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# OFDM/TDM に及ぼす送信電力アンプの影響

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あらまし　これまで，筆者らは PAPR を低減するために，OFDM と時分割多重(TDM)を組み合わせた OFDM/TDM を提案した．周波数領域等化（FDE)を用いることで優れた BER 特性が得られる． OFDM/TDM では，完全に PAPR を除去できないので信号の歪みを避けるために，送信電力アンプの飽和点からバックオフ（IBO）が必要である． FDE ではチャネル推定が必要である．もし，IBO を注意深く選ばないと，IBO が受信機におけるチャネル推定精度に影響を与えてしまう．本論文では，パイロットチャネル推定を用いる OFDM/TDM に及ぼす送信電力アンプの影響について考察している．時間領域で低振幅を持つパイロットを用いた場合でも，アンプの非線形性によりチャネル推定誤差が増加してしまう．しかし，IBO を注意深く設定すれば，OFDM/TDM は OFDM よりも低いバックオフを許容できる．

# Effect of High-power Amplifier on OFDM/TDM

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**Summary**: Recently, to reduce a high peak-to-average power ratio (PAPR) of OFDM we proposed OFDM combined with time division multiplexing (OFDM/TDM). Using the frequency-domain equalization (FDE), improved BER performance is achieved. Since the OFDM/TDM cannot completely solve the PAPR problem, some amount of input back-off (IBO) from the saturation point of high-power amplifier (HPA) may be required to reduce the signal distortion caused by the HPA nonlinearity. Moreover, if IBO is not carefuly chosen it may also affect the channel estimation (CE) required for FDE. In this paper, by computer simulation, we study the impact of HPA nonlinearity on OFDM/TDM with pilot-assisted CE over a frequency-selective fading channel. It is shown that the HPA nonlinearity increases the estimation error even when a pilot with constant amplitude in the time-domain is used. However, it is shown in this paper that if IBO is carefully chosen, OFDM/TDM allows lower IBO for the given BER in comparison with OFDM, leading to higher amplifier efficiency.

**Key words**: *OFDM/TDM, channel estimation, HPA nonlinearity.*

## 1. Introduction

Orthogonal frequency division multiplexing (OFDM) signals have a problem with high peak-to-average power ratio (PAPR) that causes the signal distortion in a nonlinear high-power amplifier (HPA). Recently, OFDM combined with time division multiplexing (OFDM/TDM) was proposed to reduce the high PAPR of OFDM [1]. Moreover, OFDM/TDM owns its good bit error rate (BER) performance to frequency-domain equalization based on minimum mean square error criteria (MMSE-FDE) [1].

MMSE-FDE requires accurate channel estimation (CE). Various channel estimation techniques for OFDM are studied in [2], but they cannot be directly applied to OFDM/TDM since, in the OFDM/TDM receiver, FFT over a several concatenated OFDM signals is applied for FDE [1]. Therefore, in [3], a pilot-assisted CE for OFDM/TDM is presented, but a tracking ability against fast fading tends to be lost. To improve the tracking ability, a pilot-assisted CE with frequency-domain interpolation was presented, but the BER gets worse [4]. To improve the BER performance while improving the tracking ability, a pilot-assisted CE with time-domain first-order filtering and frequency-domain interpolation is presented [5].

Nonlinear distortions are primarily due to the transmitter HPA, which must be driven as close to its saturation point as possible in order to make its operation power efficient. The effect of HPA nonlinearity on an OFDM signal was investigated in [6] and the new solid-state power amplifier (SSPA; hereinafter HPA) model was proposed. According to the model proposed in [6], the OFDM system performance with HPA and ideal CE was studied in [7]-[12]. In particular, in [3]-[5], the pilot with constant amplitude in time-domain was used to eliminate the negative effect of amplitude clipping on pilot-assisted CE. However, the nonlinearity was not fully taken into consideration and the simple linear HPA model used in [3]-[5] may not be accurate for modeling real HPA's.

In this paper, we discuss on the impact of HPA parameters on OFDM/TDM with CE scheme presented in [5]. In addition to the above, even in the case when pilot sequence with constant amplitude in time-domain is used (e.g., Chu sequence [13]), the estimation error may increase due to HPA nonlinearity. To the best of author's knowledge, the impact of HPA nonlinearity was not fully investigated for OFDM/TDM.

The rest of the paper is organized as follows. In Sect. 2, we describe OFDM/TDM system model with HPA. We evaluate the system performance by computer simulation in Sect. 3. Sect. 4 concludes the paper.

## 2. OFDM/TDM System Model with HPA

The OFDM/TDM system model is illustrated in Fig. 1, where a $T_c$-spaced discrete time representation is used ($T_c$ represents FFT sampling period).

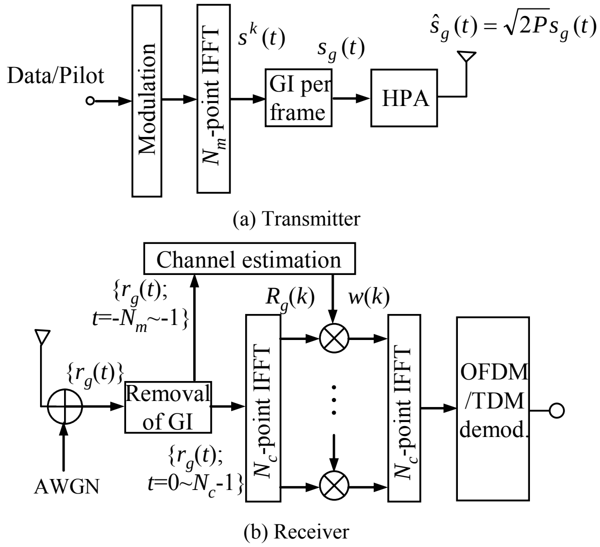


Fig. 1. OFDM/TDM transmitter/receiver structure.

### 2.1 Transmit OFDM/TDM Signal

The signaling interval of conventional OFDM with $N_c$ subcarriers is divided into $K$ slots, i.e., OFDM/TDM frame. A sequence of data-modulated symbols is divided into blocks with $N_m$=$N_c/K$ symbols and fed to $N_m$-point IFFT to generate time-domain OFDM signals. Then, a GI is inserted over $K$ OFDM signals to generate the $g$th frame OFDM/TDM signal as [1]

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

for $t$=0~$N_c$-1, where $u(t)$=1(0) for $t$=0~$N_m$-1 (elsewhere) and $s^k(t)$ is the $k$-th OFDM signal with $N_m$ subcarriers [1].

### 2.2 HPA Model

Before elaboration of the received signal, in this section, we describe a nonlinear HPA model. To simplify the discussion further, in this paper we assume a memoryless nonlinearity. This assumption is often made in the literature since many commonly used nonlinear devices, such as amplitude limiter and HPA, can be accurately model as memoryless devices. Most practical nonlinear devices exhibit a saturation property, which can be expressed as $|s_g(t)| \le \beta$, where β is an HPA saturation level. For the sake of convenience, the OFDM/TDM signal of Eq. (1) can be written in polar coordinates as

$$s_g(t) = \left|s_g(t)\right| e^{j\phi}, \tag{2}$$

where $|s_g(t)|$ and ϕ denote the amplitude and phase of OFDM/TDM signal. Using Eq. (2), the complex envelope of the HPA output can be expressed as

$$\hat{s}(t) = G(|\, s(t)\,|)\, e^{j(\phi + \Phi(|s(t)|))}, \tag{3}$$

where $G(\rho)$ and $\Phi(\rho)$ denote, respectively, the AM/AM and AM/PM conversion characteristics of HPA. According to the model proposed in [6], the AM/AM and PM/PM characteristic of HPA is given by

$$G(\rho) = \frac{\rho}{\left[1 + \left(\frac{\rho}{\beta}\right)^{2p}\right]^{\frac{1}{2p}}} \text{ and } \Phi(\rho) \approx 0, \tag{4}$$

where $p$ is the Rapp parameter. Nonlinear distortions primarily depend on the input back-off (IBO) of HPA defined as the ratio of the normalized saturation power and the average input power. The Rapp parameter $p$ controls the smoothness of the transition from the linear region to the saturation region; as $p$ decreases, the AM/AM curve becomes more nonlinear (see Fig. 2). For $p \to \propto$, the SSPA model approximates the soft limiter model of HPA used in [3]-[5]. Substituting Eq. (4) into Eq. (3) the OFDM/TDM signal after HPA is given by

$$\hat{s}_g(t) = G(|\, s_g(t)\,|) e^{j\phi}, \tag{5}$$

In Fig. 1, power amplification is represented with power coefficient $P$. Finally, the OFDM/TDM signal is transmitted over a frequency-selective fading channel.

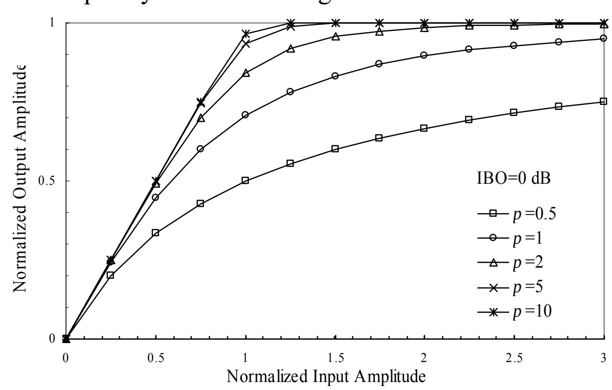


Fig. 2. AM/AM characteristic of HPA.

### 2.3 FDE

The $g$th frame's GI, (i.e., pilot signal) $\{\tilde{r}_g(t)$ ; $t$=-$N_m$~-1$\}$ is stored for CE, while the received signal $\{r_g(t)$; $t$=0~$N_c$-1$\}$ is decomposed into $N_c$ frequency components $\{R_g(n)$; $n$=0~$N_c$-1$\}$ for FDE as

$$R_g(n) = \sqrt{2P} S_g(n) H_g(n) + N_g(n), \tag{6}$$

where $P$, $S_g(n)$, $H(n)$ and $N_g(n)$, respectively, denote the power coefficient, the Fourier transforms of $g$-th frame OFDM/TDM signal, the instantaneous channel gain and the AWGN noise at the $n$th frequency. One-tap FDE is applied to $R_g(n)$ as [14]

$$\hat{R}_g(n) = w(n) R_g(n), \tag{7}$$

where $w(n)$ is the MMSE equalization weight, given as [5]

$$w_g(n) = \frac{H_g^*(n)}{\left|H_g(n)\right|^2 + \left(\frac{P}{\sigma^2}\right)^{-1}}. \tag{8}$$

where $\sigma^2$ and $(\cdot)^*$ denote the noise plus distortion power and the complex conjugate operation, respectively. The time-domain OFDM/TDM signal is recovered by applying $N_c$-point IFFT to $\{\hat{R}_g(n);\ n=0\sim N_c-1\}$, and then, the demodulation of OFDM signal with $N_m$ subcarriers is done using $N_m$-point FFT [1].

### 2.4 Channel Estimation

A pilot signal $\{p(i);\ i=0\sim N_m-1\}$ is inserted into $(K-1)$th slot (i.e., $d^{K-1}(i)=p(i)$ for $i=0\sim N_m-1$) and copied as a cyclic prefix into a GI at the beginning of the frame. Hence, the $(g-1)$th frame's pilot slot acts as a cyclic prefix for the $g$th frame's GI (see Fig. 3). To increase the SNR of pilot signal we apply the first-order filtering on a slot-by-slot basis as shown in Fig. 3 [5]. The $g$th frame's GI is filtered as

$$\overline{R}_g(q) = \gamma\widetilde{R}_g(q) + (1-\gamma)\overline{R}_{g-1}(q) \tag{9}$$

with $q=\lfloor n/K \rfloor$ for $n=0\sim N_c-1$, where $\lfloor x \rfloor$ denotes the largest integer smaller than or equal to $x$. $\widetilde{R}_g(q)$ is FFT of the $\widetilde{r}_g(t)$ with the initial condition $\overline{R}_0(q)=\widetilde{R}_0(q)$ and $\gamma$ is the filter coefficient. The instantaneous channel gain estimate at the $q$th subcarrier is obtained by the reverse modulation and then, the high-resolution frequency-domain interpolation is applied to obtain all estimated channel frequency components $\{H_e(n);\ n=0\sim N_c-1\}$ [5]. The noise plus distortion power estimate $\sigma_e^2$ is obtained by averaging the noise component that is estimated by subtracting the received pilot component $H_e(q)P(q)$ from $\overline{R}_g(q)$ [5], where $P(q)$ is a known pilot. Note that, for FDE, $H_g(n)$ and $\sigma^2$ in Eq. (8) are replaced by $H_e(n)$ and $\sigma_e^2$, respectively.

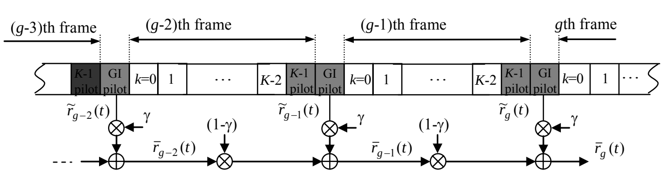

Fig. 3. Time-domain first-order filtering.

## 3. Simulation Results

We assume QPSK data-modulation with $N_c$=256 and $N_m$=16. The propagation channel is an $L$=8-path frequency-selective block Rayleigh fading channel having uniform power delay profile. The path gains stay constant at least over one frame, but varies frame-by-frame. $f_DT_s$ is the normalized Doppler frequency with $1/T_s=1/T_cN_m$ (e.g., $f_DT_s$=0.0001 corresponds to mobile terminal moving speeds of about 11 km/h for 5GHz carrier frequency and transmission data rate of 100M symbols/sec).

The nonlinearity of HPA is determined through IBO. As IBO increases, the BER decrease; but the power efficiency of HPA reduces. Fig. 4 shows the MSE=$E[|H_e(n)-H_g(n)|^2]$ of channel estimator as a function of $p$ with IBO as a parameter. It can be seen from the figure that the MSE of CE with first-order filtering is minimized when $p$>8 (4) for IBO=3, 6 and 9 dB. A larger gap between IBO=0 and 3 dB is observed because, for low IBO value, the nonlinearity of HPA is high and thus, a nonlinear distortion propagates from previous frames. It should be emphasized, however, that when IBO=0 dB, even for high $p$ (>10), the HPA is highly nonlinear and the estimation error will increase even in the case when pilot sequence with constant amplitude in time-domain is used. Consequently, for accurate CE, not only the constant amplitude pilot is required, but also HPA working point must be carefully chosen. In the following, we only consider CE with first-order filtering and frequency-domain interpolation.

Fig. 5 shows the MSE of channel estimator as a function of $\gamma$ with IBO and $f_DT_s$ as a parameter for $p$=10. It can be seen from the figure that HPA nonlinearity (through IBO) only impacts the value of MSE (i.e., MSE increases as IBO reduces and vice versa) and does not impact the value of optimum filter coefficient $\gamma_{opt}$. This is because $\gamma_{opt}$ is only a function of channel time-selectivity (i.e., $f_DT_s$); as the fading becomes faster, larger $\gamma_{opt}$ is required. The optimum $\gamma_{opt}$, for minimizing the MSE, is $\gamma_{opt}$=0.05 for $f_DT_s$=0.0001, $\gamma_{opt}$=0.15 for $f_DT_s$=0.001 and $\gamma_{opt}$=0. 5 for $f_DT_s$=0.01.

The Rapp factor $p$ also determines the HPA nonlinearity as shown in Fig. 2. Fig. 6 shows the MSE of channel estimator as a function of the $E_b/N_0$ with $p$ as a parameter for IBO=3 dB and $f_DT_s$=0.0001. Optimum $\gamma_{opt}$ is used. Although we have used Chu pilot with constant amplitudes in time-domain, it can be seen from the Fig. 6 that the channel estimator's performance is affected by nonlinearity of HPA; as $p$ increases from 1 to 5, the MSE will decreases; but, for $p$>5 the performance is almost the same. This is because, for low $p$, the HPA nonlinearity (see Fig. 2) will cause the pilot degradation and consequently, the performance will degrade, while for larger $p$ the HPA characteristic becomes almost linear.

For a fair comparison, we consider OFDM with time-division multiplexed (TDM)-pilot signal, where Chu pilot signal is followed by $N_p=N_m$ OFDM data signals [3]. Also we assume OFDM with frequency-domain multiplexed (FDM)-pilot, where $N_p$ pilots are transmitted using $N_p=N_m$ subcarriers and thus, CE with frequency-domain interpolation is required [2]. Furthermore, an $N_m$-sample GI is used to keep the same transmission efficiency as our OFDM/TDM. Fig. 7 shows the average BER as a function of IBO for the $E_b/N_0$=15 dB with $p$=2 and 10. It can be seen from the figure that as $p$ reduces from 10 to 2 (i.e., HPA nonlinearity increases), the BER performance will degrade. However, OFDM/TDM provides a better performance with lower IBO for the given BER in comparison with OFDM, which leads to higher amplifier power efficiency.

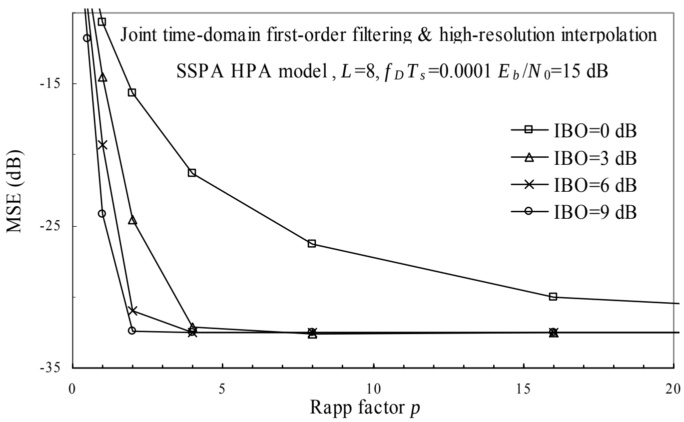


Fig. 4. MSE vs. $p$.

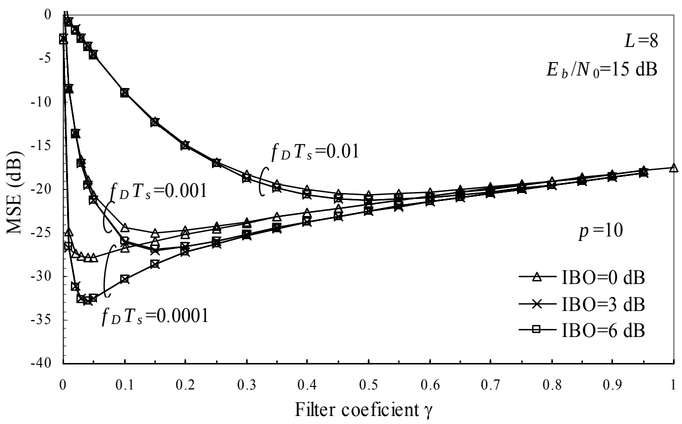


Fig. 5. MSE vs. $\gamma$.

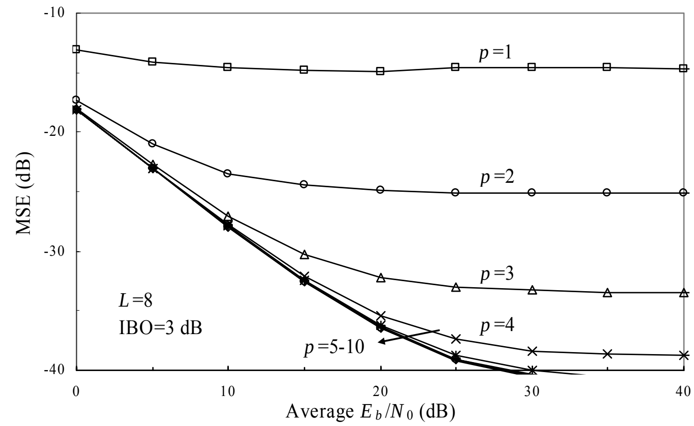


Fig. 6. MSE vs. $E_b/N_0$.

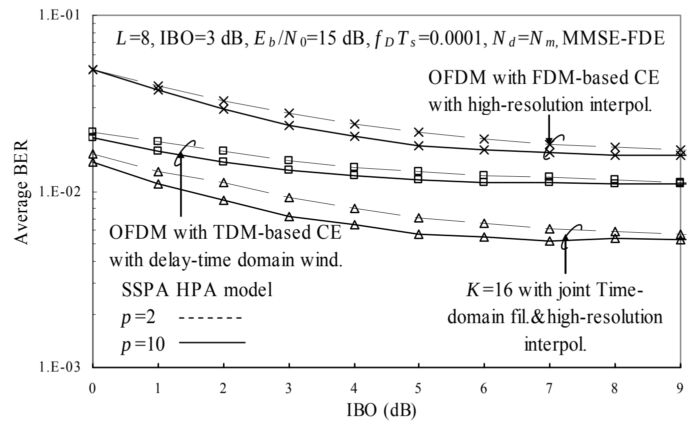


Fig. 7. Average BER vs. IBO; $p$=2 and 10.

## 4. Conclusions

In this paper, the effect of HPA nonlinearity on the pilot-assisted CE for OFDM/TDM in a fast frequency-selective fading channel was studied. It was shown that when IBO=0 dB, even for high Rapp parameter $p$ (>10), the HPA is highly nonlinear and the estimation error will increase even in the case when TDM-pilot sequence with constant amplitude is used. Therefore, for accurate CE, not only the constant amplitude pilot sequence is required, but also HPA working point must be carefully chosen. OFDM/TDM provides a better performance with lower IBO of HPA for the given BER in comparison with OFDM.

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