BER Performance of OFDM Combined with TDM Using Frequency-Domain Equalization

Haris Gacanin, Shinsuke Takaoka, and Fumiyuki Adachi

Abstract: **Orthogonal frequency division multiplexing (OFDM) combined with time division multiplexing (TDM), in this paper called OFDM/TDM, can overcome the high peak-to-average-power ratio (PAPR) problem of the conventional OFDM and improve the robustness against long time delays. In this paper, the bit error rate (BER) performance of OFDM/TDM in a frequency-selective Rayleigh fading channel is evaluated by computer simulation. It is shown that the use of frequency-domain equalization based on minimum mean square error criterion (MMSE-FDE) can significantly improve the BER performance, compared to the conventional OFDM, by exploiting the channel frequency-selectivity while reducing the PAPR or improving the robustness against long time delays. It is also shown that the performance of OFDM/TDM designed to reduce the PAPR can bridge the conventional OFDM and single-carrier (SC) transmission by changing the design parameter.**

Index Terms: **Frequency-domain equalization, frequency-selective fading, orthogonal frequency division multiplexing (OFDM), peak-to-average-power ratio (PAPR).**

I. INTRODUCTION

In a mobile radio channel (e.g., multipath environment), the received signal is a superposition of several delayed and scaled copies of the transmitted signal giving rise to a frequency-selective fading, which significantly degrades the transmission performance [1]. Recently, a block-based (i.e., hereinafter frame-based) orthogonal frequency division multiplexing (OFDM) and single carrier (SC) transmission have been attracting much attention since the insertion of a guard interval (GI) between consecutive data frames eliminates the inter-frame interference (IFI) that may arise due to frequency-selective fading and allows a simple one-tap frequency domain equalization (FDE) [2], [3]. The frame-based OFDM transmission system has already been adopted in some wireless communication systems [4], [5].

The OFDM signals have a behavior similar to that of a Gaussian random process. This yields a drawback of having a large amplitude dynamic range, i.e., a large peak-to-average power ratio (PAPR) [4], [5]. Various approaches to reduce the PAPR have been proposed [6]–[10]. Noting that the PAPR is proportional to the number of subcarriers, a straightforward approach to alleviate the PAPR problem is to reduce the number of subcarriers. However, this approach obviously reduces the bandwidth efficiency since the length of GI needs to be kept constant. In this paper, to reduce the PAPR, we consider OFDM combined with time division multiplexing (TDM) [11] in this paper called OFDM/TDM). Work done in [11] aims to increase the transmission data rate while keeping the same bandwidth as the conventional OFDM, and is not intended to alleviate the PAPR problem. Our objective is to show that OFDM/TDM can improve the bit error rate (BER) performance compared to the conventional OFDM while reducing the PAPR without sacrificing the transmission data rate at all. Unlike the conventional OFDM approach, FDE is performed over the entire OFDM/TDM frame rather than separately to each time slot (this will be presented in Sections II-C and III-D).

In OFDM-based transmission systems, to avoid IFI, the GI is added as a cyclic prefix to the OFDM signal. However, the presence of multipaths with time delays longer than the GI produces IFI, thereby significantly degrading the BER performance. Recently, several equalization techniques have been proposed to reduce the performance degradation due to long time delays exceeding the GI [12], [13]. To improve the robustness against long time delays, a straightforward approach is to enlarge the GI length, but this reduces the transmission data rate for the given bandwidth. In this paper, the OFDM/TDM frame is expanded in comparison to the conventional OFDM so that longer GI can be inserted (this will be presented in Section II-B).

The remainder of this paper is organized as follows. Section II presents the OFDM/TDM design for reducing the PAPR, improving the robustness against long time delays and application of FDE. The OFDM/TDM signal transmission model is presented in Section III. In Section IV, we evaluate, by computer simulation, the BER performance of OFDM/TDM with FDE in a frequency-selective Rayleigh fading channel, and then, compare it with those of the conventional OFDM and SC transmission. Section V concludes the paper.

II. OFDM/TDM DESIGN

The OFDM/TDM frame structure is illustrated in Fig. 1. We assume the conventional OFDM with N_c subcarriers and N_g-sample GI as shown by Fig. 1(a). OFDM/TDM can be designed for reducing the PAPR or for improving the robustness against long time delays without sacrificing the transmission data rate at all.

A. PAPR Reduction

To reduce the PAPR, the inverse fast Fourier transform (IFFT) time window for the conventional OFDM is divided into K slots (which constitute the OFDM/TDM frame) as illustrated

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in Fig. 1(b); an OFDM signal with reduced number of subcarriers ($N_m = N_c/K$) is transmitted during each time slot without inserting the GI between consecutive OFDM signals. The N_g-sample GI is inserted only at the beginning of each OFDM/TDM frame the same as in the conventional OFDM. Hence, the transmission data rate is kept the same as the conventional OFDM, while the number of subcarriers is reduced by a factor of K, thus reducing the PAPR by the same factor. Note that the insertion of GI eliminates IFI, but the inter-slot interference (ISI) arises since the GI is not inserted between consecutive slots. This can be reduced by FDE.

B. Robustness Against Long Time Delays

To improve the robustness against long time delays, the OFDM/TDM frame is expanded K times in comparison to conventional OFDM so that a K times longer GI (i.e., KN_g samples) can be inserted. In this case, the OFDM/TDM signal has the same PAPR as the conventional OFDM signal since an OFDM signal with N_c subcarriers is transmitted during each time slot; but the number of data symbols transmitted per OFDM/TDM frame is KN_c, and hence, the transmission data rate is kept the same (see Fig. 1(c)).

C. Application of FDE

Our work can be seen as an extension and modification of the work done in [11]. However, the objective of [11] is different from ours, and is to increase the transmission data rate for the given bandwidth (OFDM/TDM of [11] is equivalent to Fig. 1(c) with reduced GI from KN_g to N_g samples). Furthermore, in [11], only zero-forcing frequency-domain equalization (ZF-FDE) is considered. Various FDE techniques can be applied to exploit the channel frequency-selectivity and improve the BER performance of OFDM/TDM. Unlike the conventional approach, FDE is performed over the entire OFDM/TDM frame (i.e., over K OFDM signals), rather than applying it separately to each slot. We consider FDE techniques based on ZF, maximal ratio combining (MRC), and minimum mean square error (MMSE) criteria used for equalization in SC transmission [14], multicarrier code division multiple access (MC-CDMA) [15]–[17], and quite recently in direct sequence CDMA (DS-CDMA) [18], [19].

The GI is inserted at the beginning of the OFDM/TDM frame to eliminate IFI for FDE. It will be shown by computer simulation in Section IV that the BER performance of OFDM/TDM can be significantly improved compared to the conventional OFDM by applying the MMSE-FDE. MMSE-FDE is applied to reduce ISI and exploit the frequency diversity effect (i.e., the probability that the received signal powers at different frequencies fade simultaneously is reduced considerably as the channel frequency-selectivity becomes stronger). An important property of OFDM/TDM designed to reduce the PAPR is that if MMSE-FDE is applied, the OFDM/TDM performance can bridge the conventional OFDM and SC transmission; OFDM/TDM becomes conventional OFDM when $K = 1$ and becomes SC when $K = N_c$ (this will be discussed in Section IV). Because of this property, the OFDM/TDM designed for reducing the PAPR provides flexibility in designing OFDM-based transmission systems. This property has not been presented in [11]. Note that the OFDM/TDM designed to improve the robustness against long time delays is not a scaled version of OFDM/TDM designed to reduce the PAPR and does not bridge the conventional OFDM and SC transmission.

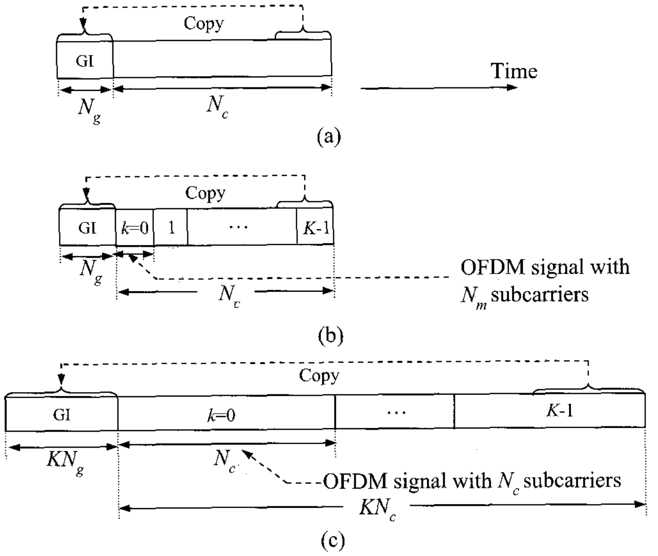

Fig. 1. OFDM/TDM frame structure: (a) Conventional OFDM with Nc subcarriers, (b) OFDM/TDM for PAPR reduction, (c) OFDM/TDM for improving delay robustness.

III. OFDM/TDM TRANSMISSION MODEL

We first present a general propagation channel model considering two OFDM/TDM designs. However, for the sake of brevity, we only present the signal transmission system using OFDM/TDM design to reduce the PAPR.

A. Channel Model

The fading channel is assumed to be composed of L discrete propagation paths having sample-spaced time delays. A discrete-time channel impulse response $h(t)$ is expressed as

$$h(t) = \sum_{l=0}^{L-1} h_l \delta(t - \tau_l) \tag{1}$$

where h_l and τ_l denote the l-th path gain and time delay, respectively, and $\delta(t)$ is the delta function. $\{h_l; l = 0 \sim L-1\}$ are zero-mean independent complex variables with $E[\sum_{l=0}^{L-1} |h_l|^2] = 1$. Without loss of generality, we assume $\tau_0 = 0 < \tau_1 < \cdots < \tau_{L-1}$ and that the l-th path time delay is $\tau_l = l\Delta$, where Δ (≥ 1) denotes the time delay separation between adjacent paths. We assume an L-path channel having an exponential power delay profile $\Omega(\tau)$ with a decay factor β as

$$\begin{aligned}\Omega(\tau) &= \sum_{l=0}^{L-1} E[|h_l|^2]\delta(\tau - \tau_l) \\ &= \frac{1-\beta^{-1}}{1-\beta^{-L}} \sum_{l=0}^{L-1} \beta^{-l}\delta(\tau - \tau_l).\end{aligned} \tag{2}$$

The reference OFDM is the conventional OFDM with N_c subcarriers and N_g-sample GI, as shown in Fig. 1(a). For the OFDM/TDM designed to reduce the PAPR, we assume a GI of length N_g (see Fig. 1(b)) and that the maximum channel time delay τ_{L-1} is shorter than N_g. On the other hand, for the OFDM/TDM designed to improve the robustness against long time delays, we assume a GI of length KN_g (see Fig. 1(c)) and that the τ_{L-1} is longer than N_g, but shorter than KN_g, i.e., $N_g \leq \tau_{L-1} \leq KN_g$.

In the following subsections, for the sake of brevity, we only describe the OFDM/TDM designed for reducing the PAPR, and we assume that GI is longer than the maximum channel delay time, i.e., $N_g \geq \tau_{L-1}$. As described in Section II, in OFDM/TDM designed for PAPR reduction, a sequence of K OFDM signals with a reduced number of subcarriers (i.e., $N_m = N_c/K$) is transmitted during an N_c-sample OFDM/TDM frame. If the number of subcarriers, N_m, is replaced by N_c irrespective of K, the FFT/IFFT size for FDE (the OFDM/TDM frame length) is extended to KN_c, and furthermore, N_g is replaced by KN_g, the transmission system model becomes the one designed for improving the robustness against long time delays.

B. Transmit OFDM/TDM Signal

Our OFDM/TDM transmission system model is illustrated in Fig. 2. Similar to conventional OFDM, a sequence of N_g data-modulated symbols $\{d(i); i = 0 \sim N_c - 1\}$ with $E[|d(i)|^2] = 1$ is transmitted during one OFDM/TDM frame, where $E[\cdot]$ denotes the ensemble average operation. The IFFT time window for OFDM/TDM is kept the same as for the conventional OFDM. A data-modulated sequence $\{d(i); i = 0 \sim N_c - 1\}$ is divided into K blocks of N_m symbols each. The k-th block symbol sequence is denoted as $\{d^k(i); i = 0 \sim N_m - 1\}$, where $d^k(i) = d(kN_m + i)$. N_m-point IFFT is applied to each data block to generate a sequence of K OFDM signals with $N_m = N_c/K$ subcarriers as shown by Fig. 1(b). The resulting OFDM/TDM signal can be expressed using the equivalent lowpass representation as

$$s(t) = \sqrt{\frac{2E_s}{T_c N_m}} \sum_{i=0}^{N_m-1} d^{\lfloor \frac{t}{N_m} \rfloor}(i) \exp\left(j2\pi t \frac{i}{N_m}\right) \quad (3)$$

for $t = 0 \sim N_c - 1$, where E_s and T_c represent the modulated-data symbol energy and the sampling period, respectively, and $\lfloor x \rfloor$ represents the largest integer smaller than or equal to x. Before transmission, the last N_g samples of the OFDM/TDM signal are copied as a cyclic prefix and inserted into the GI. The GI-inserted OFDM/TDM signal $\{s(t \mod N_c); t = -N_g \sim N_c - 1\}$ is transmitted over a frequency-selective fading channel.

C. Received OFDM/TDM Signal

The received baseband OFDM/TDM signal is given as

$$r(t) = \sum_{l=0}^{L-1} h_l s(t \bmod N_c - \tau_l) + n(t) \quad (4)$$

for $t = -N_g \sim N_c - 1$, where $n(t)$ is a zero-mean complex Gaussian noise process with a variance of $2N_0/T_c$ due to the additive white Gaussian noise (AWGN) with single-sided power spectrum density N_0. After the removal of the GI, the received time-domain signal $\{r(t); t = 0 \sim N_c - 1\}$ is decomposed into N_c frequency components $\{R(n); n = 0 \sim N_c - 1\}$ by applying N_c-point FFT:

$$\begin{aligned} R(n) &= \frac{1}{N_c} \sum_{t=0}^{N_c-1} r(t) \exp\left(-j2\pi n \frac{t}{N_c}\right) \\ &= S(n)H(n) + N(n) \end{aligned} \quad (5)$$

where $S(n)$, $H(n)$, and $N(n)$ are the signal component, the propagation channel gain, and the noise component at the n-th frequency, respectively, and are given by

$$\begin{aligned} S(n) &= \frac{1}{N_c} \sum_{t=0}^{N_c-1} s(t) \exp\left(-j2\pi n \frac{t}{N_c}\right) \\ H(n) &= \sum_{l=0}^{L-1} h_l \exp\left(-j2\pi n \frac{\tau_l}{N_c}\right) \\ N(n) &= \frac{1}{N_c} \sum_{t=0}^{N_c-1} n(t) \exp\left(-j2\pi n \frac{t}{N_c}\right). \end{aligned} \quad (6)$$

Since N_c-point FFT is performed over the entire OFDM/TDM frame, the n-th frequency component $S(n)H(n)$ in (5) includes the ISI produced by frequency-selective fading.

D. FDE

In OFDM/TDM, a GI is not inserted between consecutive slots but only at the beginning of each OFDM/TDM frame. Therefore, IFI is completely eliminated, but the ISI arises due to multipath fading and degrades the BER performance. To overcome this problem, we apply one-tap FDE over the entire OFDM/TDM frame, unlike the conventional FDE as introduced in Section II. FDE is carried out as [14]

$$\begin{aligned} \hat{R}(n) &= w(n)R(n) \\ &= S(n)\hat{H}(n) + \hat{N}(n) \end{aligned} \quad (7)$$

where $w(n)$ is the equalization weight for the n-th frequency and

$$\begin{aligned} \hat{H}(n) &= H(n)w(n) \\ \hat{N}(n) &= N(n)w(n). \end{aligned} \quad (8)$$

We apply ZF-, MRC-, or MMSE-FDE similar to SC, MC-CDMA and DS-CDMA. The equalization weights for ZF, MRC, and MMSE are given by [15]–[19]

$$w(n) = \begin{cases} H^*(n)/|H(n)|^2 & \text{for ZF} \\ H^*(n) & \text{for MRC} \\ H^*(n)/\left(|H(n)|^2 + (\frac{E_s}{N_0})^{-1}\right) & \text{for MMSE} \end{cases}$$

where * denotes the complex conjugate operation. Comparing (5) and (7), in this paper, $\hat{H}(n)$ denotes the equivalent channel gain. $\hat{N}(n)$ in (7) is the noise after equalization.

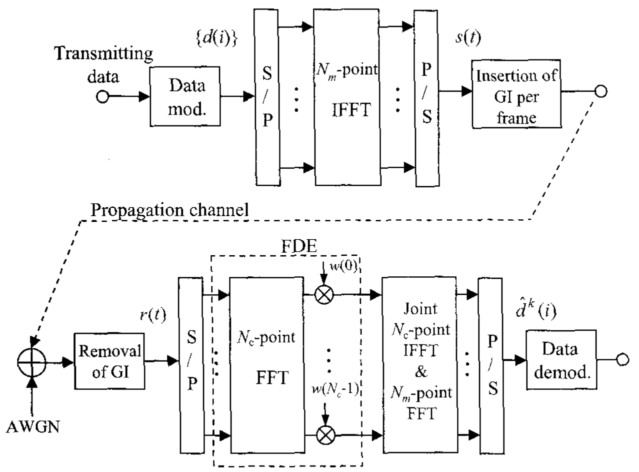

Fig. 2. OFDM/TDM transmission system model.

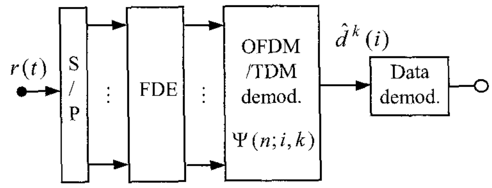

Fig. 3. OFDM/TDM demodulation using frequency-domain filtering.

Table 1. OFDM/TDM parameters.

OFDM /TDM	PAPR reduction	No. of subcarriers	$N_m = N_c/K$
		GI	N_g
		Frame length	$N_c + N_g$
	GI extension	No. of subcarriers	N_c
		GI	KN_g
		Frame length	$K(N_c + N_g)$
Conventional OFDM		No. of subcarriers	N_c
		GI	N_g
		Frame length	$N_c + N_g$

Since OFDM transmission is a block-based transmission, FDE is also a block processing. The residual ISI limits the performance improvement of OFDM/TDM. To further improve the BER performance, some interference cancellation technique must be used in conjunction with FDE (however, the interference cancellation technique is out the scope of this paper).

E. OFDM/TDM Demodulation

For OFDM/TDM signal demodulation, we first perform N_c-point IFFT on $\{\hat{R}(n); n = 0 \sim N_c - 1\}$ to obtain time-domain signal $\{\hat{r}(r); t = 0 \sim N_c - 1\}$ as

$$\hat{r}(t) = \sum_{n=0}^{N_c-1} \hat{R}(n)\exp\left(j2\pi t\frac{n}{N_c}\right) \tag{9}$$

for $t = 0 \sim N_c - 1$. Then, we perform N_m-point FFT separately for each recovered OFDM signal to obtain soft decision variable $\hat{d}^k(i)$ for data demodulation. We have

$$\hat{d}^k(i) = \frac{1}{N_m}\sum_{t=kN_m}^{(k+1)N_m-1} \hat{r}(t)\exp\left(-j2\pi i\frac{t}{N_m}\right) \tag{10}$$

for $i = 0 \sim N_m - 1$ and $k = 0 \sim K - 1$.

In the above, we have presented the OFDM/TDM signal demodulation using N_c-point IFFT and N_m-point FFT operations, which can be replaced by frequency-domain filtering. Using (10) and (11), we obtain

$$\hat{d}^k(i) = \frac{1}{N_m}\sum_{n=0}^{N_c-1} \hat{R}(n) \sum_{t=kN_m}^{(k+1)N_m-1} \exp\left(j2\pi t\frac{n-Ki}{N_c}\right). \tag{11}$$

Taking summation with respect to t, (12) is written as

$$\hat{d}^k(i) = \sum_{n=0}^{N_c-1} \hat{R}(n)\Psi(n; i, k) \tag{12}$$

where

$$\Psi(n;i,k) = \frac{1}{N_m}\frac{\sin\{\pi N_m \frac{n-Ki}{N_c}\}}{\sin\{\pi\frac{n-Ki}{N_c}\}} \times \exp\left\{j\pi((2k+1)N_m - 1)\frac{n-Ki}{N_c}\right\} \tag{13}$$

is the frequency-domain filter response. OFDM/TDM demodulation using the frequency-domain filter $\Psi(n; i, k)$ instead of N_c-point IFFT and N_m-point FFT operations is illustrated in Fig. 3.

IV. COMPUTER SIMULATION

The BER performance of OFDM/TDM with FDE is evaluated by computer simulation and compared with conventional OFDM. In our simulation, we assume QPSK data modulation with $|d(i)| = 1$, $N_c = 256$, and $N_g = 32$. OFDM/TDM parameters, compared to conventional OFDM, are shown in Table 1. An $L = 16$-path frequency-selective Rayleigh fading channel having an exponential power delay profile with decay factor β is assumed. For the OFDM/TDM designed for reducing the PAPR, we assume $\Delta = 1$ so that $\tau_{L-1} = L - 1 < N_g$, while for the OFDM/TDM designed for improving the robustness against long time delays, $\Delta = 3$ is assumed such that $N_g \le \tau_{L-1} = (L-1)\Delta < KN_g$. We assume a block fading where the path gains stay constant over the conventional OFDM signaling interval (i.e., one OFDM/TDM frame when OFDM/TDM is designed for PAPR reduction or one slot when OFDM/TDM is designed for improving the robustness against long time delays). Ideal channel estimation is assumed.

First, we will show the simulation results of OFDM/TDM for reducing the PAPR and then the results for improving the robustness against long time delays.

A. OFDM/TDM for Reducing the PAPR

The PAPR benefit of OFDM/TDM is evaluated by the probability density function (PDF) and complementary cumulative

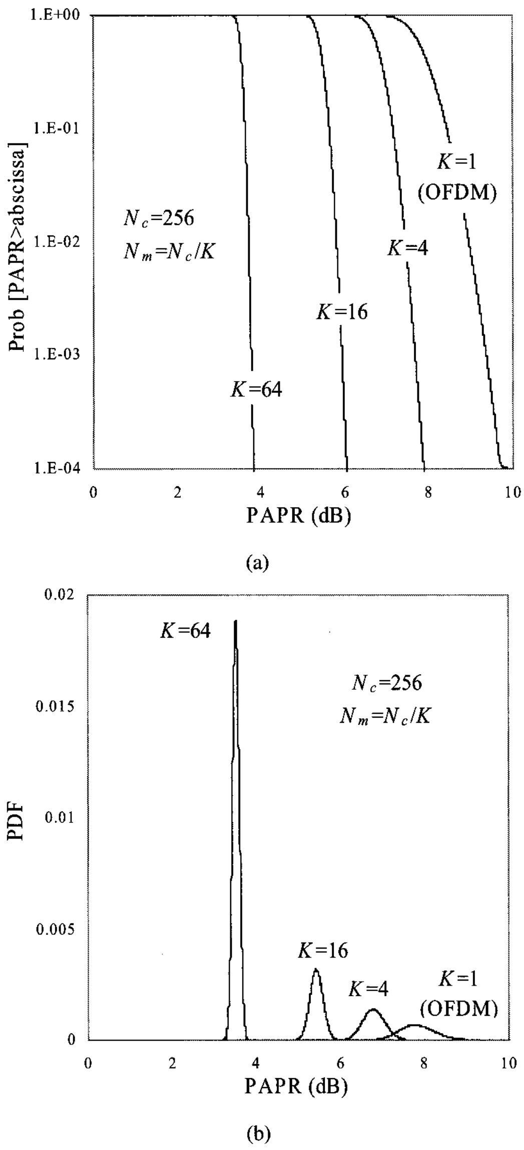

Fig. 4. Distribution of PAPR: (a) CCDF, (b) PDF.

distribution function (CCDF) of the PAPR. In OFDM/TDM, the PAPR is defined as the peak power over an OFDM/TDM frame normalized by the ensemble average power. The PAPR of the observed frame is defined as

$$\text{PAPR} = \frac{\max\limits_{0\leq t\leq N_c-1}\{|s(t)|^2\}}{\text{E}\{|s(t)|^2\}} \tag{14}$$

where $\text{E}\{|s(t)|^2\}$ is the ensemble average of the transmitted OFDM/TDM signal power. Fig. 4 plots the PAPR distribution as a function of K when $N_c = 256$ (obtained by computer simulation over 20 million OFDM/TDM frames). As expected, as K increases, the probability of PAPR taking small values increases due to the reduced number of subcarriers in OFDM/TDM frame (see Fig. 4(a)). Fig. 4(b) illustrates the CCDF of the PAPR as a function of K. It can be seen from Fig. 4(b) that the $\text{PAPR}_{10\%}$ level, which the PAPR of OFDM/TDM exceeds with a probability of 10%, is about 8.5, 7.2, 5.7, and 3.7 dB for K =1, 4, 16, and 64, respectively. This clearly shows the advantage of OFDM/TDM.

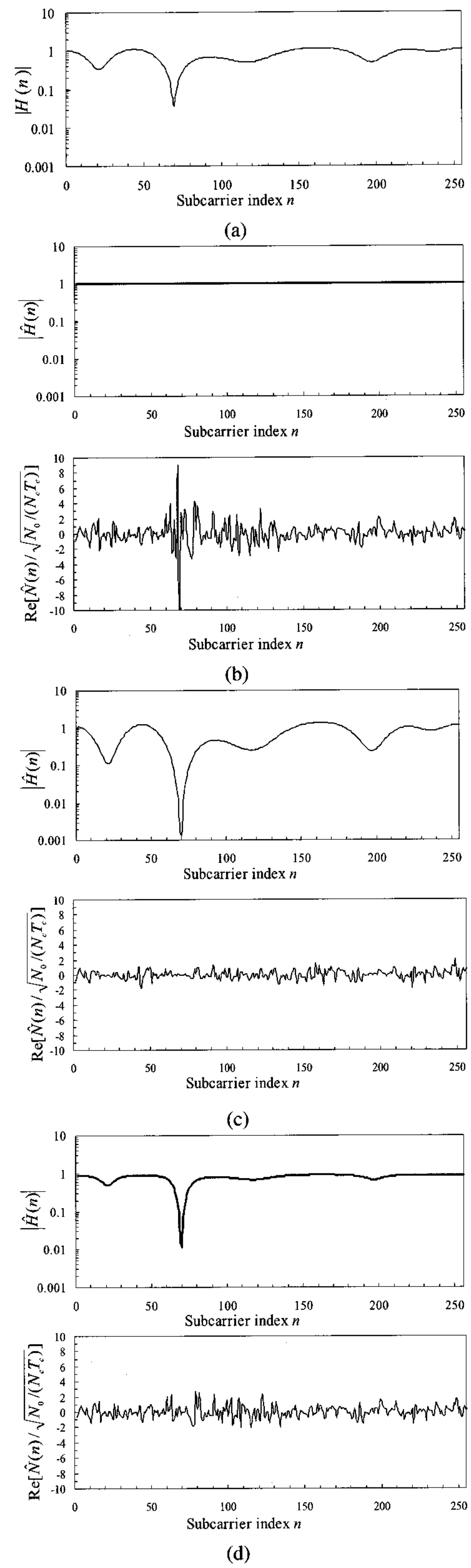

Fig. 5. Equivalent channel gain $\hat{H}(n)$ and AWGN noise component $\text{Re}[\hat{N}(n)/\sqrt{N_0/(N_cT_c)}]$: (a) Original channel gain, (b) ZF, (c) MRC, (d) MMSE.

To discuss the difference between ZF-, MRC-, and MMSE-FDE, we illustrate, in Fig. 5, one shot observation of the propagation channel gain $H(n)$, the equivalent channel gain $\hat{H}(n)$ and the AWGN noise component $\mathrm{Re}[\hat{N}(n)/\sqrt{N_0}/(N_cT_c)]$ for ZF-, MRC-, and MMSE-FDE. By employing ZF-FDE (see Fig. 5(b)), the frequency-nonselective channel is perfectly restored, but noise enhancement is observed at the subcarriers where channel gain drops. For MRC-FDE (see Fig. 5(c)), noise enhancement is suppressed, but the channel frequency-selectivity is enhanced. With MMSE-FDE (see Fig. 5(d)), perfect restoration of the channel frequency-nonselectivity is not achieved, but noise enhancement is avoided. A trade-off between the frequency-selectivity reduction and the noise enhancement is present. Therefore, MMSE-FDE gives the optimum trade-off and provides the best BER performance.

The average BER performances of the OFDM/TDM using ZF-, MRC- and MMSE-FDE are illustrated in Fig. 6 as a function of the average signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0 for various values of K ($K = 1 \sim 256$), where $E_b/N_0 = 0.5(E_s/N_0) \times (1 + N_g/N_c)$, in which the power loss due to the GI insertion is taken into account. A uniform power delay profile ($\beta = 0$ dB) is assumed, which produces the strongest frequency-selectivity for the given number of paths.

Since ZF-FDE perfectly restores the frequency-nonselective channel (because perfect channel estimation is assumed), the BER performance of OFDM/TDM with $K \geq 2$ is similar to the conventional OFDM ($K = 1$) for $E_b/N_0 > 15$ dB (see Fig. 6(a)). However, it is observed that the BER performance degrades as K increases in a low E_b/N_0 region of $E_b/N_0 < 15$ dB, where the predominant cause of errors is the AWGN noise. This is because the noise enhanced by ZF-FDE, at a frequency experiencing deep fade, is spread over the entire OFDM/TDM frame by N_c-point IFFT.

On the other hand, the BER performance with MRC-FDE degrades rapidly as K increases, and error floors are observed (see Fig. 6(b)). Reason for this BER performance degradation is due to the enhanced channel frequency-selectivity.

The conventional OFDM gives the same BER performance irrespective of channel frequency-selectivity, since data-modulated symbols are transmitted over orthogonal subcarriers that experience frequency-nonselective fading. On the other hand, in OFDM/TDM, each slot transmits an $N_m(= N_c/K)$-subcarrier OFDM signal without GI insertion and hence, ISI arises. MMSE-FDE can reduce the ISI and exploit the channel frequency-selectivity to improve the BER performance. It is seen from Fig. 6(c) that as K increases, the MMSE-FDE consistently improves the BER performance. The best performance is obtained when $K = N_c$ (SC) while the worst is achieved when $K = 1$ (conventional OFDM). This is because, as K increases, the transmitted symbol energy is distributed over a K times wider bandwidth and MMSE-FDE is used to reduce ISI and exploit the channel frequency-selectivity through the frequency diversity effect. The required E_b/N_0 for the average BER=10^{-4} can be reduced by about 7.5, 13.5, 17.6, and 18.5 dB, in comparison to the conventional OFDM, when $K = 4$, 16, 64, and 256 (SC), respectively (see Fig. 6 (c)). Since MMSE-FDE provides the best BER performance irrespective of K, we only consider MMSE in the following.

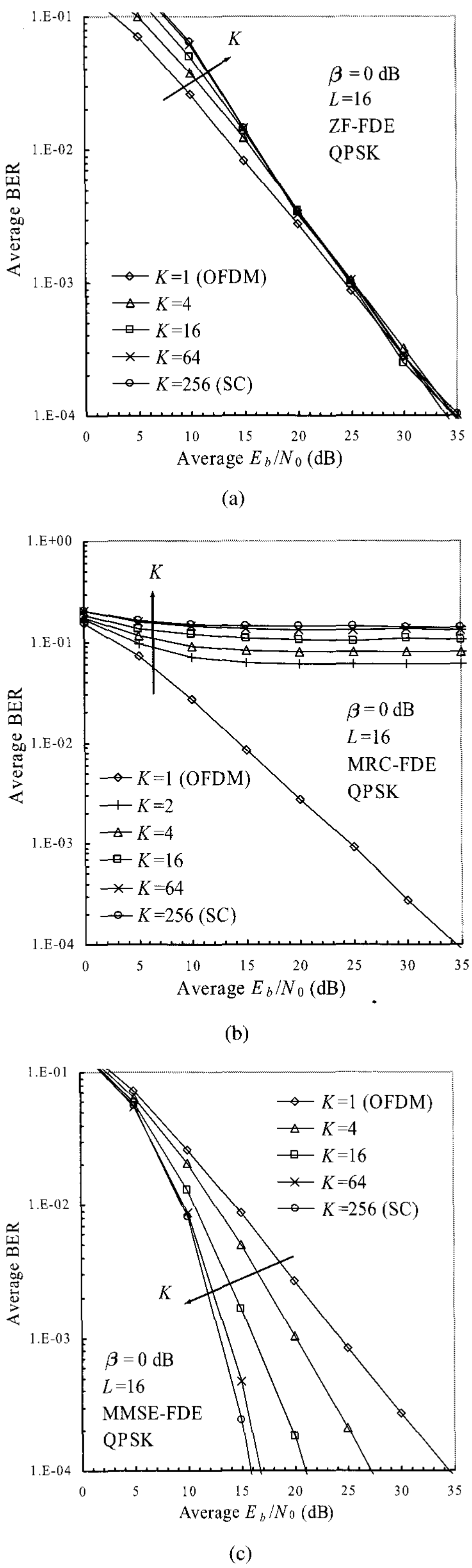

Fig. 6. Average BER performance with K as a parameter: (a) ZF, (b) MRC, (c) MMSE.

The channel frequency-selectivity is determined by the decay factor β. As β increases, the channel is becoming less frequency-selective and when $\beta \rightarrow \propto$ dB it becomes a frequency-nonselective channel (i.e., single-path channel). The impact of the channel frequency-selectivity on the BER performance of OFDM/TDM with $K = 32$ is shown in Fig. 7.

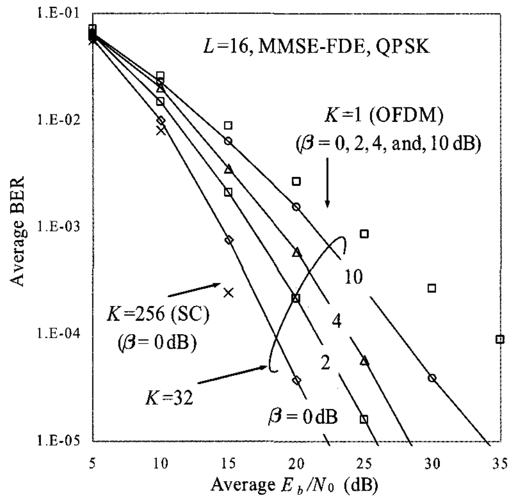

Fig. 7. Dependency of BER performance on β.

The BER performance of the conventional OFDM ($K = 1$) is independent of the channel frequency-selectivity and equal to the case of the single path. On the other hand, the BER performance of OFDM/TDM depends on β. As the channel frequency-selectivity becomes weaker, the BER performance will degrade due to reduced frequency diversity effect; the best BER performance is obtained when $\beta = 0$ dB (i.e., strongest frequency-selectivity). The loss in the required E_b/N_0 for achieving BER=10^{-4} from the case of $\beta = 0$ dB is about 3.3, 5.4 and 9.3 dB when $\beta = 2$, 4, and 10 dB, respectively. Note that the OFDM/TDM performance approaches that of the conventional OFDM as $\beta \to \infty$ dB.

B. OFDM/TDM for Improving Robustness Against Long Time Delays

So far, we have evaluated the BER performance of the OFDM/TDM for reducing the PAPR and found that the use of MMSE-FDE significantly improves the BER performance in comparison with the conventional OFDM. Here, we discuss the BER performance of the OFDM/TDM designed to improve the robustness against long time delays. The OFDM/TDM frame length is expanded K times in comparison to the conventional OFDM (see Fig. 1(c)). Therefore, in this case, the time-selectivity of the channel may affect the BER performance of the OFDM/TDM. The normalized Doppler frequency f_DT_s is an important factor that affects the BER performance, where $1/T_s = 1/[T_c(1 + N_g/N_c)]$ is the transmission symbol rate (e.g., $f_DT_s = 10^{-4}$ corresponds to mobile terminal moving speeds of 11 km/h for 5 GHz carrier frequency and transmission data rate of 100 M symbols/sec). As stated earlier, we assume a block fading, where the path gain is constant over one slot (same as the conventional OFDM signaling interval), but varies slot-by-slot during the OFDM/TDM frame. We assume a time delay separation between adjacent paths of Δ samples (i.e., $\tau_l = l\Delta$) and $N_g \le L < KN_g$. Only MMSE-FDE is assumed because it gives the best BER performance as found in Section IV-A. Figs. 8(a)–(c) show the average BER performances of OFDM/TDM ($K = 2 \sim 8$) and the conventional OFDM ($K = 1$) as a function of the average E_b/N_0 with Δ as a parameter for a very slow fading of $f_DT_s = 0.0001$ (under this assumption, the path gains can be considered to remain almost constant over the OFDM/TDM frame). The GI

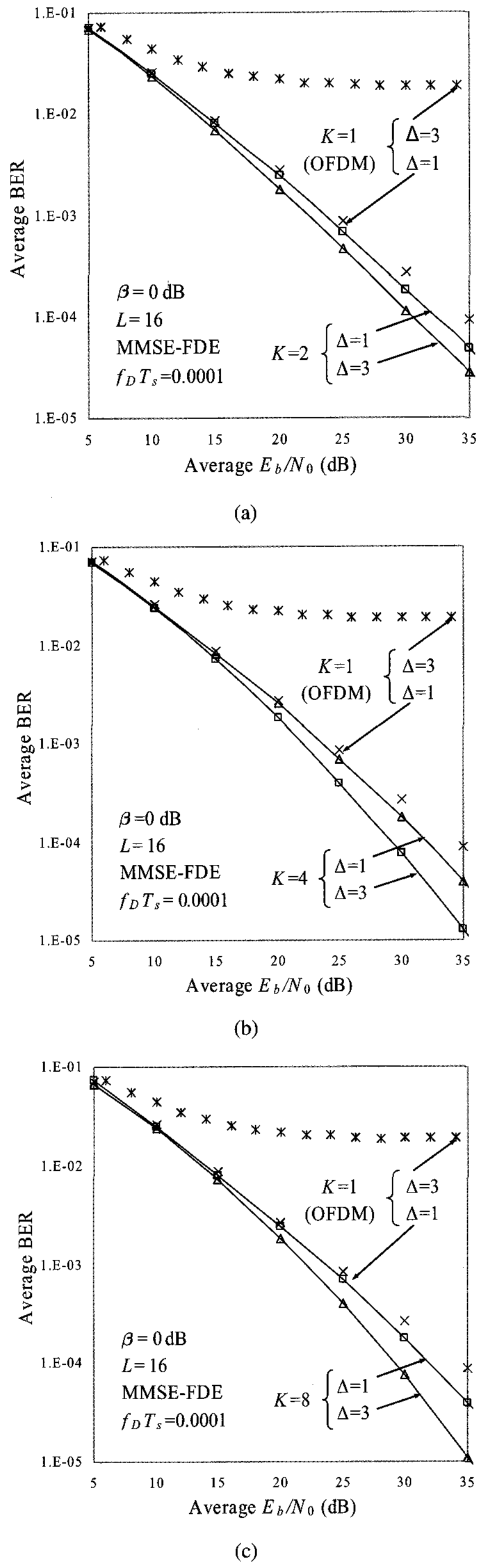

Fig. 8. Average BER performance with Δ as a parameter: (a) $K = 2$, (b) $K = 4$, (c) $K = 8$.

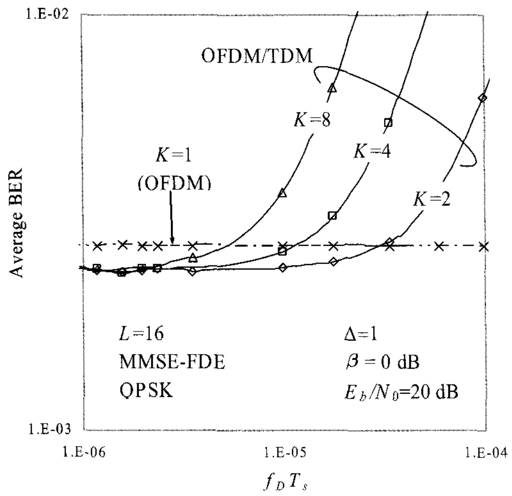

Fig. 9. Effect of fading Doppler frequency when $\Delta = 1$.

length of OFDM/TDM is $32K$ samples, while that of OFDM is 32 samples. It can be seen from Fig. 8(a) that when $\Delta = 3$, the BER performance of conventional OFDM significantly degrades due to IFI. This is because the maximum channel time delay ($\tau_{L-1} = (L-1)\Delta = 45$ samples) exceeds the GI. However, the GI length of OFDM/TDM with $K = 2$ is 64 samples, which is longer than the maximum time delay and therefore, no IFI is produced; the BER performance of OFDM/TDM improves compared to the case of $\Delta = 1$ due to the larger frequency diversity gain obtained by MMSE-FDE. It can be seen from Figs. 8(a)–(c), that as K increases, the OFDM/TDM becomes more robust against long time delays and furthermore, its BER performance improves.

So far, we have evaluated the effect of channel frequency-selectivity on the OFDM/TDM performance. The OFDM/TDM designed to improve the robustness against long time delays expands the frame length K times in comparison with conventional OFDM, and therefore, the path gains may vary during the frame for fast fading. As the fading becomes faster, the performance of OFDM/TDM may be degraded since KN_c-point FFT cannot extract proper frequency components of the transmitted OFDM/TDM signal. This means that the OFDM/TDM can only be designed to improve the robustness against long time delays at the cost of reducing the robustness against fast fading. Fig. 9 plots the average BER as a function of f_DT_s when $\Delta = 1$ for $E_b/N_0 = 20$ dB. For comparison, the BER of the conventional OFDM is also plotted. Note that an assumption of $\Delta = 1$ is disadvantageous compared with OFDM/TDM since no path exceeds the GI and hence, the conventional OFDM exhibits no performance degradation. As K increases, the performance of OFDM/TDM is affected by the channel time-selectivity and as f_DT_s increases, the BER increases. However, it should be noted that OFDM/TDM gives a lower BER than conventional OFDM if f_DT_s is below 3.1×10^{-5}, 1.25×10^{-5}, and 5.2×10^{-6} for $K = 2$, 4, and 8, respectively. This clearly indicates that the proposed OFDM/TDM is very robust against long time delays while achieving a better BER performance than conventional OFDM.

V. CONCLUSION

In this paper, OFDM/TDM design was presented for PAPR reduction and for improvement of the robustness against long time delays. For the PAPR reduction, a sequence of K OFDM signals with a reduced number of subcarriers is transmitted in each OFDM/TDM frame. For improving the robustness against long time delays, the OFDM/TDM frame length is expanded to enlarge the GI while keeping the number of OFDM/TDM subcarriers same as the conventional OFDM. The BER performance of OFDM/TDM with ZF-, MRC-, and MMSE-FDE techniques was evaluated by computer simulation. It was shown that MMSE-FDE provides the best BER performance. An important property of OFDM/TDM is that OFDM/TDM designed for reducing the PAPR bridges the conventional OFDM and SC transmission.

Since this paper was intended to reveal the fundamental properties of OFDM/TDM, we have assumed ideal channel estimation and ideal timing synchronization. Channel estimation error or timing error may degrade the achievable BER performance of OFDM/TDM. On the other hand, the BER performance can be improved by the use of a transmit/receive antenna diversity technique, channel coding, etc.

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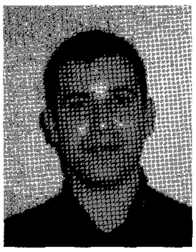

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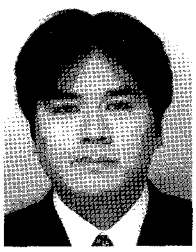

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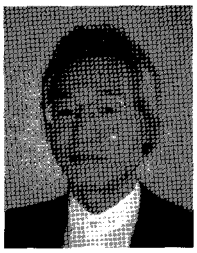

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