Optimal Communication with Multi-Antenna, Multi-Group and Multi-Way Relaying

Frank Banaseka Kataka
Lecturer
Data Link Institute
katakabanaseka@yahoo.com

Benuwa, Ben-Bright
Lecturer
Data Link Institute
benuwa778@gmail.com

ABSTRACT: *Relying on the broadcast nature of the wireless media, a relay assisted communication system emulates a virtual Multiple Input Multiple Output (MIMO) system and exploits diversity techniques to increase the transmission reliability and coverage, without expanding the expenditure of the scarce transmission resources. A multi-group multi-way relaying scenario is considered. Each node has to transmit an individual message and has to receive the messages of all other nodes within its group. These multi-way communications between the multi-antenna nodes are performed via an intermediate multi-antenna relay station. Self as well as known-interference cancellations are exploited at the nodes and are considered for the application of the relay transceiver filter. Furthermore, to achieve high spectral efficiency, a transmission strategy which exploits the ideas of network coding is proposed. The proposed transmission strategy combined with the applied relay transceiver filter requires less antennas at the relay station and achieves higher sum rates compared to conventional approaches which do not fully exploit the interference cancellation capabilities of the nodes.*

I.   INTRODUCTION

Wireless communication has seen an incredibly fast advancement and has become vital to modern society. Today, mobile phones have turned into an important business and social communication tool. Wireless local area networks are replacing wired Ethernet in homes, campuses, hotels and airports. Continuous efforts have been devoted to enhancing the designs of wireless communication systems in order to accommodate coverage, communication reliability and high data rate services to various applications. Current radio Frequency (RF) device's technology does not allow adding multiple antennas that are sufficiently spaced, to a mobile device without increasing the size and/or cost of the device.

One-way relay assisted communication, also known as cooperative communication, has been considered recently [10] and [8] as a promising approach to increase the wireless transmission reliability (via

Invoking spatial diversity gain) without the need for adding multiple antennas to a mobile device. In [12], non-regenerative multi-antenna two-way relaying in a single-pair scenario is investigated and a minimum mean square error (MMSE) relay transceiver filter exploiting self-interference cancellation is derived. Non-regenerative multi-pair two-way relaying with single-antenna nodes and a multi-antenna relay station has been considered in [14] [2] and [11]. The design of network codes for multi-user multi-hop networks has been investigated in [13] and references therein.

Considering multi-antenna nodes and exploiting the multiplexing gain increases the achievable sum rates. The authors of [9] [3] investigated a pairwise communication of multi-antenna nodes via an intermediate multi-antenna relay as shown in figure 1 below. Applications such as video conferences or multiplayer gaming as well as emerging applications usually require the data exchange between multiple nodes. If each node of a group wants to share its data with all other nodes within its group, multi-way communications can be performed [4] and [6] to enable spectrally efficient transmissions.

To support multiple multi-way communications via an intermediate half duplex relay station, multi-antenna techniques can be used to spatially separate the communication groups and to enable the simultaneous communication of all nodes. In [6], the full-duplex multi-group multi-way relay channel is investigated. Non-regenerative multi-way relaying via a half-duplex multi-antenna relay station for a single group as well as for a multi-group scenario is considered in [4] and [1], respectively. However, multiple antennas at the nodes are not considered to further increase the sum rate and the proposed transmission schemes do not fully exploit network coding. A key characteristic of wireless channels that makes wireless communications different and challenging compared with wired communications is

the fading phenomenon caused by the multi-path effect.

Traveling from transmitter to receiver, electromagnetic waves reflect from the ground and the surrounding objects. Hence, the received signal is a superposition of multiple copies of the transmitted signal that have been attenuated differently and arrive at the receiver at different times. These waves sum up at the receiver constructively or destructively and therefore cause fluctuations in signal strength and distort the signal. The paper is structured as follows. In Section II, we have Diversity Techniques to combat fading. In Section III, the system model is given.

A hybrid uni-/multicasting transmission strategy which exploits network coding is presented in Section IV. Simulation results in Section V confirm the analytical investigations and Section VI concludes the paper.

II.   DIVERSITY TECHNIQUES TO COMBAT FADING

For a narrowband fading channel model, where the inter-arrival times of the transmitted signal copies at the receiver are negligible compared with the symbolic time, we can mathematically model fading as a multiplication noise coefficient, denoted as h. Consider a point-to-point communication system with one transmit and one receive antenna.

Let $\mathbf{x}$ and $\mathbf{y}$ denote the transmitted signal and the received signal respectively at the output of the matched filter. Also, let $\mathbf{n}$ denote the random additive thermal noise generated by the receiver electronic devices, which is often modeled as complex white Gaussian noise. We can write:

$$\mathbf{y} = \mathbf{hx} + \mathbf{n} \qquad (1)$$

This signal representation is different from the one for the additive white Gaussian noise (AWGN) channel model, in which simply

$$\mathbf{y} = \mathbf{x} + \mathbf{n} \qquad (2)$$

When the number of scattering objects is large we can invoke the central limit theorem and approximate each fading channel gain h as a complex Gaussian random variable. When the channel gain h is zero mean, the channel gain amplitude |h| follows the Rayleigh distribution, hence the name "Rayleigh fading" [5]. When there is a line-of-sight (LOS) path between the transmitter and receiver, the channel

gain is not zero mean and the channel gain amplitude |h| follows a Rician distribution, hence the name "Rician fading" [5].

To better understand the severe fading effects on the performance of wireless communication systems, we compare the bit error rate (BER) of several digital modulation schemes, versus signal-to-noise ratio (SNR) for AWGN and Rayleigh fading channel models. We note that the BER of a digital modulation scheme, when being transmitted over AWGN channels, decays exponentially as SNR increases. However, for Rayleigh fading channels the BER decays linearly, as SNR increases. For instance, to achieve a BER of 10^{-5} - 10^{-6}, we need to increase the transmitted SNR about 30dB when transmitting over Rayleigh fading channels, as opposed to AWGN channels. In the power constrained and interference-limited systems, it is not desirable to increase the transmit power 1000 times to overcome the fading effects.

One of the main techniques to alleviate the effects of fading is diversity. Diversity provides the receiver with multiple copies of a single transmitted signal, where the copies experience independent fading. Note that the probability that all the received copies are simultaneously deeply faded is much smaller than the probability that a single received copy is deeply faded. Hence, diversity techniques increase the transmission reliability, via diversity gain. Let d denote the diversity gain. Recall the BER of a digital modulation scheme when being transmitted over Rayleigh fading channels decays linearly, as SNR increases, i.e., at high SNR we observe that the BER is proportional to 1/SNR.

Diversity changes the slope of the BER decay with respect to SNR such that the BER is proportional to 1/SNR d at high SNR. There are various ways of realizing a diversity gain. The widely adopted diversity techniques are:
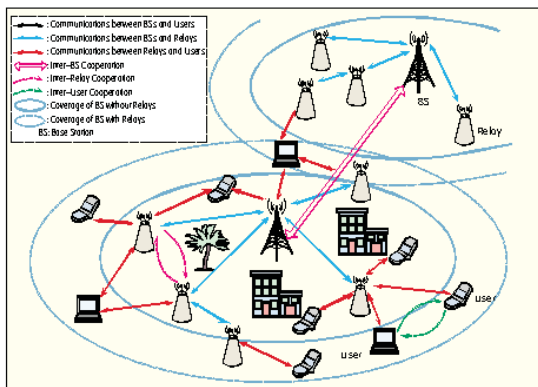
Time diversity: The same information is repeated transmitted at different time intervals, such that the two consecutive time intervals are separated by at least one channel coherence time.

Frequency diversity: The same information is repeated transmitted at different frequency bands, such that the two consecutive frequency bands are separated by at least one channel coherence bandwidth.

Spatial diversity: The same information is repeated transmitted over multiple transmit antennas. The

BER of a digital modulation scheme when being transmitted over Rayleigh fading channels can be significantly improved as two transmit antennas are used to invoke the spatial diversity.

Among these three techniques, spatial diversity has gained a lot of interest as it does not require any additional bandwidth. In fact, the advances in Multiple-Input Multiple Channel coherence time is defined as the longest time period (say between two transmitted pulses) where the channel appears static [5]. Channel coherence bandwidth is defined as the spectral spread of a signal that would experience the same channel [5].

▲ Figure 1. Relay–assisted communications network.

A. SYSTEM MODEL

A relaying scenario with multi-antenna nodes and multi-antenna relay stations (RS) is considered in Fig. 2 below. The scenario consists of G = 2 groups marked by marked by different colors N = 3 nodes per group. Nodes S_1, S_2 and S_3 from the first communication group G_1 and the nodes S_4, S_5 and S_6 from the second communication group G_2.

The communications are performed via single subcarrier. In general G ≥ 1 group and N ≥ 2 nodes per group are considered. The total number of nodes is given by T_n = G.N and the term S_k, k = 1, 2, ... is used to label the nodes. In each group the nodes are equipped with A_k ≥ 1, k =1, 2, … antennas and simultaneously transmit one data stream per antenna. With N_a the number of antennas at RS, the following constraint has to be fulfilled for the transmission on one subcarrier to suppress the interferences between the groups and to enable a proper relay transceiver filter design within each group:

$$N_a \geq \sum_{k=1}^{n} N.A_k - \min(A_k) \qquad (3)$$

The required number of antennas N_a at RS can be smaller than the total number of simultaneously transmitted data streams because network coding is applied to cancel self as well as known interferences. The transmit power at each node and RS is limited by $P_{MS, max}$, respectively. The channel $H_k \in C^{NaxAk}$ from node S_k of group G_k to RS is assumed to be constant during the transmission cycle of the multi way scheme which is described in the following and channel reciprocity is assumed. RS is assumed to have perfect channel state information (CSI) and the nodes have received CSI and can subtract self and known interferences.

All signals are assumed to be statistically independent and the noise at RS and at the nodes are assumed to be additive white Gaussian (AWG) with variance $\delta_{n, RS}^2$ and δ_n^2 Respectively. The system's equation in baseband for multi-way relaying are presented in the following where all nodes simultaneously transmit to RS in the first time slot t = 1. The transmitted symbols of S_k are contained in the vector XS_k and the transmit filter at S_k is assumed to be

$$Q_k = \sqrt{\frac{P_{MS, max}}{A_k}} - I_{Ak}.$$ Thus, the received signal at RS is given by

$$y_{RS} = \sum_{k=1}^{k}(H_k Q_k X_{Sk} + n_{RS}) \qquad (4)$$

Where n_{RS} represents the complex white Gaussian noise vector at RS. Afterwards, the transmission of RS to the nodes are performed in N − 1 time slots. Thus, N time slots are required to perform the multi-way communication of all nodes. In time slots t = 2, t = 3, …, t = N, RS linear processes the received signal using the transceiver filter matrices G2, G3, …, GN respectively. The relay transceiver filter for the time slot is given by

$$G_t = \Upsilon \check{G}_t \qquad (5)$$

Where $\check{G}_t$ is the transceiver filter at RS which does not implicitly fulfill the power constant and Υ is the scalar value to satisfy the relay power constraint. It is given by

$$\Upsilon = \sqrt{\frac{P_{RS, max}}{\sum_{k=1}^{k} \|Q_k \check{G}_t H_k\|_2^2 + \|\check{G}_t\|_2^2 \delta_{n, RS}^2}} \qquad (6)$$

The relay transmits the linearly processed version of y_{RS} to all nodes the received signal $y_{Sk, t}$ using the receiver filter $D_{k, t}$ at node S_k in time slot t is given by

$$y_{S_k,\ t} = \boldsymbol{D}_{k,\ t}(\boldsymbol{H}_k^T \boldsymbol{G}_t y_{\text{RS}} + \boldsymbol{n}_{k,\ t}) \quad (7)$$

Where $n_{k,\ t}$ represents the complex white Gaussian noise vector at S_k. In this paper $\boldsymbol{D}_{k,\ t} = \boldsymbol{I}_{Ak}$ is assumed for the received filtering at the nodes.

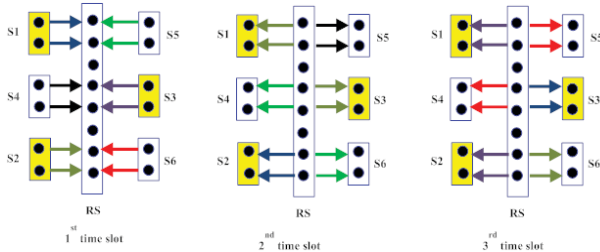

Fig. 2. Signals of the proposed transmission strategy for a multi-group multi-way relaying scenario with G = 2 groups, N = 3 nodes per group and $A_1 = A_2 = 2$ antennas per node

B. HYBRID UNI-/MULTICASTING STRATEGY WITH NETWORK CODING

Previous research on uni-/multicasting strategy as well as multicasting strategy proposed to perform multi-way relaying in N time slots do not fully exploit the application of network coding. For the hybrid uni-/multicasting strategy, self and known interference cancellation capabilities of the nodes are not considered in the relay transceiver filter design. In the multicasting strategy, self and known interference cancellations are considered but network coding is not fully exploited. Furthermore, the transmit power at RS is not efficiently used for the multicasting strategy and the strategy suffers from an increase of forwarded noise power at RS. [4]

Thus, we propose an enhanced hybrid uni-/multicasting Strategy which exploit the utilization of Network Coding. The overall communication is performed in N time slots. In the first time slot, all nodes simultaneously transmit to RS and in the remaining N − 1 time slots, RS retransmits linearly processed versions of the received signals back to the nodes. From the hybrid uni-/multicasting Strategy of previous research, [7] in each time slot t = 2, 3, …, one signal is unicasted to the nodes and another signal is multi-casted to the remain nodes of the group.

Nevertheless, in contrast to this strategy, we do not consider the unicasted signal as interference at the nodes which receive the multi-cast signal and vice versa. To simplify the description, we assume that the signal of the first node in each group is always

unicasted and the signals of the remaining nodes are multi-cast. Optimizing the selection of the unicasted signal can further improve the performance.

A scenario consisting of G ≥ 1 groups with N = 4 nodes per group is exemplary considered. For simplicity, we focus on the first group G1, which consists of the nodes S_1, S_2, S_3 and S_4 to describe the transmissions within each group. Similar to the hybrid uni-/multicasting strategy of [4], in time slot t, the signal of S1 is unicasted to S_t and the signal of S_t is multi-casted to the remaining nodes of the group.

However, as already mentioned before, the unicasted signal is not considered as interference at the nodes which receive the multi-cast signal and vice versa. Thus, the network coding capabilities of the nodes are exploited. The considered desired signals, self- and known-interferences are summarized in Table I. In each time slot t = 2, 3, ..., it is assumed that the nodes can subtract the back propagated self-interferences. Furthermore, it is assumed that the nodes can subtract known interferences, i.e., interferences which are known as the nodes due to successful decoding of the corresponding signals in a previous time slot, e.g., each node knows the multi-cast signals of the previous time slots. Additionally, the unicasted signal is always assumed to be known as the nodes which receive the multi-cast signal.

This assumption is possible because the unicasted signal is received and estimated at so in time slot t = k and afterwards known-interference cancellation can be applied to the signals received in previous or subsequent time slots.

H, The indices of the nodes whose signals are assumed to be self- or known-interferences at node S_k in time slot t are collected in the subset $N_{k,t}$. Self- and known-interferences can be subtracted at each node S_k assuming that the overall channels $\boldsymbol{H}_l^T \boldsymbol{G}_t \boldsymbol{H}_l \ \forall l \in N_{k,t}$ are perfectly known at S_k. The signal, interference and noise covariance matrices after self and known-interference cancellation for the reception of the desired signal of S_k at S_l in time slot t are given by

$$A_t^{S_k,\ t} = H_l^T G_t H_l Q_k R_{xS_k} Q_k^H H_k^H G^H H_l^*,$$

$$B_t^{S_k,\ t} = H_l^T G_t \left(\sum_{j=1, j \notin N_{l,\ t}}^{k} H_j Q_j R_{xS_j} Q_j^H H_j^H \right) Q_t^H H_l^*,$$

$$C_t^{S_k,\ t} = H_l^T G_t R_{nRS} G_t^H H_l^* + R_{nS_k} \quad (8)$$

Respectively, with R_{xS_k} the signal covariance matrix of XS_k and R_{nS_k} and R_{nS_l} the noise covariance matrix at RS and S_l respectively.

Assuming that optimal Gaussian codebooks are used for each data stream, the achievable data rate from S_k to S_l in time slot t is given by

$$C_{S_k,l,t} = \frac{1}{N} log_2 \left| \left(I_M + A_t^{S_k,\ t} + C_t^{S_k,\ t}\right)^{-1}\right| \quad (9)$$

Where N is the number of required time slots to perform all multi-way transmissions. The maximum achievable multi-way rate for the transmission of S_k is determined by the minimum over all achievable rates from S_k to any other node within the same group. Thus, it is given by

$$C_{sum} = \sum_{k=1}^{K} C_{S_k,max} \quad (10)$$

Transmission strategy for a group of N = 4 nodes

	Receiving node	S_1	S_2	S_3	S_4
t=2	Desired signal	S_2	S_1	S_3	S_4
	Self-interference	S_1	S_2	S_3	S_4
	Known-interference			S_1	S_1
t=3	Desired signal	S_3	S_3	S_1	S_3
	Self-interference	S_1	S_2	S_3	S_4
	Known-interference	S_2	S_1	-	S_1, S_2
t=4	Desired signal	S_4	S_4	S_4	S_1
	Self-interference	S_1	S_2	S_3	S_4
	Known-interference	S_2, S_3	S_1, S_3	S_1, S_2	-

III. SIMULATION OF RESULTS

In this section, numerical results on the achievable sum rates for the proposed transmission strategy are presented. It is assumed that $P_{MS,\ max} = P_{RS,\ max}$ and $\delta_{RS}^2 = \delta_n^2$. The path-loss on the i.i.d. Rayleigh fading channels is represented by an average receive signal to noise ratio (SNR) at RS. An average receives SNR at RS of 15dB is assumed. For comparison, the (Minimum Mean Square error) MMSE and Zero-forcing (ZF) relay transceiver filters of previous work are considered using the hybrid uni-/multicasting strategy presented in [4]. For the MMSE relay transceiver filter of [4], two cases are distinguished.

First, it is assumed that only self-interference cancellation can be performed at the nodes, termed" MMSE, SI@nodes". Secondly, it is assumed that self- and known-interference cancellation can be performed at the nodes, termed " MMSE,

SKI@nodes". For the proposed MMSE-SKI relay transceiver filter, two different cases are investigated, too.

First, only a self-interference aware relay transceiver filter design is considered combined with only self-interference cancellation at the nodes, termed "MMSE-SI, SI@nodes". Secondly, a self- and known interference aware relay transceiver filter design as described in Section IV is considered combined with considering self and known-interference cancellation at the nodes, termed "MMSE-SKI, SKI@nodes". The average achievable sum rates over different numbers L of antennas at RS for the scenario with G = 2 groups and N = 3 single-antenna nodes per group.

The ZF relay transceiver filter requires $N_a \geq 6$ antennas. The proposed strategy combined with the MMSE-SKI relay transceiver filter "MMSE-SKI, SKI@nodes" clearly outperforms the other approaches because it better exploits the network coding capabilities of multi-way relaying by considering self- and known-interference cancellation at the nodes and for the relay transceiver filter design.

The performance of only considering self-interference cancellation "SI@nodes" is worse than considering self- and know-interference cancellation "SKI@nodes". The average achievable sum rates over different numbers L of antennas at RS for the scenario with G = 1 group, N = 4 nodes per group and M1 = 2 antennas per node are shown in Figure 3. In this scenario, the ZF relay transceiver filter requires $N_a \geq 8$ antennas.

In comparison to the aforementioned results, the performance gap between only considering self-interference cancellation and considering self- and know-interference cancellation is increased due to considering an increased number of nodes per group and no inter-group interference. Similar to the aforementioned results, the proposed strategy combined with the MMSE-SKI relay transceiver filter outperforms the other approaches.
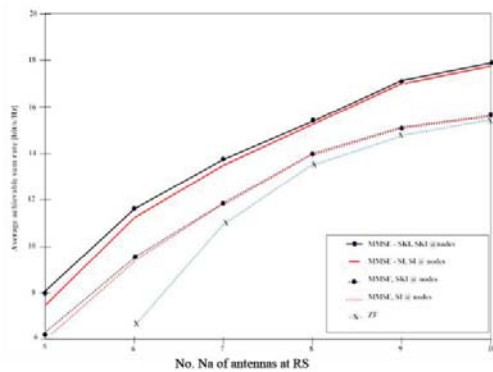
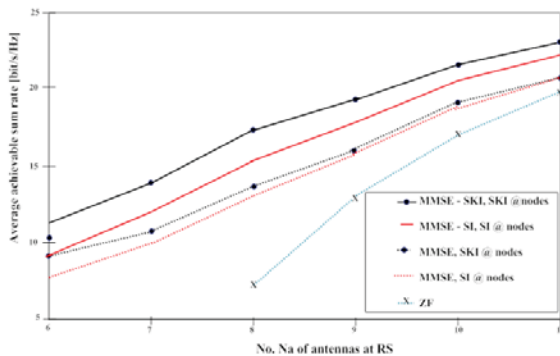Fig. 3.   Average achievable sum rates over number N_a of antennas at RS for single-antenna nodes, G = 2, N = 3

Fig. 4.   Average achievable sum rates over number N_a of antennas at RS for multi-antenna nodes, G = 1, N = 4, A_1 = 2.

IV.   CONCLUSION

A multi-group multi-way relaying scenario has been investigated. A transmission strategy is proposed which exploits network coding to increase the achievable sum rates. To better understand and combat fading, diversity techniques have analyzed. Among these techniques, spatial diversity has gained a lot of interest as it does not require any additional bandwidth. Furthermore, an analytical solution for a self and known interference aware relay transceiver filter considering multi-antenna nodes is derived. The derived relay transceiver filter applies to the proposed transmission strategy which significantly increases the achievable sum rates compared to conventional approaches.

V.   REFERENCES

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