A Performance of Cooperative Relay Network Based on OFDM/TDM Using MMSE-FDE in a Wireless Channel

Haris Gacanin and Fumiyuki Adachi
Department of Electrical and Communication Engineering
Graduate School of Engineering, Tohoku University, Sendai, Japan
Email: haris@mobile.ecei.tohoku.ac.jp

***Abstract*—Cooperative networking schemes provide spatial diversity gain (named cooperative diversity gain) using the antennas of spatially distributed users to form a multi antenna transmit situation. A variety of algorithms for orthogonal frequency division multiplexing (OFDM) networks have been developed to achieve cooperative diversity gain. OFDM signals, however, have a problem with a high peak-to-average power ratio (PAPR) leading to lower power efficiency, which may significantly increase the user power consumption. In this paper, instead of conventional OFDM, we present the performance of cooperative network based on OFDM combined with time division multiplexing (OFDM/TDM) using minimum mean square error frequency-domain equalization (MMSE-FDE) in a frequency-selective fading channel. To fully exploit the channel frequency-selectivity and achieve a larger frequency diversity gain the equalization weights required for OFDM/TDM signaling based on MMSE criteria are derived.**

***Index Terms*—Cooperative network, power efficiency, OFDM/TDM, FDE.**

I. Introduction

The future wireless networks are envisaged to offer broadband data services. To meet such demands in a limited available bandwidth, multi-antenna techniques are good candidates [1]. However, their application often encounters practical implementation problem if a large number of antennas is to be deployed. In order to overcome this problem, a new mode of transmit diversity, called cooperative diversity, was proposed based on user cooperation [2]-[4], where the antennas of the sender and the partners together form a multiple transmit antenna situation. A variety of algorithms have been developed to obtain cooperative diversity gain; such as repetition coding [5], distributed space-time and space-frequency block coding [6]-[9] and conventional channel coding integrated into cooperation [10]. Most of the work in this area preclude the power requirement of multicarrier signaling due to high peak-to-average power ratio (PAPR).

Orthogonal frequency division multiplexing (OFDM) [11] technology has been adopted in many wireless network standards to cope with the channel frequency-selectivity. The undesirable feature of OFDM, however, is its large PAPR that renders the OFDM particularly sensitive to nonlinear distortions (e.g., high-power amplifier (HPA)) leading to a lower power efficiency. OFDM combined with time division multiplexing [12] (in this paper called OFDM/TDM) can be used to solve the PAPR problem to some extent [13]. In OFDM/TDM design, the inverse fast Fourier transform (IFFT) time window (i.e., OFDM/TDM frame) of conventional OFDM is divided into K slots. Within each slot an OFDM signal with reduced number of subcarriers is transmitted without the guard interval (GI) insertion. Unlike the conventional OFDM, only one GI is inserted in each frame and frequency domain equalization is used to exploit the channel frequency-selectivity.

In this paper, we present the performance of cooperative relay network based on OFDM/TDM using minimum mean square error frequency domain equalization (MMSE-FDE) [13] in a frequency-selective fading channel. To fully exploit the channel frequency-selectivity and achieve a larger frequency diversity gain the equalization weights required for OFDM/TDM signaling based on MMSE criteria are derived. Unlike cooperative relay network based on conventional OFDM, the use of OFDM/TDM achieves a better quality of service (i.e., a lower bit error rate (BER)) with a higher transmit power efficiency.

The remainder of this paper is organized as follows. Section II presents the system model. We derive the required equalization weights for OFDM/TDM to achieve improved performance in Sect. III. In Sect. IV, computer simulation results and discussions are presented. Section V concludes the paper.

II. System Model Overview

We assume that source terminal have a direct line-of-sight communication with an access point (henceforth relay) and destination during the first stage, while the destination is out of the source's coverage area during the second stage. Throughout this paper, T_c-spaced discrete-time signal representation is user, where T_c represents FFT sampling period.

A data-modulated symbol sequence $\{d(i);\ i=0\sim N_c-1\}$ is chosen from a complex-valued finite constellation such as quadrature phase shift keying (QPSK) modulation. $\{d(i)\}$ is divided into K subblocks each having N_m (=N_c/K) data-modulated symbols. The kth subblock $\{d^k(i);\ i=0\sim N_m-1\}$ is transmitted in the kth slot as shown in Fig. 1, where $d^k(i)=d(kN_m+i)$ for $k=0\sim K-1$. The OFDM/TDM signal can be

978-1-4244-2515-0/09/$25.00 ©2009 IEEE

expressed using the equivalent low-pass representation as

$$s(t)=\sqrt{P_s}\sum_{i=0}^{N_m-1} d^{\lfloor \frac{t}{N_m}\rfloor}(i)\exp\left\{j2\pi t\frac{i}{N_m}\right\} \qquad (1)$$

for $t=0\sim N_c-1$, where P_s $(=E_s/T_cN_c)$ denotes the source transmit power (E_s is the data-modulated symbol energy). We note here that OFDM/TDM signal with $K=1$ (i.e., $N_m=N_c$) reduces to the conventional OFDM system with N_c subcarriers. After insertion of the GI the OFDM/TDM frame signal is transmitted over a wireless channel.

The signal propagates through a wireless channel with a discrete-time channel impulse response $h_{xy}(\tau)=\sum_{l=0}^{L-1} h_{l,xy}\delta(\tau-\tau_l)$, where $h_{l,xy}$, τ_l and $\delta(\cdot)$ are the path gain between x and y terminals, the time delay of the lth path and the delta function.

The information is transmitted via two stages as shown in Fig. 2. The source, transmits the data to the destination, while the relay is listening during the first stage. In the second stage the relay sends the received data after processing to the destination as well, where the two received signals are combined. As proposed in [5], orthogonal channels are used for two stages using TDM.

Stage I: The OFDM/TDM frame signal transmitted by the source during the first stage is given by Eq. (1). At the destination, an N_c-point FFT is applied over entire OFDM/TDM frame to decompose the received signal into N_c frequency components represented by

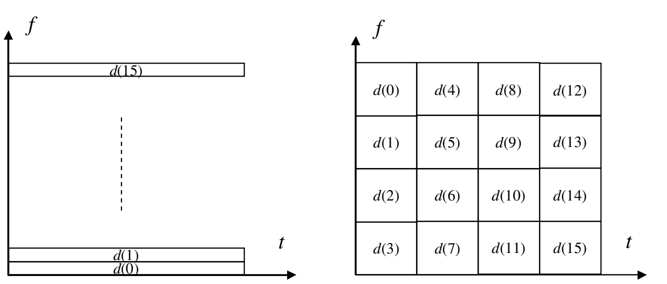
$$R_{d,1}(n)=S(n)H_{sd}(n)+I_{d,1}(n)+N_{d,1}(n) \qquad (2)$$

for $n=0\sim N_c-1$, where $S(n)$, $H_{sd}(n)$, $I_{d,1}(n)$ and $N_{d,1}(n)$ denote the Fourier transforms of the OFDM/TDM signal, the channel gain between source and destination, the inter-slot interference (ISI) and the additive white gaussian noise (AWGN) having power spectral density $2N_0/T_cN_c$, respectively.

The signal received at the relay during the first stage can be represented by

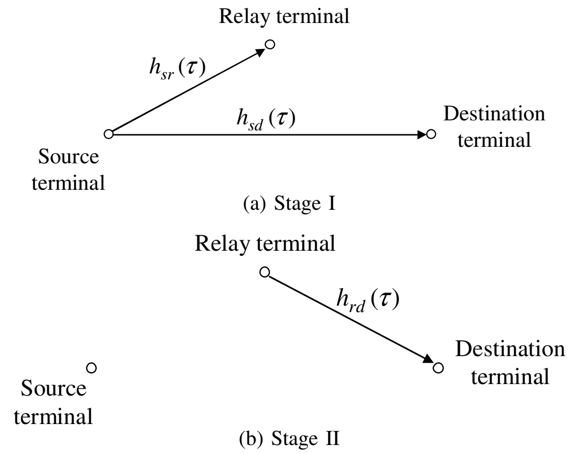
$$R_r(n)=S(n)H_{sr}(n)+I_r(n)+N_r(n) \qquad (3)$$

for $n=0\sim N_c-1$, where $I_r(n)$, $H_{sr}(n)$ and $N_r(n)$ denote the Fourier transforms of the ISI, the channel gain between source and relay, and the AWGN at the relay, respectively.



(a) Conventional OFDM (N_c=16) (b) OFDM/TDM (N_c=16; N_m=4, K=4)

Fig. 1. Time and frequency data mapping.



(a) Stage I

(b) Stage II

Fig. 2. Network protocol.

Stage II: The relay normalizes the received signal by a factor of $\sqrt{E[|R_r(n)|^2]/P_r}$ (so that the average energy is unity) and retransmits the signal $\tilde{R}_r(n)$ during the second time slot, where $P_r=P_s$ is the average transmit power at the relay.

At the destination, N_c-point FFT is applied over entire OFDM/TDM frame to decompose the relayed signal into N_c frequency components represented by

$$\begin{aligned} R_{d,2}(n) &= \sqrt{P_r}S(n)H_{sr}(n)H_{rd}(n)+\sqrt{P_r}H_{rd}(n)I_r(n) \\ &\quad +I_{d,2}(n)+\sqrt{P_r}H_{rd}(n)N_r(n)+N_{d,2}(n), \qquad (4)\end{aligned}$$

where the first term denotes the desired signal components. The second and third terms denote the ISI, while the last two terms denote the AWGN with a slightly increased power. Note that $I_{d,1}(n)=I_r(n)=I_{d,2}(n)=0$ for conventional OFDM.

III. Combining Method - MMSEC

In this section we derive the equalization weights that are required for OFDM/TDM transmission to achieve frequency diversity gain. The destination node process its received signal by first appropriately combining the signals from the two stages using one of a variety of combining techniques; in the sequel, we focus on a minimum mean square error combiner (MMSEC) for OFDM/TDM transmission.

Signal combining and MMSE equalization is done over the entire OFDM/TDM frame (see Fig. 1) using Eqs. (2) and (4) to combat the channel frequency-selectivity as

$$\begin{aligned}\hat{R}_d(n) &= \sum_{m=1}^{2}\hat{R}_{d,m}(n) \\ &= \sum_{m=1}^{2} R_{d,m}(n)w_m(n), \qquad (5)\end{aligned}$$

where $w_m(n)$ is the equalization weight during the mth stage ($m=1,2$). The equalization weights are chosen to minimize the mean square error $(MSE_m(n))$ term $E[|\hat{R}_{d,m}(n)-S(n)|^2]$ at the nth frequency (note that in OFDM/TDM frequency components are used instead of subcarriers in conventional OFDM ($K=1$)). Thus, $MSE_m(n)$ term during the first and second signaling stage can be expressed as

$$\begin{aligned} MSE_1(n) &= \frac{E_s}{T_cN_c}|H_{sd}(n)|^2|w_1(n)|^2 \\ &+ \frac{2N_0}{T_cN_c}|w_1(n)|^2 + \frac{E_s}{T_cN_c} \\ &- 2\frac{E_s}{T_cN_c}\Re\Big\{E\Big[H_{sd}(n)w_1(n)\Big]\Big\}, \end{aligned} \quad (6)$$

and

$$\begin{aligned} MSE_2(n) &= \frac{E_s}{T_cN_c}|H_{sr}(n)|^2|H_{rd}(n)|^2|w_2(n)|^2 \\ &+ \frac{2N_0}{T_cN_c}\frac{E_s}{T_cN_c}|H_{rd}(n)|^2|w_2(n)|^2 \\ &+ \frac{2N_0}{T_cN_c}|w_2(n)|^2 + \frac{E_s}{T_cN_c} \\ &- 2\frac{E_s}{T_cN_c}\Re\Big\{E\Big[H_{sr}(n)H_{rd}(n)w_2(n)\Big]\Big\}, \end{aligned} \quad (7)$$

where $\Re\{z\}$ denotes the real part of the complex number z. From $\frac{\partial MSE_m(n)}{\partial w_m(n)}=0$ we obtain the equalization weights by

$$\begin{cases} w_1(n)=\frac{H^*_{sd}(n)}{|H_{sd}(n)|^2+(\frac{E_s}{2N_0})^{-1}} \\ w_2(n)=\frac{H^*_{sr}(n)H^*_{rd}(n)}{|H_{sr}(n)|^2|H_{rd}(n)|^2+(|H_{sr}(n)|^2+|H_{rd}(n)|^2+1)(\frac{E_s}{2N_0})^{-1}} \end{cases}, \quad (8)$$

where $(\cdot)^*$ denotes the complex conjugate operation. We note here that the reason why factor 2 exists in denominator of Eq. (8) is because the source and the relay transmit with the half of the total available power.

We note here that in the case of conventional OFDM ($K = 1$) equalization weights based on maximum ratio combining (MRC) will achieve the same performance as the above derived equalization weights since the subcarriers in conventional OFDM ($K=1$) experience non-selective fading. Hence, with the equalization based on MMSE criteria only the performance of OFDM/TDM can be improved as presented in the following section.

The time-domain OFDM/TDM signal is recovered by applying N_c-point IFFT to $\{\hat{R}_d(n);\ n=0\sim N_c-1\}$. OFDM demodulation is carried out using N_m-point FFT to obtain decision variables $\{\hat{d}^k(i);\ i=0\sim N_m-1\}$ [13].

IV. Simulation Results and Discussions

Computer simulation parameters are summarized in Table I. In our computer simulation we assume an OFDM/TDM frame size of $N_c = 256$ samples with the GI length of $N_g = 32$ samples, single relay ($M=1$), and ideal coherent QPSK data modulation/demodulation. The propagation channel is an L-path block Rayleigh fading channel having uniform power delay profile, where the path gains $\{h_{l,xy};\ l = 0 \sim L-1\}$ remain constant over one OFDM/TDM frame length and vary frame-by-frame. The path gains are zero-mean independent complex variables with $E[|h_{l,xy}|^2] = 1/L$, where all paths in any channel are independent with each other (we assume the same number of paths in each link). Without loss of generality, we assume $\tau_0 = 0 < \tau_1 < \cdots < \tau_{L-1}$ and that the lth path time delay is $\tau_l = l\Delta$, where Δ (≥ 1) denotes the time delay separation between adjacent paths. The maximum time delay of the channel is less than the GI length (i.e., $L < N_g$). We assume no knowledge of the channel state information at the transmitters, the perfect channel state information at the destination and perfect synchronization. The assumption on synchronization is most critical since synchronization becomes increasingly challenging in larger networks.

TABLE I
Simulation parameters.

Transmitter	Data modulation	QPSK
	Frame length	N_c=256
	IFFT size	N_m=N_c/K
	No. of slots	K=16
	GI	$N_g=32$
Relaying	$M=1$ single relay	
Channel	L-path block Rayleigh fading with Δ=1	
Receiver	FFT size	N_c=256
	FDE	MMSE
	Channel Estimation	Ideal

A. BER Performance

The BER performance of OFDM/TDM with and without relaying as a function of the average signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0 $(= 0.5 \times (E_s/N_0)\times(1+N_g/N_c))$ with K as a parameter is illustrated in Fig. 3. The BER performance without relaying [13] is also plotted as a reference under the same transmit power constraint. The figure shows that the BER performance of OFDM/TDM with $K=16$ and conventional OFDM ($K=1$) with relay assistance improves in comparison with the case without relaying; for for BER=10^{-3}, the E_b/N_0 gain of about 4 and 7 dB is obtained, respectively. It can be seen further seen from the figure that, for BER=10^{-3}, OFDM/TDM using MMSE-FDE when $K=16$ achieves the E_b/N_0 gain of about 3 dB over the conventional OFDM ($K=1$). The E_b/N_0 gain further increase for lower BER due to enhanced frequency diversity gain through MMSE-FDE. It should be noted here that the BER performance will further improve for $K>16$, while decrease for $K<16$ (the performance of OFDM/TDM is bounded between conventional OFDM ($K>1$) and SC-FDE ($K>N_c$) [13]). The performance with different K is not plotted in Fig. 3 for the sake of clear illustration.

We also need to consider the required peak transmit power because it is an important design parameter of transmit power amplifiers. For conventional OFDM transmission, high PAPR causes signal degradation due to non-linear power amplification and the BER performance degrades. The achievable BER performance of both OFDM/TDM using MMSE-FDE and conventional OFDM as a function of the peak transmit power is illustrated in Fig. 4. The BER performance without relaying is also plotted as a reference under the same transmit power constraint. We consider the $\text{PAPR}_{10\%}$ level, which the PAPR of OFDM/TDM exceeds with a probability of 10% [13]. The required peak power for the average BER$= 10^{-3}$ can be

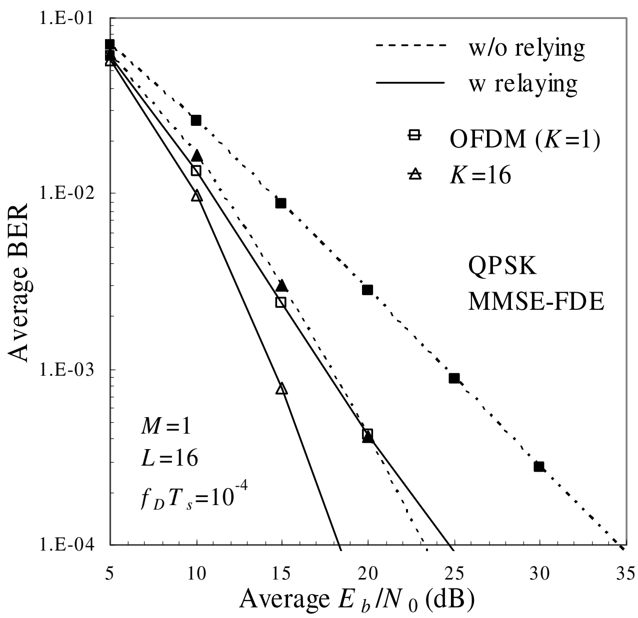


Fig. 3. Average BER vs. average E_b/N_0

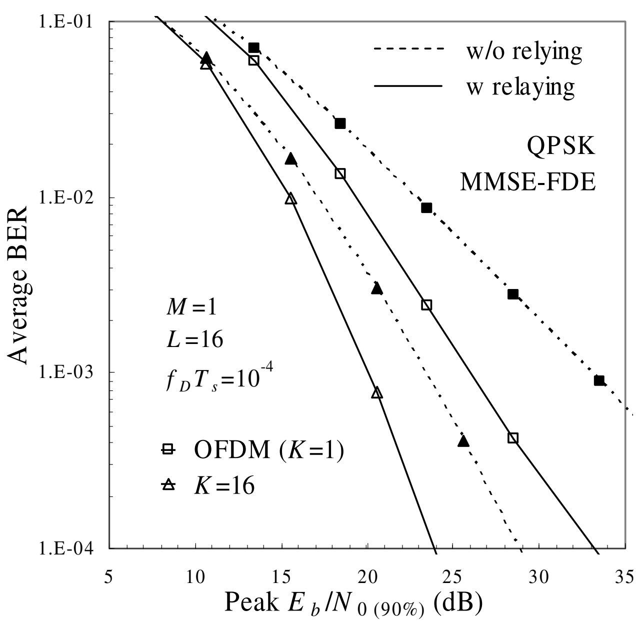


Fig. 4. Average BER vs. peak $E_b/N_{0\ (90\%)}$

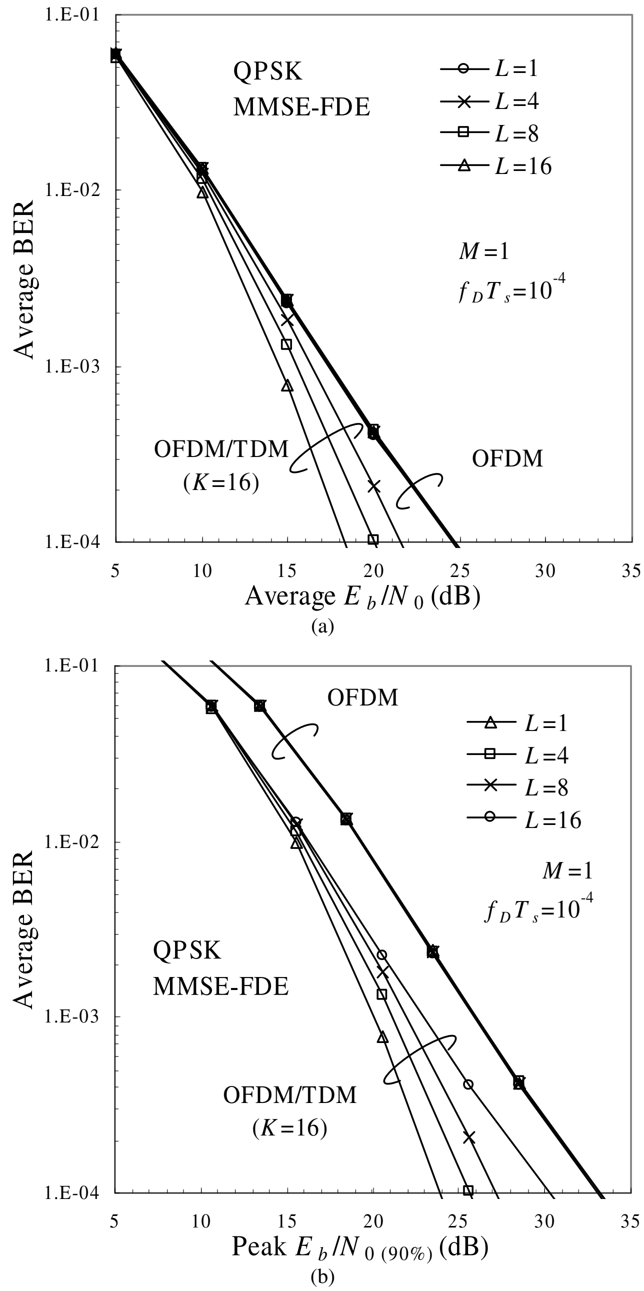


Fig. 5. Impact of channel frequency-selectivity: (a) average power efficiency and (b) peak power efficiency.

reduced by about 6 dB in comparison with the conventional OFDM ($K=1$) with relaying.

In the following we only consider the performance with cooperative relaying.

B. Impact of Channel Frequency-selectivity

The performance of OFDM/TDM with MMSE-FDE is largely determined by the channel itself (i.e., the channel frequency-selectivity) and thus, in this subsection we investigate the effect of different propagation scenarios. The channel frequency-selectivity is a function of the number of paths L; as L decreases the channel becomes less frequency-selective and when $L=1$ it becomes a frequency-nonselective channel (i.e., single-path channel).

Figure 5(a) illustrates the dependency of BER performance on the average E_b/N_0 with L as a parameter. It can be seen from the figure that the BER performance of OFDM/TDM degrades as L decreases. This is because as L decreases the channel becomes less frequency-selective and lower frequency diversity gain is obtained through MMSE-FDE. In the case of $L = 1$ (i.e., single path channel) the performance of OFDM/TDM and conventional OFDM is the same. Figure

5(b) illustrates the BER dependency on the peak $E_b/N_{0\ (90\%)}$ with L as a parameter. It can be seen from the figure that the BER performance of OFDM/TDM for $L = 1$ (i.e., single path channel) gives better performance in comparison with conventional OFDM due to lower power requirement.

V. Conclusion

In this paper, the performance of cooperative network based on OFDM/TDM using MMSE-FDE in a frequency-selective fading channel was presented. Unlike conventional OFDM, to fully exploit the channel frequency-selectivity and achieve a larger frequency diversity gain the equalization weights based on MMSE criteria were derived. It was shown that the use of OFDM/TDM instead of conventional OFDM achieves a better quality of service with a higher transmit power efficiency.

Acknowledgment

This work in part was supported by Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science (JSPS).

References

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communications in fading environment when using multiple antennas," IEEE Wireless Pers. Commun., vol. 6, pp. 311-335, Mar. 1998.

[2] E. Meulen, "Three-terminal communication channels," Adv. Appl. Probability, vol. 3, no. 1, pp. 120-154, Spring 1971.

[3] T. Cover and A. El-Gamal, "Capacity theorems for the relay channel," IEEE Trans. Inform. Theory, vol. 25, no. 5, pp. 572-584, Sep. 1979.

[4] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity-part I, II" IEEE Trans. Commun., vol. 51, pp. 1927-1948, Nov. 2003.

[5] J. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," IEEE Trans. Inform. Theory, vol. 50, no. 11, pp. 3062-3080, Dec. 2004.

[6] R. U. Nabar, H. Bolcskei, and F. W. Kneubiihler, "Fading relay channels: performance limits and space-time signal design," IEEE J. Select. Areas Commun. vol. 22, pp. 1099-1109, Aug. 2004.

[7] Y. Jing and B. Hassibi, "Distributed space-time coding in wireless relay networks," IEEE Trans. Wireless Commun., Vol. 5, pp. 3524-3536, Dec. 2006.

[8] W. Zhang. Y. Li, X. Xia, P. C. Ching and K. B. Letaief, "Distributed Space-frequency coding in broadband ad hoc networks," 2007. ICASSP 2007. IEEE International Conference on Acoustics, Speech and Signal Processing, 15-20 April 2007, Honolulu, HI, USA.

[9] P. A. Anghel and M. Kaveh, "Relay assisted uplink communication over frequency-selective channels," The 2003 IEEE Signal processing advances for wireless communications (SPAWC 2003), pp. 125-129, 15-18 Jun. 2003, Rome, Italy.

[10] A. Stefanov and E. Erkip, "Cooperative coding for wireless networks," IEEE Trans. Commun., Vol. 52, pp. 1470-1476, Sept. 2004.

[11] S. Hara and R. Prasad, Multicarrier Techniques for 4G Mobile Communications, Artech House, June 2003.

[12] C. V. Sinn, J. Gotze and M. Haardt, "Common architectures for TD-CDMA and OFDM based mobile radio systems without the necessity of a cyclic prefix," Proc. of MS-SS Workshop, DLR, Oberpfaffenhofen, Germany, 24-25 Sep 2001.

[13] H. Gacanin, S. Takaoka and F. Adachi, "BER performance of OFDM combined with TDM using frequency-domain equalization," Journal of Communication and Networking (JCN), Vol. 9, No. 1, pp. 34-42, March 2007.