STBC AF Relay for Unmanned Aircraft Systems

Fumiyuki Adachi, Hiroyuki Miyazaki, Chikara Endo
Dept. of Communications Engineering, Graduate School of Engineering, Tohoku University
6-6-05 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan

ABSTRACT

If a large scale disaster similar to the Great East Japan Earthquake 2011 happens, some areas may be isolated from the communications network. Recently, unmanned aircraft system (UAS) based wireless relay communication has been attracting much attention since it is able to quickly re-establish the connection between isolated areas and the network. However, the channel between ground station (GS) and unmanned aircraft (UA) is unreliable due to UA's swing motion and as consequence, the relay communication quality degrades. In this paper, we introduce space-time block coded (STBC) amplify-and-forward (AF) relay for UAS based wireless relay communication to improve relay communication quality. A group of UAs forms single frequency network (SFN) to perform STBC-AF cooperative relay. In STBC-AF relay, only conjugate operation, block exchange and amplifying are required at UAs. Therefore, STBC-AF relay improves the relay communication quality while alleviating the complexity problem at UAs. It is shown by computer simulation that STBC-AF relay can achieve better throughput performance than conventional AF relay.

Keywords: Unmanned aircraft system, cooperative relay communication, space-time block coding

1. INTRODUCTION

Wireless communication networks have advanced significantly and are now playing an important role in our society. However, once a large scale disaster similar to the Great East Japan Earthquake 2011 happens, communications networks may be paralyzed due to electric power supply outage and communication cable cutoff and as consequence, some area may be isolated from the network. Therefore, it is important to re-establish the connection between the isolated area and the network as quickly as possible in such an emergency situation. The unmanned aircraft system (UAS) based wireless relay communication may be an efficient approach to quickly recover the communication function [1-3].

An unmanned aircraft (UA) flying over the isolated area serves as a relay node to connect the isolated area with normal (not damaged) area. Therefore, UAS based wireless relay communication is able to quickly extend the communication services to the isolated area. However, in UAS based wireless relay communication, the channel between ground station (GS) and UA may be unreliable due to UA's swing motion [3]. Furthermore, UAS based wireless relay communication suffers from interference from other wireless network. And as consequence, the relay communication quality degrades. To solve this problem, we have been studying space-time block coded (STBC) cooperative relay for UAS [4,5]. A group of UAs forms single frequency network (SFN) for STBC cooperative relay. Applying STBC transmit diversity [6-9] can improve the relay communication quality while alleviating the complexity problem at UA relay.

Recently, we proposed STBC decode-and-forward (DF) relay for UAS [5]. In STBC-DF relay, STBC with transmit frequency-domain equalization (FDE) [6,7] and STBC with receive FDE [8,9] are used for the source GS-to-UA link and UA-to-the destination GS link, respectively. Therefore, STBC-DF relay does not require channel state information (CSI) at UA relays. However, in STBC-DF relay, data exchange is required between UA relays to perform STBC decoding and as consequence, UA relay's structure may remain still complicated. In this paper, we introduce STBC amplify-and-forward (AF) relay, which can keep UA relay's structure simpler than STBC-DF relay. We evaluate, by computer simulation, its throughput performances and show that STBC-AF relay can achieve better throughput performance than conventional AF relay while keeping UA relay's structure much simpler than STBC-DF relay.

The remainder of this paper is organized as follows. STBC-AF relay are introduced and compared to STBC-DF relay in Section 2. Section 3 discusses the computer simulation results and Section 4 offers conclusion.

*adachi@ecei.tohoku.ac.jp; phone +81-22-795-7082-1234; fax +81-22-263-9168

2. STBC COOPERATIVE RELAY FOR UAS

Figure 1 illustrates the conceptual structure of STBC cooperative relay for UAS. A group of UAs forms SFN to perform STBC cooperative relay. Multiple UAs serve as distributed antennas and therefore, large spatial diversity gain can be obtained. It is well known that maximal-ratio transmit diversity can maximize the received signal-to-noise power ratio (SNR) [10]. However, maximal-ratio transmit diversity requires channel state information (CSI) at both transmitter and receiver and hence, it makes UA structure complicated. Therefore, STBC transmit diversity is applied to alleviate the complexity problem at UA relay.

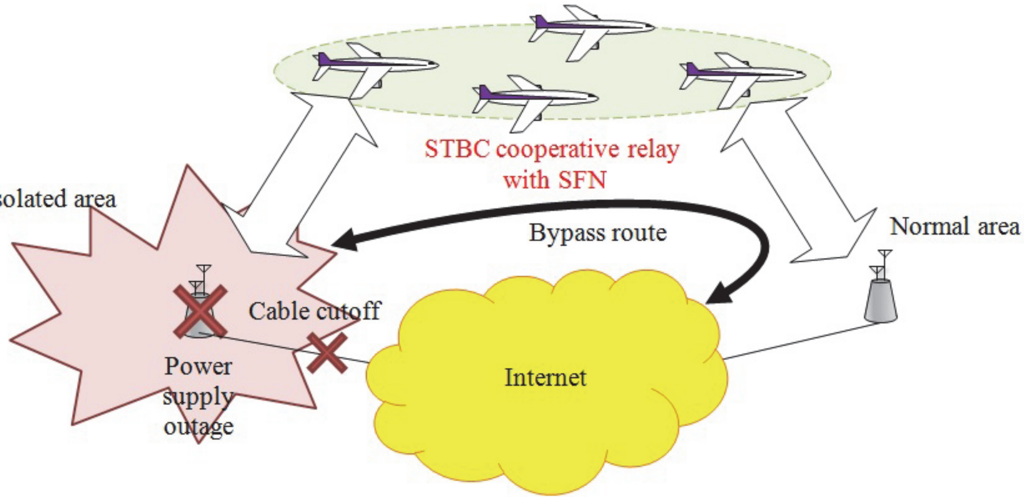

Figure 1. UAS relay network.

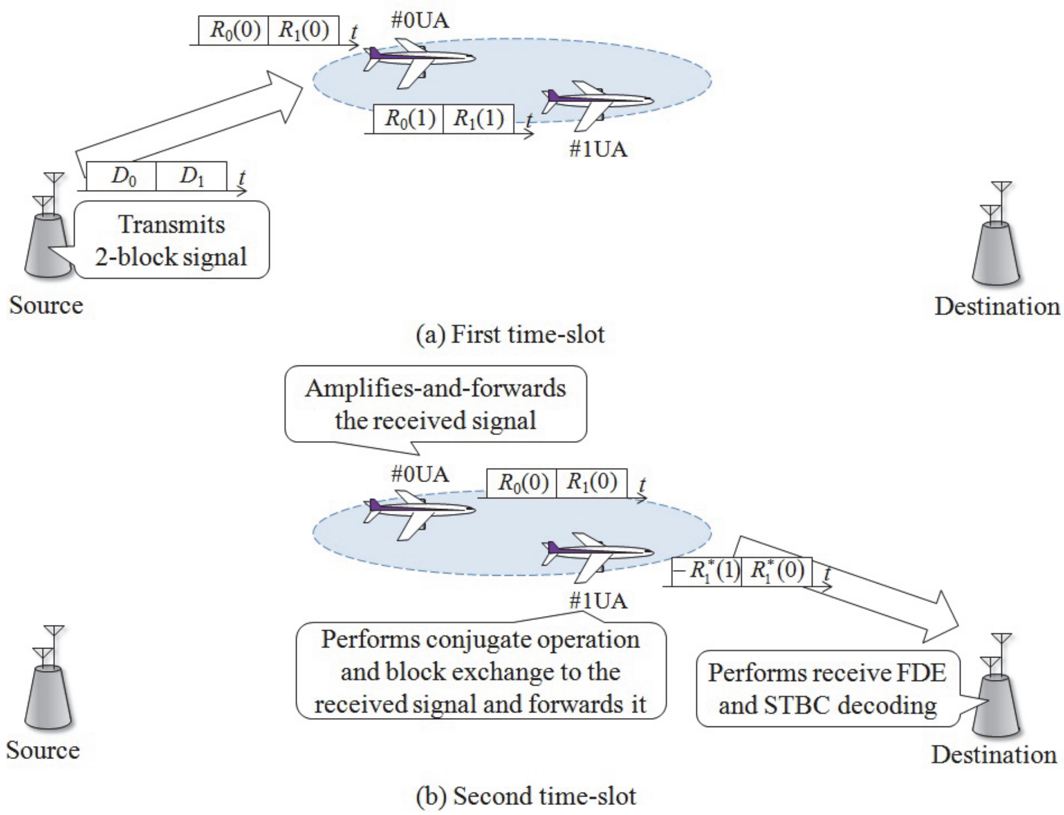

Figure 2. Behavior of STBC-AF relay.

In this paper, we consider the source GS and the destination GS have N_S and N_D antennas, respectively. Each UA has single antenna and a group of N_U UAs forms SFN to perform STBC-AF relaying using orthogonal frequency division multiplexing (OFDM). The GS-to-UA link may be a line-on-sight and therefore, the channel of the GS-to-UA link is assumed to be characterized by frequency-selective Nakagami-Rice fading channel.

2.1 STBC-AF relay

Below, the STBC-AF relay operation when N_U=2 is described. Figure 2 shows the behavior of STBC-AF relay in each time-slot. In the first time-slot, the source GS broadcasts uncoded 2-block signal to UA relays. Then, the 0th UA relay amplifies the waveform received signal. On the other hand, the 1st UA relay performs conjugate operation and block exchange to the waveform received signal and then amplifies it. These operations correspond to modified STBC encoding [4]. Then, UA relays forward their transmit signals to the destination GS in the second time-slot. The destination GS receiver performs the receive FDE and STBC decoding considering the concatenation of the channels between the source GS and UA relays and between UA relays and the destination GS as an equivalent channel. In STBC-AF relay, only conjugate operation, block exchange and amplifying are required at UA relays. Therefore, STBC-AF relay can improve the relay transmission quality while alleviating the complexity problem at UA relays.

At the source GS transmitter, the data symbol sequence to be transmitted is divided into a sequence of J=2 blocks of N_c data modulated symbols each. After applying N_c-point inverse discrete Fourier transform (IDFT) and CP insertion, the source GS transmitter broadcasts the OFDM signal to UA relays in the first time-slot. Throughout the paper, without loss of generality, the subcarrier index is omitted.

At UA relays, the received OFDM signal is decomposed into N_c subcarrier components by N_c-point DFT. Then, UA relays perform modified STBC encoding to the waveform received signal. Representing the jth (j=0,1) received signal at the n_Uth UA as $R_j(n_U)$, the qth (q=0,1) STBC encoded signal, $X_q(n_U)$, at the n_Uth UA can be given as

$$\mathbf{X}=\begin{pmatrix} X_0(0) & X_1(0) \\ X_0(1) & X_1(1) \end{pmatrix}=\begin{pmatrix} R_0(0) & R_1(0) \\ -R_1^*(1) & R_0^*(1) \end{pmatrix}, \tag{1}$$

where $(.)^*$ indicates the conjugate operation. The modified STBC encoding matrix given by Eq. (1) is a transposed version of conventional 2×2 STBC encoding matrix [8]. It is understood from Eq. (1) that the STBC encoded signal at the 0th UA relay, which is represented by the first row of $\mathbf{X}$, is the same as its received signal while the STBC encoded signal at the 1st UA relay, which is represented by the second row of $\mathbf{X}$, can be generated by performing the conjugate operation and exchanging 2-blocks to its received signal. The modified STBC encoding requires the conjugate operation at the 1st UA relay only unlike the conventional STBC encoding. The STBC encoded signal is transformed into the OFDM signal by N_c-point IDFT. After CP insertion, the UA relays amplify-and-forward it to the destination GS.

At the destination GS receiver, the received OFDM signal is decomposed into N_c subcarrier components by N_c-point DFT. The received OFDM signal can be expressed as a concatenation of the equivalent channel matrix of the source GS-to-UA relay-to-the destination GS link and the STBC encoded signal matrix [4]. Therefore, STBC decoding can be done after performing the receive FDE by taking into account the equivalent channel. Representing N_D×2 received signal matrix at each OFDM subcarrier as $\mathbf{R}$, N_U×2 received signal matrix after the received FDE is given as

$$\hat{\mathbf{R}}=\mathbf{W}_r\mathbf{R}=\begin{pmatrix} \mathbf{H}_{S-D}^H(0) \\ \mathbf{H}_{S-D}^H(1) \end{pmatrix}\mathbf{R}=\begin{pmatrix} \mathbf{H}_{S-D}^H(0)\mathbf{H}_{S-D}(0) & \mathbf{H}_{S-D}^H(0)\mathbf{H}_{S-D}(1) \\ \mathbf{H}_{S-D}^H(1)\mathbf{H}_{S-D}(0) & \mathbf{H}_{S-D}^H(1)\mathbf{H}_{S-D}(1) \end{pmatrix}\begin{pmatrix} S_0 & S_1 \\ -S_1^* & S_0^* \end{pmatrix}+\mathbf{W}_r\mathbf{N}=\mathbf{HS}+\mathbf{W}_r\mathbf{N}, \tag{2}$$

where $\mathbf{W}_r$ is an N_U×N_D FDE weight matrix, $\mathbf{H}_{S-D}(n_U)$ is an N_D×1 equivalent channel matrix of the source GS-UA relay-destination GS link, S_j is the jth block signal (j=0,1) transmitted from the source GS and $\mathbf{N}$ is 2×2 noise matrix. $\mathbf{H}_{S-D}(1)$ and $\mathbf{H}_{S-D}(2)$ are given by

$$\begin{cases} \mathbf{H}_{S-D}(0)=G(0)H_{S-U}(0)\mathbf{H}_{U-D}(0) \\ \mathbf{H}_{S-D}(1)=G(1)H_{S-U}^*(1)\mathbf{H}_{U-D}(1) \end{cases}, \tag{3}$$

where $G(n_U)$ is the amplifying factor of the n_Uth relay, $H_{S-U}(n_U)$ is the channel gain of the source GS-to-the n_Uth UA relay link and $\mathbf{H}_{U-D}(n_U)$ is an N_D×1 channel matrix of the n_Uth UA relay-to-the destination GS link, respectively. It is understood from Eq. (2) that the received signal matrix after FDE is the product of the equivalent channel matrix $\mathbf{H}$

(Hermitian matrix) after the received FDE and the STBC-encoded transmit signal matrix **S**. Therefore, the linear STBC decoding which consists of addition, subtraction, and conjugate operation only can be used to recover the transmitted signal. Representing the n_Uth row and jth column element of the received signal matrix $\hat{\mathbf{R}}$ after FDE as $\hat{R}_j(n_u)$, the jth block signal $\hat{D}_j$ after STBC decoding is obtained by

$$\begin{cases}\hat{D}_0 = \hat{R}_0(0) + \hat{R}_1^*(1) \\ \hat{D}_1 = \hat{R}_1(0) - \hat{R}_0^*(1)\end{cases}. \tag{4}$$

Finally, data demodulation is carried out.

2.2 Comparison between STBC-AF relay and STBC-DF relay

Figure 3 compares the transmitter/receiver structures in STBC-AF relay and STBC-DF relay [5]. It is understood from Figure 3 that STBC-DF relay requires STBC decoding, data de-modulation, re-modulation and STBC encoding at UA relays while STBC-AF relay requires modified STBC encoding, which consists of conjugate operation and block exchange only. Also understood from Figure 3 is that STBC-DF relay uses STBC with transmit FDE for the source GS-to-UA relay link and therefore, it makes the source GS's structure complicated. On the other hand, in STBC-AF relay, the source GS transmits uncoded 2-block signal. Therefore, STBC-AF relay can keep the source GS's structure simple as well as UA relays. Table 2 summarizes the features of STBC-AF relay and STBC-DF relay. Both STBC-AF relay and STBC-DF relay do not require CSI at UA relays and can use an arbitrary number of the destination GS antennas for the given STBC coding rate. However, STBC-AF relay must use single source GS antenna (i.e., N_S=1) while STBC-DF relay can use an arbitrary number of source GS antennas for the given STBC coding rate. STBC-AF relay requires CSI at the destination GS only while STBC-DF relay requires it at both the source GS and the destination GS. Note that STBC-AF relay does not require data exchange between UA relays while STBC-DF relay requires it to perform STBC decoding. Therefore, STBC-AF relay can keep the UA structure much simpler than STBC-DF relay.

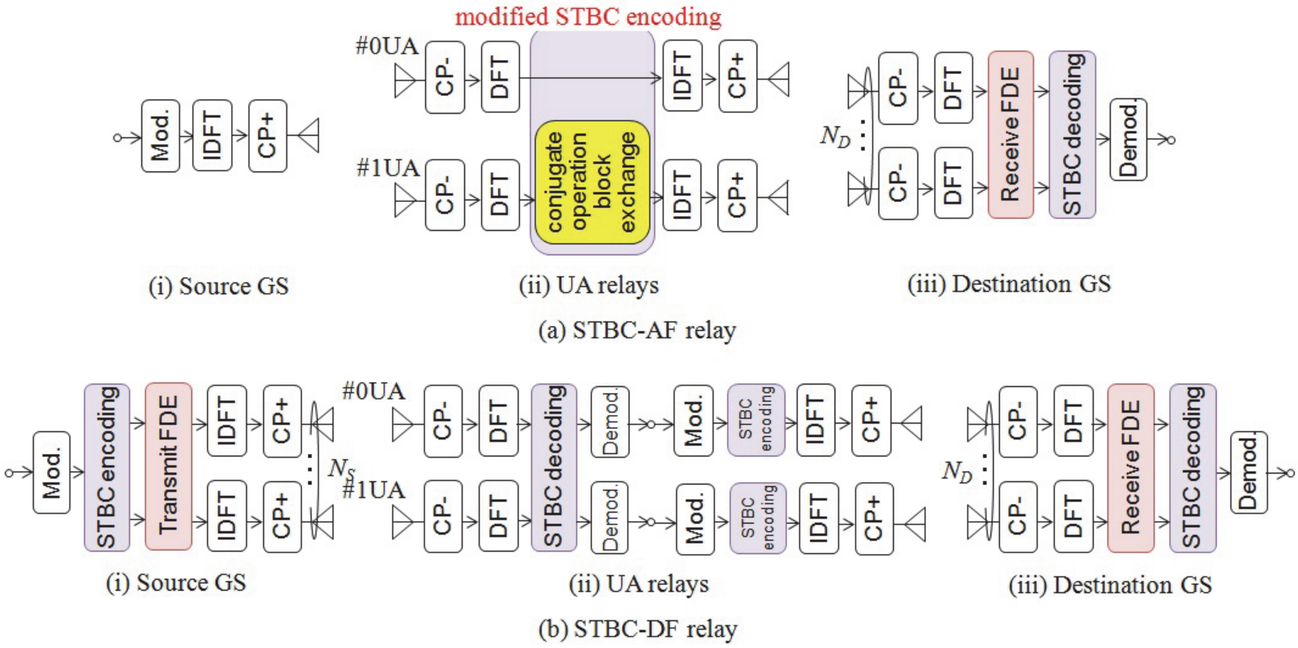

Figure 3. Transmitter/receiver structures.

Table 1. Comparison between STBC-DF relay and STBC-AF relay.

Protocol		Number of antennas for the given STBC coding rate	CSI	Data exchange
STBC-AF	Source GS	1	Not required	Not required
	UA relays	2	Not required	
	Destination GS	Arbitrary	Required	
STBC-DF	Source GS	Arbitrary	Required	Required
	UA relays	2	Not required	
	Destination GS	Arbitrary	Required	

3. COMPUTER SIMULATION RESULTS

The throughput performance of STBC-AF relay is evaluated by computer simulation. Packet transmission of 1536bits/packet using QPSK data modulation is considered. OFDM with N_c=64 subcarriers and N_{cp}=16-symbol CP is assumed. The channel is assumed to be a symbol-spaced L=8 path frequency-selective block Nakagami-Rice fading with K factor 10dB [11]. The perfect CSI is assumed to be available at the destination GS.

3.1 Comparison to conventional AF relay

Figure 4 shows the throughput performance, where $\Gamma_{S\text{-}U}$ (dB) and $\Gamma_{U\text{-}D}$ (dB) denote the received SNR of the source GS-to-UA relay link and that of UA relay-to-the destination GS link, respectively. Throughput S is evaluated using $S = 0.5Z(1-PER)N_c/(N_c+N_{cp})$ where Z is the number of bits per symbol and PER is the packet error rate. The number N_S of the source GS antennas, the number N_U of UA relays and the number N_D of the destination GS antennas are set to N_S=1, N_U=N_D=2, respectively. For the comparison, the throughput performance when using conventional AF relay (N_S=N_U=N_D=1) and STBC-DF relay (N_S=N_U=N_D=2) are also shown in Figure 4. It is seen from Figure 4 that STBC-AF relay improves the throughput performance compared to the conventional AF relay. When the required throughput is S=0.72bps/Hz, STBC-AF relay can reduce the required source GS transmit power and the required UA transmit power by about 3dB and 5dB, respectively. This is because high spatial diversity gain can be obtained by STBC cooperative relay.

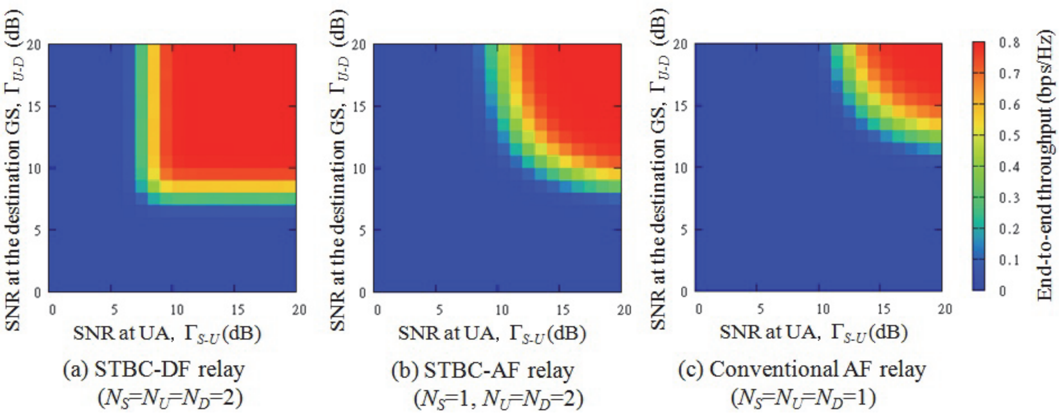

Figure 4. Throughput performances.

3.2 Impact of the number of destination GS antennas

Figure 5 shows the throughput performances when increasing the number of destination GS antennas to 2, 3 and 4. It is seen from Figure 5 that the throughput performance of STBC-AF relay can further improve by increasing the number of destination GS antennas. For example, the use of N_D=4 can reduce the required UA relays power for S=0.72bps/Hz by about 3dB compared to the use of N_D=2.

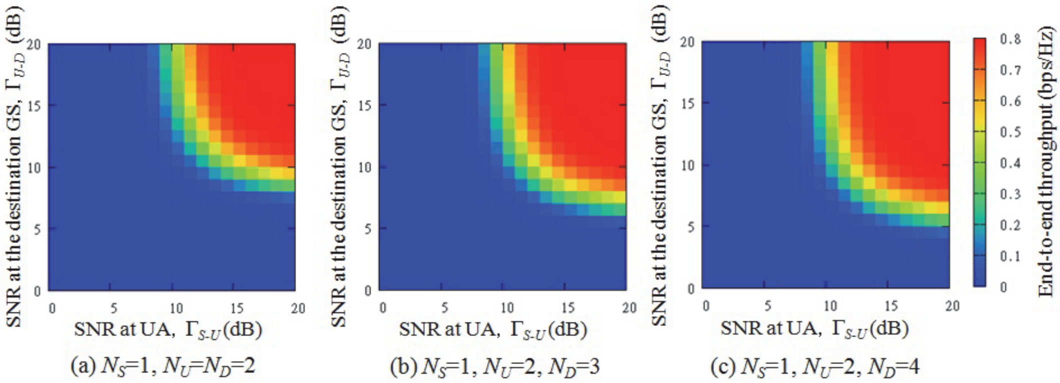

Figure 5. Impact of the number of destination GS antennas.

4. CONCLUSION

In this paper, we introduced STBC-AF relay for UAS based wireless relay communication. It was shown by computer simulation that STBC-AF relay can improve the throughput performance compared to conventional AF relay while alleviating the complexity problem at UA relays.

REFERENCE LINKING

This study was partially funded by "R&D on Cooperative Technologies and Frequency Sharing Between Unmanned Aircraft Systems (UAS) Based Wireless Relay Systems and Terrestrial Network," supported by the Ministry of Internal Affairs and Communications.

REFERENCES

[1] Frew E. W., Brown T. X., "Airborne communication networks for small unmanned aircraft systems," Proceedings of the IEEE, Papers 96(12), 2008-2027 (2008).

[2] Miura R., Inoue M., Owada Y., Takizawa K., Ono F., Suzuki M., Tsuji H., Hamaguchi K., "Disaster-resilient wireless mesh network –experimental test-bed and demonstration-," Proc. WPMC2013 (2013)

[3] Takizawa K., Suzuki M., Tsuji H., Miura R., "Performance evaluation on path diversity in radio links between unmanned aerial vehicle," Proc. PIMRC2013 (2013).

[4] Endo C., Miyazaki H., Adachi F., "Space-time block coded amplify-and-forward cooperative relay without channel state information at relay station," Proc. WPMC2014 (2014)

[5] Adachi F., Miyazaki H., "STBC decode-and-forward relay for unmanned aircraft system," Proc. APMC2014 (2014)

[6] Tomeba H., Takeda K., Adachi F., "Space-time block coded joint transmit/receive diversity in a frequency-nonselective Rayleigh fading channel," IEICE Trans. Commun., Papers E89-B(8), 2189-2195 (2006).

[7] Tomeba H., Takeda K., Adachi F., "Frequency-domain space-time block coded joint transmit/receive diversity for direct-sequence spread spectrum signal transmission," IEICE Trans. Commun, Papers E90-B(3), 597-606 (2007).

[8] Alamouti S. M., "A simple transmit diversity technique for wireless communication," IEEE J. Sel. Areas. Commun., Papers 17(3), 451-460 (1998).

[9] Tarokh V., Jafarkhani H., Calderbank A. R., "Space-time block coding for wireless communications: performance results," IEEE J. Sel. Areas. Commun., Papers 17(3) 451-460 (1999)

[10] Dighe P. A., Mallik R. K. and Jamuar S. S., "Analysis of transmit-receiver diversity in Rayleigh fading," Proc. IEEE GLOBECOM'2001, 1132-1136 (2001).

[11] Venkatasubramanian S. N., Haneda K., Takizawa K., Vainilainen P., "Propagation channel model between unmanned aerial vehicles for emergency communications," EUROCOSTIC1004 (2013).