Effectiveness evaluation of FTN signaling in the presence of nonlinear distortion under multipath fading channels

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Abstract: This study investigates the throughput performance of faster-than-Nyquist (FTN) signaling in the presence of nonlinear distortion under multipath fading channels. In our performance evaluation, we use a practical transmission method, in which single-carrier with frequency-domain equalization (SC-FDE) is applied to FTN signaling for broadband wireless communications. For a radio propagation model, the 3GPP tapped delay line (TDL) model is used to evaluate the effect of multipath fading, and the Rapp model is adopted as a power amplifier (PA) model that provides the impact of nonlinear distortion. We compare the throughput performance of FTN signaling with that of Nyquist signaling under the same transmission rate via computer simulations, which clarifies the applicability of FTN signaling to practical broadband wireless communications.

Keywords: Faster-than-Nyquist (FTN) signaling, nonlinear distortion, multipath fading, peak-to-average power ratio (PAPR), throughput.

Classification: Wireless Communication Technologies

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1 Introduction

The diversification of mobile network services has led to an increase in the number of wireless devices, and hence, the growth of mobile traffic. The number of global mobile connections is expected to increase to 13.1 billion by 2023 [1]. Faster-than-Nyquist (FTN) signaling is a promising technique for improving spectral efficiency [2, 3, 4]. This is because FTN signaling performs non-orthogonal transmission that compresses the symbol period in the time domain while allowing inter-symbol interference (ISI), thereby increasing the transmission rate compared with Nyquist signaling. Thus, FTN signaling is considered suitable for application to systems such as mobile communications systems and broadcasting satellite systems [3].

In FTN signaling, because the induced ISI affects the peak-to-average power ratio (PAPR) of the transmitted signal, the performance evaluation considering the nonlinear distortion caused by the power amplifier (PA) is meaningful and important. In [5], a performance comparison between FTN signaling and traditional Nyquist signaling for DVB-S2 under a constant transmission rate was provided. This study showed that FTN signaling has great potential to improve the system capacity while retaining a low PAPR because of the use of lower modulation levels owing to the compressed symbol period. However, because this study assumed only an additive white Gaussian noise (AWGN) channel, a performance evaluation under multipath fading channels is expected considering its applicability to broadband wireless communications. In particular, because FTN signaling essentially requires equalization at the receiver, its performance is strongly affected by both ISI and multipath fading.

Considering the background described above, we investigate the throughput performance of FTN signaling in the presence of nonlinear distortion under multipath fading channels. Single-carrier with frequency-domain equalization (SC-FDE) is applied to FTN signaling as a practical transmission method for broadband wireless communications [4]. As a radio propagation model, the 3GPP tapped delay line (TDL) model is considered [6], which enables us to consider the applicability of FTN signaling to millimeter-wave (mmWave) bands below 100 GHz. For the PA model, the Rapp model is adopted [7, 8], which makes it possible to ensure the

impact of nonlinear distortion on FTN signaling. The performance comparisons between FTN signaling and Nyquist signaling are demonstrated by means of computer simulations, which clarifies the applicability of FTN signaling to broadband wireless communications under multipath fading channels.

2 System model

In this section, we briefly introduce the operating principles of FTN signaling. Fig. 2 illustrates the system configuration of FTN signaling employing SC-FDE. At the transmitter, the modulated signal with an N_G -length guard interval (GI) $a[n]$ is pulse-shaped by a low-pass filter (LPF) $g(t)$. The pulse-shaped signal $s(t)$ is given by

$$s(t) = \sum_n a[n]g(t - n\tau T), \quad (1)$$

where T denotes the symbol period under the Nyquist criterion, and τ ($0 < \tau \leq 1$) is the compression factor. It should be noted that the transmission rate of FTN signaling can be increased up to $1/\tau$ times that of Nyquist signaling ($\tau = 1$). The pulse-shaped signal is enhanced by a power amplifier (PA) and then transmitted.

At the receiver, the received signal $r(t)$ is passed through the matched filter $g^*(-t)$ and then sampled every time τT . In multipath fading channels, which should be considered, especially in mobile broadband communications, the received signal after the matched filter $y[n]$ is represented by

$$\begin{aligned} y[n] &= \int_{-\infty}^{\infty} r(t)g^*(-(t - n\tau T)) dt \\ &= \sum_{l=0}^{L-1} \sum_{m=-\nu}^{+\nu} a[m]h[l]q[n - (l + m)] + \eta[n], \end{aligned} \quad (2)$$

where $h[l]$ is the channel impulse response, L is its effective length, $(2\nu + 1)$ corresponds to the tap length consisting of the transmitting and receiving filters, and $q[n - m]$ and $\eta[n]$ are defined as

$$q[n - m] = \int_{-\infty}^{\infty} g(t - m\tau T)g^*(-(t - n\tau T)) dt, \quad (3)$$

$$\eta[n] = \int_{-\infty}^{\infty} n(t)g^*(-(t - n\tau T)) dt. \quad (4)$$

Here, $n(t)$ is the white Gaussian noise with power spectral density N_0 . By using Eq. (2), the received signal vector $\mathbf{y}$ for each N_F -length block can be expressed as follows:

$$\mathbf{y} = \mathbf{H}\mathbf{Q}\mathbf{a} + \mathbf{n}, \quad (5)$$

where $\mathbf{a} = [a[0], a[1], \dots, a[N_F - 1]]^T \in \mathbb{C}^{N_F}$ and $\mathbf{n} = [\eta[0], \eta[1], \dots, \eta[N_F - 1]]^T \in \mathbb{C}^{N_F}$ are the modulated signal and colored noise vectors, respectively; $\mathbf{H} \in \mathbb{C}^{N_F \times N_F}$ and $\mathbf{Q} \in \mathbb{C}^{N_F \times N_F}$ are circulant matrices populated with tap coefficients $h[\cdot]$ and $q[\cdot]$, respectively. The time-domain received signal vector $\mathbf{y}$ is transformed into the frequency-domain signal $\mathbf{y}_f$, which is represented by

$$\begin{aligned} \mathbf{y}_f &= \mathbf{F}(\mathbf{H}\mathbf{Q}\mathbf{a} + \mathbf{n}) \\ &= \mathbf{\Lambda}\mathbf{a}_f + \mathbf{n}_f, \end{aligned} \quad (6)$$

Fig. 1. System configuration of FTN signaling employing SC-FDE.

where $\mathbf{F} \in \mathbb{C}^{N_F \times N_F}$ denotes the N_F -point fast Fourier transform (FFT) matrix, and the circulant matrix $\mathbf{H}\mathbf{Q}$ can be diagonalized by $\mathbf{H}\mathbf{Q} = \mathbf{F}^H \mathbf{\Lambda} \mathbf{F}$. $\mathbf{a}_f \in \mathbb{C}^{N_F}$ and $\mathbf{n}_f \in \mathbb{C}^{N_F}$ are the frequency-domain modulated signal and noise vectors, respectively. Here, the (k, l) element of $\mathbf{F}$ is given by

$$[\mathbf{F}]_{k,l} = \frac{1}{\sqrt{N_F}} \exp\left(-j \frac{2\pi kl}{N_F}\right). \quad (7)$$

Assuming the minimum mean square error (MMSE) as the equalization criterion, the FDE weight matrix $\mathbf{W} \in \mathbb{C}^{N_F \times N_F}$ is given by [4]

$$\begin{aligned} \mathbf{W} &= \mathbf{\Lambda}^H \left(\mathbf{\Lambda} \mathbf{\Lambda}^H + \frac{1}{E_s} \mathbb{E}[\mathbf{n}_f \mathbf{n}_f^H] \right)^{-1} \\ &\simeq \mathbf{\Lambda}^H \left(\mathbf{\Lambda} \mathbf{\Lambda}^H + \frac{1}{E_s} \mathbf{\Phi} \right)^{-1}, \end{aligned} \quad (8)$$

where $\mathbf{\Phi} = \text{diag}(\phi[0], \phi[1], \dots, \phi[N_F - 1]) \in \mathbb{C}^{N_F \times N_F}$ is a diagonal matrix whose elements are calculated by

$$\begin{aligned} \phi[k] &= \mathbb{E} \left[\frac{1}{N_F} \left| \sum_{m=0}^{N_F-1} \eta[m] e^{-j \frac{2\pi km}{N_F}} \right|^2 \right] \\ &= \frac{N_0}{N_F} \sum_{n=0}^{N_F-1} \sum_{m=0}^{N_F-1} q[n-m] e^{-j \frac{2\pi(n-m)k}{N_F}}. \end{aligned} \quad (9)$$

Using the diagonal weight matrix $\mathbf{W} \simeq \text{diag}(W[0], W[1], \dots, W[N_F - 1])$ of Eq. (8), the time-domain signal after FDE $\hat{\mathbf{a}} \in \mathbb{C}^{N_F}$ is obtained as follows:

$$\hat{\mathbf{a}} = \mathbf{F}^H \mathbf{W} \mathbf{F} \mathbf{y}. \quad (10)$$

3 Numerical results

In this section, we present a performance comparison between FTN and Nyquist signaling in the presence of nonlinear distortion under multipath fading channels by means of computer simulations. Table I lists the simulation parameters. In our performance evaluation, a 4-bit transmission was assumed. Specifically, the 8PSK

Table I. Simulation parameters

Carrier frequency f_c	70 GHz
Bandwidth B	1.0 GHz
Sampling period T_{sam}	0.375 ns
Modulation	8PSK (FTN, $\tau = 0.75$), 16QAM (Nyquist), 16APSK (Nyquist, Radius ratio = 2.57)
Number of FFT points N_F	2048
GI length N_G	512
Pulse shaping filter	Root-raised cosine (RRC)
Roll-off factor α	0.5
Channel model	3GPP TDL-D [6]
Delay spread τ_{rms}	26 ns
Channel estimation	Perfect

modulation by FTN signaling with $\tau = 0.75$ was compared with the 16APSK and 16QAM modulations by Nyquist signaling. Moreover, a root-raised-cosine (RRC) filter with a roll-off factor of $\alpha = 0.5$ was used as a pulse-shaping filter [9]. At the transmitter, the Rapp model was adopted for a PA, and its input-output relationship was given by [7, 8]

$$A_{out}(t) = \frac{G_0 A_{in}(t)}{\left[1 + \left(\frac{A_{in}(t)}{A_{sat}}\right)^{2\rho}\right]^{\frac{1}{2\rho}}}, \quad (11)$$

where G_0 is the power gain, $A_{in}(t)$ and $A_{out}(t)$ are the input and output signal amplitudes, respectively, and A_{sat} is the saturation input amplitude. Herein, the nonlinear factor ρ and input back-off (IBO) ζ were set to 0.81 and 0.5 dB, respectively [8]. Furthermore, considering that the propagation environment is mainly at line-of-sight (LOS) in mmWave broadband communications, the 3GPP TDL-D model [6] was assumed as the radio propagation model, where the delay spread τ_{rms} was set to 26 ns in the carrier frequency $f_c = 70$ GHz. It was noted that the GI length N_G was longer than the filter and channel delay; therefore, there was no effect of the inter-block interference (IBI).

Fig. 2(a) shows the complementary cumulative distribution function (CCDF) of the PAPR. From Fig. 2(a), it is observed that the PAPR of FTN signaling with 8PSK is significantly smaller than that of Nyquist signaling with 16QAM. This is because by compressing the symbol period, FTN signaling can reduce the modulation level while retaining the transmission rate. Moreover, the FTN signaling with 8PSK achieves almost the same PAPR as Nyquist signaling with 16APSK, characterized by a relatively small number of possible amplitude levels.

Fig. 2(b) shows the throughput performance versus the average carrier-to-noise ratio (CNR) Γ . Here, the throughput is calculated by [4, 10]

$$\text{Throughput} = \frac{N_F}{N_F + N_G} \cdot \frac{\log_2 M}{\tau(1 + \alpha)} \cdot (1 - H(P_e)), \quad (12)$$

where M is the modulation level, $H(\cdot)$ is the binary entropy function, and P_e is the uncoded bit error rate obtained by computer simulations. In the absence of nonlinear distortion ($\zeta = \infty$), as shown in Fig. 2(b)-(i), the throughput of FTN signaling is better than that of Nyquist signaling when $\Gamma < 10$ dB. This is because the reduction of the modulation level in FTN signaling leads to improved robustness

Fig. 2. Performance comparison between FTN signaling and Nyquist signaling.

against noise. In the presence of nonlinear distortion ($\zeta = 0.5$ dB), as shown in Fig. 2(b)-(ii), the CNR region where FTN signaling outperforms Nyquist signaling is enlarged. In particular, the difference between FTN signaling and Nyquist signaling with 16QAM increases. This is because FTN signaling with 8PSK has a lower PAPR, which alleviates the impact of nonlinear distortion.

4 Conclusion

In this study, we investigated the throughput performance of FTN signaling by employing SC-FDE in the presence of nonlinear distortion under multipath fading channels. In our performance evaluation, the effect of frequency-selective fading channels, as well as nonlinear distortion, which should be considered for broadband wireless communications, were incorporated. The numerical results showed that the PAPR of FTN signaling with 8PSK becomes dramatically smaller than that of Nyquist signaling with 16QAM because FTN signaling can reduce the modulation level while retaining the transmission rate. Moreover, the throughput of FTN signaling is better than that of Nyquist signaling, which indicates that the use of a lower modulation level with receiver equalization is robust against multipath fading as well as nonlinear distortion.