A Comprehensive Performance Comparison of OFDM/TDM Using MMSE-FDE and Conventional OFDM

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***Abstract*—Orthogonal frequency division multiplexing (OFDM) is currently under intense research for broadband wireless transmission due to its robustness against multipath fading. However, OFDM signals have a problem with high peak-to-average power ratio (PAPR) and thus, a power amplifier must be carefully manufactured to have a linear input-output characteristic or to have a large input power backoff. Recently, OFDM combined with time division multiplexing (OFDM/TDM) using minimum mean square error frequency domain equalization (MMSE-FDE) was proposed to improve the bit error rate (BER) performance of conventional OFDM while reducing the PAPR. In this paper, by extensive computer simulation, we present a comprehensive performance comparison between OFDM/TDM using MMSE-FDE and conventional OFDM over a frequency-selective fading channel. We discuss about the trade-off among the transmit peak-power efficiency, the spectrum splatter and the BER performance. Our results show that OFDM/TDM using MMSE-FDE achieves almost the same coded BER performance with a several decibels better peak-power efficiency than conventional OFDM, which is significant reduction of amplifier transmit-power backoff, but with a slight decrease in spectrum efficiency.**

***Index Terms*—*OFDM/TDM, BER, FDE, power spectrum density, amplifier power efficiency*.**

I. Introduction

In a wireless channel, a signal propagates over a number of different paths that give rise to a frequency-selective fading, which produce inter-symbol interference (ISI) and degrades the transmission performance [1]. To solve this problem, an intense research efforts based on frequency domain channel equalization (FDE) are currently ongoing in two directions; (i) orthogonal frequency division multiplexing (OFDM) and (ii) single carrier (SC)-FDE [2]-[3]. In OFDM, however, orthogonal subcarriers may be used for dynamic resource allocation (DRA) leading to improved transmission performance [4]. To avoid the performance degradation of OFDM due to high PAPR, the high transmit power amplifier (HPA) must be operated in linear regime (i.e., with a large input backoff (IBO)), where the power conversion is inefficient. This may have a deleterious effect on battery lifetime in low-cost mobile applications, where the drawback of high PAPR may outweigh all the potential benefits of OFDM.

Of late, various approaches to reduce the PAPR of OFDM and improve the efficiency of HPA have been proposed; see [5]-[14]. Some work has been done to evaluate the power amplifier efficiency of OFDM with respect to certain PAPR reduction techniques [15]-[18]. In [19], conventional OFDM and SC-FDE are compared with respect to their PAPR, carrier frequency offset and computational complexity with and without coding. Recently, we proposed OFDM combined with time division multiplexing (OFDM/TDM) [20] using minimum mean square error FDE (MMSE-FDE) [21] to improve the transmission performance of conventional OFDM in terms of bit error rate (BER) and the PAPR. The PAPR, however, cannot be completely eliminated. Hence, some additional PAPR reduction must be applied. In [22] we analyzed the theoretical performance of amplitude clipped and filtered OFDM/TDM using MMSE-FDE and the conventional OFDM with respect to their uncoded BER performances. However, to unveil potential of OFDM/TDM using MMSE-FDE, a more detailed transmission performance comparison in terms of transmit peak-power, the spectrum splatter and coded BER performance of OFDM/TDM using MMSE-FDE and the conventional OFDM is required.

In this paper, we provide a comprehensive performance comparison among OFDM/TDM using MMSE-FDE and conventional OFDM. A trade-off among the transmit peak-power reduction (i.e., IBO reduction), the power spectrum efficiency and the coded BER performance is discussed. To our knowledge, such performance comparison on OFDM/TDM using MMSE-FDE and the conventional OFDM has not been reported. We aim to show that OFDM/TDM using MMSE-FDE can be used in practical systems to overcome the conventional OFDM with respect to lower power supply requirement (i.e., lower battery consumption) by the cost of slight decrease in spectrum efficiency. Due to multi-carrier property of OFDM/TDM using MMSE-FDE, DRA can be applied similar as in conventional OFDM that may lead to improved transmission performance.

The remainder of this paper is organized as follows. Section II presents OFDM/TDM using MMSE-FDE system model. The computer simulation results and discussions on the performances of OFDM/TDM using MMSE-FDE and the conventional OFDM are presented in Sect. III. Section IV concludes the paper.

II. PRINCIPLE OF OFDM/TDM USING MMSE-FDE

The OFDM/TDM transmission system model is illustrated in Fig. 1. Throughout this paper, T_c-spaced discrete time representation is used, where T_c represents the fast Fourier transform (FFT) sampling period.

Information bit sequence of length M is channel coded [23] with a coding rate R and mapped into the transmit data symbols, corresponding to quadrature phase shift keying (QPSK) modulation scheme. This sequence is divided into blocks $\{d_m(i);\ i = 0 \sim N_c - 1\}$ for $m = 0 \sim M/N_c - 1$, each of having N_c data-modulated symbols with $E[|d(i)|^2]$=1. $E[\cdot]$ denotes the ensemble average operation. In this work, we consider a transmission of N_c data-modulated symbols without loss of generality and thus, the block index m is omitted in what follows. $\{d(i)\}$ is parsed into K sequences each of having N_m (=N_c/K) data-modulated symbols. The kth block symbol sequence is denoted by $\{d^k(i);\ i{=}0{\sim}N_m{-}1\}$, where $d^k(i){=}d(kN_m{+}i)$ for $k{=}0{\sim}K{-}1$. Then, JN_m-point IFFT is applied to generate an interpolated time-domain OFDM signal with N_m subcarriers as

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

for $t{=}0{\sim}JN_m{-}1$, where E_s and J denote the data-modulated symbol energy and oversampling ratio (in this paper J=8), respectively. The OFDM/TDM signal can be expressed using the equivalent low-pass representation as

$$s(t) = \sum_{k=0}^{K-1} s^k(t - kN_m) u(t - kN_m) \quad (2)$$

for $t{=}0{\sim}N_c{-}1$, where $u(t) = 1(0)$ for $t{=}0{\sim}N_m{-}1$ (elsewhere). After insertion of guard interval (GI) the OFDM/TDM signal is transmitted over a frequency-selective fading channel.

The OFDM/TDM signal propagates through the channel with a discrete-time channel impulse response $h(\tau)$ given as

$$h(\tau) = \sum_{l=0}^{L-1} h_l \delta(\tau - \tau_l) \quad (3)$$

where h_l and τ_l are the path gain and time delay of the lth path with $E[|h_l|^2] = 1/L$. We assume that the maximum channel delay is less than the GI length.

At the receiver, N_c-point FFT is applied over entire OFDM/TDM frame to decompose the received signal into Nc frequency components represented by $\{R(n);\ n{=}0{\sim}N_c{-}1\}$. One-tap MMSE-FDE is applied to $\{R(n)\}$ as [3]

$$\hat{R}(n) = R(n)w(n), \quad (4)$$

where $w(n)$ is the MMSE equalization weight, which includes the degradation due to clipping noise. $\{w(n)\}$ is given by [9]

$$w(n) = \frac{H^*(n)}{|H(n)|^2 + (\frac{E_s}{N_0})^{-1}}, \quad (5)$$

where N_0 denotes the single-sided power spectrum density. The time-domain OFDM/TDM signal is recovered by applying N_c-point IFFT to $\{\hat{R}(n);\ n = 0 \sim N_c - 1\}$. OFDM demodulation is carried out using N_m-point FFT to obtain decision variables $\{\hat{d}^k(i)\ i = 0 \sim N_m - 1\}$ [21] required for the log-likelihood ratio (LLR) computation and channel decoding [23].

We note here that OFDM/TDM using MMSE-FDE for K=1 collapses to the conventional OFDM system with N_c=256 subcarriers.

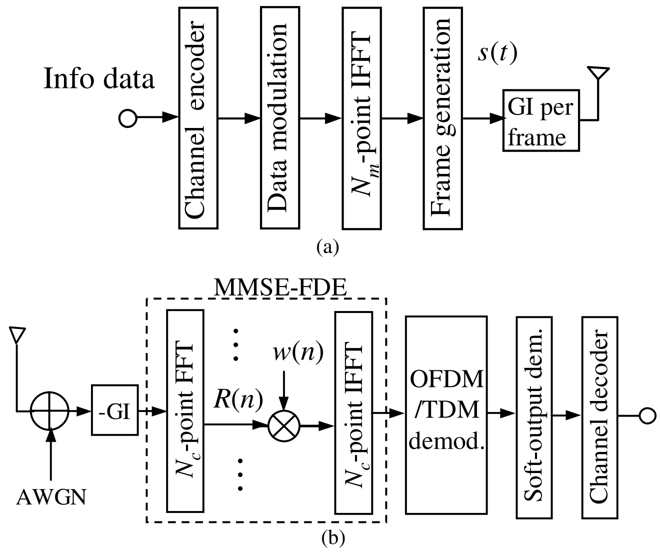

Fig. 1. OFDM/TDM transmitter/receiver structure: (a) Transmitter, (b) Receiver.

TABLE I
SIMULATION PARAMETERS.

Transmitter	Data modulation	QPSK
	Frame length	$N_c = 256$
	IFFT size	$N_m = N_c/K$
	No. of slots	$K = 1,\ 4,\ 16$ and 64
	GI	$N_g = 32$
Channel	L=16-path frequency-selective Rayleigh fading	
Receiver	FFT size	$N_c = 256$
	FDE	MMSE
	Channel Estimation	Ideal

III. SIMULATION RESULTS AND DISCUSSIONS

The computer simulation parameters are given in Table I. We assume an OFDM/TDM frame size of N_c=256 samples, GI length of N_g=32 samples and ideal coherent QPSK data modulation/demodulation. As the propagation channel, we assume an L=16-path block Rayleigh fading channel with channel decay factor β=0 dB (the strongest channel frequency-selectivity) as shown in Fig. 3 [21]. It is assumed that the maximum channel delay is less than the GI length. A (2048, 1024) low density parity check (LDPC) encoder is assumed with R=1/2 and sum product algorithm (SPA) decoder having *column weight*=1 and *row weight*=8 [23]. The information bit sequence length is taken to be M=1024 bits.

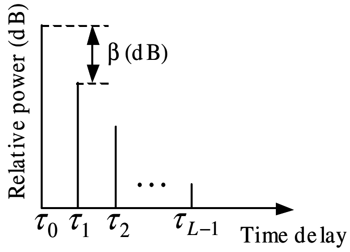

Fig. 2. Channel power delay profile.

TABLE II
PAPR COMPARISON BETWEEN OFDM/TDM AND CONVENTIONAL OFDM

Parameters	N_c=256, $N_m=N_c/K$	PAPR level (dB)
Conventional OFDM	K=1, N_m=256	24.08
OFDM/TDM	K=4 (16), N_m=64 (16)	18.06 (12.04)

A. OFDM/TDM Peak-power Efficiency

In this section, we first address the PAPR and then, the HPA efficiency is discussed.

1) PAPR Comparison: In OFDM/TDM, the PAPR is defined as the maximum instantaneous peak power over an OFDM/TDM frame normalized by the ensemble average power. The PAPR of the observed frame is defined as

$$PAPR = \frac{max\{|s(t)|^2\}_{t=0\sim N_c-1}}{E\{|s(t)|^2\}} \tag{6}$$

where $E\{|s(t)|^2\}$ is the ensemble average of the transmitted OFDM/TDM signal power. Thus, by definition, it can be shown that the theoretical PAPR of OFDM/TDM is proportional to number of subcarriers N_m (=N_c/K). The PAPR values (in decibels) of OFDM/TDM and conventional OFDM for QPSK constellation are presented in Table II. It can be seen from Table II that the PAPR of OFDM may become as large as 24 dB while for OFDM/TDM with $K=4$ and 16 the PAPR reduces to 18 and 12 dB, respectively. Although the PAPR increases linearly with the number of subcarriers N_m, the probability that such a peak will occur decreases exponentially with N_m. Therefore, in the following part, we evaluate the HPA efficiency with respect to the PAPR obtained by computer simulation.

2) HPA Efficiency: In what follows, we evaluate the HPA efficiency for OFDM/TDM. We assume an ideal linear model (i.e., soft limiter) for the HPA, where linear amplification is achieved until the saturation level. If the required PAPR outage probability for an OFDM signal with N_c (e.g., 256) subcarriers is fixed, to obtain that no more than 1 out of 10000 frames are affected by HPA, the corresponding power amplifier's IBO must be equivalent to PAPR at probability of 10^{-4}. It was shown, by computer simulation, in [22], that the $\text{PAPR}_{40\%}$ level is about 12, 9.3, 7.4 and 4.8 dB for K=1 (OFDM), 4, 16 and 64, respectively.

Suppose that the maximum output P_o (curve (1)) in Fig. 3 of HPA for the conventional OFDM system is fixed according to $\text{PAPR}_{40\%}$ level defined above. Reduced IBO level with OFDM/TDM is illustrated in Fig. 3 by curve (2). We assume OFDM/TDM (K=16) and conventional OFDM (K=1) with $\text{PAPR}_{40\%}$ levels of 7.4 and 12 dB, respectively. We note that the class A amplifier power efficiency (=P_{ave}/P_{DC}) is 50% [24] with $P_{DC} = 2P_{sat}$, where P_{sat}, P_{ave} and P_{DC} represent the saturation power level, the average signal power and direct current source power (i.e., battery supply in mobile terminal that should be reduced). For example, assume that P_{ave} and output power P_o are set to the predetermined values corresponding to the above $\text{PAPR}_{40\%}$ level of conventional OFDM (i.e., 12 dB). If P_{ave} is kept constant then the IBO (=7.4-12 dB) with OFDM/TDM is reduced and thus, P_o is reduced to $0.6P_o$ as shown in Fig. 3 (see curve (2)). Therefore, the initial value of P_o (curve (1)) is reduced to $P_{red} = 0.6P_o$ and $P_{DC} = 1.2P_{sat}$. Therefore, a peak-power reduction from initial P_o (i.e., 12 dB) to $P_{red} = 0.6P_o$ (i.e., 7.4 dB) is achieved. This leads to -4.6 dB IBO reduction, which results in lower battery consumption for about $0.8P_{DC}$.

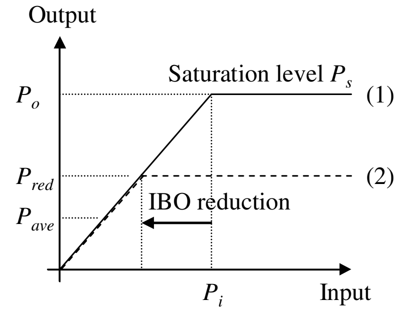

Fig. 3. HPA input-output characteristic.

B. OFDM/TDM Power Efficiency

Figure 4(a) plots the average uncoded and coded BER performance of OFDM/TDM with MMSE-FDE as a function of the average bit energy-to-AWGN power spectrum density ratio E_b/N_0 (=$0.5\times R\times(E_s/N_0)\times(1+N_g/N_c)$, with K as a parameter. The uncoded BER performance was discussed in [21] and is illustrated as a reference.

As shown in Fig. 4(a), the coded performance of OFDM/TDM using MMSE-FDE, irrespective of K, is almost the same as the conventional OFDM (K=1), but with significantly lower PAPR as discussed in the previous section. Note that different coding techniques may give different BER performances, but the impact of different codes is out the scope of this paper. The conventional OFDM, however, is attractive since DRA can be applied to improve the transmission performance. We bring the readers attention to the fact that OFDM/TDM obtains some properties of the conventional OFDM (i.e., $N_m = N_c/K$ subcarriers), and therefore, DRA may be applied to OFDM/TDM for additional transmission performance improvement. This is left as interesting future work.

We also consider the required peak transmit power because it is an important design parameter of transmit HPA. Figure 4(b) show the BER performance of coded OFDM/TDM using

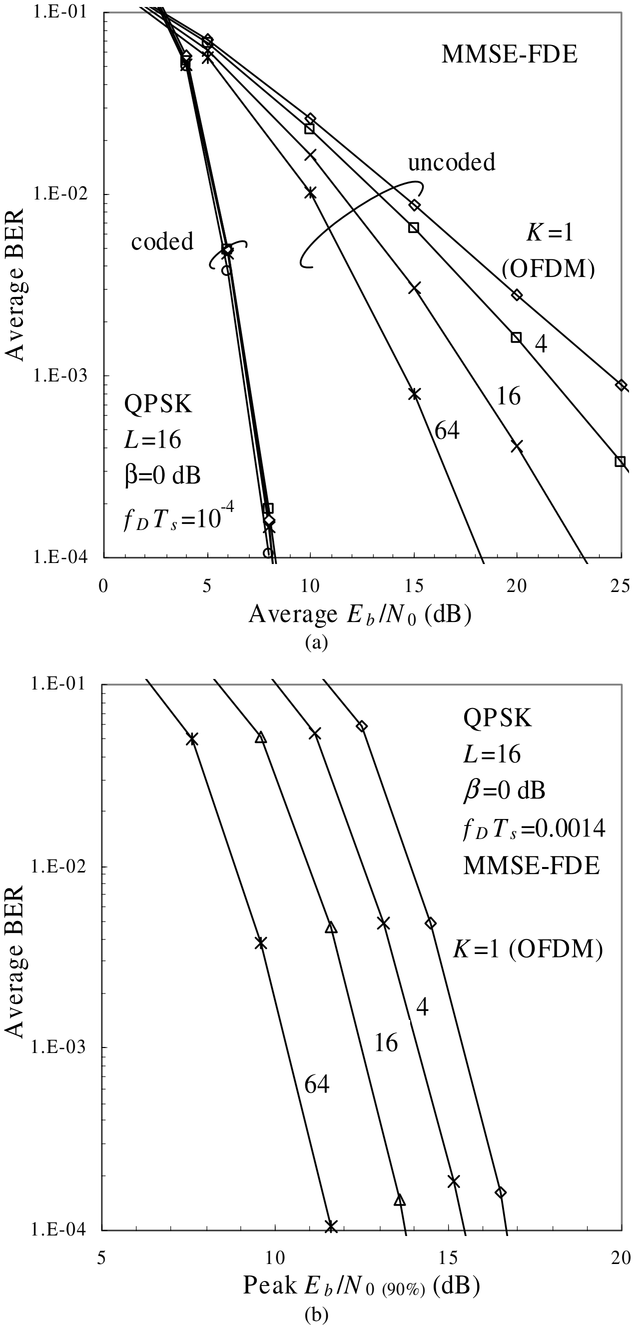

Fig. 4. Average BER performance: (a) Average-power efficiency, (b) Peak-power efficiency.

MMSE-FDE as a function of the peak transmit power with K as a parameter. It can be seen from the figure that the conventional OFDM (K=1) gives the worst performance due to large PAPR. As K increases the required peak-power (i.e., IBO) of OFDM/TDM is reducing; for the average BER=10^{-4}, IBO can be reduced by about 1.3, 2.9 and 5.1 dB, compared to the conventional OFDM, when K=4, 16 and 64, respectively as shown in Fig. 4(b). The performance improvement presented above is paid with lower spectral efficiency as presented in the following section.

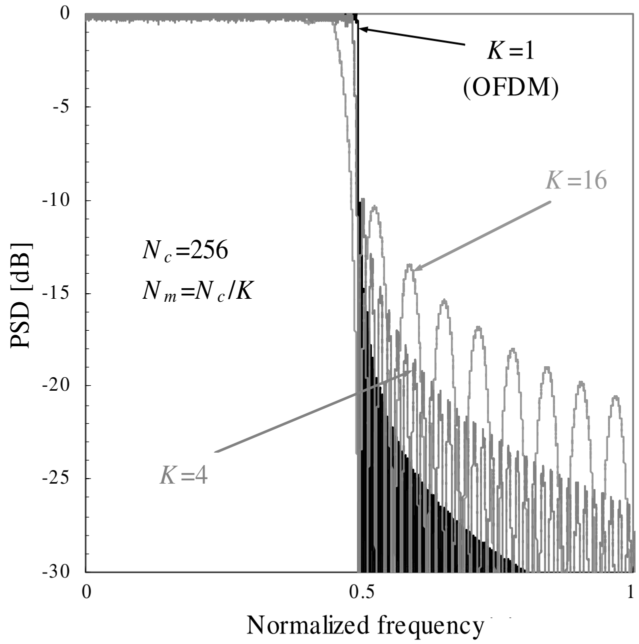

Fig. 5. PSD performance.

C. Power Spectral Density Issue

In this section, our focus is on the spectral efficiency of the OFDM/TDM and conventional OFDM. The power spectrum density (PSD) is computed over a sequence of 64000 OFDM/TDM frames and averaged 10^6 times. Figure 5 illustrates the PSD of OFDM/TDM (K=4 and 16) and conventional OFDM (K=1) as a function of normalized frequency. It can be seen from Fig. 5 that OFDM/TDM achieves a lower spectral efficiency in comparison with the conventional OFDM; the spectral efficiency decreases as K increases. This is because OFDM/TDM signals have discontinuity in their waveforms within the OFDM/TDM frame and cause a higher order spectral spreading. However, a better PSD performance of conventional OFDM in comparison with OFDM/TDM is paid with significantly higher PAPR, a higher BER and a lower peak-power efficiency (i.e., higher IBO) as discussed above. Therefore, a trade-off among improvement of peak-power efficiency, the BER performance and spectrum efficiency is observed for OFDM/TDM using MMSE-FDE.

IV. Conclusion

In this paper, a comprehensive performance comparison between OFDM/TDM using MMSE-FDE and the conventional OFDM is presented. A trade-off between the peak-power reduction, the BER performance and the spectrum efficiency was discussed. It was shown that the OFDM/TDM reduces the peak-transmit power (i.e., IBO) for the same BER, but with a slight increase in PSD in comparison with the conventional OFDM. For additional transmission performance improvement DRA may be applied to OFDM/TDM due to its multicarrier property (i.e., Nm subcarriers), but a trade-off among the

PAPR improvement and the reduction of degree of freedom for DRA is present. This is left as interesting future work.

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