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周波数領域等化を用いる OFDM/TDM におけるチャネル推定

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あらまし直交周波数多重(OFDM)と時分割多重(TDM)を組み合わせた OFDM/TDM は，従来の OFDM での問題である高ピーク対平均電力比の低減をはかることが出来るとともに，平均 2 乗誤差最小(MMSE)規範に基づいた周波数領域等化(FDE)により優れたビット誤り率(BER)特性を得ることができる．MMSE-FDE では高精度なチャネル推定が必要である．本論文では，時間領域及び周波数領域でほぼ振幅一定となるパイロット系列を用いるチャネル推定について述べ，OFDM/TDM の伝送特性を計算機シミュレーションで明らかにしている．

Effect of pilot-assisted Channel Estimation on the BER performance of the OFDM/TDM with Frequency-domain Equalization

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Abstract: Orthogonal frequency division multiplexing (OFDM) combined with time division multiplexing (TDM), called OFDM/TDM, can overcome the high peak-to-average-power ratio (PAPR) problem of the conventional OFDM. Its bit error rate (BER) performance in a frequency-selective fading channel is improved by adoption of frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion. However, MMSE-FDE requires accurate channel estimation. In this paper, a pilot-assisted channel estimation scheme suitable for OFDM/TDM with MMSE-FDE is presented and the achievable BER performance is evaluated by computer simulation.

Keyword: OFDM/TDM, frequency-domain equalization, pilot-assisted channel estimation.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) has been attracting considerable attention because of its robustness against frequency-selective fading [1]. However, OFDM signal has high peak-to-average-power ratio (PAPR) problem [2]. Recently it was shown [3], [4] that, assuming ideal channel estimation, OFDM combined with time division multiplexing (TDM) [5], called OFDM/TDM, can overcome the PAPR problem of the conventional OFDM while improving the bit error rate (BER) performance by the use of simple one-tap frequency-domain equalization (FDE) based on minimum mean square error (MMSE) criterion. It was also shown [3], [4] that, the OFDM/TDM with MMSE-FDE bridges OFDM and single carrier (SC) transmission. However, MMSE-FDE requires accurate channel estimation (CE). In [6], the pilot-assisted channel estimation techniques for OFDM have been evaluated. For accurate CE, a known pilot sequence with the constant amplitude in the frequency-domain can be periodically inserted into the subcarriers. However, large amplitude variations may appear in the time-domain resulting in high PAPR, which is not desirable for the SC transmission as a special case of OFDM/TDM. In [7], a design of the pilot sequence with constant amplitude in the frequency-domain and small amplitude variations in the time-domain has been proposed.

In this paper, we propose a combined pilot-assisted CE with delay-time domain windowing [6]. A selection of pilot sequence is very important. We use the pilot sequence design proposed in [7]. The BER performance of OFDM/TDM with pilot-assisted CE is evaluated by computer simulation and compared with ideal CE case. Due to delay-time domain windowing, the noise on channel estimates is significantly reduced and the CE accuracy is improved. The rest of the paper is organized as follows. Section 2 briefly describes OFDM/TDM transmission model. In Sect. 3, the pilot-assisted CE is presented. Sect. 4 evaluates, by computer simulations, the BER performance of the OFDM/TDM using pilot-assisted CE with and without delay-time domain windowing in a frequency-selective Rayleigh fading channel. Sect. 5 provides some conclusions and future works.

2. OFDM/TDM Transmission Model

The OFDM/TDM frame structure is illustrated and compared with the conventional OFDM in Fig.1. Assume that the conventional OFDM has N_c subcarriers. The inverse fast Fourier transform (IFFT) block size for the conventional OFDM is divided into K slots (which constitutes the OFDM/TDM frame) as illustrated in Fig.1(b); an OFDM signal with reduced number of subcarriers (N_m=N_c/K) is transmitted during each time slot. Note that OFDM/TDM becomes SC when K=N_c while for K=1 becomes conventional OFDM.

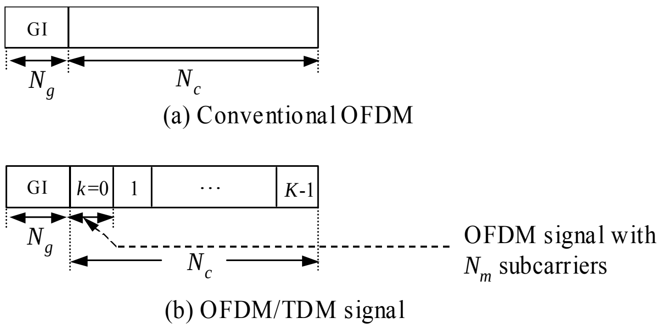


Figure 1. OFDM/TDM frame structure

Figure 2 illustrates the OFDM/TDM transmitter and receiver structures. The sequence of N_c data-modulated symbols {$d(i)$; i=0~N_c-1} is transmitted during one OFDM/TDM frame with a length of N_c=KN_m samples. Firstly, N_c data-modulated symbol sequence is divided into K data blocks, each having N_m data symbols. Than, N_m-point IFFT is applied on each block to generate a sequence of K OFDM signals with N_m (=N_c/K) subcarriers each. Finally, N_g sample GI is inserted at the beginning of the frame and the GI-inserted OFDM/TDM signal is transmitted over the frequency-selective fading channel.

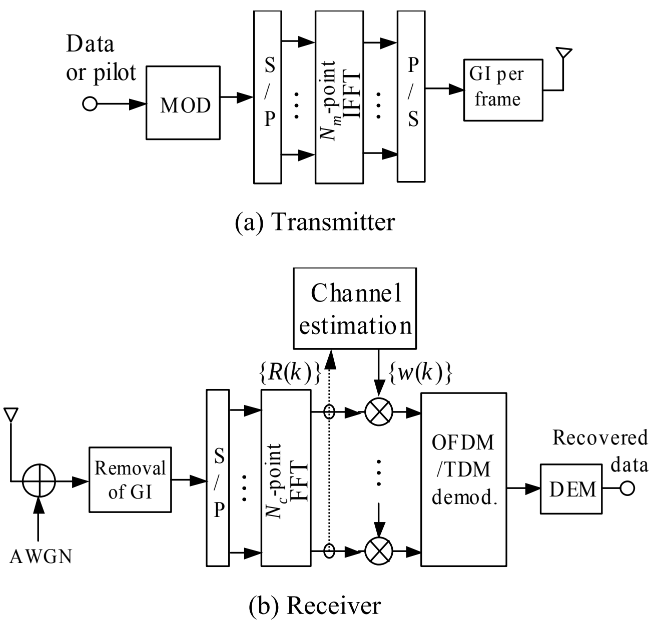


Figure 2. OFDM/TDM transmission system model.

Since, the GI is not inserted between consecutive slots but only at the beginning of each OFDM/TDM frame, the inter-symbol interference (ISI) arises due to frequency-selective fading and degrades the BER performance. To overcome this problem, we apply one-tap MMSE-FDE. It should be noted that FDE is not applied to each OFDM signal with N_m subcarriers, but to OFDM/TDM signal over the entire frame. At the receiver, the GI is removed and the received time-domain signal {$r(t)$; t=0~N_c-1} is decomposed into N_c frequency components {$R(k)$; k=0~N_c-1} by N_c-point FFT. Then, MMSE-FDE is applied as

$$\hat{R}(k) = w(k)R(k), \tag{1}$$

where $w(k)$ is the MMSE equalization weight for the kth frequency given by [8]-[11]

$$w(k) = \frac{H^*(k)}{|H(k)|^2 + \left(\frac{1}{K}\frac{E_s}{N_0}\right)^{-1}}. \tag{2}$$

In Eq.(2), $H(k)$, E_s and * represent the kth frequency channel gain, the symbol energy and the complex conjugate operation, respectively. Finally, the OFDM/TDM demodulation is performed to recover the transmitted data symbol sequence [3].

As seen from Eq.(2) channel estimate is necessary for computing the MMSE-FDE weight. This will be discussed in Sect. 3.

3. Pilot-assisted Channel Estimation

3.1. Channel Estimation Using Delay-time Domain Windowing

For pilot-assisted CE, a known pilot sequence is periodically transmitted followed by N_d OFDM/TDM data frames as shown in Fig. 3. Figure 4 illustrates the block diagram for pilot-assisted CE. Firstly, by reverse modulation, the instantaneous channel gain at the kth frequency is obtained as

$$\tilde{H}_e(k) = \frac{R(k)}{P(k)} \tag{3}$$

for k=0~N_c-1, where $P(k)$ is the kth frequency component of the pilot sequence. $\tilde{H}_e(k)$ is expressed as

$$\tilde{H}_e(k) = H(k) + \frac{N(k)}{P(k)}, \tag{4}$$

where $N(k)$ represents the noise component due to additive white Gaussian noise (AWGN). If $|P(k)|\approx 0$, a large noise enhancement is produced, thereby degrading the channel estimation accuracy. To avoid this noise enhancement, it is necessary that $|P(k)|\approx$const for all k. To further reduce the noise effect, the delay-time domain windowing (or zero padding) [6] is applied on the estimated instantaneous channel impulse response. N_c-point IFFT is performed on $\{\widetilde{H}_e(k)\}$ to obtain the instantaneous channel impulse response $\{\widetilde{h}_e(t);\ t=0\sim N_c-1\}$. Assuming that the channel impulse response is present only within the GI, the estimated channel impulse response is zero-padded beyond the GI to reduce the noise as [6], [7]

$$h_e(t)=\begin{cases}\widetilde{h}_e(t), & 0<t<N_g\\ 0, & N_g\le t<N_c\end{cases}. \tag{5}$$

Then, N_c-point FFT is applied to $\{h_e(t)\}$ to obtain the improved channel gain estimates $\{H_e(k)\}$.

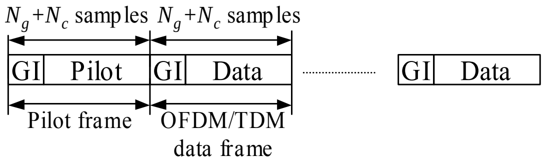


Figure 3. OFDM/TDM pilot block arrangement

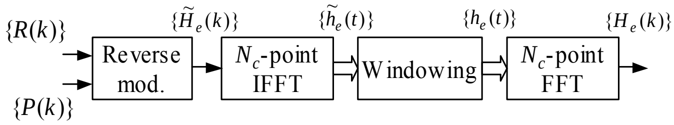


Figure 4. Pilot-assisted CE.

3.2. Pilot Sequence Generation

The noise enhancement is produced in $\widetilde{H}_e(k)$ if $|P(k)|\approx 0$, resulting in less accurate CE. To avoid this noise enhancement, as said earlier, it is desirable that $P(k)$ has constant amplitude for all k. However, large amplitude variations may appear in the time-domain if $|P(k)|$=const for all k; this is not desirable for SC transmission. Therefore, we allow small amplitude variations in the time-domain in order to keep almost constant amplitude in the frequency-domain. We apply an iterative generation method proposed in [7]. The pilot generation procedure is shown in Fig.5. The pilot sequence $p(t)$ in the time-domain is generated as follows:

- The initial frequency-domain sequence $\{P^{(0)}(k);\ k=0\sim N_c-1\}$ is randomly selected from QPSK constellation diagram
- N_c-point IFFT is performed on $\{P^{(0)}(k)\}$ to obtain $\{p^{(0)}(t);\ t=0\sim N_c-1\}$
- $p^{(0)}(t)$ is input to an ideal hard-limiter, producing a modified sequence $p_{HL}^{(0)}(t)=\exp\left(j\arg\left(p^{(0)}(t)\right)\right)$
- N_c-point FFT is performed on $\{p_{HL}^{(0)}(t)\}$ to obtain $\{P_{HL}^{(0)}(k)\}$
- $P_{HL}^{(0)}(k)$ is input to the ideal hard-limiter, producing a modified sequence $P^{(1)}(k)=\exp\left(j\arg\left(P_{HL}^{(0)}(k)\right)\right)$
- Repeat this procedure a sufficient number of times

The time-domain representation of the generated pilot sequence after i iterations is denoted as $p^{(i)}(t)$ and the frequency-domain representation by $P^{(i)}(k)$. Using the pilot generation method of [7], the amplitude of the pilot sequence in the frequency-domain is always constant. The generated pilot sequence represented in the time-domain is shown in Fig. 6. It can be seen that, after 1000 iterations, the generated pilot sequence has almost constant amplitude in the time-domain while the amplitude in the frequency-domain is kept constant. This is also confirmed by the probability density function (PDF) of the normalized amplitude of the pilot sequence in the time-domain in Fig. 7. From Figs. 6 and 7 it can be understood that the generated pilot sequence after 1000 iterations has sufficiently small variations in time-domain. Because of this, in our following simulations shown in Sect. 4, the number of iterations is set to 1000.

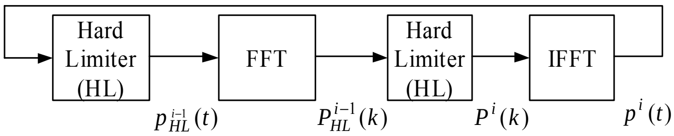
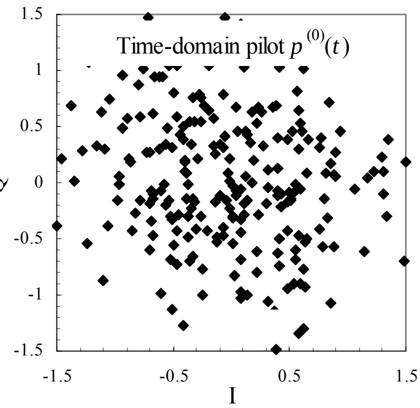
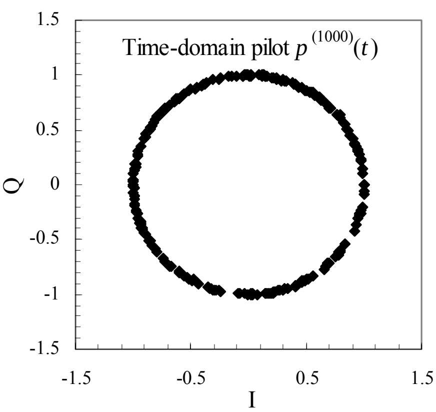


Figure 5. Iterative generation of pilot signal.



(a) Initial pilot $p^{(0)}(t)$



(b) Pilot sequence $p^{(1000)}(t)$

Figure 6. Pilot sequence in time-domain.

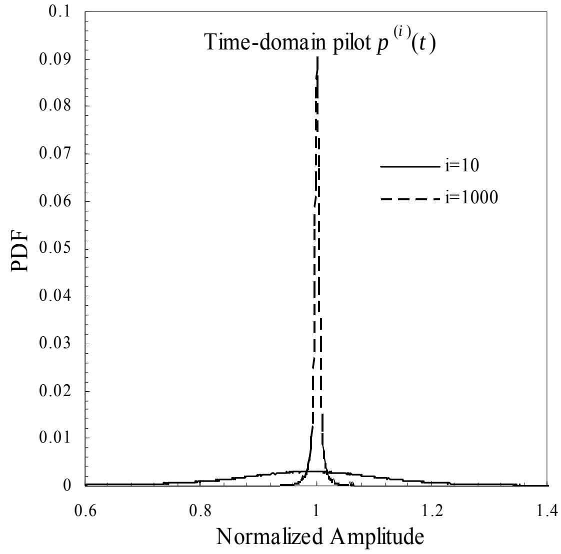


Figure 7. Amplitude PDF of the pilot sequence in time-domain.

4. Performance evaluation

In this section, we present the BER performance of the OFDM/TDM with pilot-assisted CE. Simulation conditions are shown in Table 1. We assume QPSK data-modulation with N_c=256 and N_g=32. The propagation channel is a frequency-selective block Rayleigh fading channel having sample-spaced L=16-path exponential power delay profile with decay factor β, where path gains stay constant over one OFDM/TDM frame (e.g., N_g+N_c samples).

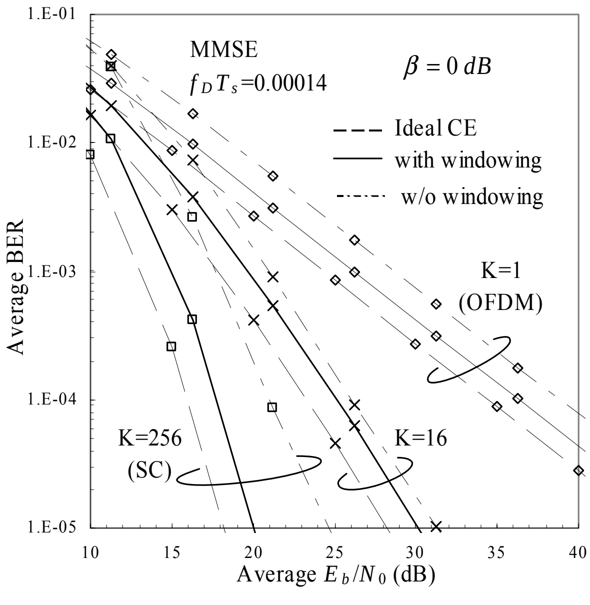
Table 1. OFDM/TDM parameters

Transmitter	Data modulation	QPSK
	Number of IFFT points	N_m=256/K
	Number of slots per frame	K=1~256
	Frame length	N_c=256
	GI	N_g=32
Channel	L=16-path frequency-selective Rayleigh fading with decay factor β	
Receiver	Number of FFT points	N_c=256
	Frequency-domain equalization	MMSE

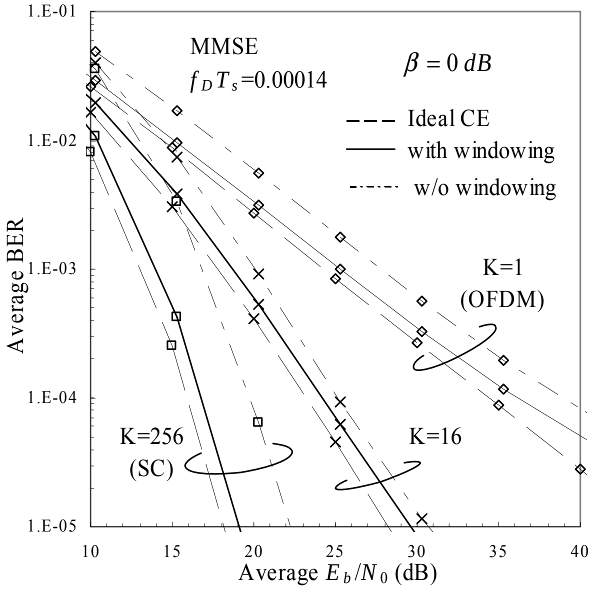
The average BER performance of OFDM/TDM with pilot-assisted CE without and with delay-time domain windowing is plotted in Fig. 8, as a function of the average received bit energy-to-AWGN power spectrum density ratio E_b/N_0 (=0.5(E_s/N_0)×(1+N_g/N_c)) for the normalized Doppler frequency f_DT_s=0.00014 where $1/T_s=1/[T_c(1+N_g/N_c)]$ is the transmission symbol rate (f_DT_s=0.00014 correspond to mobile terminal moving speeds of 80km/h for 5GHz carrier frequency and transmission data rate of 100M symbols/sec). The BER performance with an ideal CE is also plotted for comparison.

It can be seen, from Fig.8 (a) and (b), that the BER performance can be significantly improved by adoption of delay-time domain windowing. When delay-time domain windowing is used, the signal-to-noise ration (SNR) of the channel estimates is improved by a factor of N_c/N_g, leading to an improved BER performance. Without delay-time domain windowing, E_b/N_0 degradation for an average BER=10^{-4} from the ideal CE case is about 4.3 (4.1) dB for K=1 and about 4.9 (4) dB for K=256 when N_d=3 (15). However, when the delay time-domain windowing method is used, the E_b/N_0 degradation becomes as small as 1.8 (1.6) dB for K=1 and 1.7 (0.9) dB for K=256 when N_d=3 (15). In the following, we only consider CE with delay-time domain windowing.

How the fading rate impacts on achievable BER performance with the proposed CE is discussed below. Figure 9 plots the average BER as a function of f_DT_s for N_d=3 and 15 when E_b/N_0=20 dB. For comparison the BER for an ideal CE is also plotted. Ideal CE refers to the case with no AWGN (e.g., only tracking error against the channel time variations is present). The BER performance degrades with the increase of f_DT_s because of two factors. First one is the increased channel estimation error due to AWGN (e.g., second term in Eq.(4)) and the second one is a tracking error against the channel time variations. For N_d=3, the estimation error due to AWGN is predominant compared to the tracking error and the BER slowly increases as f_DT_s increases. However, for N_d=15 the channel tracking error is predominant in addition to channel estimation error and the BER severely degrades when f_DT_s increases. Therefore, N_d=3 is preferable at the cost of slight performance degradation in a very slow fading environment.



(a) N_d=3



(b) N_d=15

Figure 8. BER performance.

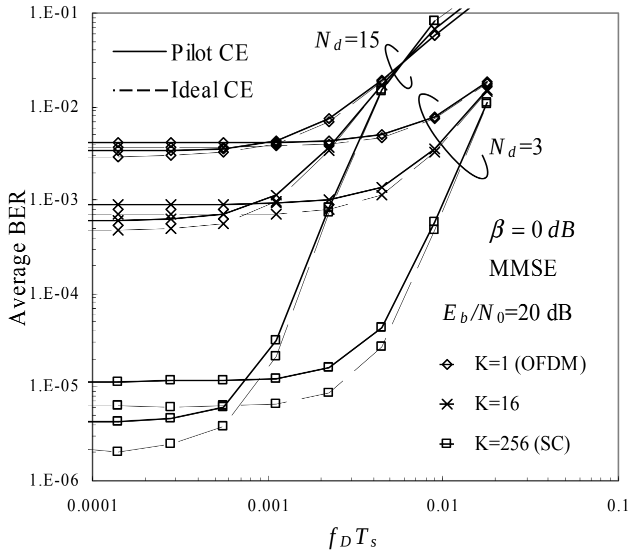


Figure 9. Impact of Doppler frequency.

The channel frequency-selectivity is an important parameter that affects the BER performance of the OFDM/TDM [3], [4]. Figure 10 plots the average BER with delay-time domain windowing CE, for N_d=3 and E_b/N_0=20 dB, as a function of β. The BER degrades in comparison to ideal CE due to channel estimation error, and as β increases the BER also increases because the channel becomes less frequency-selective, which reduces the frequency diversity effect.

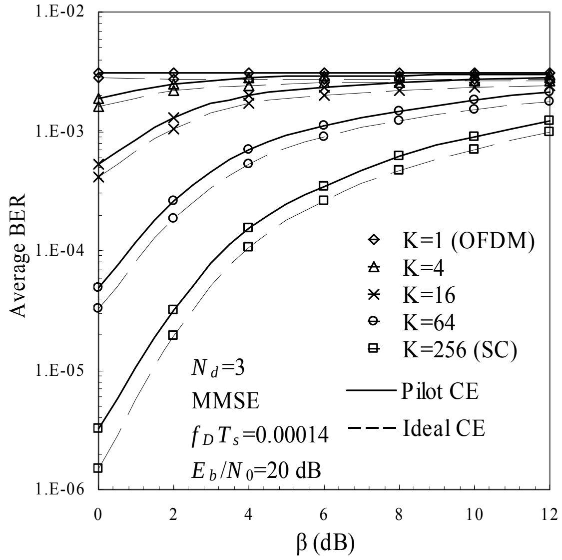


Figure 10. Impact of channel decay factor β.

5. Conclusions

In this paper, we presented the pilot-assisted CE with delay-time domain windowing for OFDM/TDM with MMSE-FDE. The achievable BER performance in a frequency- and time-selective Rayleigh fading channel was evaluated by computer simulation. Due to delay-time domain windowing, the effect of noise in channel estimation is significantly reduced. A pilot sequence generation with constant amplitude in the frequency-domain and small amplitude variations in the time-domain was used. It was shown that the proposed pilot-assisted CE with delay-time domain windowing achieves an E_b/N_0 degradation of less than 1 dB from the ideal CE case when N_d=15 is used. When $f_D T_s$ increases, due to tracking error against the channel time variations, the BER performance degrades. However, the use of N_d=3 shows better tracking abilities than the use of N_d=15. For further improving the tracking ability some techniques are necessary. This is left as interesting future work.

References

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

[2] R. D.J. van Nee, R. Prasad and R. van Nee, OFDM for wireless multimedia communications, Artech House, Jan. 2000.

[3] H. Gacanin, et. al., “Generalized OFDM with frequency-domain equalization,” IEICE Technical Report, RCS2003-306, pp.19-24, March 2004.

[4] H. Gacanin, et al., “Generalized OFDM for Bridging between OFDM and Single-carrier transmission,” Proc. 9th Intern. Conf. on Comm. Syst., Singapore, Sept. 2004.

[5] C. V. Sinn, et. al.,“Common architectures for TD-CDMA and OFDM based mobile radio systems without the necessity of a cyclic prefix,” MS-SS Workshop, Oberpfaffenhofen, Germany, Sept. 2001.

[6] S. Coleri, M. Ergen, A. Puri, and A. Bahai, “Channel estimation techniques based on pilot arrangement in

OFDM systems," IEEE Trans. on Broad., Vol. 48, No. 3, Sept. 2002.

[7] R. Dinis, et al., "Channel estimation for MIMO systems employing single-carrier modulations with iterative frequency-domain equalization," 60th IEEE VTC, 26-29. Sept., LA, USA . 2004. [6] S. Haykin, Adaptive filter theory, 4th Ed., Prentice Hall, 2002.

[8] D. Falconer, S.L. Ariyavisitakul, A. Benyamin-Seeyar and B. Eidson, "Frequency-domain equalization for single-carrier broadband wireless systems," IEEE Commun. Mag., Vol. 40, pp.58-66, April 2002.

[9] S. Hara and R. Prasad, "Overview of multicarrier CDMA," IEEE Commun. Mag., pp.126-144, Dec. 1997.

[10] M. Helard, R. Le Gouable, J.-F. Helard, and J.-Y. Baudais, "Multicarrier CDMA techniques for future wideband wireless access," Ann. Telecommun., Vol. 56, pp. 260-274, 2001.

[11] F. Adachi, T. Sao and T. Itagaki, "Performance of multicode DS-CDMA using frequency domain equalization in frequency selective fading channel," Electronic Letters, Vol.39, No.2, pp.239-241, Jan. 2003.