ON THE USE OF MULTIPLE ACCESS CODING IN COOPERATIVE SPACE-TIME RELAY TRANSMISSION AND ITS MEASUREMENT DATA BASED PERFORMANCE VERIFICATION

Aihua Hong, Reiner Thomä

Institute for Information Technology
Technische Universität Ilmenau
PSF 100 565, D-98684 Ilmenau, Germany
`aihua.hong@tu-ilmenau.de`

Tad Matsumoto

Center for Wireless Communications
University of Oulu
P.O.Box 4500, FI-90014, Oulu, Finland
`tadashi.matsumoto@ee.oulu.fi`

ABSTRACT

A goal of this paper is to combine the advantageous properties of multiple access codes (MAC) and space-time transmission (STT) in wireless relay communication systems. The use of MAC provides transmission with the separability of the signals transmitted from multiple users, and STT the diversity gain. It is shown both by model-based numerical results and measurement data-based simulation results that the combined use of MAC and STT achieves significant improvement in bit error rate (BER) as well as signaling throughput of relay systems.

1. INTRODUCTION

Recently, relay networks have become one of the core topics in wireless communications research community due to the recognition that wireless relay networks shall provide a promising solution to the coverage problem of 3rd generation systems and their extensions. Decode-and-forward wireless relay networks exploit the signaling redundancy in the time domain without violating the causality. Space-time coded relaying exemplifies the concept, where at the first transmission time-slot the transmitters transmit their originated signals and at the second time-slot the relay stations forward their neighboring station's signal in a space-time coded format. The destination receiver has to detect those signals simultaneously transmitted at the first time-slot, however, the signal separability may not always be guaranteed, especially when the destination has only one receive antenna.

It is well known that multiple access coding (MAC) techniques can always achieve the signal separability at the receiver side in multiple access channels by exploiting the redundancy in the time domain. Despite the redundancy incurred by MAC, it can achieve the throughput gain due to the increased number of the codewords having the same code length. Reference [1] proposes a class of MAC for binary phase-shifted keying (BPSK) in additive white Gaussian channels. The code proposed by [1] can easily be extended to the system using quadrature phase shift keying (QPSK) in frequency-flat Rayleigh fading channels, where the codewords can be uniquely decoded at the receiver side regardless of fading channel realizations, while also increasing the signaling throughput.

Therefore, if MAC is used in conjunction with the space-time transmission (STT) techniques in relay system, performance improvements can be expected due to the two beneficial points, one signal separability, and another diversity gain; and simultaneously also throughput enhancement can be expected by the increased number of MAC codewords. Moreover, a joint error detection of the direct and relay links with STT at the destination can further improve the system performance. This paper investigates the performance of the relay networks using the above-stated protocol. In a 3-user and one destination, as an example, system throughput and bit error rate (BER) are evaluated.

This paper is organized as follows. Section 2 provides an introduction to the system model. In Section 3 the proposed protocols applicable to the introduced system set up are presented. Section 4 describes the measurement campaigns conducted to collect a data set in a scenario representing a wireless relay network. Results of the model-based and measurement data-based simulation are presented in Section 5. Finally, Section 6 concludes the paper.

2. SYSTEM MODEL

We consider a communication system with N+1 nodes, each having one single antenna, comprised of one destination and N users, as shown in Fig. 1. The n^{th} user in Fig. 1 is blocked from the destination by obstacles. In this case, with the help of the neighboring users, the signal from the n^{th} user is relayed by neighboring users to the destination and vice verse. In uplink case for example, the N users transmit their signals to the destination at the first time-slot. The n^{th} user's signal is received by the all other N nodes. Hence, the received signal

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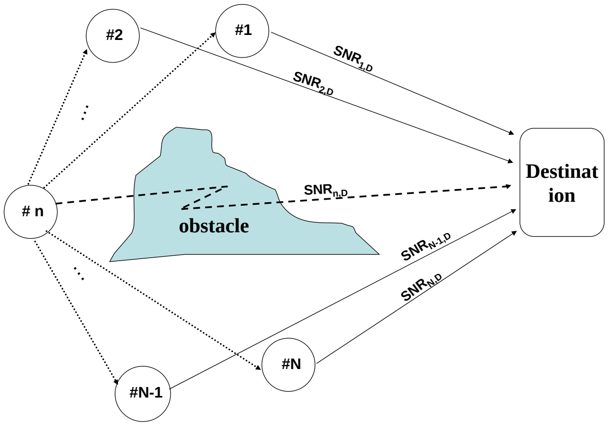

Fig. 1. System model with N+1 nodes, N source nodes, one destination, and the n^{th} user is blocked.

r_D as shown in Fig 2 at the first times lot at the destination can be expressed as,

$$\mathbf{r_D} = \sum_{i=1}^{N} \sqrt{\rho_{i,D}} h_{i,D} s_{i,D} + n_0, \tag{1}$$

where $\rho_{i,D}$ stands for the transmitted power of the i^{th} user, $h_{i,D}$ the power-normalized channel between the i^{th} user and the destination, $s_{i,D}$ the i^{th} user's transmitted signal, and n_0 the additive white complex Gaussian noise with a unit power.

Let us assume that all nodes can decode and forward the received signal, and that the N-1 neighboring users of the n^{th} user have a perfect connection to the n^{th} user (straight dashed lines in Fig. 1) and good connection with the destination (straight lines in Fig. 1). Thus, the N-1 users decode the signal from the n^{th} user without any error, of which situation is denoted as $r_{RS} \rightarrow s_{n,D}$, and re-encode it in a cooperative manner [2] [3]. At the second time-slot, the re-encoded signal is forwarded to the destination. The received signal at the second time-slot at the destination as shown in Fig. 3 is,

$$\mathbf{r_{RS,D}} \quad = \quad \rho \bullet \mathbf{h} \bullet CO(r_{RS}) + n_1 \tag{2}$$

with

$$\begin{aligned} &\rho = \\ &diag\left(\left[\sqrt{\rho_{1,D}}, ..., \sqrt{\rho_{(n-1),D}}, \sqrt{\rho_{(n+1),D}}, ..., \sqrt{\rho_{N,D}}\right]\right), \\ &\mathbf{h} = [h_{1,D}, ..., h_{(n-1),D}, h_{(n+1),D}, ..., h_{N,D}], \end{aligned} \tag{3}$$

and the $CO(r_{RS})$ being the cooperative transmission for r_{RS} at the relay stations. Here we limit the total value $\sum \rho$, and assume that different power is allocated to each relay station during the cooperative transmission.

Furthermore, it is assumed that the channel between any of two nodes in the system setup is suffering from an independent flat Rayleigh fading which stays the same during transmission of one block. In Eqns. (1) and (2), signal-to-noise ratio (SNR) of the link between the i^{th} user and the destination $\mathbf{SNR_{i,D}}$ is equal to 10lg$\rho_{i,D}$. As a reference, we fix the SNR value of the first user, i.e. $\mathbf{SNR_{1,D}}$ and introduce two parameters: **SIR** and $\delta_{SNR_{1,u}}$, which are defined, respectively, as:

$$\mathbf{SIR} = \mathbf{SNR_{1,D}} - \mathbf{SNR_{n,D}}, \tag{4}$$

and

$$\delta_{SNR_{1,u}} = \mathbf{SNR_{1,D}} - \mathbf{SNR_{u,D}}, \tag{5}$$

with $1 < u \leq N$ and $u \neq n$.

3. PROPOSED PROTOCOLS

Based on the system model introduced in Section 2, the following protocol is proposed: multiple access coding at the first time-slot (ref. Fig. 2) to provide the separability of users at the destination without ambiguity and meanwhile to improve the total throughput; STT at the second time-slot (ref. Fig. 3) to achieve spatial diversity gain in flat fading Rayleigh channel; joint error detection (ref. Fig. 3) to provide additional diversity gain from two independent transmissions.

3.1. Multiple access coding at the first time-slot

MAC is first proposed by Kasami in [1] which guarantees for any realization of the real-valued channels the separability of symbols belonging to the code book. The Kasami code can easily be extended to complex-valued channel cases. Assume that the i-th user uses the i-th codebook C_1 where 1¡=i¡=N with L_1 codewords. The transmitted vector S collects the transmitted symbols from the all users be denoted as S = $[s_{1,D}, s_{2,D}...s_{N,D}]$ with $s_{i,D} \in C_i$. Thus, the set **S** has totally $\prod_{i=1}^{N} \mathbf{L}_i$ elements. Even though each user is allocated to the same time or frequency, they could be uniquely decoded and identified without ambiguity at the destination if and only if, for any vector X with $X \in$ **S**, no Y ($Y \in$ **S** and $Y \neq X$) exists, so that

$$\sum_{i=1}^{N} \sqrt{\rho_{i,D}} h_{i,D} \left(X(i) - Y(i)\right) = 0. \tag{6}$$

As an extension to the Kasami's code [1] defined over the field GF(2), the code in this paper is defined over field GF(4) with QPSK. After computer search, 2-user MAC is obtained as $\mathbf{C_1}$ = $\{00, 11, 22, 33\}$ and $\mathbf{C_2}$ = $\{00, 01, 02, 03, 10, 12, 20, 21, 30\}$. With the orthogonal radio resource allocation, total signaling throughput of the two-user system is only 4 bit/symbol with QPSK. With the 2-user MAC, total signaling throughput is 5.17 bit/symbol. Obviously, therefore, with the same resource consumption, 2-user MAC outperforms the traditional orthogonal resource allocation scheme with 1.17 bit/symbol throughput gain. As indicated by Eqn. 6, the signals from different users can be separated and uniquely identified at the destination (The color in Fig. 2 stands for identifiable codeword of each user), regardless of their channel realizations.

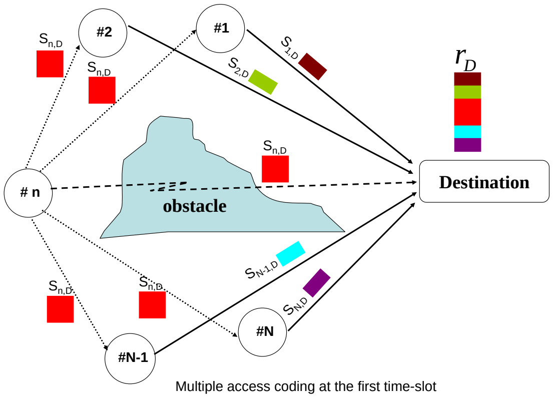

Fig. 2. The transmission at the first time-slot.

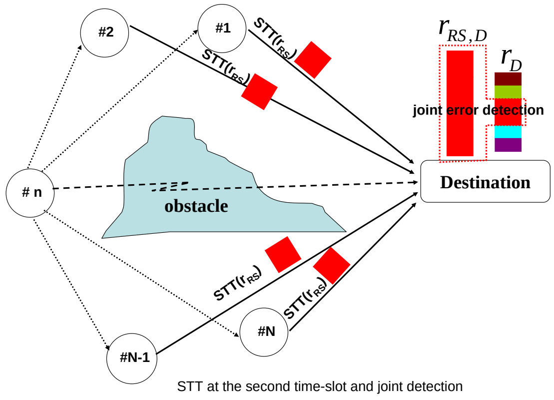

Fig. 3. The transmission at the second time-slot.

3.2. Space-time transmission at the second time-slot

At the second time-slot, as a cooperative protocol, distributed STT is proposed at the relay stations as shown in Fig. 3. Namely CO in Eqn. (2) now stands for space-time code. Distributed space-time code is applied to the group of K symbols r_{ST} = $[r_{RS}(1)\ r_{RS}(2)\ ...\ r_{RS}(K)]$ over the N-1 relay stations. From each relay station antenna, a complex linear combination of symbols in r_{ST} or their conjugate complexes is transmitted. It is assumed that relay stations are synchronized and no delay difference among STT is observed at the destination. An simple example of the STT is Alamouti code [2] over 2 symbols r_{ST} = $[r_{RS}(1)\ r_{RS}(2)]$ in T symbol intervals with coding matrix,

$$AL(r_{ST}){=}\begin{array}{c|cc|cc} & r_{RS}(1) & r_{RS}(2) & \leftarrow & time\ t \\ & -r_{RS}(2)^{*} & r_{RS}(1)^{*} & \leftarrow & time\ t+T \\ & \uparrow & \uparrow & & \\ & antenna\ 1 & antenna\ 2 & & \end{array} \tag{7}$$

where $AL\left(r_{ST}\right)$ stands for the Alamouti transmission of r_{ST}. the superscript * denotes the complex conjugate operation.

3.3. Maximum likelihood detection

At the destination, r_D in Eqn. (1) is sent to the maximum likelihood detector directly to recover the transmitted signals, while $r_{RS,D}$ in (2) is sent first to the space-time combiner and then to the maximum likelihood detector. As a result of the space-time combiner, $\tilde{r}_{RS,D}$ is obtained. Under the assumption that the perfect channel state information (CSI) is available at the destination, the maximum likelihood detector minimizes the metric,

$$\left|r-\hat{H}\hat{s}\right|^2, \tag{8}$$

where r represents r_D at the first time-slot and $\tilde{r}_{RS,D}$ at the second time-slot, $\hat{H}$ indicates the estimate of the channel matrix including ρ, and $\hat{s}$ stands for the possible combination of the transmitted signals. r_D at the first time-slot contains $\prod_{i=1}^{N}\mathbf{L}_i$ combination probabilities, while r_{RS} at the second time-slot has only $\mathbf{L}_n$ combination probabilities. Thus, more users, and more complex the maximum likelihood detector is.

3.4. Joint error detection

After the maximum likelihood detection, the n^{th} user's transmitted signal is identified at both time-slots. The red rectangular at the destination in Fig. 3 represent the signals of the n^{th} user. Even though the direct link of the n^{th} user is significantly attenuated, the contribution from the direct link should not be ignored. Now, these two detected vectors of the n^{th} user, $\hat{s}_{n,D}$ and $\hat{s}_{RS,D}$, are jointly detected. This means that an error message is returned for the n^{th} user if and only if the error occurs at the same received symbol position, both at the first time-slot and at the second time-slot. Otherwise, the signal could be recovered without error. Therefore, the symbol error rate (SER) may be computed as,

$$P(error(\hat{s}_n(k))=1)= \\ P(error(\hat{s}_{n,D}(k))=1)\times P(error(\hat{s}_{RS,D}(k))=1). \tag{9}$$

In Eqn. (9), $P(error(\hat{s}_n(k))=1)$ means the SER of the k^{th} symbol of the detected vector $\hat{s}_n$. The multiplication of $P(error(\hat{s}_{n,D}(k))=1)$ and $P(error(\hat{s}_{RS,D}(k))=1)$ yields to the reduction of the SER and enhancement of the system performance.

4. MEASUREMENT DATA

The measurement data used for the performance verification was collected in a pedestrian zone of the Ilmenau city center, Germany, using RUSK MIMO channel sounder [6]. This scenario represents a typical urban deployment of wireless relay network because some users in this scenario have line of

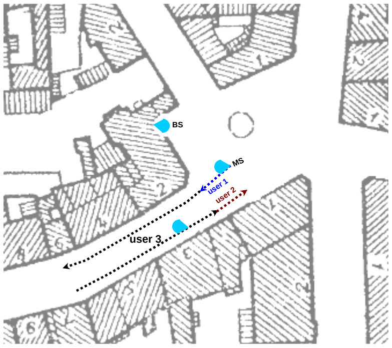

Fig. 4. map of measurement campaigns.

sight (LOS) with base station (BS) (the users at the position of the red and blue curves in Fig. 4), whereas, some users are blocked from the BS because of the corner of the buildings (the users at the position shown as black dash curves in Fig. 4). The signal of the blocked users is relayed by the users in the LOS regions to the BS.

The measurement setup information of the measurement campaign could be found in [4]. To match the simulation requirements, the measurement data was pre-processed according to what are described in [5]. Finally, SISO flat fading Rayleigh channels between BS and users are created. The beam patterns of the BS and users are shown in Fig. 4 as bright blue color.

5. SIMULATION RESULTS

An example scenario with 4 nodes, 3 users and one destination, is studied in this section to assess the system performance. As performance measure, we consider signaling throughput and average BER.

5.1. Model-based simulation

5.1.1. Multiple access coding

A 3-user MAC was used in the simulation that has 4, 4, and 36 codewords for each user respectively. In the same manner as explained in Section 3.1, it is found that this 3-user MAC improves the signaling throughput of the three access channel because of 3.17 bit/symbol sum throughput gain. Based on the 2-user and 3-user MAC, we can conclude that more the users, larger the signaling throughput gain can be achieved using MAC, whereas, more complex the maximum likelihood detection.

Due to the throughput degradation of the blocked user because of half-duplexing, we assign the codebook with the largest codewords to the blocked user (namely user 3). With the same symbol frame length, more bits could be transmitted for the blocked user so that the throughput reduction could be partly compensated. The other 2 users use the rest two codebooks with 4 codewords. When $\mathbf{SNR_{1,D}}$=$\mathbf{SNR_{2,D}}$=$\mathbf{SNR_{3,D}}$, the BER performance of the 3-user MAC is shown in Fig. 5. The curves in Fig. 5 with circle, upward pointing triangle, and plus sign are the BER curves of user 1, user 2, and user 3 respectively. As a simple reference illustration, the BER curve of the uncoded case is presented in the same figure. The gap between the uncoded case and 3-user MAC case is about 5 dB. This 5-dB gain comes from the 3-user MAC design.

5.1.2. Space-time protocol and joint error detection

For the space time cooperative transmission at the relay stations, 2-antenna Alamouti protocol [2] as described in Eqn. (7) is used.

The BER curves of user 3 with proposed protocols in Sections 3.2 and 3.4 are shown in Fig. 5. The line group with square stands for the BER results with joint error detection, while the dashed line group presents the BER results without joint error detection. Each group has 4 curves. These two groups show the dependence of the BER performance on $\mathbf{SIR}$ when $\delta_{SNR_{1,2}} = 0$ and on δ_{SNR} when $\mathbf{SIR} = 0$, respectively. Both $\mathbf{SIR}$ and δ_{SNR} vary from 0 to 15 dB with step 5 dB. With variable $\mathbf{SIR}$ it is observed that larger the $\mathbf{SIR}$ is, nearer the curve approaches the curve group without joint error detection. With the increasing $\mathbf{SIR}$, the contribution of the direct link comes to be decreased. As a consequence, the gain resulting from the joint error detection will be reduced and the joint error detection case will be shifted to case without joint error detection. With variable δ_{SNR} it is observed that larger the SNR difference between the two relay stations, nearer the dashed line approaches the curves of the 3-user MAC. As δ_{SNR} increases, the system shifts from 2-antenna case to 1-antenna case. The diversity gain will be impaired and the performance will return to performance of the 3-user MAC case.

5.2. Measurement data based simulation

As stated in Section 4, the blocked user is placed at the NLOS regions while the other users are placed at the LOS regions. For the practical scenario, user 1 and user 2 are placed at position of the red and blue curves while user 3 is placed at the position of the black curves. From all user positions, 100 different channel realizations are randomly selected for user 1, user 2, and user 3 respectively. Ideal power control is assumed so that the mean SNR value of user1 or user 2 over 100 LOS channel realizations is 10dB, whereas, user 3 has 1dB mean SNR value over 100 NLOS channel realizations.

Using the 100 sets of randomly selected real field channel data, the performance of the studied wireless relay system with proposed protocols can be evaluated and verified. Fig. 6

shows the cumulative distribution function (CDF) curves of BER performance of user 1, user 2, user 3 with direct transmission, user 3 with Alamouti transmission, and user 3 with joint error detection. It is observed from Fig. 6 that the performances of user 1 and user 2 are very similar because of the same mean SNR value. In 70% the case, user 1 and user 2 can achieve tranmission perforamnce with the BER value smaller or equal than 10^{-3}. As a comparison, the performance of user 3 with direct transmission is much worse because user 3 is blocked from BS and has a very low mean SNR value. In more than 90% case, the BER value of user 3's direct transmission is larger than 10^{-1}. With the help of user 1 and user 2's Alamouti relay transmission, user 3's performance can be signifcantly enhanced. In more than 80% case, the BER value of user 3 with Alamouti relay transmission is smaller than 10^{-2}. However, even with Alamouti tranmission, BER perforamnce of user 3 is not better than that of user 1 and user2. The reason comes from the fact that, during the Alamouti transmission at user 1 and user 2, even though the mean SNR value stays the same, 10 dB, but more bits per symbol have to be transmitted for user 3 because of larger codeword number. With joint error detection at the destination, CDF curve of user 3 is further shifted to the left side. Now in more than 90% case, the BER value of user 3 is smaller than 10^{-2}. Furthermore, in the smaller BER value area, user 3's BER performance is better user 1's and user 2's. This observation indicates that joint error detection plays a more important role when the temporary **SIR** becomes smaller.

Based on both model-based simulation and measurement data based simulation, the performance of the investigated example system has been evaluated and verified. It is observed that the BER performance of the blocked user can be significantly improved with cooperative relay transmission. Joint error detection at the destination can further reduce the BER value of the blocked user especially when the **SIR** value becomes smaller. The conclusions drawn in this section can be easily extend to more general cases: at first to the case where the number of the relay stations is bigger than 2. In this case, we can perform user selection technique to select the best two users to conduct Alamouti relay transmission. Secondly, the practical application can be extended to more general urban micro-cell scenarios because of the representation of the considered scenario.

6. CONCLUSIONS

In this paper, MAC and distributed STT have been studied for the cooperative relaying wireless communication systems. The signaling throughput has been calculated to illustrate the gain of MAC. Furthermore, the BER performance of the 3-user MAC has been presented to provide insight to the performance benefits achieved by proposed protocols. Using the real field channel data, the performance of the investigated system has been further verified.

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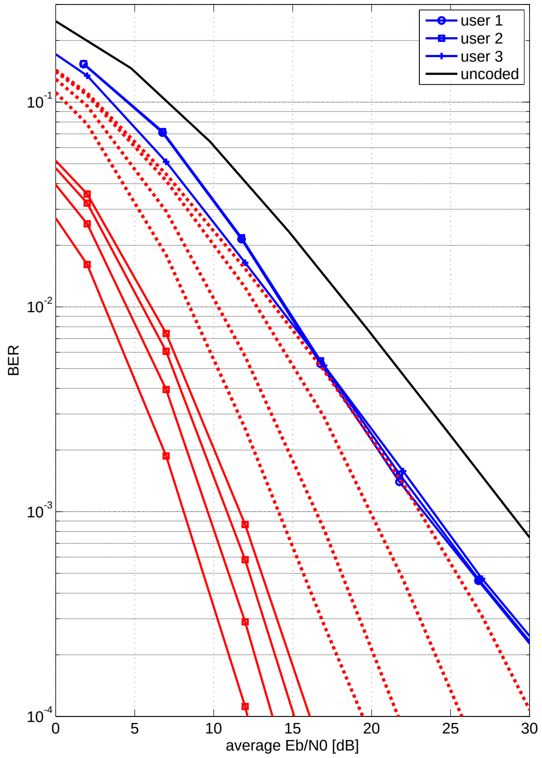

Fig. 5. BER performance of multiple access coding, Alamouti scheme with and w/o joint error detection.

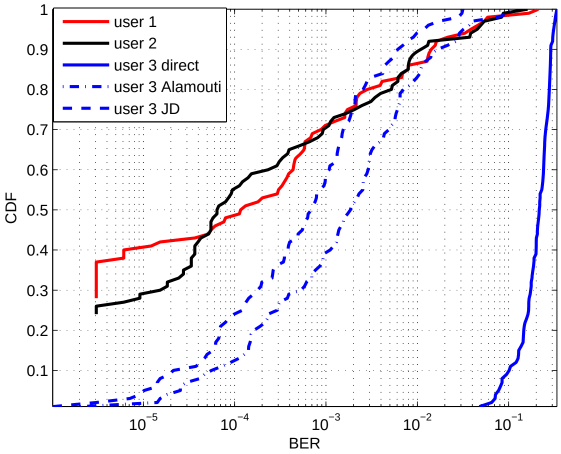

Fig. 6. BER performance of user 1, user 2, and user 3 (direct link only, Relay link only, and joint error detection) based on measurement data.