Cyclic Delay Pilot Channel Estimation for Space-Time Block Coded AF Relay

Chikara ENDO†, Hiroyuki MIYAZAKI†, and Fumiyuki ADACHI‡
Dept. of Communications Engineering, Graduate School of Engineering, Tohoku University
6-6-05 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan
†{endo, miyazaki}@mobile.ecei.tohoku.ac.jp, ‡adachi@ecei.tohoku.ac.jp

***Abstract*—Recently, we proposed OFDM space-time block coded amplify-and-forward (STBC-AF) relay for unmanned aircraft (UA). For decoding STBC signals, the channel state information (CSI) is necessary at the destination ground station (GS). In this paper, we propose a cyclic delay pilot channel estimation (CDP-CE) for STBC-AF relay. Each of two UAs performs pilot removal, conjugate operation and multiplying cyclic delay pilot to the received pilot and then, amplifies and forwards it to the destination GS. At the destination GS, two equivalent relay channels, each of which is a concatenation of the source-to-UA link and the UA-to-destination link, is estimated simultaneously. We confirm, by the computer simulation, the effectiveness of proposed CDP-CE.**

Keywords—cyclic delay pilot channel estimation; space-time block coding; amplify-and-forward relay

I. INTRODUCTION

When a large scale disaster occurs, many base stations (BSs) will be destroyed and/or power supply to BSs is cut down and hence, connection to the network is lost in a wide area. In such a situation, wireless relay transmission system using unmanned aircrafts (UAs) can be used to provide the connection to the alive network quickly [1]. However, the fading caused by a flying UA makes source-to-relay link and relay-to-destination link unreliable [2]. The use of space-time block coded (STBC) diversity [3, 4] improves communication links.

Recently, we proposed an OFDM STBC amplify-and-forward (STBC-AF) relay [5] for UA system (UAS). STBC-AF relay is a combination of STBC diversity and AF relay. In the 1st time-slot, the source ground station (GS) broadcasts 2 signal blocks to two UAs. Then, two UAs perform AF-STBC encoding, which is transposed version of Alamouti STBC encoding matrix [3], on the 2 received signal blocks. In the 2nd time-slot, two UAs amplify and forward the STBC encoded 2 block signals to the destination GS. At the destination GS, a series of receive frequency-domain equalization (FDE), diversity combining and STBC decoding is performed by viewing the concatenation of the source-to-UA link and the UA-to-destination link as an equivalent channel.

In the STBC-AF relay, the channel state information (CSI) is not required at UAs but is required at the destination GS. In this paper, we propose a cyclic delay pilot channel estimation (CDP-CE) [6] for STBC-AF relay. Each of two UAs participating in STBC-AF relay performs pilot removal, conjugate operation and multiplying cyclic delay pilot to the received pilot and then, amplifies and forwards it to the destination GS. At the destination GS, two equivalent channels, each of which is a concatenation of the source-to-UA link and the UA-to-destination link, are estimated simultaneously by using pilot removal and delay time-domain windowing. We evaluate by computer simulation the throughput performance and the average BER performance to show the effectiveness of the proposed CDP-CE.

The rest of this paper is organized as follows. Sect. 2 overviews the STBC-AF relay and Sect. 3 presents CDP-CE for STBC-AF relay. The computer simulation results are discussed in Sect. 4. Sect. 5 offers some concluding remarks.

II. STBC-AF RELAY

In this paper, we consider OFDM-STBC-AF relay. OFDM-STBC-AF relay model is described in Fig.1. A group of UAs flying over the source GS and the destination GS forms single frequency network (SFN) to perform STBC-AF relay. We assume that the source GS has single antenna, each UA has single antenna and the destination GS equips with N_D antennas, respectively. Fig.2 shows the frame structure. We assumed that N_p pilot block is inserted in every N_B data blocks. Fig.3 shows behavior of STBC-AF relay. In the 1st time-slot, the source GS broadcasts a frame to UAs. At UAs, pilot removal, conjugate operation and cyclic delay pilot multiplication are performed to the received pilot block while AF-STBC encoding is carried out to the received data blocks. Then, UAs amplify and forward it to the destination GS in the 2nd time-slot. At the destination GS, two equivalent channels are estimated simultaneously by performing pilot removal and delay time-domain windowing to the received pilot block. Then, a series of FDE, diversity combining and STBC decoding is carried out to the received data blocks.

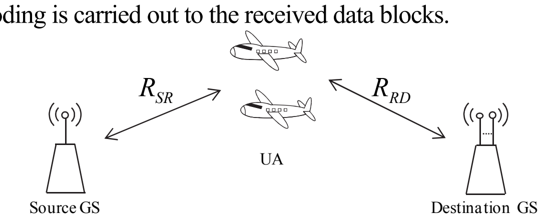

Fig. 1. OFDM-STBC-AF relay model.

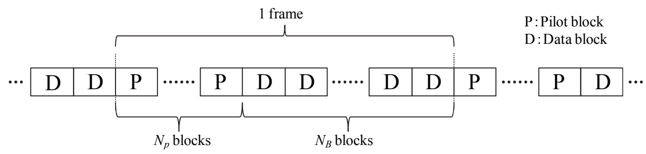

Fig. 2. Frame structure.

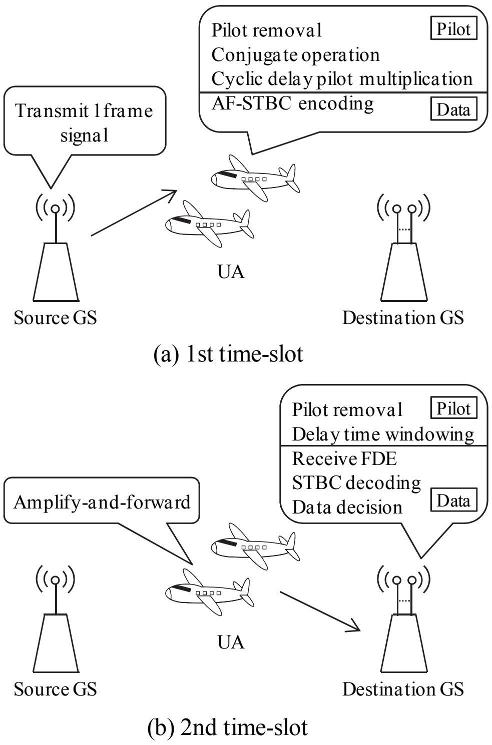

Fig. 3. Behavior of OFDM-STBC-AF relay.

A. Signal processing to data blocks

Fig.4 shows the source GS /UA/destination GS structures. Below, the symbol-spaced discrete time signal representation is used.

At the source GS, the transmit symbol sequence is divided into uncoded 2 signal blocks of N_c symbols each and then, OFDM signal is generated by N_c-point inverse fast Fourier transform (IFFT). After inserting cyclic prefix (CP) into the beginning of each block, the source GS broadcasts uncoded 2 OFDM signal to UAs in the 1st time-slot. At UAs, after CP removal, the received signal is divided into N_c subcarriers by N_c-point fast Fourier transform (FFT) and then, the 0th UA keeps the received signal as it stands while the 1st UA performs conjugate operation and block exchange to the received signal. These operations correspond to AF-STBC encoding [5]. Representing the kth subcarrier received signal at UAs as $R_{R,m}(n_R,k)$ $\{k=0,\ldots,N_c-1,\ m=0,1,\ n_R=0,1\}$, AF-STBC encoded signal matrix $\mathbf{X}_R(k)$ can be expressed as

$$\mathbf{X}_R(k)=\begin{pmatrix} R_{R,0}(0,k) & R_{R,1}(0,k) \\ -R^*_{R,1}(1,k) & R^*_{R,0}(1,k) \end{pmatrix}, \quad (1)$$

The AF-STBC encoded signal is transformed back to the OFDM signal by N_c-point IFFT. After CP insertion UAs amplify and forward the signal to the destination GS in the 2nd time-slot. At the destination GS, after CP removal, the received signal is divided into N_c subcarriers by N_c-point FFT. The N_D×2 kth subcarrier received signal matrix at the destination GS in the 2nd time-slot is represented as $\mathbf{R}_D(k)$. $\mathbf{R}_D(k)$ can be expressed as [5]

$$\mathbf{R}_D(k)=\left(\mathbf{H}_{SRD}(0,k)\quad \mathbf{H}_{SRD}(1,k)\right)\begin{pmatrix} S_0(k) & S_1(k) \\ -S_1^*(k) & S_0^*(k) \end{pmatrix}+\mathbf{N}_D(k), \quad (2)$$

where $\{S_m(k)\ :\ k=0,\ldots,N_c-1,\ m=0,1\}$ is the kth subcarrier component of the mth OFDM transmit signal. $\mathbf{H}_{SRD}(n_R,k)$ is the N_D×1 equivalent channel of the source-to-the n_Rth UA-to-destination link. It can be expressed as

$$\begin{cases} \mathbf{H}_{SRD}(0,k)=H_{SR}(0,k)\mathbf{H}_{RD}(0,k) \\ \mathbf{H}_{SRD}(1,k)=H^*_{SR}(1,k)\mathbf{H}_{RD}(1,k) \end{cases}, \quad (3)$$

where $H_{SR}(n_R,k)$ is the channel gain between the source GS and the n_Rth UA. $\mathbf{H}_{RD}(n_R,k)=G(n_R)\left[H_{RD}(n_R,0,k),\ldots,H_{RD}(n_R,N_D-1,k)\right]^T$ is the N_D×1 channel gain matrix between the n_Rth UA and the destination GS and $H_{RD}(n_R,n_D,k)$ is the channel gain between the n_Rth UA and the n_Dth destination GS antenna. $G(n_R)$ is amplification factor of the n_Rth UA. $\mathbf{N}_D(k)$ is the N_D×2 noise matrix including the noise amplified and forward by UAs and the noise at the destination GS. Each element of the noise matrix is zero mean complex-valued additive white Gaussian noise (AWGN) having variance $2N_0/T_s$ with N_0 and T_s being the single-sided power spectrum density of AWGN and the symbol duration, respectively. At the destination GS, a series of receive FDE, diversity combining, STBC decoding and finally, data demodulation is performed.

B. Channel state information required at the destination GS

It is seen from (2) that the equivalent channel $\mathbf{H}_{SRD}(n_R,k)$ of the source-to-UA-to-destination link are only required at the destination GS to perform a series of receive FDE, diversity combining and STBC decoding. This means that the destination GS does not have to estimate the channels of source-to-UA link and UA-to-destination link separately. It is seen from (3) that the equivalent channel $\mathbf{H}_{SRD}(0,k)$ is a concatenation of the channel of source-to-UA link and that of UA-to-destination link while the equivalent channel $\mathbf{H}_{SRD}(1,k)$ is a concatenation of the conjugate version of the channel of source-to-UA link and that of UA-to-destination link. These two equivalent channels can be estimated simultaneously by using CDP-CE [6].

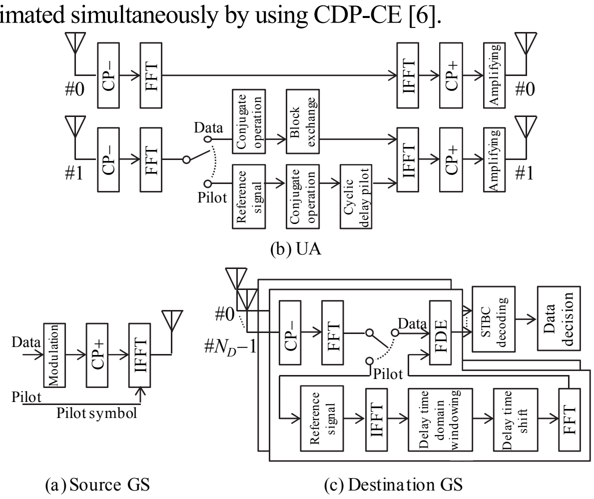

Fig. 4. Source GS/UA/destination GS structures.

III. Cyclic Delay Pilot Channel Estimation

In this paper, we propose cyclic relay pilot channel estimation for STBC-AF relay. In this channel estimation, the source GS broadcasts a pilot block to UAs in the 1st time-slot. At UAs, the 0th UA keeps the received signal as it stands while the 1st UA performs pilot removal, conjugate operation and cyclic delay pilot multiplication to the received pilot signal. Then, UAs amplify and forward it to the destination GS in the 2nd time-slot. At the destination GS, the two equivalent channels of source-to-UA-to-destination link are simultaneously estimated by using pilot removal and delay time-domain windowing [7]. In this scheme, pilot removal and conjugate operation are performed at the 1st UA to obtain the conjugate version of the channel of source-to-UA link. Then, cyclic delay pilot multiplication is performed at the 1st UA to estimate two equivalent channels simultaneously at the destination GS. In this scheme, pilot removal, conjugate operation and cyclic delay pilot multiplication are only required at UA. Therefore, the structure of UA can be kept simple. Furthermore, two equivalent channels of source-to-UA-to-destination link can be estimated simultaneously.

A. Channel estimation of the source-to-UA-to-destination link

At the source GS, a transmit pilot block of N_c symbols is generated. After CP insertion, the source GS broadcasts the pilot signal to UAs. At UAs, after CP removal, the received signal is transformed into the frequency-domain signal by N_c-point FFT. Representing the frequency-domain received pilot signal of the n_Rth UA as $\{Y_R(n_R,k)\ ;k=0,\ldots,N_c-1\}$, the frequency-domain received pilot signal vector $\mathbf{Y}_R(k)=[\,Y_R(0,k)\,,Y_R(1,k)\,]^T$ at UAs can be expressed as

$$\mathbf{Y}_R(k)=\mathbf{H}_{SR}(k)P(k)+\mathbf{Z}_R(k)\,, \tag{4}$$

where $\mathbf{H}_{SR}(k)=[H_{SR}(0,k),H_{SR}(1,k)]^T$ is the 2×1 channel gain matrix between the source GS and UA. $\mathbf{Z}_R(k)=[\,Z_R(0,k)\,,Z_R(1,k)\,]^T$ is the noise vector at UAs and $Z_R(n_R,k)$ is the zero mean complex-valued AWGN having variance $2N_0/T_s$.

Then, the 0th UA keeps the received signal as it stands while the 1st UA performs pilot removal, conjugate operation and cyclic delay pilot multiplication to the received pilot signal. The transmit pilot signal vector $\mathbf{P}_R(k)=[P_R(0,k), P_R(1,k)]^T$ at UAs is given as

$$\begin{aligned}\mathbf{P}_R(k)&=\begin{pmatrix} Y_R(0,k) \\ \left(\dfrac{Y_R(1,k)}{P(k)}\right)^{*} P(k)\exp\left(-j\dfrac{2\pi k\theta}{N_c}\right)\end{pmatrix}\\ &=\begin{pmatrix} H_{SR}(0,k) \\ H^{*}_{SR}(1,k)\exp\left(-j\dfrac{2\pi k\theta}{N_c}\right)\end{pmatrix}P(k)+\mathbf{Z}'_R(k)\end{aligned}\;, \tag{5}$$

where θ is the number of cyclic delay samples. $\mathbf{Z}'_R(k)=[\,Z'_R(0,k)\,,Z'_R(1,k)\,]^T$ is the noise vector after performing pilot removal, conjugate operation, and cyclic delay pilot multiplication. The frequency-domain transmit pilot signal is transformed into the time-domain signal by N_c-point IFFT. After CP insertion, UAs amplify and forward the signal to the destination GS.

At the destination GS, after CP removal, the received signal in the 2nd time-slot is transformed into the frequency-domain signal by N_c-point FFT. Representing the frequency-domain received pilot signal at the n_Dth destination GS antenna as $\{Y_D^{2nd}(n_D,k)\,;k=0,\ldots,N_c-1,\ n_D=0,\ldots,N_D-1\}$, the frequency-domain received pilot signal vector $\mathbf{Y}_D^{2nd}(k)=[\,Y_D^{2nd}(0,k)\,,\ldots,Y_D^{2nd}(N_D-1,k)\,]^T$ can be expressed as

$$\mathbf{Y}_D^{2nd}(k)=\mathbf{H}_{RD}(k)\mathbf{P}_R(k)+\mathbf{Z}_D^{2nd}(k)\,, \tag{6}$$

where $\mathbf{H}_{RD}(k)=[\,\mathbf{H}_{RD}(0,k)\,,\mathbf{H}_{RD}(1,k)\,]$ is the N_D×2 channel gain matrix between the source GS and UAs. $\mathbf{Z}_D^{2nd}(k)=[\,Z_D^{2nd}(0,k),\ldots,Z_D^{2nd}(N_D-1,k)\,]^T$ is the noise vector in the 2nd time-slot and $Z_D^{2nd}(n_D,k)$ is the zero mean complex-valued AWGN having variance $2N_0/T_s$. From (3) and (5), (6) can be written as

$$\begin{aligned}\mathbf{Y}_D^{2nd}(k)&=\left\{\mathbf{H}_{SRD}(0,k)+\mathbf{H}_{SRD}(1,k)\exp\left(-j\dfrac{2\pi k\theta}{N_c}\right)\right\}P(k)\\ &\quad+\mathbf{Z}'^{2nd}_D(k)\end{aligned}\;, \tag{7}$$

where $\mathbf{Z}'^{2nd}_D(k)$ is the noise vector which includes the noise amplified and forwarded by UAs and the noise at the destination GS. The destination GS estimates the composite channel by performing pilot removal to the received cyclic delay pilot signal. The composite channel estimate $\hat{\mathbf{H}}_{comp}(k)$ is given as

$$\hat{\mathbf{H}}_{comp}(k)=\frac{\mathbf{Y}_D^{2nd}(k)}{P(k)}\,. \tag{8}$$

Then, the composite channel estimate is transformed into the time-domain signal by N_c-point IFFT and the destination GS obtains the composite channel impulse response estimate $\{\hat{h}_{comp}(n_D,\tau)\ :\ n_D=0,\ldots,N_D-1,\ \tau=0,\ldots,N_c-1\}$. The composite channel impulse response estimate can be expressed as

$$\begin{aligned}\hat{h}_{comp}(n_D,\tau)&=h_{SRD}(0,n_D,\tau)\\ &\quad+h_{SRD}(1,n_D,(\tau-\theta)\bmod N_c)+z'^{2nd}_D(\tau)\end{aligned}\;, \tag{9}$$

where $h_{SRD}(n_R,n_D,\tau)$ is the impulse response of the equivalent channel of the source-to-the n_Rth UA-the n_Dth destination GS antenna link. Fig. 5 shows the magnitude of composite channel impulse response estimate. The channel is assumed to be L=8-path frequency-selective Nakagami-Rice fading having Rician K-factor of K=10dB. The number of cyclic delay samples is set to θ=32. It is seen from (9) and Fig.5 that two impulse responses of equivalent channel are orthogonal in delay time-domain. Therefore, two impulse responses of equivalent channel can be separated by performing delay time-domain windowing and delay time shift removal. It is also seen from Fig.5 that the impulse response $h_{SRD}(1,n_D,\tau)$ of the equivalent channel is spread over $\theta-L<\tau<\theta+L$ while the impulse response $h_{SRD}(0,n_D,\tau)$ of the equivalent channel is spread over $0<\tau<2L$. This is because the equivalent channel $\mathbf{H}_{SRD}(1,k)$ is a concatenation of the conjugate version of the channel of source-to-UA link and that of UA-to-destination link. Therefore, the number of cyclic delay samples should be set so as to satisfy $3N_g<\theta<N_c-N_g$ to avoid interference between two impulse

responses of equivalent channel. The impulse response estimate of the equivalent channel $\{ h_{SRD}^{est}(n_R, n_D, \tau)$:n_R=0,1, n_D=0,…,N_D−1, τ=0,…,N_c−1} after delay time-domain windowing is given as

$$h_{SRD}^{est}(0, n_D, \tau) = \begin{cases} \hat{h}_{comp}(n_D, \tau) & \text{if } 0 \le \tau < 2N_g \\ 0 & \text{if } 2N_g \le \tau < N_c \end{cases}$$
$$h_{SRD}^{est}(1, n_D, \tau) = \begin{cases} \hat{h}_{comp}(n_D, \tau - \theta) & \text{if } 0 \le \tau < N_g \\ 0 & \text{if } N_g \le \tau < N_c - N_g \\ \hat{h}_{comp}(n_D, \tau - \theta + N_c) & \text{if } N_c - N_g \le \tau < N_c \end{cases} \quad ,(10)$$

Finally, the impulse response estimate of equivalent channel is transformed into frequency-domain signal by N_c-point FFT to obtain the equivalent channel estimate of the source-the n_Rth UA-destination link $\mathbf{H}_{SRD}^{est}(n_R, k)$ =[$H_{SRD}^{est}(n_R, 0, k)$,…, $H_{SRD}^{est}(n_R, N_D - 1, k)$].

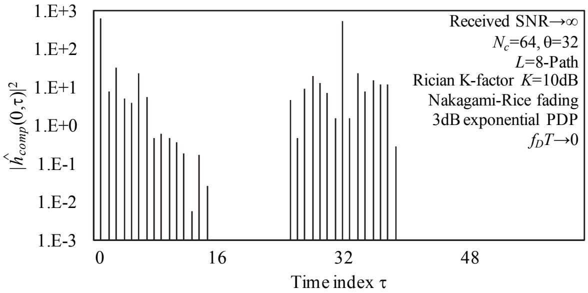

Fig. 5. Composite channel inpulse response (0th destination antenna).

IV. Computer Simulation

We evaluate, by computer simulation, throughput performance and the average BER performance of the STBC-AF relay when using proposed CDP-CE. The simulation conditions are summarized in Table I.

We consider QPSK data modulation. FFT block size N_c and CP length N_g are set to N_c=64 symbols and N_g=16 samples, respectively. The channel is assumed to be a K=10dB frequency-selective Nakagami-Rice fading having symbol spaced L=8 path 3dB exponential power delay profile [8].

TABLE I. Computer simulation conditions

Transmission model	Data Modulation	QPSK
	FFT block size	N_c=64
	CP length	N_g=16
	No. of block	N_B=12
Channel model	Channel estimation	CDP-CE, Ideal
	Fading type	Nakagami-Rice fading
	K-factor	K=10dB
	Power delay profile	3dB exponential PDP
	No. of paths	Symbol spaced L=8

A. *Throughput performance*

Fig. 6 shows the throughput performance as a function of the received SNR when using proposed CDP-CE. For the comparison, the performance of perfect CSI case is also plotted in Fig.6 (Ideal). In this paper, using packet error rate (PER), we calculate throughput (bps/Hz) as

$$\text{Throughput} = \frac{M(1 - PER)}{2}\left(\frac{N_c}{N_c + N_g}\right)\left(\frac{N_c N_B}{N_c N_B + N_c N_P}\right),(11)$$

where M is the number of bits per symbol and N_P=2 is the number of pilot blocks per frame. The channel is assumed to be a quasi-static fading channel (i.e., Doppler frequency f_D→0). It is seen from Fig. 6 that the throughput performance improves as the number of destination GS antennas increases in both cases of CDP-CE and Ideal. For example, Increasing the number of destination GS antennas from 1 to 2 can reduce the receive SNR for the throughput of 0.6bps/Hz about 1.8dB. This is because higher spatial diversity gain can be obtained by increasing the number of destination GS antennas. It is also seen from Fig. 6 that the proposed CDP-CE can achieve about 0.8dB receive SNR degradation from perfect CSI case.

B. *Inpact of Doppler frequency*

Fig.7 shows the average BER performance as a function of the normalized Doppler frequency f_DT when using proposed CDP-CE, where T=(N_c+N_g)T_s denotes OFDM symbol length with T_s being sampling duration. The receive E_b/N_0 at UAs and destination GS is set to E_b/N_0=15dB. For the comparison, the performance when using conventional AF relay [9, 10] is also plotted in Fig.7. It is seen from Fig.7 that, in Ideal CSI case, STBC-AF relay underperforms the conventional AF relay when f_DT>4.0×10^{-2} while STBC-AF relay outperforms the conventional AF relay when f_DT<4.0×10^{-2}. The reason for this is explained below. In low f_DT region, the performance depends on the received SNR at the destination GS. In STBC-AF relay, spatial diversity gain can be obtained by STBC diversity. Therefore, STBC-AF relay can achieve higher received SNR than the conventional AF relay and accordingly, it achieve improved performance. On the other hand, in high f_DT region, the performance depends on signal-to-interference ratio (SIR) rather than SNR because interference is caused by rapid channel variation. In particular, STBC-AF relay suffers from not only inter-carrier interference but also interference due to the orthogonaloty distortion of STBC codeword [11]. Therefore, STBC-AF relay underperforms the conventional AF relay in high f_DT region. It is seen from Fig. 7 that, in CDP-CE case, STBC-AF relay achieves the same performance as AF relay in high f_DT region. This is because, in CDP-CE case, the performance in high f_DT region depends on channel estimation error rather than the interference caused by rapid channel variation. It is also seen from Fig. 7 that the allowable normalized Doppler frequency for BER=10^{-3} is f_DT=1.0×10^{-2} in both STBC-AF relay and the conventional AF relay. Assuming carrier frequency of 5GHz and transmission band width of 20MHz, f_DT=1.0×10^{-2} corresponds to the velocity of 100km/h. It is known that the velocity of UA is lower than 100km/h [12]. Therefore, we can say that STBC-AF relay using CDP-CE can achieve better transmission performance than the conventional AF relay using CDP-CE even in actual UA based wireless relay communication.

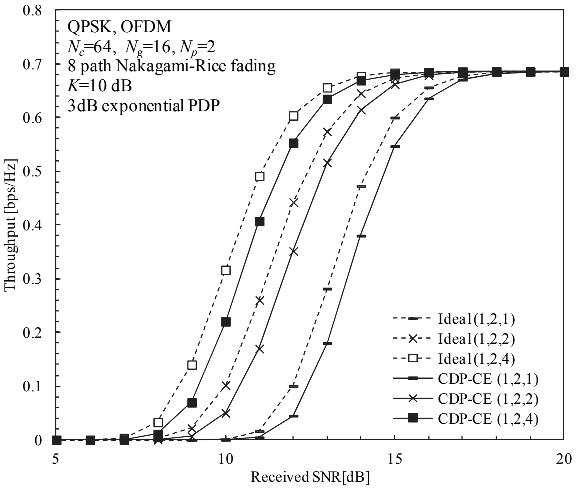

Fig. 6. Throughput performance

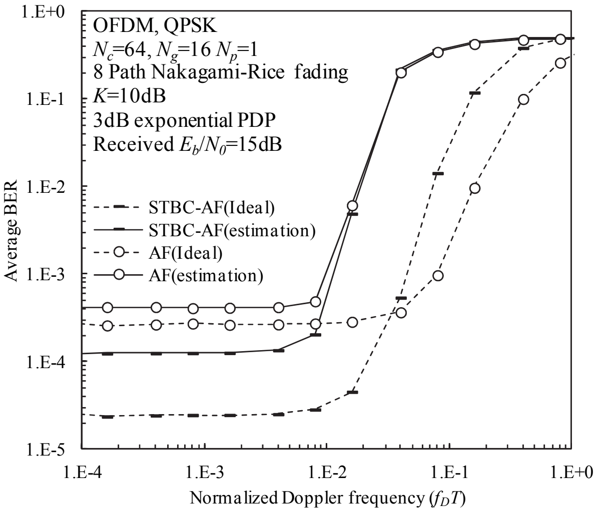

Fig. 7. Impact of Doppler frequency

V. Conclusion

In this paper, we proposed CDP-CE for STBC-AF relay. In proposed CDP-CE, UAs perform pilot removal, conjugate operation and cyclic delay pilot multiplication to the received pilot signal and then, amplifies and forwards it to the destination GS. At the destination GS, two equivalent channels are estimated simultaneously by using pilot removal and delay time-domain windowing. We showed, by the computer simulation, that CDP-CE can achieve about 0.8dB receive SNR degradation from perfect CSI case. It was also shown that STBC-AF relay using CDP-CE can achieve sufficient allowable normalized Doppuler frequency for UA based wireless relay communication.

Acknowledgment

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