Closed-form BER Expression for OFDM with Pilot-assisted Channel Estimation in a Nonlinear Multipath Fading Channel

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***Abstract*—Orthogonal frequency division multiplexing (OFDM) system with frequency domain equalization (FDE) requires reliable channel estimation (CE). OFDM has a problem of high peak-to-average power ratio (PAPR), which makes it very sensitive to nonlinear distortions, affecting the channel estimation accuracy. In this paper, we investigate the effect of the nonlinearity to the the OFDM system with pilot-assisted CE based on time or frequency division multiplexed (TDM/FDM) pilot. A closed-form bit error rate (BER) expressions for OFDM system are derived in a nonlinear and frequency-selective fading channel. The analysis is based on the Gaussian approximation of the nonlinear noise, which is also confirmed by computer simulation. Our results in terms of BER and mean square error (MSE) show, that FDM-pilot based CE is more sensitive to nonlinear distortions as compared to CE based on TDM-pilot.**

***Index Terms*—OFDM, closed-form BER, nonlinearity, channel estimation.**

I. Introduction

In radio channel the transmitted signal reaches the receiver through multiple propagation paths, each of them having different relative delay and gain. This produces inter-symbol interference (ISI) and gives rise to frequency selective fading [1]. Orthogonal frequency division multiplexing (OFDM) can be used to overcome the channel frequency selectivity, but it requires accurate channel estimation (CE) for coherent detection. Various CE schemes generally based on the use of pilot signals in given positions have been proposed for OFDM [2]-[5]. The pilot signal can be multiplexed either in the time domain (TDM-pilot), or in the frequency domain (FDM-pilot). For pilot-assisted CE with TDM-pilot the tracking ability against fast fading is lost. On the other hand, the CE with FDM-pilot improves the tracking against fast fading.

The main drawback of OFDM is its high peak-to-average power ratio (PAPR), which makes the system very sensitive to nonlinear distortions due to analog components such as high power amplifier (HPA), digital-to-analog (DA) and analog-to-digital (AD) converters. Consequently, the CE accuracy may be degraded. In [6], the nonlinear effects on pilot-assisted CE with both TDM- and FDM-pilot are evaluated by computer simulation. To the best of the author's knowledge, to date, the theoretical analysis of nonlinear degradation on pilot-assisted CE has not been presented.

In this paper, we present the theoretical perfomance analysis of OFDM system with pilot-assisted CE in a nonlinear and frequency-selective fading channel. We derive a closed-form bit error rate (BER) expressions for pilot-assisted CE with TDM- and FDM-pilots. We also compare the mean square error (MSE) of the channel estimator for both cases. Our analysis is based on the Gaussian approximation of the nonlinear noise, which is also confirmed by computer simulations. The results show that the BER performance with pilot-assisted CE based on FDM-pilot is more sensitive to the nonlinear distortion in comparision with the CE based on TDM-pilot.

The rest of the paper is organized as follows. Section II gives an overview of the system model. Analitical derivation is given in Sect. III. Numerical results and discussions are presented in Sect. IV. Section V concludes the paper.

II. System Model

The OFDM transmission system model is illustrated in Fig. 1. Signal representations of OFDM system and CE schemes are presented in the following section. Throughout this paper, T_c-spaced discrete time representation is used, where T_c represents the fast Fourier transform (FFT) sampling period.

A. Mathematical Signal Representation

The mth $(m = ..., -1, 0, 1, ...)$ frame of N_c data-modulated symbols $\{d_m(k);\ k = 0 \sim N_c - 1\}$ with $E[|d_m(k)|^2] = 1$ is transmitted during one T_cN_c interval. The time-domain OFDM signal $\{s_m(t);\ t = 0 \sim N_c - 1\}$ is obtained by feeding the data-modulated symbol sequence $d_m(k)$ to an N_c- point inverse FFT (IFFT). The impact of nonlinear device (e.g., HPA) is approximated with

$$\hat{s}_m(t) = \begin{cases} s_m(t), & |s_m(t)| < \beta \\ \beta\frac{s_m(t)}{|s_m(t)|}, & \text{otherwise}, \end{cases} \tag{1}$$

for $t = 0 \sim N_c - 1$, where β denotes the amplitude saturation level. As a result of this operation, the maximum peak power is suppressed.

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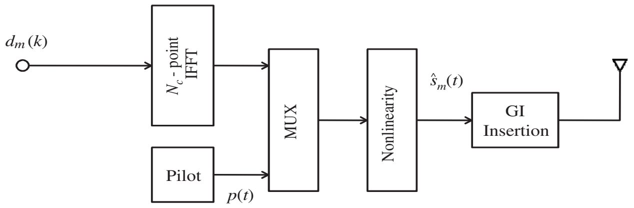
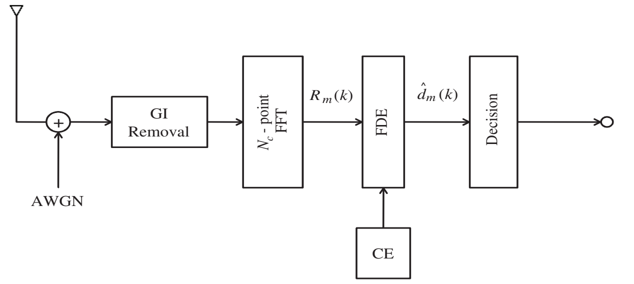


(a) Transmitter



(b) Receiver

Figure 1. OFDM system model.

To eliminate the inter-symbol interference (ISI) N_g- sample guard interval (GI) is inserted at the beginning of each OFDM frame. Finally, the signal is amplified which is represented by the multiplication with the power coefficient $\sqrt{2E_s/T_c}$, where E_s denotes the data-modulated symbol energy. Using the Bussgang theorem [7], a nonlinear output can be expressed as a sum of a useful attenuated input replica and an uncorrelated nonlinear distortion as [8]

$$\hat{s}_m(t) = \sqrt{\frac{2E_s}{T_c N_c}}[\alpha s_m(t) + \tilde{s}_m(t)], \tag{2}$$

where α and $\tilde{s}_m(t)$, respectively, denote the attenuation constant and noise due to nonlinearity. The attenuation constant α is chosen to minimize the MSE term $E[|\hat{s}_m(t) - \alpha s_m(t)|^2]$ [8]. It is shown in [8], [9] that for amplitude saturation level $\beta >$ 7dB, $\alpha \to 1$. For lower β, α can be well approximated as $\alpha = 1 - \exp(-\beta^2) + \frac{\sqrt{\pi}}{2}\mathrm{erfc}\{\beta\}$ [10].

After removing the GI, the received signal is decomposed into N_c frequency components $\{R_m(k);\, k = 0 \sim N_c - 1\}$ by applying N_c-point FFT as

$$R_m(k) = \sqrt{\frac{2E_s}{T_c N_c}}[\alpha S_m(k) + \tilde{S}_m(k)]H_m(k) + \Pi_m(k), \tag{3}$$

where $S_m(k)$, $H_m(k)$, $\tilde{S}_m(k)$ and $\Pi_m(k)$, respectively, denote the mth frame's transmitted signal, the propagation channel gain, the distorted part of the output signal due to nonlinearity and the AWGN noise component (which includes quantization noise introduced by AD and DA converters) at the kth frequency.

To correct the channel distortion on each subcarrier one tap FDE is applied to $R_m(k)$ as [11]

$$\hat{d}_m(k) = \sqrt{\frac{2E_s}{T_c N_c}}[\alpha S_m(k) + \tilde{S}_m(k)]\hat{H}_m(k) + \hat{\Pi}_m(k) \tag{4}$$

with

$$\begin{cases} \hat{H}_m(k) = H_m(k)w_m(k), \\ \hat{\Pi}_m(k) = \Pi_m(k)w_m(k). \end{cases}$$

In (4), $w_m(k)$ denotes the maximum ratio combining (MRC) equalization weight for the kth frequency given by [11]

$$w_m(k) = H_m^*(k). \tag{5}$$

In the above expression $H_m(k)$ is replaced by the estimation channel gain $H_{m,e}(k)$, which is estimated by using the method presented below.

B. Channel Estimation

In this section, we first give a short overview of pilot-assisted CE with TDM-pilot and then, of CE with FDM-pilot.

1) CE with TDM-pilot: For CE with TDM-pilot, the frame structure is shown in Fig. 2a. Pilot signal is transmitted in the first frame $(m = 0)$ followed by $N_d - 1$ OFDM data signals. Since we have chosen Chu pilot sequence, the nonlinearity will not affect the pilot signal.

Fig. 2b illustrates the block diagram for CE with TDM-pilot. For $m = 0$, the instantaneous channel gain estimate at the kth frequency is obtained by reverse modulation as

$$\tilde{H}_0(k) = \frac{R_0(k)}{P(k)} = \sqrt{\frac{2E_s}{T_c N_c}}H_0(k) + \frac{\Pi_0(k)}{P(k)} \tag{6}$$

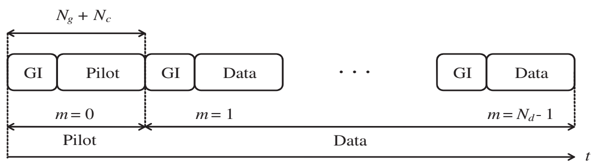
for $k = 0 \sim N_c - 1$, where $P(k)$ is the kth frequency component of the time-domain pilot signal $p(t)$. N_c-point IFFT is performed on $\{\tilde{H}_0(k);\, k = 0 \sim N_c - 1\}$ to obtain the instantaneous channel impulse response $\{\tilde{h}_0(t);\, t = 0 \sim N_c - 1\}$. Assuming that the channel impulse response is present only within the GI, the estimated channel impulse response beyond the GI is replaced with zeros to reduce the noise. Then, N_c-point FFT is applied to obtain the improved channel gain estimates $\{H_{0,e}(k);\, k = 0 \sim N_c - 1\}$.

2) CE with FDM-pilot: In CE scheme with FDM-pilot interpolation is used over N_m equally-spaced pilot subcarriers as a subset of N_c subcarriers.

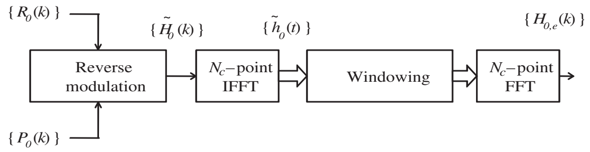
First, by reverse modulation, the instantaneous channel gain estimate $\{\tilde{H}_m(q); IH\, q = \left\lfloor \frac{k}{N_m} \right\rfloor$ for $k = 0 \sim N_c - 1\}$ at the pilot subcarriers is obtained by

$$\tilde{H}_m(q) = \frac{R_m(q)}{P(q)} = \sqrt{\frac{2E_s}{T_c N_c}}[\alpha\frac{S_m(q)}{P(q)} + \frac{\tilde{S}_m(q)}{P(q)}]H_m(q) + \frac{\Pi_m(q)}{P(q)}, \tag{7}$$

where $\lfloor x \rfloor$ represents the largest integer smaller than or equal to x and N_m is the number of pilot subcarriers. Since $q = \left\lfloor \frac{k}{N_m} \right\rfloor$, the channel estimates are obtained only at frequencies $k = 0,\, N_m,\, 2N_m, \ldots, N_c - 1$ as shown in Fig. 3. Hence, the interpolation is required to obtain channel gains for all frequencies (i.e., $k = 0 \sim N_c - 1$). First, N_m-point IFFT is performed on $\{\tilde{H}_m(q);\, q = 0 \sim N_m - 1\}$ to obtain the instantaneous channel impulse response $\{\tilde{h}_m(t);\, t = 0 \sim N_m - 1\}$. Using (7) and after N_c-point FFT the interpolated channel gain estimates $\{H_{m,e}(k);\, k = 0 \sim N_c - 1\}$ for all N_c frequencies can be expressed as



(a) Frame structure



(b) Block diagram

Figure 2. Frame structure and block diagram for CE with TDM-pilot.

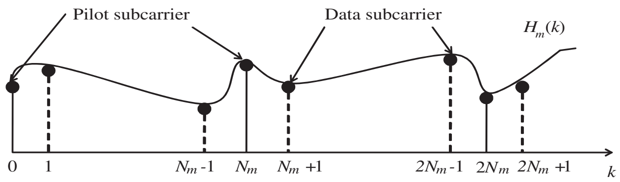


Figure 3. Pilot arrangements for CE with FDM-pilot.

$$\begin{aligned} H_{m,e}(k) \quad &= \textstyle\sum_{q=0}^{N_m-1} \tilde{H}_m(q)\Psi(k,q) \\ &= H_m(k) + \textstyle\sum_{q=0}^{N_m-1} \frac{\tilde{S}_m(k)}{P(k)}\Psi(k,q) + \\ &+ \textstyle\sum_{q=0}^{N_m-1} \frac{\Pi_m(k)}{P(k)}\Psi(k,q), \end{aligned} \tag{8}$$

where $\tilde{S}_m(k)$ and $\Pi_m(k)$, respectively, denote the distorted part of the output signal due to nonlinearity and the AWGN noise component at the kth frequency and

$$\Psi(k,q) = \frac{sin(\pi N_m(\frac{(N_m/N_c)q-k}{N_c}))}{sin(\pi(\frac{(N_m/N_c)q-k}{N_c}))}\exp(-j\pi(N_m-1)\frac{(N_m/N_c)q-k}{N_c})$$

is the frequency domain interpolation function with $q = \left\lfloor \frac{k}{N_m} \right\rfloor$ for $k = 0 \sim N_c - 1$.

III. Analitical Derivation

In this section, we first evaluate MSE and then, the closed-form BER expressions are presented for pilot-assisted CE with both TDM- and FDM-pilot in a nonlinear and frequency-selective fading channel. We evaluate channel estimation error by computer simulations and show that it can be approximated as zero mean random Gaussian variable. Fig. 4 shows channel estimation error in terms of probability density functions (PDFs) for both TDM- and FDM-pilot CE. We can see from the plot that standard deviation is higher for the case of FDM-pilot CE since the channel estimation error values are spread over wider range. That is because the pilot subcarriers are affected by nonlinearity for the CE with FDM-pilot.

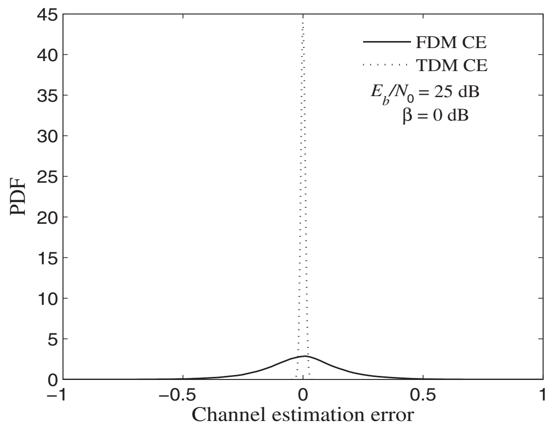


Figure 4. PDF of the CE error.

A. MSE of channel estimation

We define the MSE of the mth frame at the kth subcarrier as $\text{MSE}_m(k) = E[|e_m(k)|^2] = E[|H_{m,e}(k) - H_m(k)|^2]$and assume that the amplitude saturation level β is known at the receiver.

1) TDM-pilot: CE with TDM-pilot introduces a small amount of nonlinear distortions, which can be neglected since Chu pilot sequence with a constant amplitude in both time- and frequency-domain is used. Thus, the attenuation constant $\alpha = 1$. Using (6) we obtain MSE expression for CE with TDM-pilot for zero frame as

$$\text{MSE}_{TDM} = \frac{1}{2}\left(1 + \frac{N_g}{N_c}\right)\left(\frac{E_b}{N_0}\right)^{-1}, \tag{9}$$

where $\frac{E_b}{N_0} = \frac{1}{2}(1 + \frac{N_g}{N_c})\frac{E_s}{N_0}$ denotes the signal energy per bit-to-AWGN power spectrum density ratio.

2) FDM-pilot: For CE with FDM-pilot frequency interpolation is required. We obtain average MSE of the channel estimator with FDM-pilot given by

$$\text{MSE}_{FDM} = \frac{N_m}{N_c}(1-\exp(-\beta^2)-\alpha^2)+\frac{N_m}{2}(1+\frac{N_g}{N_c})\left(\frac{E_b}{N_0}\right)^{-1}, \tag{10}$$

where the first term denotes the negative effect of nonlinearity.

B. Closed-form BER

In the following we assume the quadrature-phase shift keying (QPSK) for data modulation. The equlized signal with practical CE can be represented using (4) as

$$\hat{d}_m(k) = R_m(k)H^*_{m,e}(k). \tag{11}$$

The BER for the mth frame is obtained as [1]

$$\begin{aligned} P_{b,m} \quad &= \text{Prob}[\text{Re}(R_m(k)H^*_{m,e}(k)) < 0] \\ &= \tfrac{1}{2}(1 - \rho_m) \end{aligned} \tag{12}$$

with [1]

$$\rho_m = \frac{\text{Real}[\mu]}{\sqrt{1 - \text{Im}^2[\mu]}}, \tag{13}$$

where μ is the normalized covariance given by [1]

$$\mu = \frac{m_{xy}}{\sqrt{m_{xx} m_{yy}}}. \tag{14}$$

In the above expression $m_{xx} = E[|X|^2]$, $m_{yy} = E[|Y|^2]$ and $m_{xy} = E[XY^*]$ with $X = R_m(k)$ and $Y = H_{m,e}(k)$ [1].

The average BER performance is given by [1]

$$P_b = \frac{1}{N_d - 1} \sum_{m=1}^{N_d - 1} \frac{1 - \rho_m}{2}. \tag{15}$$

Below, we derive closed-form BER expression in a nonlinear and frequency-selective fading channel with both TDM- and FDM-pilot.

1) TDM-pilot: Using (3) and (6) for CE with TDM-pilot we obtain

$$\begin{cases} X = \sqrt{\frac{2E_s}{T_c N_c}}[\alpha S_m(k) + \tilde{S}_m(k)]H_m(k) + \Pi_m(k) \\ Y = \sqrt{\frac{2E_s}{T_c N_c}} H_0(k) + \frac{\Pi_0(k)}{P(k)}, \end{cases} \tag{16}$$

where $\Pi_0(k)$ denotes the AWGN noise component at the kth frequency. Using (16) we obtain

$$\begin{cases} m_{xx} = \frac{2E_s}{T_c N_c}\alpha^2 + \frac{2E_s}{T_c N_c}\frac{1}{N_c}\left(1 - \exp(-\beta^2) - \alpha^2\right) + \frac{2N_0}{T_c N_c}, \\ m_{yy} = \frac{2E_s}{T_c N_c}(A_1 + A_2), \\ m_{xy} = \frac{2E_s}{T_c N_c} A_3 \end{cases}$$

with

$$\begin{cases} A_1 = E[|H_0(k)|^2] = 1, \\ A_2 = \frac{N_0}{Es} = \frac{1}{2}\left(1 + \frac{N_g}{N_c}\right)\left(\frac{E_b}{N_0}\right)^{-1}, \\ A_3 = \alpha J_0(2\pi f_D T_s m). \end{cases}$$

Therefore, normalized covariance μ^{TDM} for CE with TDM-pilot can be given as

$$\mu^{TDM} = \frac{A_3}{\sqrt{[\alpha^2 + B_1 + B_2][A_1 + A_2]}} \tag{17}$$

with $B_1 = \frac{1}{N_c}(1 - \exp(-\beta^2) - \alpha^2)$ and $B_2 = \frac{1}{2}(1 + \frac{N_g}{N_c})(\frac{E_b}{N_0})^{-1}$. Using (17) we compute (13) and finally the average BER is obtained by using (15).

2) FDM-pilot: Using (3) and (8) for CE with FDM-pilot we obtain

$$\begin{cases} X = \sqrt{\frac{2E_s}{T_c N_c}}[\alpha S_m(k) + \tilde{S}_m(k)]H_m(k) + \Pi_m(k), \\ Y = \sqrt{\frac{2E_s}{T_c N_c}}[H_m(k) + \sum_{q=0}^{N_m-1}\frac{\tilde{S}_m(k)}{P(k)}\Psi(k,q)] + \\ \quad + \sum_{q=0}^{N_m-1}\frac{\Pi_m(k)}{P(k)}\Psi(k,q). \end{cases} \tag{18}$$

Using (18) we obtain

$$\begin{cases} m_{xx} = \frac{2E_s}{T_c N_c}\alpha^2 + \frac{2E_s}{T_c N_c}\frac{1}{N_c}(1 - \exp(-\beta^2) - \alpha^2) + \\ \quad + \frac{2N_0}{T_c N_c}, \\ m_{yy} = \frac{2E_s}{T_c N_c}\alpha + \frac{2E_s}{T_c N_c}\frac{N_m}{N_c}(1 - \exp(-\beta^2) - \alpha^2) + \\ \quad + \frac{2N_0}{T_c N_c}, \\ m_{xy} = \frac{2E_s}{T_c N_c}\alpha + [\frac{2E_s}{T_c N_c}\frac{N_m}{N_c}(1 - \exp(-\beta^2) - \alpha^2) + \\ \quad + \frac{2N_0}{T_c N_c}]\sum_{q=0}^{N_m-1}\Psi(k,q). \end{cases}$$

Thus, normalized covariance μ^{FDM} for CE with FDM-pilot can be given as

$$\mu^{FDM} = \frac{\alpha + N_m(B_1 + B_2)}{\sqrt{[\alpha^2 + B_1 + B_2][1 + N_m B_1 + N_m B_2]}}. \tag{19}$$

Now, using (19) we obtain (13) and compute the average BER using (15), but for the case of CE with FDM-pilot, $N_d \to \infty$.

Table I. Numerical parameters.

Transmitter	Data modulation	QPSK
	IFFT/FFT size	$N_c = 256$
	GI	$N_g = 16$
Channel	L=8-path frequency-selective block Rayleigh fading	
Receiver	FDE	MRC
	Channel estimation	TDM- and FDM-pilots

IV. Numerical Results and discussions

The computer simulation conditions are given in Table I. We assume an OFDM signal with $N_c = 256$ subcarriers, $N_g = 16$, $N_m = 16$ and QPSK data modulation. As the propagation channel, we assume an $L = 8$-path block Rayleigh fading channel with uniform power delay profile; $\{h_l; l = 0 \sim 7\}$ are independent and identically distributed zero-mean complex Gaussian variables having variance $1/8$. It is assumed that the time delay of the lth path is $\tau_l = l$ samples (i.e., the maximum delay difference is less than the GI length since $L < N_g$).

We have choosen $f_D T_s = 0.0001$ for normalized Doppler frequency (where $1/T_s = 1/[T_c(1 + N_g/N_c)]$) which corresponds to moving terminal speed of 40 km/h for 2 GHz carrier frequency. In the case of CE with TDM-pilot we use a Chu-sequence as a pilot given by $\{p(t) = \exp(j\pi t^2/N_c);\ t = 0 \sim N_c - 1\}$ [6]. We note that case of $\beta \to \infty$ represents linear HPA.

We first investigate the effect of nonlinearity on the channel estimator with both TDM- and FDM-pilots by numerically evaluating its MSE. For the CE with TDM-pilot we select $N_d = 4$, while $N_m = 16$ for the CE with FDM-pilot and consequently, the same transmission data rate is maintained. The MSE of the channel estimator in a nonlinear and frequency-selective fading channel is shown in Fig. 5. It can be seen from the figure that the amplitude saturation level β does not affect the MSE of the channel estimator for the CE using TDM-pilot. This is because the performance of CE using TDM-pilot is not affected by nonlinearity, since we are using Chu pilot sequence which has constant amplitude in both time- and frequency-domain. It can be seen from Fig. 5 that in the case

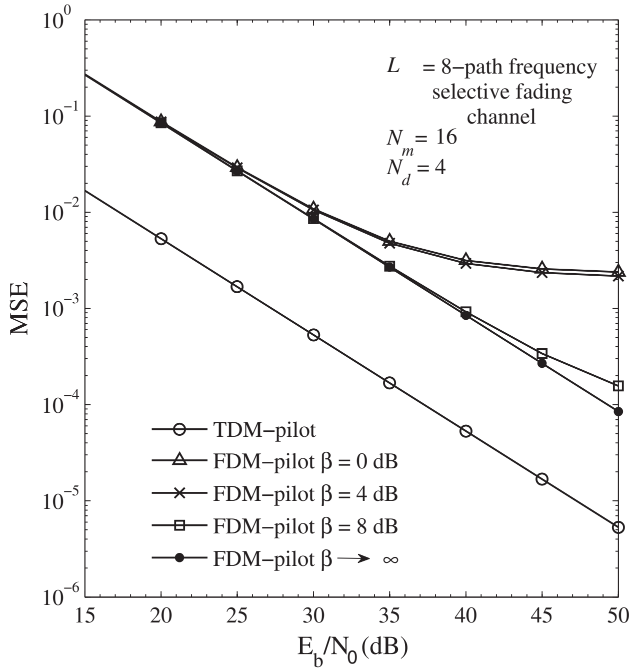


Figure 5. MSE of the channel estimator.

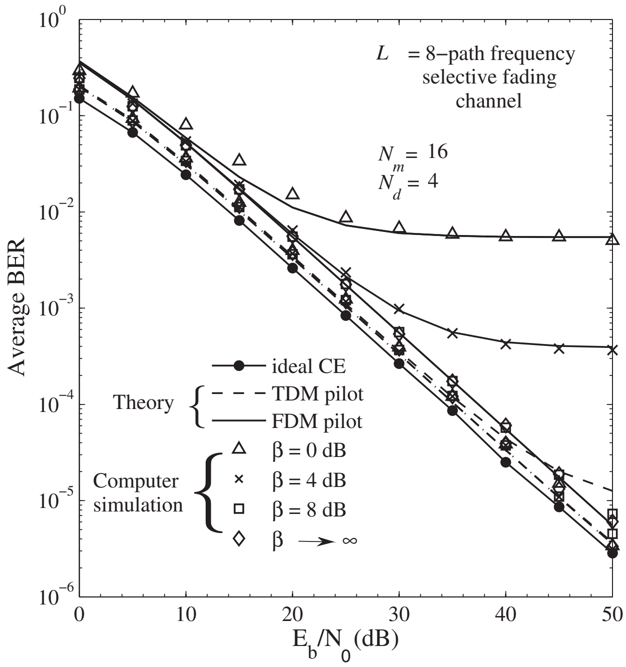


Figure 6. BER performance.

of FDM-pilot, amplitude saturation level β affects the MSE of the channel estimator; MSE floor is observed for $E_b/N_0 > 30$ dB. This is because the pilot signals are multiplexed in the frequency domain before transmission and consequently, the higher PAPR will cause the performance degradation.

Next, we evaluate the BER performance with pilot-assisted CE using both TDM- and FDM-pilots in a nonlinear and frequency-selective fading channel. The average BER performance with pilot-assisted CE using TDM- and FDM-pilots as a function of the E_b/N_0 with amplitude saturation level β as a parameter are illustrated in Fig. 6. In terms of BER performance CE with FDM-pilot is more sensitive to the nonlinear distortion in comparision to the CE based on TDM-pilot. This is because the nonlinearity affects the pilot subcarriers leading to the worse estimation performance as discussed in the previous paragraph.

V. Conclusions

In this paper, the impact of nonlinear distortions is evaluated, due to analog components, on accuracy of the pilot-assisted channel estimation based on both TDM- and FDM-pilots in OFDM system. In our analysis nonlinear noise is approximated with Gaussian random variable that we confirm by computer simulation. Closed-form BER expressions are derived for the CE with TDM- and FDM-pilot in a nonlinear and frequency-selective channel. The MSE of the channel estimator is also evaluated. It was shown that the system performance is more affected with nonlinear distortions for the case of CE with FDM-pilot than with TDM-pilot. This is because for the case of CE with FDM-pilot the nonlinearity affects the pilot subcarriers.

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