$

$$\mathbf{R}_{\mathbf{y}_{S-D}} = \mathbf{H}_{S-D}\mathbf{R}_{\mathbf{x}_s}\mathbf{H}_{S-D}^H + \mathbf{R}_{\mathbf{n},S-D} \tag{7}$$

Their cross-correlation matrix equals:

$$\mathbf{R}_{\mathbf{y}_{S-D},\mathbf{y}_{S-R}} = \mathbf{H}_{S-D}\mathbf{R}_{\mathbf{x}_s}\mathbf{H}_{S-R}^H \tag{8}$$

Like Wyner in [5], let assume that the relay computes the Bayesian estimate of its observation $\mathbf{y}_{S-R}$ given the knowledge of the destination observation $\mathbf{y}_{S-D}$. Thus, let define the vector $\mathbf{z}$ of distribution $p\left(\mathbf{y}_{S-R}\middle|\mathbf{y}_{S-D}\right)$. This vector is also complex gaussian with mean and covariance given by [10]:

$$\mathbf{m}_{\mathbf{z}}\left(\mathbf{y}_o\right) \triangleq E\left\{\mathbf{y}_{S-R}\middle|\mathbf{y}_{S-D} = \mathbf{y}_o\right\} = \mathbf{R}_{\mathbf{y}_{S-R},\mathbf{y}_{S-D}}\mathbf{R}_{\mathbf{y}_{S-D}}^{-1}\mathbf{y}_o \tag{9}$$

and

$$\begin{aligned}\mathbf{R}_{\mathbf{z}} &\triangleq E\left\{\left(\mathbf{z}-\mathbf{m}_{\mathbf{z}}\left(\mathbf{y}_o\right)\right)\left(\mathbf{z}-\mathbf{m}_{\mathbf{z}}\left(\mathbf{y}_o\right)\right)^H\right\} = \\ &= \mathbf{R}_{\mathbf{y}_{S-R}} - \mathbf{R}_{\mathbf{y}_{S-R},\mathbf{y}_{S-D}}\mathbf{R}_{\mathbf{y}_{S-D}}^{-1}\mathbf{R}_{\mathbf{y}_{S-D},\mathbf{y}_{S-R}}\end{aligned} \tag{10}$$

Since we are interested in a lower-bound on the rate, we assume the relay can achieve rate-distortion function when coding vector $\mathbf{z}-\mathbf{m}_{\mathbf{Z}}(\mathbf{y}_0)$. It is well known that the minimum distortion for source coding of a real Gaussian vector is achieved by reverse water-filling [11] on the eigenvalues of its covariance matrix. Here the vector to encode is complex, so one could think of stacking real and imaginary parts and perform reverse water-filling with total squared distortion d over $2N_CN_R$ eigenvalues. However, using properties of circularly symmetric complex gaussian vectors [9], it can be checked that the rate can also be obtained by reverse water-filling with same value of d over the N_CN_R eigenvalues of $\mathbf{R}_{\mathbf{z}}$, and multiplying the rate obtained by 2.

Note that since we assumed $\mathbf{R}_{\mathbf{x}_S}$ was diagonal, the covariance matrices defined previously are all block-diagonal. This enables to diagonalize $\mathbf{R}_{\mathbf{z}}$ as:

$$\mathbf{R}_z = \operatorname{diag}\left\{\mathbf{U}_k\mathbf{S}_k\mathbf{U}_k^H\right\}_{k=1}^{N_C} \text{ with } \mathbf{S}_k \triangleq \operatorname{diag}\left\{\sigma_{k,l}^2\right\}, 1 \le l \le N_R$$

The reverse water-filling algorithm is applied to all the eigenvalues of $\mathbf{R}_{\mathbf{z}}$. The number of bits required to represent $\mathbf{z}-\mathbf{m}_{\mathbf{Z}}(\mathbf{y}_0)$ with a total distortion d thus equals:

$$r(d) = \sum_{k=1,l=1}^{k=N_C,l=N_R} \log\left(\frac{\sigma_{k,l}^2}{d_{k,l}}\right) \tag{11}$$

where $d_{k,l} = \begin{cases} \lambda & \text{if} \quad \lambda < \sigma_{k,l}^2 \\ \sigma_{k,l}^2 & \text{if} \quad \lambda \ge \sigma_{k,l}^2 \end{cases}$ and λ is a constant computed such that $\sum_{k=1,l=1}^{k=N_C,l=N_R} d_{k,l} = d$.

The vector actually quantized is $\mathbf{U}^H\left(\mathbf{z}-\mathbf{m}_{\mathbf{Z}}(\mathbf{y}_0)\right)$. Assuming that the distortion on this vector is complex AWGN, the noise plus distortion vector $\boldsymbol{\eta}_{S-R}$ defined by (5) has a block diagonal covariance matrix with the kth block affecting the kth OFDM sub-carrier and equal to:

$$\mathbf{R}_{\eta,S-R}^k = \sigma_{n,R}^2\mathbf{I}_{\mathrm{N_R}} + \mathbf{U}_{\mathrm{k}}\operatorname{diag}\left(\mathrm{d}_{\mathrm{k},1}, d_{k,2}, \ldots, d_{k,N_R}\right)\mathbf{U}_k^H \tag{12}$$

Finally, an upper-bound on mutual information is found from (5) and (12) by maximizing w.r.t. time sharing:

$$I_{S-D} \le \max_t \frac{t}{T_S}\sum_{k=1}^{N_C}\log_2\left|\mathbf{I}_{N_D+N_R} + \frac{P_S}{N_S}\mathbf{H}_{coop}^k\left(\mathbf{H}_{coop}^k\right)^H\left(\mathbf{R}_{n,coop}^k\right)^{-1}\right| \tag{13}$$

Note that the conditions of equality in (13), and the assumptions under which Wyner-Ziv coding might reach the bound, are left for future work. Also note that the optimization of the time-sharing variable requires the knowledge of Channel State Information on the three links S-R, R-D and S-D. Now that an upper-bound has been derived, it would be of interest to evaluate how far from the bound a system can operate if it employs source coding without side information and scalar quantization. Next section attempts to address these questions.

4. A SUB-OPTIMUM QUANTIZATION SCHEME

In the previous section, we computed an upper-bound on the mutual information between source and destination when the relay employs Wyner-Ziv coding, exploiting the correlation of observations on S-R and S-D links. If this correlation is not exploited, then it is still possible to quantize the observation at the relay. Let assume we apply the Karhunen-Loeve transform to the FFT output at the relay before quantization. The Karhunen-Loeve matrix is formed by the eigenvectors of the covariance matrix of the relay observation and is well known [12] to be the linear transform that minimizes squared distortion. By definition, the $N_c N_R$ components of output vector $\mathbf{u}$ are uncorrelated with variance

$$s_{k,l} = \lambda_{k,l}^2 \frac{P_S}{N_S} + \sigma_{n,R}^2 \qquad 1 \le k \le N_c; 1 \le l \le N_R \tag{14}$$

where the $\lambda_{k,l}^2$ are eigenvalues of $\mathbf{H}_{S-R}^k \left(\mathbf{H}_{S-R}^k\right)^H$.

The complex output $u_{k,l}$ is quantized with $2m_{k,l}$ bits. Assuming gaussian $u_{k,j}$ and Lloyd-Max quantizer, the average squared distortion is [12]:

$$d_{k,l} = \frac{\sqrt{3}}{2} \pi \frac{s_{k,l}}{2^{2m_{k,l}}} \tag{15}$$

Let assume we want to minimize the squared distortion $d = \sum_{k,l} d_{k,l}$ w.r.t. the $N_c N_R$ variables $m_{k,l}$ with a constraint on the total number of bits $m_T = \sum_{k,l} m_{k,l}$ and with the additional constraint that all $m_{k,l}$ are positive. This problem is a standard convex optimization problem. The Karush-Kuhn-Tucker conditions give the solution:

$$m_{k,l} = \left(\frac{1}{2}\log_2\left(s_{k,l}\right) - \alpha\right)^+ \tag{16}$$

where α is a constant such that the total number of bits equals m_T. It can be solved by an iterative algorithm similar to water-filling. Note that in order to get an integer number of bits per quantized $u_{k,l}$, we decided in our simulations to round $m_{k,l}$ to the nearest integer. This leads to slightly different values for m_T and time sharing variable t than the initial target.

Finally, the noise plus distortion covariance matrix can be computed as in (12), and the mutual information can be obtained as in (13) by maximization over time share t. Of course, since side information at D is not exploited, the mutual information will be lower than with Wyner-Ziv coding, and a fortiori lower than the upper-bound (13). It remains to quantify this capacity reduction in a practical scenario.

5. SIMULATION RESULTS

We simulated under various channel models the mutual information of the sub-optimum Karhunen-Loeve scheme, compared to the upper-bound and to various existing cooperative schemes. The context is a wireless cellular system similar to IEEE802.16. An operator deploys one Base Station (BS) per cell, with sectored antennas. We assume that each sector has 4 antenna elements. Moreover, a Relay Station (RS) is deployed in each cell sector, in order to improve coverage/capacity. This RS can be mounted on a rooftop or lamp pole. It also has 4 antenna elements and may even be equipped with directional antenna pointed towards the BS. It transmits at higher power than Mobile Terminals (MT), which are equipped with 2 antennas. Therefore, the capacity of the BS-RS link is much higher than that of the BS-MT and RS-MT links. We know that when the link between the source and the relay has much higher capacity than other links, cooperative D&F with uncorrelated codewords outperforms other schemes [2]. This corresponds to the downlink of the cellular system we just described. Therefore, we will focus on the uplink: we assume an average SNR equal to 0dB on the S-D and S-R links, and 30 dB on the R-D link. This occurs for instance when the MT is located in a shadowed area, having a bad link with both BS and RS. Before simulating a MIMO-OFDM system, we first monitor the outage mutual information of a MIMO system in Rayleigh channel, i.e. with no spatial correlation. On Figure 1, we plotted the cumulative density function of the mutual information for various schemes including "no relaying", which means direct transmission between S and D, conventional and cooperative D&F relaying, cooperative A&F, plus the Karhunen-Loeve Q&F technique of section 3 and the Wyner-Ziv upper-bound of section 2. We also plotted for comparison an upper-bound on capacity which is the $N_S \times (N_R + N_D) = 2\times 8$ "virtual" MIMO channel, that can be approached if the second phase duration tends to zero while distortion is maintained at a level much lower than noise. It can be observed that at 10% outage probability, the Karhunen-Loeve Q&F (solid black curve) outperforms other techniques, increasing by about 25% the outage mutual information. This represents more than half of the gain achievable with Wyner-Ziv C&F, as indicated by its upper-bound (dashed black curve). The remaining gap between Wyner-Ziv C&F and virtual MIMO (dotted black curve) could be reduced by making the ratio between the capacity of the 4x4 R-D link and the capacity of other links even larger. This phenomenon could be observed for instance if the source had a single antenna.

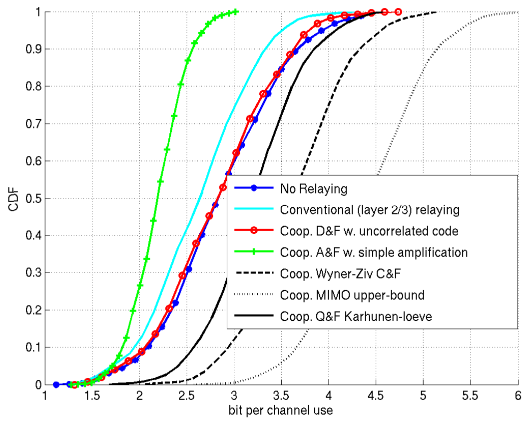

Figure 1: Outage Mutual Information of various cooperative relaying schemes in a Rayleigh MIMO 2x4x4 configuration

Also note that A&F yields about half the virtual MIMO mutual information. This is due to the fact that the R-D time slot has the same duration as the S-R slot, in effect dividing capacity by 2. As shown in [2], re-use of the R-D slot in cellular systems may significantly improve A&F capacity, but in this paper we focused on a single link and thus re-use cannot be assumed.

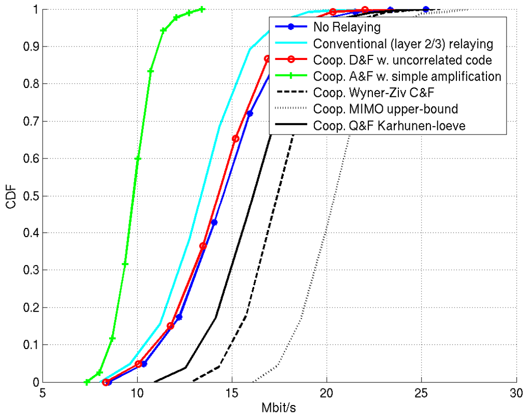

Figure 2: Outage Mutual Information of various cooperative relaying schemes in a MIMO-OFDM 2x4x4 configuration, urban micro-cell channel, 256 subcarriers

We now simulate on Figure 2 a MIMO-OFDM system with 10 MHz channel spacing, 192 data subcarriers and an FFT size of 256. The cyclic prefix represents 1/8 of the OFDM symbol duration. The propagation conditions correspond to a multipath Non Line Of Sight (NLOS) Urban micro-cell channel model valid between 2GHz and 5GHz, as described in [13]. The rest of the assumptions are similar to those of Figure 1. The outage probability depends on the number of paths of the impulse response and the angular spread of each path [8]. It turns out that roughly the same relative performance gains as on Figure 1 can be obtained with C&F compared to other relaying techniques. Thus, the C&F relaying approach presents an interest for future cellular systems based on MIMO-OFDM.

6. CONCLUSIONS AND FUTURE WORK

We have derived an upper-bound on the mutual information of cooperative MIMO-OFDM C&F relaying when Wyner-Ziv coding is employed. We have also quantified how much degradation is undergone when source coding at the relay does not exploit side information at the destination. Finally, we have checked that cooperative C&F relaying presents a practical interest in the uplink of Beyond-3G MIMO-OFDM systems. Several aspects of this work deserve more investigation. One of them is the exploitation of channel state information to optimize transmit covariance matrices. Another interesting topic for future work is the extension of capacity considerations from the link level to the network level.

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