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Frequency-domain Interleaving for OFDM/TDM Using MMSE-FDE

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***Abstract*—In this paper, frequency-domain interleaving on a frame-by-frame basis for orthogonal frequency division multiplexing combined with time division multiplexing (OFDM/TDM) using minimum mean square error frequency-domain equalization (MMSE-FDE) is presented. The OFDM/TDM frame signal (i.e., several concatenated OFDM signals) frequency components are interleaved to enhance channel frequency-selectivity and then, MMSE-FDE is applied at the receiver to obtain frequency diversity gain. The bit error rate (BER) performance of OFDM/TDM with and without channel coding is evaluated by computer simulation. It was shown, that frequency-domain interleaving on the frame-by-frame basis for OFDM/TDM using MMSE-FDE achieves a better BER performance in comparison with conventional OFDM due to enhanced frequency diversity gain.**

***Index Terms*—*OFDM/TDM, MMSE-FDE, frequency-domain interleaving, channel frequency-selectivity*.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM), which is robust against multipath fading, has a drawback of having a large peak-to-average power ratio (PAPR) [1]. This undesirable feature renders the OFDM particularly sensitive to nonlinear distortions (e.g., high-power amplifier (HPA)). Recently, we proposed OFDM combined with time division multiplexing [2] (in this paper called OFDM/TDM) using minimum mean square error frequency-domain equalization (MMSE-FDE) [3] to improve the transmission performance in terms of the bit error rate (BER) performance and the PAPR. In OFDM/TDM design, the N_c-point inverse fast Fourier transform (IFFT) time window of conventional OFDM is divided into K slots (which constitutes the OFDM/TDM frame). At the receiver, MMSE-FDE is applied over the entire OFDM/TDM frame to obtain frequency diversity gain [3]. Unlike conventional OFDM, where FDE is not designed to exploit the channel frequency-selectivity, OFDM/TDM using MMSE-FDE provides a better BER performance than conventional OFDM owing to MMSE-FDE that exploits the channel frequency-selectivity and obtains frequency diversity gain [3].

Recently, interleaved OFDM was considered in [4], [5]. In [4], an interleaved OFDM is used to increase the data rate efficiency; but, since a wireless channel is assumed to be invariant over P consecutive OFDM signals, (i.e., P is a length of the interleaver) the channel frequency-selectivity cannot be exploited and consequently, the performance cannot be improved. To improve the BER performance of conventional OFDM, two-dimensional interleaving was proposed in [5], but the interleaving size must be very long, which increases the latency (i.e., the processing delay) of the system (i.e., note that, in [5], a frame of 16,384 OFDM signals are stored in a transmitter buffer and fading is assumed to be constant over the entire frame that is also not a realistic assumption for transmission over a wireless channel). Moreover, FDE is applied to each OFDM signal separately and consequently, FDE cannot exploit the channel frequency-selectivity enhanced by two-dimensional interleaver.

In this paper, we build on our merits of MMSE-FDE we introduced in [3] and present frequency-domain interleaving on a frame-by-frame basis for OFDM/TDM using MMSE-FDE over a frequency-selective fading channel. A frame-by-frame frequency-domain interleaving for OFDM/TDM is applied at the transmitter to enhance frequency diversity gain through MMSE-FDE at the receiver. We note that, however, this is not possible with conventional OFDM because each subcarrier is independently modulated and the channel frequency-selectivity cannot be exploited through MMSE-FDE. Unlike conventional OFDM, a combination of frequency-domain interleaving for OFDM/TDM at the transmitter end and MMSE-FDE at the receiver end can be used to exploit the channel frequency-selectivity and improve the BER performance with significantly lower latency due to short interleaver size. At first, an N_c-point FFT is applied over the OFDM/TDM frame to decompose the signal into N_c frequency components and then, a block interleaver is used to permute the ordering of the frequency components. Finally, the interleaved frequency components are converted back to time-domain by applying N_c-point IFFT. It should be emphasized, however, that due to frequency-domain interleaving the PAPR of OFDM/TDM will regrow and thus, we apply deliberate amplitude clipping to pre-determined clipping level before transmission over a frequency-selective fading channel.

The paper is organized as follows. In Sect. II, principle of OFDM/TDM using MMSE-FDE is presented. Frequency-domain interleaving on a frame-by-frame basis for OFDM/TDM using MMSE-FDE is presented in Sect. III, and its performance is evaluated in Sect. IV. Sect. V concludes the paper.

II. Principle of OFDM/TDM using MMSE-FDE

An information bearing sequence is turbo coded and punctured [6], bit interleaved and data modulated to generate

M bit coded sequence. The sequence is parsed into M/N_c blocks each of having N_c data-modulated symbols, where the mth block is represented as $\{d_m(i);\ i=0\sim N_c-1\}$ for $m=0\sim M/N_c-1$. 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. $\{d(i)\}$ block is divided into K subblocks each of having N_m $(=N_c/K)$ data-modulated symbols. The kth subblock is denoted by $\{d^k(i);\ i=0\sim N_m-1\}$, where $d^k(i)=d(kN_m+i)$ for $k=0\sim K-1$. The OFDM/TDM signal is expressed using the equivalent low-pass representation as

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

for $t=0\sim N_c-1$. Frequency-domain frame-by-frame interleaving is applied (see Sect. III) and then, interleaved signal represented by $\{S_i(n);\ n=0\sim N_c-1\}$ is transformed back to time-domain signal represented by $\{s_i(t);\ t=0\sim N_c-1\}$. To limit the PAPR, deliberate amplitude clipping is applied as [7]

$$\bar{s}(t)=\begin{cases} s_i(t), & |s_i(t)|\le\beta \\ \beta\frac{s_i(t)}{|s_i(t)|} & \text{otherwise}\end{cases} \tag{2}$$

for $t=0\sim N_c-1$, where β denotes the predetermined clipping level, which is known at the receiver side. After insertion of the guard interval (GI) the OFDM/TDM signal is multiplied by power coefficient $\sqrt{\frac{2E_s}{T_c}}$ and transmitted over a frequency-selective fading channel. E_s and T_c denote the data-modulated symbol energy and the sampling duration of IFFT, respectively.

At the receiver, N_c-point FFT is applied to decompose the received signal into N_c frequency components $\{R(n);\ n=0\sim N_c-1\}$. One-tap MMSE-FDE is applied to $\{R(n)\}$ as [8]

$$\hat{R}(n)=R(n)w(n), \tag{3}$$

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

$$w(n)=\frac{\left[1-\exp\left(-\beta^2\right)+\frac{\sqrt{\pi}\beta}{2}\mathrm{erfc}\left(\beta\right)\right]H^*(n)}{\left[1-\exp(-\beta^2)\right]|H(n)|^2+(\frac{E_s}{N_0})^{-1}}, \tag{4}$$

where erfc$[x]$=$\frac{2}{\sqrt{\pi}}\int_x^\infty\exp(-t^2)dt$ is the complementary error function. In Eq. (4), $H(n)$ and N_0, respectively, denote the channel gain and the single-sided power spectrum density. $(\cdot)^*$ denotes complex conjugate operation.

After de-interleaving, the OFDM/TDM de-interleaved signal is transformed back into time-domain and then, OFDM demodulation [3] is done to obtain decision variables required for log-likelihood ratio (LLR) computation [9]. The iterative log-MAP turbo decoding [6] is performed using the LLR sequence as shown in [9].

III. Frequency-domain Interleaving for OFDM/TDM Using MMSE-FDE

To enhance frequency diversity effect we introduce a frequency-domain interleaver over the entire OFDM/TDM frame (i.e., K concatenated OFDM signals), which combined with MMSE-FDE at the OFDM/TDM receiver provides improved BER performance due to enhanced frequency diversity gain. Interleaved OFDM system considered in [3], [4] improves the transmission performance by the cost of high latency and computational complexity, but the channel frequency-selectivity is not fully exploited. This is because a subcarrier-by-subcarrier interleaving is performed over a large number of consecutive OFDM signal blocks and then, one-tap FDE is carried out on subcarrier-to-subcarrier basis for each OFDM signal independently. In our case, frequency-domain interleaving is applied over several concatenated OFDM signal frequency components so that MMSE-FDE, at the receiver, can exploit the channel frequency-selectivity and improve the BER performance.

At the transmitter (see Fig. 1(a)), after OFDM/TDM modulation, N_c-point FFT is applied over OFDM/TDM frame signal $\{s(t);\ t=0\sim N_c-1\}$ to decompose the signal into N_c frequency components $\{S(n);\ n=0\sim N_c-1\}$ as

$$S(n)=\sum_{t=0}^{N_c-1}s(t)\exp\left\{-j2\pi n\frac{t}{N_c}\right\}. \tag{5}$$

Then, OFDM/TDM signal frequency components $\{S(n);\ n=0\sim N_c-1\}$ are fed to the interleaver to permute the ordering and obtain the interleaved OFDM/TDM frequency components given by

$$S_i(n)=\pi\{S(n)\} \tag{6}$$

for $n=0\sim N_c-1\}$, where $\pi\{\cdot\}$ represents the interleaver function. The size of the interleaver is N_c as shown in Fig. 2. The frequency-domain interleaver formats the OFDM/TDM frequency components in a rectangular array of 2^a rows and 2^b columns (i.e., in this paper block interleaver is used with a=b=4). The OFDM/TDM frequency components are write-in row-wise, but they are read-out column-wise. As a result of this reordering of the OFDM/TDM signal frequency components, a channel frequency-selectivity is enhanced, which is exploited by MMSE-FDE.

After block interleaving, the permuted OFDM/TDM frequency components $\{S_i(n);\ n=0\sim N_c-1\}$ are converted by applying N_c-point IFFT to the time-domain interleaved OFDM/TDM signal $\{s_i(t);\ t=0\sim N_c-1\}$ as

$$s_i(t)=\frac{1}{N_c}\sum_{n=0}^{N_c-1}S_i(n)\exp\left\{j2\pi t\frac{n}{N_c}\right\}. \tag{7}$$

Then, time-domain interleaved signal is clipped and transmitted over a frequency-selective fading channel.

After MMSE-FDE, the OFDM/TDM frequency components must be permuted back (de-interleaved) before OFDM/TDM demodulation as shown in Fig. 1(b). The equalized OFDM/TDM signal is fed to block de-interleaver as

$$\hat{R}_{de-i}(n)=\pi^{-1}\{\hat{R}(n)\} \tag{8}$$

with the same rectangular array format as the interleaver at the transmitter side. The equalized OFDM/TDM frequency

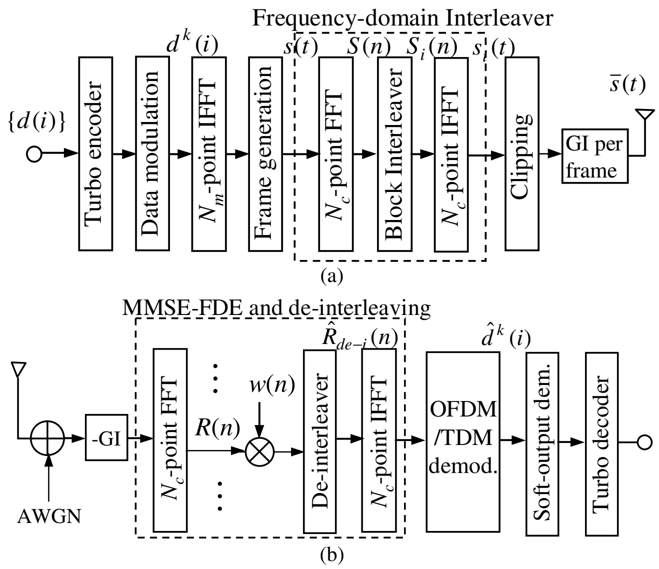

Fig. 1. OFDM/TDM transmitter/receiver structure: (a) Transmitter, (b) Receiver.

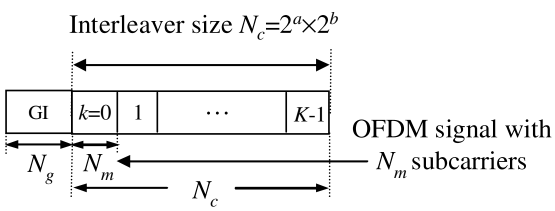

Fig. 2. OFDM/TDM frame structure

components are write-in column-wise and they are read-out row-wise. Finally, the time-domain OFDM/TDM signal is recovered by applying N_c-point IFFT to $\{\hat{R}_{de-i}(n)\ n=0\sim N_c-1\}$. Then, OFDM demodulation is carried out using N_m-point FFT to obtain decision variables $\{\hat{d}^k(i)\ i=0\sim N_m-1\}$ required for the LLR computation and turbo decoding as presented in [9].

IV. Simulation Results

The OFDM/TDM parameters are shown in Table I. We assume an OFDM/TDM frame size of $N_c=256$ samples with the GI length of $N_g=32$ samples and ideal coherent QPSK data modulation/demodulation. The propagation channel is $L=16$-path block Rayleigh fading channel having exponential power delay profile with decay factor α, where the path gains remain constant over one OFDM/TDM frame length and vary frame-by-frame. We assume that the time delay of the lth path is l=l samples with $L<N_g$. Perfect knowledge of the channel state information is assumed. For computer simulation we have chosen clipping level $\beta=4$ dB since it is a moderate clipping level in a practical wireless communication systems. A rate 1/3 turbo encoder with constraint length 4 and (13, 15) RCS component encoders is assumed. The parity bit sequences are punctured to obtain coding rate $R=1/2$. Log-MAP decoding with 8 iterations is carried out at the receiver. The information bit sequence length is taken to be $M=1024$ bits. The turbo coded and punctured parity bit sequences are interleaved before data-modulation. A block bit interleaver is used as channel interleaver.

TABLE I
Simulation parameters.

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

A. Impact of K

The BER performance of OFDM/TDM as a function of the average signal energy per bit-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 for $\alpha=0$ dB is shown in Fig. 3.

The uncoded BER performance of OFDM/TDM is discussed first. It can be seen from Fig. 3(a) that the BER performance of OFDM/TDM with frequency-domain interleaving, for BER=10^{-6}, achieves the E_b/N_0 gain of about 1.5 and 7 dB in comparison with no interleaving case when $K=64$ and 16, respectively. For conventional OFDM ($K=1$) the same BER performance is obtained with and without frequency-domain interleaving because each subcarrier is independently modulated and frequency diversity gain cannot be obtained. As shown by Fig. 3(a), the uncoded OFDM/TDM using MMSE-FDE with frequency-domain interleaving can significantly improve the BER performance over conventional OFDM ($K=1$); for BER=10^{-5} the E_b/N_0 gain of about 22.5 and 24.5 dB is achieved when $K=16$ and 64, respectively. This is because frequency-domain interleaving enhances channel frequency-selectivity and obtains a large frequency diversity gain through MMSE-FDE at the receiver.

Figure 3(b) illustrates the BER performance of coded OFDM/TDM with frequency-domain interleaving and MMSE-FDE. As can be seen from Fig. 3(b), for BER=10^{-6}, the E_b/N_0 gain of about 1 and 2.4 dB is obtained with frequency-domain interleaving over no interleaving case when $K=64$ and 16, respectively. For conventional OFDM (K=1), however, the coding gain obtained by large interleaver in the encoder will be degraded due to short-size frequency-domain interleaver and the BER performance will degrade as shown in Fig. 3(b). This is because the short-size frequency-domain interleaver will decrease the coding gain because the interleaving effect of the encoder with long-size interleaver will be reduces. It is further seen that OFDM/TDM with $K=64$ achieves a better BER performance than the conventional OFDM with frequency domain interleaving; for BER=10^{-6}, the E_b/N_0 gain of about 0.8 dB is achieved due of enhanced frequency diversity gain through MMSE-FDE.

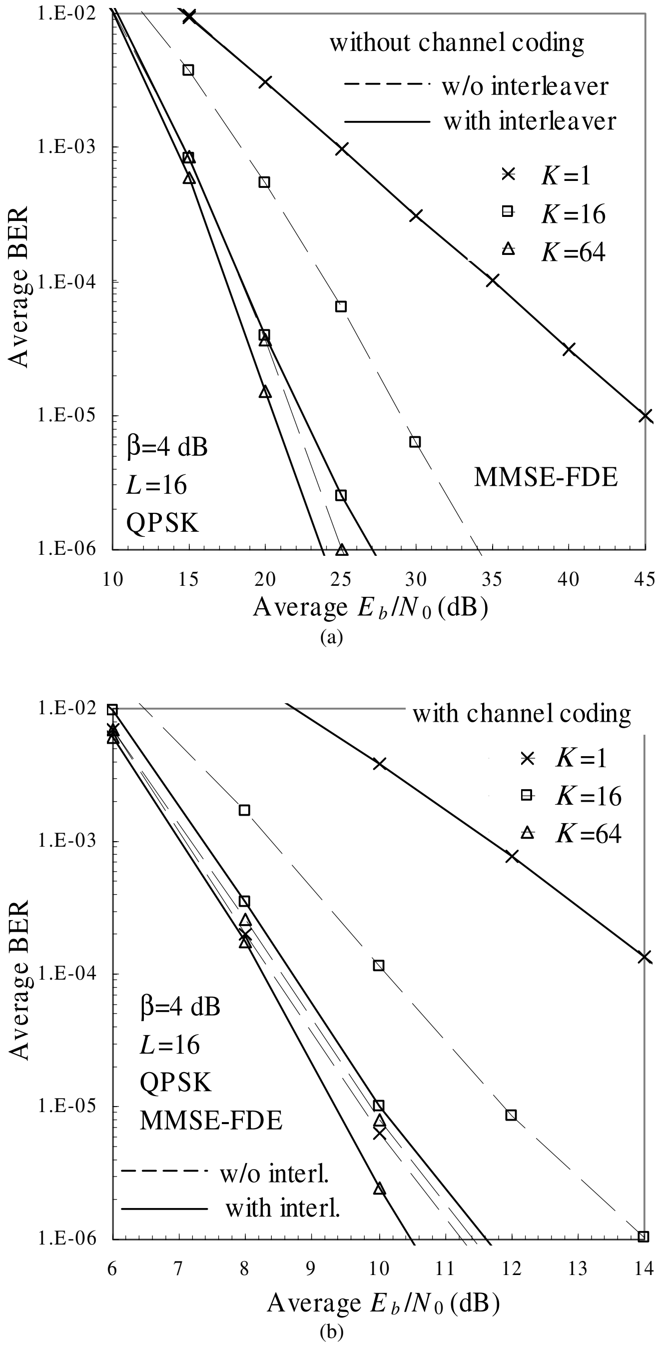

Fig. 3. Average BER vs. E_b/N_0: (a) Uncoded, (b) Coded.

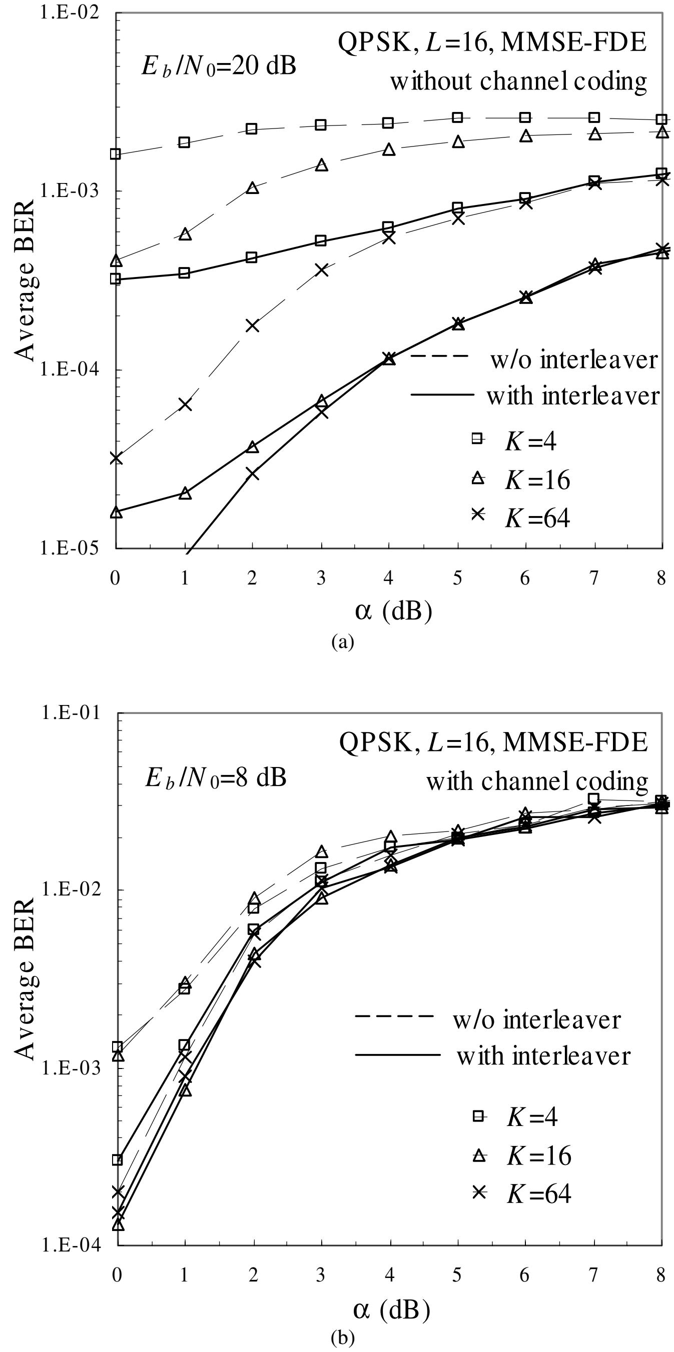

Fig. 4. Impact of channel frequency-selectivity: (a) Uncoded, (b) Coded.

Due to clarity of presentation in Fig. 3(b) curves for K=2, 4 and 8 (close to the conventional OFDM ($K = 1$) are not illustrated. However, it was confirmed by computer simulation that the performance with K=2, 4 and 8 using frequency domain interleaving outperforms the conventional OFDM ($K = 1$).

B. Impact of Channel Frequency-selectivity

The performance of OFDM/TDM with frequency-domain interleaver improves due to frequency diversity gain, which is obtained through MMSE-FDE by exploiting the channel frequency-selectivity. The channel frequency-selectivity is determined by the decay factor α; as α increases, the channel is becoming less frequency-selective and when $\alpha \to \infty$ dB it becomes a frequency-nonselective channel (i.e., single-path channel). We only consider OFDM/TDM with K=4, 16 and 64 because conventional OFDM is not affected by change of channel frequency-selectivity. $\beta = \infty$ (no clipping) is assumed since frequency diversity gain is not a function of clipping level β.

The BER performance with and without frequency-domain interleaver of OFDM/TDM using MMSE-FDE is shown in

Fig. 4 as a function of the channel decay factor α. As can be seen from Fig. 4(a), for uncoded case, the BER with interleaver is more affected with channel decay factor since as α increases the channel is less frequency selective and the frequency diversity gain due to interleaving tends to be lost. Fig. 4(b) shows the coded average BER performance with and without frequency-domain interleaver of OFDM/TDM using MMSE-FDE as a function of the channel decay factor α. As can be seen from Fig. 4(b) the coded BER performance is almost the same and degrades as α increase.

V. Conclusion

In this paper, frequency-domain interleaving for OFDM/TDM using MMSE-FDE was presented. Frequency-domain interleaving over OFDM/TDM frame signal frequency components is applied to enhance the channel frequency-selectivity and obtain frequency diversity gain through MMSE-FDE at the receiver. The BER performance of OFDM/TDM in a frequency-selective Rayleigh fading channel is evaluated by computer simulation. It was shown that, application of frequency-domain interleaving on a frame-by-frame basis for OFDM/TDM using MMSE-FDE can improve the BER performance due to enhanced frequency diversity gain in comparison with conventional OFDM.

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