Adaptive Space-time Block Coded Transmit Diversity in a High Mobility Environment

Tomoyuki SAITO, Amnart BOONKAJAY and Fumiyuki ADACHI
Research Organization of Electrical Communication, Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai, 980-8577 Japan
E-mail: saito.tmm@riec.tohoku.ac.jp, amnart@riec.tohoku.ac.jp, adachi@ecei.tohoku.ac.jp

Abstract—**Space-time block coded transmit diversity (STBC-TD) with minimum mean square error frequency-domain equalization (MMSE-FDE) and maximal-ration transmit FDE (MRT-FDE) can improve the bit error rate (BER) performance in a frequency-selective fading. Since the MMSE-FDE/MRT-FDE weights are computed by pilot-aided channel estimation (PACE) before data transmission, the BER performance degrades in a high mobility environment. In this paper, we propose an adaptive STBC-TD employing decision feedback channel estimation (DFCE) for single-carrier (SC) uplink and orthogonal frequency-division multiplexing (OFDM) downlink transmissions. Computer simulation results show that the use of DFCE increases an allowable maximum Doppler frequency, f_DT, for keeping the BER<10^{-2} by about 5.5 times for SC uplink and 3.8 times for OFDM downlink compared to the use of PACE only.**

Keywords—space-time block coded diversity, decision feedback channel estimation, TDD, SC, OFDM

I. INTRODUCTION

In the 5th generation (5G) mobile communication systems, the enhanced mobile broadband services are expected [1]. However, the severely doubly-selective fading substantially deteriorates the bit error rate (BER). One promising technique to improve the BER performance in a poor propagation environment is the space time block coded transmit diversity (STBC-TD) which allows to use multiple antennas at both base station (BS) and user equipment (UE) [2, 3] (therefore, an arbitrary high diversity order can be obtained by increasing the number of either BS or UE antennas). In this paper, we consider STBC-TD jointly used with the minimum mean square error frequency-domain equalization (MMSE-FDE) [4-6] for SC uplink transmission and that jointly used with maximum ratio transmit frequency-domain equalization (MRT-FDE) [7, 8] for OFDM downlink transmission. All the computationally demanded signal processing required for MMSE-FDE and MRT-FDE is implemented at BS. While limiting the number of UE antennas to N_{ue}=2, an arbitrary number N_{bs} of BS antennas can be used to achieve larger spatial diversity gain without reducing the STBC code rate [8-10].

The BS needs the channel state information (CSI) in order to compute the MMSE-FDE weight and the MRT-FDE weight before data transmission. Assuming time-division duplex (TDD) subframe structure shown in Fig. 1 [11], the UE transmits the uplink frequency-division multiplexed (FDM) pilot for pilot-aided channel estimation (PACE) in the first time slot (t=0) and then, the BS transmits the FDM pilot for PACE in second time slot (t=1). In a quasi-static fading channel environment, the MMSE-FDE weight for SC uplink and the MRT-FDE weight for OFDM downlink computed at t=0 can be used for succeeding data transmission period (t=2~13). In a high mobility environment, however, the BER performance degrades since the channel changes over the period of data transmission.

In this paper, we propose an adaptive STBC-TD in a high mobility environment. The well-known simple Alamouti 2×2 STBC encoding/decoding is considered. The adaptive STBC-TD employs decision feedback channel estimation (DFCE) in addition to PACE to update the MMSE-FDE weight for SC uplink and to keep the equivalent channel gain (i.e., a concatenation of MRT-FDE and the propagation channel) close to that at t=1 for OFDM downlink. The effectiveness of proposed adaptive STBC-TD is confirmed by computer simulation.

This paper is organized as follows. Sect. II proposes the adaptive STBC-TD. The BER performance achievable with the proposed adaptive STBC-TD is evaluated by computer simulation in Sect. III. Sect. IV offers some concluding remarks.

Notations: $[.]^*$ and $[.]^H$ represent complex conjugate and Hermitian transpose operations, respectively.

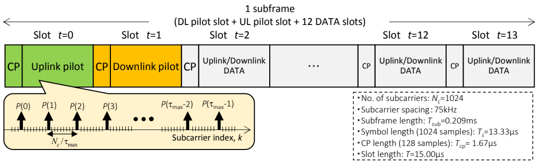


Fig. 1. TDD subframe structure
(1^{st} pilot slot + 2^{nd} pilot slot + 12 user data slots).

II. ADAPTIVE STBC-TD

We firstly describe how to initially set the MMSE-FDE weight and MRT-FDE weight and then, describe DFCE.

A. *Initial setting of MMSE-FDE and MRT-FDE*

BS and UE are assumed to be equipped with N_{bs} antennas and N_{ue}=2 antennas, respectively. By exploiting the channel reciprocity due to TDD, the BS can compute the initial MMSE-FDE weight for SC uplink reception and the initial MRT-FDE weight for OFDM downlink transmission. The initial MMSE-FDE weight and MRT-FDE weight can be computed by PACE at the first time slot t=0 as [11]

$$W_{\rm mmse}\left(k;n_{\rm ue},n_{\rm bs}\right) = \left(\begin{array}{l}\displaystyle\sum_{n_{\rm ue}=0}^{N_{\rm ue}-1}\sum_{n_{\rm bs}=0}^{N_{\rm bs}-1}\left|\hat{H}^*\left(k;t=0,n_{\rm bs},n_{\rm ue}\right)\right|^2 \\ \displaystyle +\left(\frac{1}{N_{\rm ue}}\frac{E_s}{N_0}\right)^{-1}\end{array}\right)^{-1} \times\hat{H}^*\left(k;t=0,n_{\rm bs},n_{\rm ue}\right) \quad \text{for MMSE-FDE, (1)}$$

$$W_{\rm mrt}\left(k;n_{\rm bs},n_{ue}\right) = \frac{\hat{H}^*\left(k;t=0,n_{\rm bs},n_{\rm ue}\right)}{\sqrt{\displaystyle\frac{1}{N_c}\sum_{k=0}^{N_c-1}\sum_{n_{\rm bs}=0}^{N_{\rm bs}-1}\sum_{n_{\rm ue}=0}^{N_{\rm ue}-1}\left|\hat{H}\left(k;t=0,n_{\rm bs},n_{\rm ue}\right)\right|^2}} \quad \text{for MRT-FDE, (2)}$$

where $\hat{H}(k;t=0,n_{\rm bs},n_{\rm ue})$ is the ($n_{\rm bs}$, $n_{\rm ue}$)-th element of $N_{\rm bs}\times N_{\rm ue}$ multi-input multi-output (MIMO) channel matrix estimated at t=0. E_s and N_0 are respectively the symbol energy and the single-sided additive white Gaussian noise (AWGN) power spectrum density. N_c and k (=0~N_c−1) denote respectively the number of subcarriers and the subcarrier index.

B. STBC-TD transmission

Figures 2 and 3 illustrate the STBC-TD transmission system model for SC uplink and for OFDM downlink, respectively. Below, STBC encoding/decoding for SC uplink with MMSE-FDE and that for OFDM downlink with MRT-FDE are briefly described. For detailed STBC-TD transmission operation, refer to Ref.[10]. Alamouti 2×2 STBC coding is generally 2-block wise processing and hence, we explain the signal representation by considering transmission over two consecutive slot time period t=2m and t=2m+1 with m=1~6.

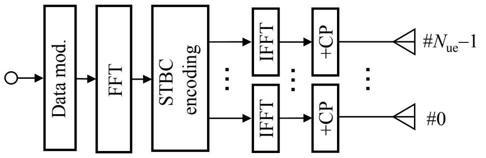
(1) SC uplink

2 consecutive symbol blocks {$d(t';\ t)$; t'=0~N_c−1} with t' representing time instant in a block, to be transformed by N_c-point fast Fourier transform (FFT) into the frequency-domain signals {$D(k;\ t)$; k=0~N_c−1}, where k represents the subcarrier index. After 2×2 Alamouti STBC encoding [2] in the frequency-domain and N_c-point inverse fast Fourier transform (IFFT), STBC-encoded SC signals are transmitted from $N_{\rm ue}$=2 antennas and are received by $N_{\rm bs}$ (=arbitrary) BS antennas.

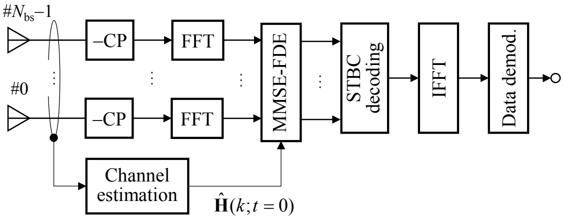
The STBC-encoded SC received signals after N_c-point FFT are denoted by {$R(k;\ n_{\rm bs},\ t)$; $n_{\rm bs}$=0~$N_{\rm bs}$−1}. MMSE-FDE combining using weights given by eq. (1) is applied to $\{R(k;n_{\rm bs},t);n_{\rm bs}=0\sim N_{\rm bs}-1\}$ to obtained the diversity combined outputs $\{\hat{R}\left(k;n_{\rm ue},t\right);n_{\rm ue}=0,1\}$. Then, STBC decoding is applied to obtain the frequency-domain signals $\{\hat{D}(k;t);k=0\sim N_c-1\}$ as

$$\hat{\mathbf{D}}(k;t=2m)=\begin{bmatrix}\hat{D}\left(k;t=2m\right)\\ \hat{D}\left(k;t=2m+1\right)\end{bmatrix} =\begin{bmatrix}\hat{R}\left(k;0,t=2m\right)+\hat{R}^*\left(k;1,t=2m+1\right)\\ \hat{R}\left(k;1,t=2m\right)-\hat{R}^*\left(k;0,t=2m+1\right)\end{bmatrix}. \quad (3)$$

Finally, N_c-point IFFT is applied to obtain the soft-decision symbol blocks $\{\hat{d}(t';t=2m)\}$ and $\{\hat{d}(t';t=2m+1)\}$.



(a) Transmitter



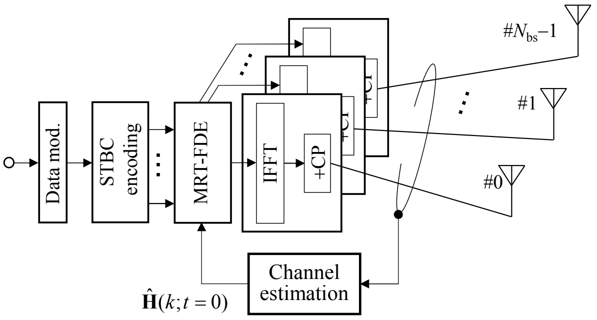
(b) Receiver

Fig. 2. STBC-TD transmission system model for SC uplink with MMSE-FDE.

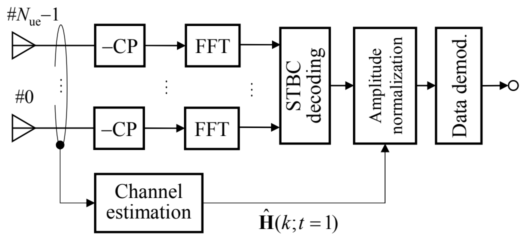
(2) OFDM downlink

2 consecutive symbol blocks {$d(k;\ t)$; k=0~N_c−1} and to be transmitted are STBC-encoded, mapped onto frequency-domain, and then multiplied by the MRT-FDE weight given by eq. (2). After N_c-point IFFT, the STBC-encoded OFDM signals are transmitted from $N_{\rm bs}$ (=arbitrary) BS antennas and are received by $N_{\rm ue}$=2 UE antennas. The STBC-encoded OFDM received signals after N_c-point FFT are denoted by $\{R(k;n_{\rm ue},t);n_{\rm ue}=0,1\}$. STBC decoding and amplitude-normalization are applied to obtain the soft-decision symbol blocks $\{\hat{d}(k;t=2m)\}$ and $\{\hat{d}(k;t=2m+1)\}$ as

$$\hat{\mathbf{d}}(k;t=2m)=\begin{bmatrix}\hat{d}\left(k;t=2m\right)\\ \hat{d}\left(k;t=2m+1\right)\end{bmatrix} =\frac{\sqrt{\displaystyle\frac{1}{N_c}\sum_{k=0}^{N_c-1}\sum_{n_{\rm bs}=0}^{N_{\rm bs}-1}\sum_{n_{\rm ue}=0}^{N_{\rm ue}-1}\left|\hat{H}\left(k;t=1,n_{\rm bs},n_{\rm ue}\right)\right|^2}}{\displaystyle\sum_{n_{\rm bs}=0}^{N_{\rm bs}-1}\sum_{n_{\rm ue}=0}^{N_{\rm ue}-1}\left|\hat{H}\left(k;t=1,n_{\rm bs},n_{\rm ue}\right)\right|^2} \times\begin{bmatrix}R(k;0,t=2m)+R^*(k;1,t=2m+1)\\ R(k;1,t=2m)-R^*(k;0,t=2m+1)\end{bmatrix}. \quad (4)$$



(a) Transmitter



(b) Receiver

Fig. 3. STBC-TD transmission system model for OFDM downlink with MRT-FDE.

C. *Updating uplink receive MMSE-FDE weight and downlink receive filter by DFCE*

In a high mobility environment, if the MMSE-FDE weight, MRT-FDE weight, and amplitude normalization, described in Sect. II-A and II-B, are used continuously during the data transmission period (i.e., t=2m, 2m+1; m=1~6), the BER performance degrades significantly. During the data transmission, MMSE-FDE weight for SC uplink can be updated by introducing DFCE, however, the MRT-FDE weight for OFDM downlink cannot be updated. Therefore, we introduce an adaptive receive filter to compensate the received signal channel variations. Below, we describe how the MMSE-FDE weight for SC uplink reception and the adaptive receive filter for downlink reception are updated.

(1) MMSE-FDE weight updating for SC uplink

The MMSE-FDE weight given by Eq. (1) can be used for the signal reception at t=2 and 3 (i.e., m=1) only. For the signal reception at t=4 and afterwards, the MMSE-FDE weight is updated by either 1st-order linear prediction (1st-order LP) or the 2nd-order linear prediction (2nd-order LP) DFCE [11].

Let us assume that STBC decoding and symbol decision are completed. In DFCE, firstly, the reverse modulation is applied to the frequency-domain received signal matrix $\mathbf{R}(k;t=2m)=[\mathbf{R}(k;t=2m),\mathbf{R}(k;t=2m+1)]$ of size $N_{\mathrm{bs}}\times 2$ with m=1~6, obtained after N_c-point FFT, to estimate the channel matrix $\mathbf{H}(k;t=2m)$ at t=2m as

$$\mathbf{H}'(k;t=2m)=\mathbf{R}(k;t=2m)\bar{\mathbf{D}}^H(k;t=2m)\times\left(\bar{\mathbf{D}}(k;t)\bar{\mathbf{D}}^H(k;t)+\mathbf{I}_{N_{\mathrm{ue}}}\left(\frac{E_s}{N_0}\right)^{-1}\right)^{-1}, \tag{6}$$

where $\bar{\mathbf{D}}(k;t=2m)$ is the frequency-domain STBC-encoded signal matrix given by

$$\bar{\mathbf{D}}(k;t=2m)=\begin{pmatrix}\bar{D}(k;t=2m) & -\bar{D}^*(k;t=2m+1)\\ \bar{D}(k;t=2m+1) & \bar{D}^*(k;t=2m)\end{pmatrix}, \tag{7}$$

with $\{\bar{D}(k;t);k=0\sim N_c-1\}$ being the N_c-point FFT of the t-th hard decision data symbol block $\{\bar{d}(k;t);k=0\sim N_c-1\}$ in the two consecutive slot time t=2m and 2m+1. Then, moving average operation with window size W is applied to reduce the negative impact of the noise and decision error and to obtain the improved channel estimate at t=2m+2 as

$$\tilde{\mathbf{H}}(k;t=2m)=\frac{1}{W}\sum_{w=-W/2}^{W/2}\mathbf{H}'(k+w;t=2m). \tag{8}$$

The channel estimate at t=2m+2 is obtained by the 1st-order LP or 2nd-order LP as

$$\hat{\mathbf{H}}(k;t=2m+2)=\begin{cases}\tilde{\mathbf{H}}(k;t=2m) & :1^{\mathrm{st}}\text{-order LP}\\ 2\tilde{\mathbf{H}}(k;t=2m)-\tilde{\mathbf{H}}(k;t=2m-2) & :2^{\mathrm{nd}}\text{-order LP}\end{cases}. \tag{9}$$

The above obtained channel estimates $\hat{\mathbf{H}}(k;t=2m)$ and $\hat{\mathbf{H}}(k;t=2m+1)$ are used to update the MMSE-FDE weight for the signal reception at t=2m and t=2m+1 (m=1~6) as follows.

$$W_{\mathrm{mmse}}(k;t=2m,n_{\mathrm{ue}},n_{\mathrm{bs}})=W_{\mathrm{mmse}}(k;t=2m+1,n_{\mathrm{ue}},n_{\mathrm{bs}})=\left(\sum_{n_{\mathrm{ue}}=0}^{N_{\mathrm{ue}}-1}\sum_{n_{\mathrm{bs}}=0}^{N_{\mathrm{bs}}-1}\left|\hat{H}(k;t=2m-2,n_{\mathrm{bs}},n_{\mathrm{ue}})\right|^2+\left(\frac{1}{N_{\mathrm{ue}}}\frac{E_s}{N_0}\right)^{-1}\right)^{-1}\times\left(\hat{H}(k;t=2m-2,n_{\mathrm{bs}},n_{\mathrm{ue}})\right)^*. \tag{10}$$

(2) Adaptive receive filtering for OFDM downlink

The STBC-encoded OFDM received signals after N_c-point FFT at t=2m and 2m+1 are denoted by matrix $\mathbf{R}$(k; t=2m)=[$\mathbf{R}$(k;t=2m), $\mathbf{R}$(k;t=2m+1)] of size $N_{\mathrm{ue}}\times 2$ and can be expressed as

$$\mathbf{R}(k;t=2m)=\sqrt{\frac{2E_s}{T}}\mathbf{H}_{\mathrm{eq}}(k;t=2m)\mathbf{X}(k;t=2m)+\mathbf{N}(t=2m), \tag{12}$$

where $\mathbf{H}_{\mathrm{eq}}$(k, t=2m) is the equivalent channel given by

$$\mathbf{H}_{\mathrm{eq}}(k;t=2m)=\mathbf{W}_{\mathrm{mrt}}(k;t=0)\mathbf{H}(k;t=2m). \tag{13}$$

In a high mobility environment, $\mathbf{H}_{\mathrm{eq}}$(k, t=2m) becomes deviate from that of t=1. We want to modify $\mathbf{R}$(k; t=2m) to that which could be seen at t=1. To achieve the above task, we introduce the receive filtering to do this.

First, reverse modulation to remove the modulation from the received signals is applied to estimate the equivalent channel matrix (i.e., a concatenation of MRT-FDE and the propagation channel) as

$$\mathbf{H}'_{\mathrm{eq}}(k;t=2m)=\mathbf{R}(k;t=2m)\left(\bar{\mathbf{d}}(k;t=2m)\right)^{-1}, \qquad (14)$$

where $\bar{\mathbf{d}}(k;t=2m)$ is a STBC-encoded signal matrix regenerated by using the hard-decision symbol blocks (note that $\bar{d}(k;t)$ denotes the hard-decision result of $\hat{d}(k;t)$ as

$$\bar{\mathbf{d}}(k;t=2m)=\begin{pmatrix}\bar{d}(k;t=2m) & -\bar{d}^{*}(k;t=2m+1)\\ \bar{d}(k;t=2m+1) & \bar{d}^{*}(k;t=2m)\end{pmatrix}. \qquad (15)$$

Then, moving average operation and DFCE similar to eqs. (8) and (9) are applied to predict the equivalent channel matrix at t=2m+2. Denoting the resulting equivalent channel matrix at t=2m+2 by $\hat{\mathbf{H}}(k;t=2m+2)$, the received signal matrix is modified as

$$\begin{aligned}\hat{\mathbf{R}}\left(k;t=2m+2\right)&=\hat{\mathbf{H}}_{\mathrm{eq}}(k;t=1)\left(\hat{\mathbf{H}}_{\mathrm{eq}}(k;t=2m+2)\right)^{-1}\\&\quad\times\mathbf{R}\left(k;t=2m+2\right)\end{aligned}. \qquad (19)$$

By using the elements of the above $\hat{\mathbf{R}}\left(k;t=2m+2\right)$ instead of $\{R(k;n_{\mathrm{ue}},t);n_{\mathrm{ue}}=0,1\}$, STBC decoding and amplitude-normalization in eq. (4) are carried out.

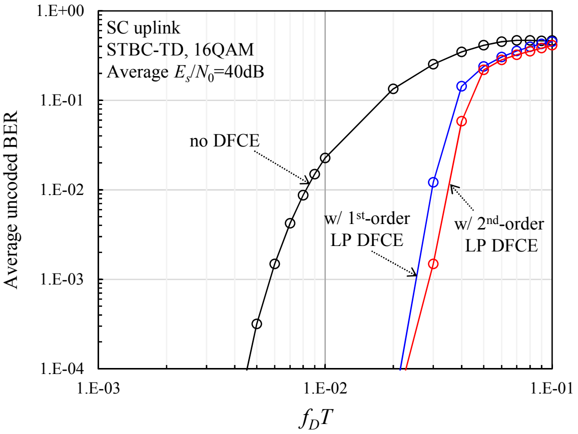
III. COMPUTER SIMULATION

We evaluate the average uncoded BER performances of STBC-TD for SC uplink and OFDM downlink transmission by computer simulation. The computer simulation parameters are summarized in Table 1.

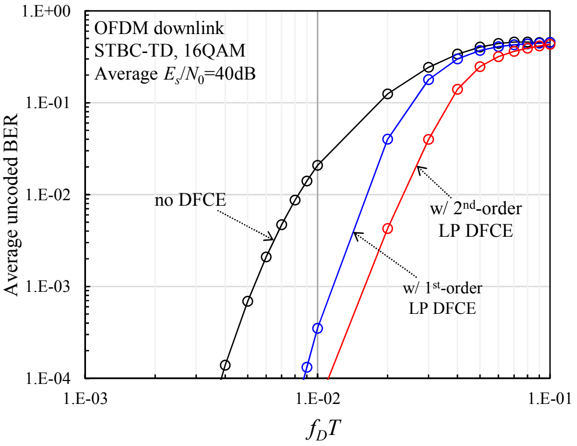
TABLE I. COMPUTER SIMULATION PARAMETERS.

Pilot structure	No. of pilot subcarriers	N_p=16
	Pilot sequence	Zdaff-Chu seq.(i=1)
Transmitter/ Receiver	No. of subcarriers	N_c=1024
	CP length	N_{cp}=128
	No. of BS antennas	N_{bs}=4
	No. of UE antennas	N_{ue}=2
Propagation channel	Frequency-selective block Rayleigh fading	
	Power delay profile (PDP) shape	16-path uniform
	Maximum delay time	$\tau_{\max}$=16

Fig. 3 plots the average uncoded BER due to fading Doppler shift for SC uplink and OFDM downlink as a function of normalized maximum Doppler frequency, f_DT. The average E_s/N_0 is set to 40dB and the BER is produced by Doppler shift only. It can be seen that the use of the 2nd-order LP DFCE improve significantly the BER performance in a high mobility environment. The use of 2nd-order LP DFCE can increase the allowable maximum f_DT for keeping BER<10^{-2} about 5.5 times and 3.8 times for SC uplink and OFDM downlink, respectively, compared to the use of PACE only. Assuming the subcarrier spacing of 75 kHz and 5GHz carrier frequency, the allowable maximum travelling speed can be increased to about 500km/h and 340km/h for SC and OFDM transmissions, respectively.



(a) SC uplink



(b) OFDM downlink

Fig. 3. f_DT vs BER performance.

IV. CONCLUSION

In this paper, we proposed an adaptive STBC-TD for SC uplink and OFDM downlink transmissions in a high mobility environment. It was confirmed by computer simulation that the proposed adaptive STBC-TD with DFCE increases the allowable maximum Doppler frequency for keeping BER<10^{-2} about 5.5 times and 3.8 times for SC uplink and OFDM downlink, compared to conventional STBC-TD with PACE only.

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REFERENCES

[1] C. X. Wang, F. Haider, and X. Gao, “Cellular architecuture and key technologies for %G wireless communication networks,” IEEE Commun. Mag., Vil. 52, Issue 2, pp. 122-130, Feb. 2014.

[2] S.M. Alamouti, “A simple transmit diversity technique for wireless communications,” IEEE J. Sel. Areas. Commun., vol.16, no.8, pp.1451-1458, Oct. 1998.

[3] V. Tarokh, H. Jafarkhani and A. R. Calderbank, “Space-time block codes from orthogonal designs,” IEEE Trans.on Inform. Theory, Vol. 45, No. 5, pp. 1456-1467, July 1999.

[4] F. Adachi, H. Tomeba, and Kazuki Takeda, “Introduction of frequency-domain signal processing to broadband single-carrier transmissions in a wireless channel,” IEICE Trans. Commun., Vol.E92-B, No.09, pp. 2789-2808, Sep. 2009.

[5] K. Takeda, T. Itagaki, and F. Adachi, “Application of space-time transmit diversity to single-carrier transmission with frequency-domain equalization and receive antenna diversity in a frequency-selective fading channel,” IEE Proc. –Commun., Vol. 151, No. 6, pp. 627-632, Dec. 2004.

[6] J. M. Auffray and J. F. Helard, “Performance of multicarrier CDMA technique combined with space-time block coding over Rayleigh channel,” Proc. IEEE Seventh International Symposium on Spread Spectrum Techniques and Applications, Vol. 2, pp. 348-352, Sept. 2002.

[7] J. K. Cavers, “Single-user and multiuser adaptive maximal ratio transmission for Rayleigh channels,” IEEE Trans. Vehi. Technol., Vol. 49, No.6, pp. 2043-2050, Nov. 2000.

[8] H. Tomeba, K. Takeda, and F. Adachi, “Space-time block coded-joint transmit/receive antenna diversity using more than 4 receive antennas,” Proc. 2008 IEEE 68th Veh. Technol. Conf. (VTC2008-Fall), Calgary, Canada, 21-25 September 2008.

[9] R. Matsukawa, T. Obara, and F. Adachi, “Frequency-domain space-time block coded transmit/receive diversity for single-carrier distributed antenna network,” IEICE Commun. Express (ComEX), Vol. 2, No. 4, pp. 141-147, 15 April, 2013.

[10] F. Adachi, A. boonkajay, Y. Seki, T. Saito, S. Kumagai and H. Miyazaki, “Cooperative Distirbuted Antenna Transmission for 5G Mobile Communications Network,” IEICE Trans. Commun., Vol. 100-B, No. 8, Aug. 2017.

[11] F. Adachi, A. Boonkajay, Y. Seki and T. Saito, “MIMO Channel Estimation for Time-Division Duplex Distributed Antenna Cooperative Transmission,” Proc. Int. Wirel. Commun. and Mobile Comput. Conf. (IWCMC 2017), Valencia, Spain, Jun. 2017.