Experimental Verification of PER Performance of STBC-based Multi-hop Cooperative Relaying

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***Abstract*—In this paper, the end-to-end packet error rate (PER) performance of a space-time block code (STBC) based multi-hop cooperative relaying system is discussed. This system consists of a source, a destination, and two STBC based cooperative relays in each hop. These relays decode their received packets and forward the packets only when no error is found. In this system, there are conditions where the end-to-end PER performance improves with the number of hops. The theoretical end-to-end PER performance of this system have been derived analytically. However, in real-world wireless systems, various practical issues, e.g., timing synchronization and imperfect channel estimation, have a large impact on the performance. To confirm the end-to-end PER performance of this system in actual setup, an in-lab experiment using a fading emulator and four transceivers is performed under Rayleigh fading environment. The experimental results clarify the PER performance of the STBC based multi-hop cooperative relaying system. In addition, the theoretical PER performance is also verified from the experimental results.**

I. Introduction

One promising technology to enhance the performance of wireless network is a multi-hop wireless network [1], [2] where relay stations forward data from a source station to a destination station. Major advantages of the multi-hop wireless network is coverage extension and mitigation of shadowing effect. However, an end-to-end packet error rate (PER) performance of a system with simple relaying scheme is severely degraded with the numbers of hops due to the error propagation through the hops.

To cope with such degradation and improve the performance of the multi-hop wireless network, cooperation among relay stations is proposed [3]. In these systems, relay stations cooperate together using transmit diversity. Space-time block code [4] is typical of transmit diversity techniques. There are conditions where the end-to-end PER performance of STBC based cooperative relaying system improves with the number of hops. This system consists of a source, a destination, and more than one STBC based cooperative relays in each hop, and relays are assumed to decode their received packets and forward it only when no error is found.

In [5], the authors have showed this unique characteristic of the multi-hop cooperative relaying system using a transmit diversity technique. A theoretical end-to-end PER performance of the system have been analytically derived. In real-world wireless systems, however, various practical issues, e.g., imperfect channel estimation, IQ imbalance and DC offset, frequency unstability, and timing synchronization between stations, have a considerable impact on the performance, especially in the efficiency of transmit diversity.

The goal of this study is to evaluate the end-to-end PER performance of the multi-hop cooperative relaying system in actual fading environments. Many papers have been reported about the implementation and experimental results of cooperative communications [6]–[8]. However, to the best of the authors' knowledge, experimental error performance evaluations on the cooperative multi-hop (more than 2-hop) transmission have not been reported. Experimental results of cooperative multi-hop transmission have reported in [9], however [9] have been focused on the timing synchronization technique. In this paper, in-lab experiments using a fading emulator and four transceivers is performed to measure the end-to-end PER performance of the STBC based multi-hop cooperative relaying system under a Rayleigh fading environment.

II. System model

We consider a multi-hop transmission system with a space-time block code (STBC) based cooperative relaying that has two relay stations in each hop as shown in Fig. 1. Each relay station always decode their received packets and perform error detection based on cyclic redundancy check (CRC) method. Each relay only forwards the received packets with no error detected. Two relay stations in each hop are allocated orthogonal codes and transmit encoded signals at the same time so that diversity gain can be obtained. In this paper, the performance is measured in terms of the end-to-end packet error rate (PER). The routing algorithm is out of the scope of this paper.

III. Theoretical packet error rate

In this section, we describe the theoretical end-to-end PER [5]. For simplicity, single-hop PER in each link is assumed to

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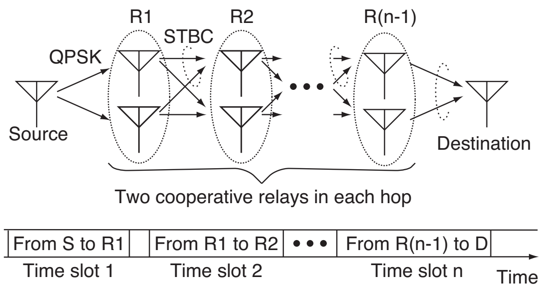

Fig. 1. STBC based cooperative n-hop relaying system.

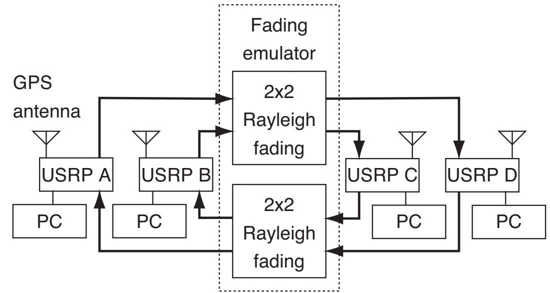

Fig. 2. Block diagram of experimental setup.

be the same. This assumption helps us understand the behavior of the multi-hop cooperative relaying system.

We use the STBC for decoding the mixed signal from two stations. The single-hop PER therefore varies with the number of transmitting stations. Accordingly, there are three states in each hop and we define S_2, S_1 and S_0 as states. In S_2 and S_1, two and one relay stations forward the received packets. S_0 shows the failed state where no relay station succeeded in receiving and do not forward any packet.

We also denote the probability distribution at k-th hop as $\boldsymbol{W}_k = \left[w_2^{(k)}, w_1^{(k)}, w_0^{(k)}\right]^{\mathrm{T}}$, where $w_2^{(k)}$, $w_1^{(k)}$, and $w_0^{(k)}$ show the probability of S_2, S_1, and S_0 at k-th hop, and $[\cdot]^{\mathrm{T}}$ denotes the transposed vector. The probability distribution at $(k+1)$-th hop can be written as

$$\boldsymbol{W}_{k+1} = \begin{bmatrix} (1-P_2)^2 & (1-P_1)^2 & 0 \\ 2P_2(1-P_2) & 2P_1(1-P_1) & 0 \\ P_2^2 & P_1^2 & 1 \end{bmatrix} \boldsymbol{W}_k = \boldsymbol{P}\boldsymbol{W}_k,$$

where P_2 and P_1 show the PER of single-hop transmission with two cooperative transmitters and one transmitter, and $\boldsymbol{P}$ shows the transition matrix.

At the first hop, one source station transmits packets; therefore, we get $\boldsymbol{W}_0 = [0, 1, 0]^{\mathrm{T}}$. Similarly, at the final hop, one destination station receives packets and the PER is shown by P_2, P_1 and 1. Finally, we get the end-to-end PER of n-hop cooperative relaying system as

$$\begin{bmatrix} P_2 & P_1 & 1 \end{bmatrix} \boldsymbol{P}^{n-1}\boldsymbol{W}_0. \tag{1}$$

IV. Experimental Setup

Figs. 2 and 3 show the block diagram and the overview of experimental setup. This experimental system consists of universal software radio peripheral (USRP) N210s as transceivers, GPS receivers for synchronizing USRPs, PCs as processors for digital baseband signals from USRPs, and a fading emulator as propagation channels. Because our fading emulator can simultaneously emulate up to eight channels, this setup repeatedly utilize two 2×2 channels as Fig. 2, and one loop is assumed to be two hops. In this system, USRP A first transmits as the source station. After finishing the cooperative relaying between USRP A, B and C, D nine times, both USRP A and B finally receive at 10-hop and do not forward.

In the STBC technique, timing and frequency synchronization is crucial. In this system, an one-pulse-per-second (1 PPS) signal and a reference signal from an onboard GPS disciplined oscillator (GPSDO) are utilized for timing and frequency synchronization. Nominal specifications of USRPs equipped with GPSDO [10] are shown in Table I. From Table I, we can say that four USRPs in this system establish timing and frequency synchronization with high accuracy.

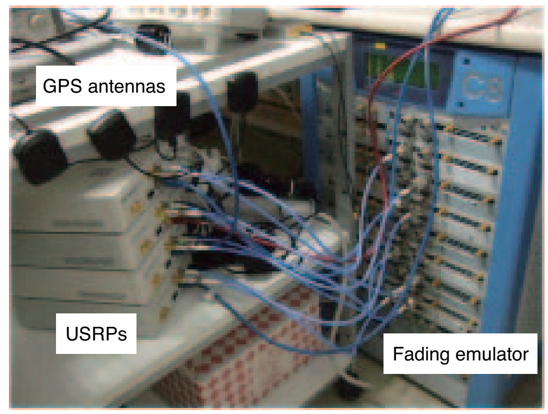

Fig. 3. Experimental setup.

TABLE I
Nominal specifications of USRP N210 with GPSDO.

Parameters	Values
Frequency accuracy	0.01 ppm
1 PPS accuracy	$\pm$50ns to UTC RMS (1-Sigma) GPS locked
Holdover stability	$< \pm 11\mu$s over 3 hour period at $+25^\circ$C

A. Process on USRP

The block diagram of USRP is shown in Fig. 4. The USRP hardware driver (UHD) is a software interface of USRP. We use USRPs with C++ programming language by UHD. Options in USRP, i.e., radio frequency (RF), intermediate frequency (IF), sampling rate, gain, etc., are set by the corresponding PC. When the USRP transmits, a transmit time in future and a baseband IQ data array are supplied from the PC to USRP; and USRP converts the baseband IQ data array into a RF signal. When USRP receives, a receive time in future is set by PC and USRP receives the RF signal on time; and USRP passes the baseband IQ data array derived from the RF signals to the PC.

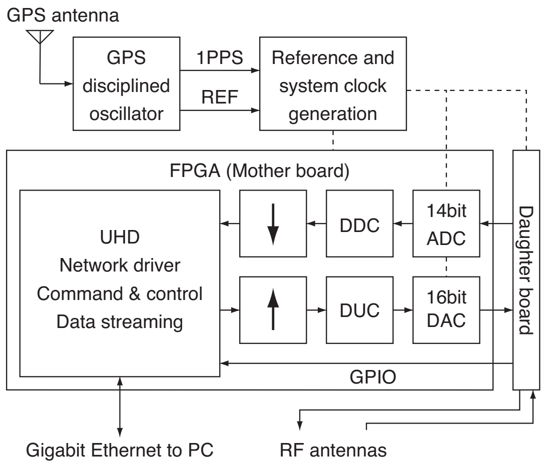

Fig. 4. Block diagram of USRP.

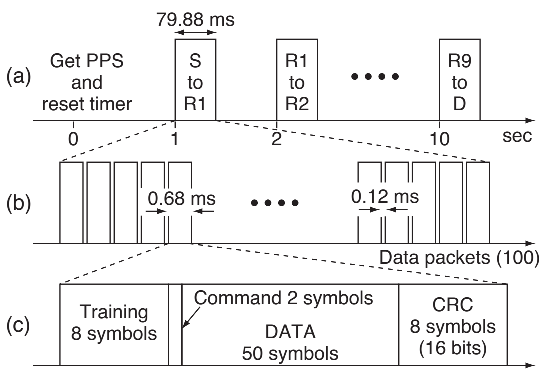

Fig. 5. Signaling format.

B. Signaling format

The signaling format is shown in Fig. 5. In our system, a general-purpose computer is used as the corresponding PC; therefore, time required for baseband IQ signal processing is not constant. To reduce the communication overhead between USRPs and PCs, we pack 100 packets into one block and put a long interval between transmissions to ensure proper signal processing on PC. In this system, timing synchronization is established by using the PPS signal from the GPSDO, however, this process requires more than one second. USRPs therefore acquire PPS signals and adjust timing in every 10-hop transmissions.

The format of packets is shown in Fig. 5 (c). The packet consists of the training sequence, command bits, the data sequence, and CRC symbols. Two orthogonal training sequences are allocated uniquely for each station. Except for the training sequences, the modulation scheme is QPSK. Command bits are utilized to control all stations from the source station. The data sequence is generated from a pseudo noise (PN) generator. CRC symbols are generated from command bits and the data sequence using the CRC-16 method.

At the transmitter side, all these symbols are 8x oversampled and pass through a root roll-off Nyquist filter with roll-off factor $\alpha = 0.7$, and are stored to IQ baseband arrays. At the receiver side, oversampled samples are utilized only for searching actual symbol points. These actual symbol points are estimated by a simple correlation technique using training sequences, and channel state informations (CSIs) are also acquired. Note that these processes are performed for each packet separately and independently.

TABLE II
MEASUREMENT SYSTEM PARAMETERS.

Parameters	Values
Number of hops	10
Radio frequency	5.109375 GHz
Modulation scheme	QPSK
Symbol rate	100 symbols/sec
Oversampling	8 samples/symbol
Packet length	68 symbols
Filter	Root roll-off Nyquist (Roll-off factor α = 0.7)
Demodulation scheme	low IF
STBC	Alamouti scheme
Error detection	CRC-16
PPS acquisition	every 11 seconds
Channel model	Rayleigh fading
Average path loss in each hop	59 dB
Doppler frequency	5 Hz

C. Other parameters

Parameters of the system are summarized in Table II. To avoid the DC offset and the IQ gain imbalance, low IF is employed in the system. We set the amplitude of symbols on PC as 0.3. We also set the receive gain of USRP as 20 dB. The transmit gain (Tx-gain) of USRP is varied by experiments.

The fading emulator emulates eight independent and identically distributed (i.i.d.) Rayleigh fading channels. In our system, however, these channels are utilized repeatedly in different hops. Propagation channels on even-numbered hops and odd-numbered hops are therefore correlated. These correlated channels are utilized every 2 seconds and the Doppler frequency of these fading channels are 5 Hz.

V. EXPERIMENTAL RESULTS

A. Single-hop performance

To confirm the performance of these implements, the single-hop BER and PER are measured. In our system, the source station transmits using QPSK without STBC, and relay stations transmit using STBC. The performance with STBC can be degraded from that without STBC because the channel estimation is not perfect. In single-hop experiments, USRP A and B shown in Fig. 2 transmitted in three mode, i.e., both USRPs transmit using STBC, one USRP transmits using STBC, and one USRP transmits without STBC.

Figs. 6 and 7 shows the single-hop BER and PER measured at USRP C. The theoretical BER performance of QPSK without cooperation is also presented in Fig. 6. As can be seen from Fig. 6, the performance degradation due to the channel estimation error etc. is not severe for modes without cooperation. We can see from Figs. 6 and 7 that the difference between the noncooperative transmission performance of with STBC and without STBC is ignorable. Also, we see from these figure that the error rate performance of STBC based cooperative transmission is better than that of noncooperative transmission.

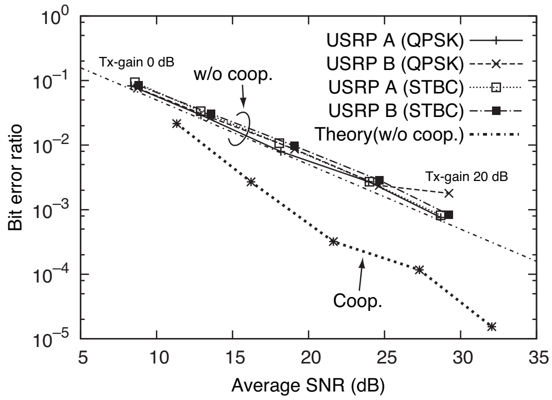

Fig. 6. Single-hop BER performance, where the receiver is USRP C.

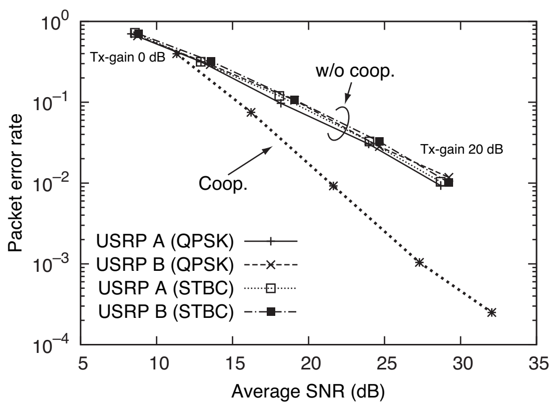

Fig. 7. Single-hop PER performance, where the receiver is USRP C.

B. 10-hop end-to-end PER

Fig. 8 shows the result of the end-to-end PER measurement. In this experiment, PER is measured only when data transfer between the USRP and the control PC finishes on time through 10-hop transmissions. We use the same setting in four USRPs. Average received SNR of USRPs were different since these USRPs are not cariblated.

The end-to-end PER shown in Fig. 8 are the average values of two PER measured on USRP A and B, or C and D in each hop. The theoretical end-to-end PER shown in Fig. 8 is calculated from (1). $P_2 = 5.6 \times 10^{-3}$ substituted for (1) is the average value of P_2 measured on every USRPs in every hops, and $P_1 = 9.7 \times 10^{-2}$ is the average value of P_1 measured on USRP C and D in the first hop.

From Fig. 8, we can see that the end-to-end PER performance improves until five hops. This improvement arises from cooperation among relay stations. In this system, there are two cooperative relay stations in each hop; therefore, even if one relay station do not forward packets, stations in the next hop can receive packets from another relay station. Also, we can see from Fig. 8 that the experimental end-to-end PER performance agrees with the theoretical end-to-end PER performance. Accordingly, the theoretical end-to-end PER performance is verified from this experiment. The difference between the PER performance of even-numbered hops and that of odd-numbered hops seen in the experimental result comes from the imbalance in performances among USRPs.

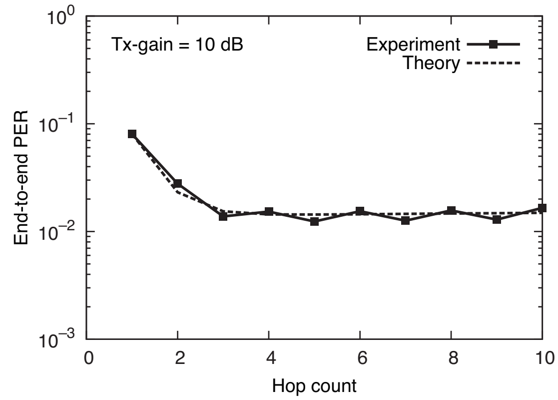

Fig. 8. End-to-end PER performance.

VI. Conclusion

In this paper, the end-to-end PER performance of the STBC based cooperative relaying system has been presented. The experimental results show that the end-to-end PER performance of this system can improve with the number of hops. In addition, the theoretical end-to-end PER performance is also verified from the experimental results.

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