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LETTER

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

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Abstract This study investigates the transmission performance of coded faster-than-Nyquist (FTN) signaling based on single-carrier with frequency-domain equalization in the presence of nonlinear distortion and multipath fading. In our performance evaluation, the effects of nonlinear distortion and channel coding were determined using a power amplifier model based on the Rapp model and turbo coding, respectively, which were incorporated into the frame error rate and throughput performance of FTN signaling. Moreover, we compared the performance of coded FTN and coded orthogonal frequency division multiplexing under the same transmission rate using computer simulations to verify the effectiveness of FTN signaling under nonlinear distortion and frequency selective fading.

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

Classification: Wireless communication technologies

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, 5]. This is because FTN signaling performs non-orthogonal transmission, which compresses the symbol period in the time domain while allowing inter-symbol interference (ISI), thereby increasing the transmission rate compared with Nyquist signaling. Therefore, FTN signaling is considered suitable for application in mobile communication systems and broadcasting satellite systems [3, 4, 6].

Because the induced ISI affects the peak-to-average power ratio (PAPR) of the transmitted signal in FTN signaling, performance evaluation considering the nonlinear distortion caused by a power amplifier (PA) is meaningful and important. In [6], a performance comparison between FTN signaling and Nyquist signaling for DVB-S2 at a constant transmission rate was implemented. This study demonstrated 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, FTN signaling requires equalization at the receiver, and hence, its performance is strongly affected by both ISI and multipath fading. Thus far, we have conducted a performance comparison of FTN and Nyquist signaling in the presence of nonlinear distortion under multipath fading channels, which demonstrated the effectiveness of FTN signaling at a constant transmission rate [7].

Nonetheless, it is important to note that in [7], the effect of channel coding was not considered in the performance evaluation. Specifically, in frequency selective fading channels, channel coding introduces a frequency diversity benefit, which makes it important to evaluate the transmission performance. Furthermore, under frequency selective fading, orthogonal frequency division multiplexing (OFDM) is widely employed in various wireless systems and exhibits good performance in channel coding applications [8]. However, OFDM exhibits performance degradation in the presence of nonlinear distortion [9], whereas FTN effectively alleviates this distortion because of its lower PAPR. Therefore, a performance comparison between coded FTN and OFDM, including the effects of nonlinear distortion and frequency selective fading, is highly significant. In [6], a performance evaluation of coded FTN was performed assuming nonlinear distortion, but in the context of AWGN channels, which did not consider the effect of multipath fading and provided no comparison with OFDM.

We investigate the transmission performance of FTN in the presence of nonlinear distortion and frequency selective fading in the context of the above background discussion. The aim of this study is to provide a comparative evaluation with coded OFDM (COFDM), which exploits the full frequency diversity benefits in a wide range of recent wireless systems. In our performance evaluation, the effects of nonlinear distortion and channel coding are determined using a PA model based on the Rapp model [10, 11] and turbo coding [12], respectively, which are incorporated into the frame error rate (FER) and throughput performance of FTN signaling. Performance comparisons between the coded FTN and COFDM under the same transmission rate demonstrate the effectiveness of FTN signaling under nonlinear distortion and frequency selective fading based on computer simulations.

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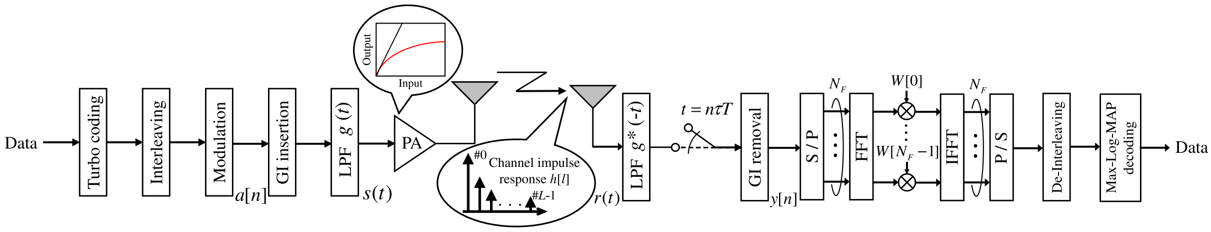


Fig. 1 System configuration of coded FTN signaling employing SC-FDE.

2. System model

In this section, the operating principles of FTN signaling are briefly introduced. Figure 1 shows the system configuration of coded FTN signaling employing single-carrier with frequency-domain equalization (SC-FDE). At the transmitter, the coded bits with turbo encoding are interleaved within one SC symbol with a random interleaver and modulated according to an arbitrary modulation scheme with a sampling period of T_{sam}. The guard interval (GI) to prevent inter-block interference (IBI) is then added to the modulated SC symbols. The modulated signal with an N_G-length GI $a[n]$ is pulse-shaped using a low-pass filter (LPF) $g(t)$. The pulse-shaped signal $s(t)$ is given by

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

where T denotes the symbol period under the Nyquist criterion, and τ $(0 < \tau \le 1)$ 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 amplified using a 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, particularly in mobile broadband communications, the received signal after the matched filter $y[n]$ is represented by

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

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 $\gamma[n-m]$ and $\eta[n]$ are defined as

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

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

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:

$$\mathbf{y} = \mathbf{H\Gamma a} + \mathbf{n}, \tag{5}$$

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

$$\mathbf{y}_f = \mathbf{F}(\mathbf{H\Gamma a} + \mathbf{n}) = \mathbf{\Lambda a}_f + \mathbf{n}_f, \tag{6}$$

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 $\mathbf{H\Gamma}$ can be diagonalized by $\mathbf{H\Gamma} = \mathbf{F}^{\mathrm{H}}\mathbf{\Lambda F}$. $\mathbf{a}_f \in \mathbb{C}^{N_F}$ 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

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

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]

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

where E_s denotes the transmit power, and $\mathbf{\Phi} = \mathrm{diag}(\phi[0], \phi[1], \cdots, \phi[N_F - 1]) \in \mathbb{C}^{N_F \times N_F}$ is a diagonal matrix whose elements are calculated by

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

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

$$\hat{\mathbf{a}} = \mathbf{F}^{\mathrm{H}}\mathbf{W}\mathbf{F}\mathbf{y}. \tag{10}$$

Finally, channel decoding is performed after de-interleaving to correct the communication errors of this time-domain signal.

3. Numerical results

We evaluated the transmission performance of coded FTN and Nyquist signaling in the presence of nonlinear distortion and frequency selective fading. Table I lists the simulation parameters used in this study. In our performance evaluation, SC-FTN signaling with a compression factor τ of 0.75 using 8PSK was compared with SC-Nyquist signaling using

Table I Simulation parameters

Modulation	8PSK (SC-FTN, τ = 0.75), 16QAM (SC-Nyquist and OFDM-Nyquist), 16APSK (SC-Nyquist, Radius ratio = 2.57)
Number of FFT points N_F	256
GI length N_G	64
Pulse shaping filter	Root-raised cosine (RRC)
Roll-off factor α	0.35
Channel coding	Turbo coding / Max-Log-MAP decoding (Iteration = 7)
Coding rate R	3/4
Constrained length K	4 (8-state)
Channel model	16-ray exponentially decaying Rayleigh fading
Delay spread τ_{rms}	4.0 T_{sam}
Channel estimation	Perfect

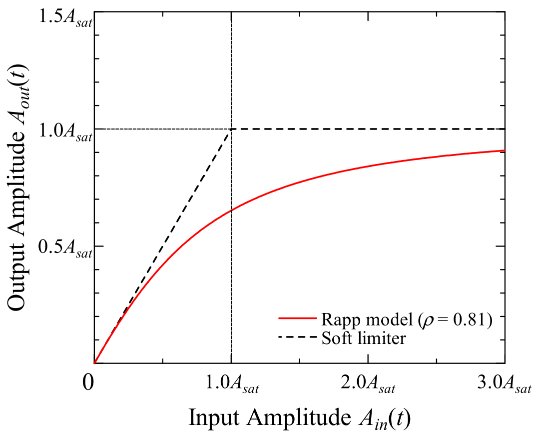
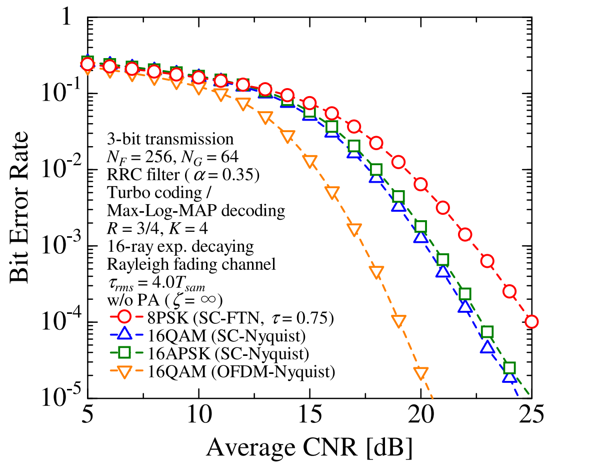
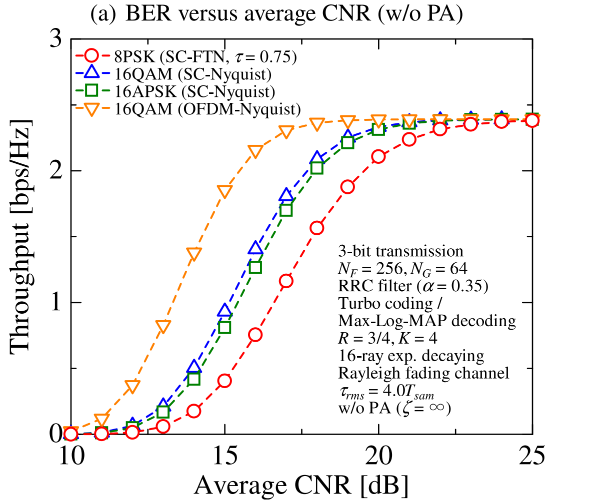


Fig. 2 The input-output relationship of the Rapp model, where the nonlinear factor $\rho = 0.81$.



(a) BER versus average CNR (w/o PA)



(b) Throughput versus average CNR (w/o PA)

Fig. 3 Performance comparison between FTN and Nyquist signaling without nonlinear distortion.

16QAM and 16APSK, as well as with OFDM-Nyquist signaling using 16QAM. Turbo coding and Max-Log-MAP decoding were employed as the channel coding scheme, with a coding rate of $R = 3/4$ and constraint length of $K = 4$. Consequently, a 3-bit identical transmission rate was assumed for the entire systems. A root-raised-cosine (RRC) filter with a roll-off factor of $\alpha = 0.35$ was used as a pulse-shaping filter. Furthermore, we assumed a 16-ray exponentially decaying Rayleigh fading channel as the radio propagation model, where the delay spread τ_{rms} was set to $4.0T_{sam}$. It should be noted that the GI length N_G was longer than the filter and channel delay; therefore, there was no effect of IBI.

The Rapp model was adopted to determine the effects of PA non-linearity. The input–output relationship of a PA employing the Rapp model can be expressed as [10, 11]

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

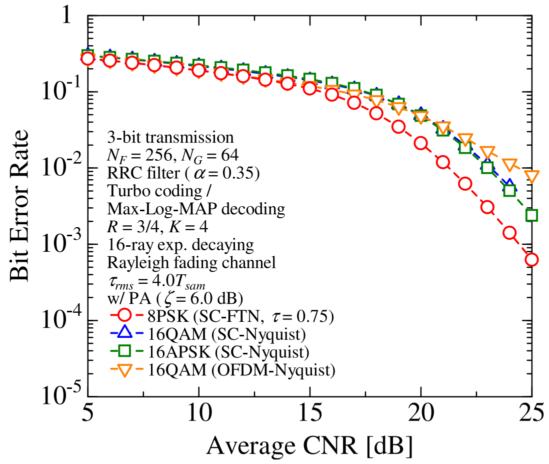
where G_0 is the power gain, and $A_{in}(t)$ and $A_{out}(t)$ are the input and output signal amplitudes, respectively. A_{sat} is the saturation input amplitude determined by the input back-off (IBO) $\zeta = |A_{sat}|^2/E[|s(t)|^2]$. The effect of the Rapp model on the input-output relationship of a PA is depicted in Fig. 2. Here, the nonlinear factor ρ was set to 0.81 [11] and G_0 was set to 1 without loss of generality.

Figure 3 shows the bit error rate (BER) and throughput versus average carrier-to-noise ratio (CNR) without nonlinear distortion. Here, the throughput is calculated as

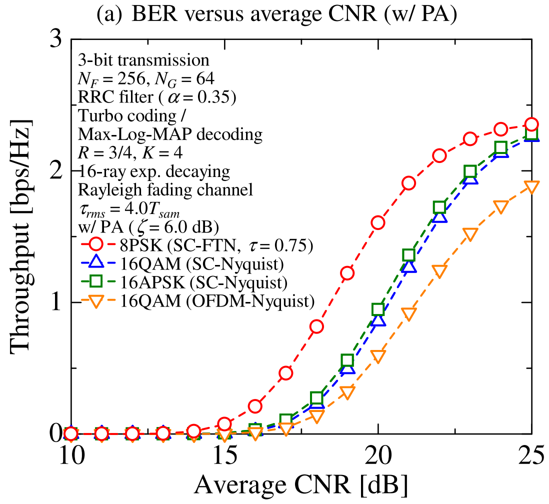
$$\text{Throughput} = R \cdot \frac{N_F}{N_F + N_G} \cdot \frac{\log_2 M}{\tau} \cdot (1 - \text{FER}), \tag{12}$$

where M is the modulation level and FER is the frame error rate. It can be observed from Fig. 3 that in the absence of nonlinear distortion, the throughput of OFDM-Nyquist is better than those of SC-FTN and SC-Nyquist signaling. This is because OFDM can achieve a higher channel coding gain than SC in multipath environments owing to the frequency diversity benefit. Moreover, the throughput of SC-FTN signaling degrades compared with those of SC-Nyquist and OFDM-Nyquist signaling owing to the ISI caused by symbol compression.

Figure 4 shows the BER and throughput versus average CNR in the presence of nonlinear distortion, where ζ = 6.0 dB. The figure also shows that the throughput of SC-FTN signaling is better than those of SC-Nyquist and OFDM-Nyquist signaling in the presence of nonlinear distortion, unlike the plot in Fig. 3. This is because FTN signaling with 8PSK can use a smaller modulation level compared with Nyquist signaling at the same transmission rate, and hence, can reduce the PAPR, thereby mitigating the effect of nonlinear distortion. On the other hand, the throughput of OFDM-Nyquist signaling is significantly degraded owing



(a) BER versus average CNR (w/ PA)



(b) Throughput versus average CNR (w/ PA)

Fig. 4 Performance comparison between FTN and Nyquist signaling with nonlinear distortion.

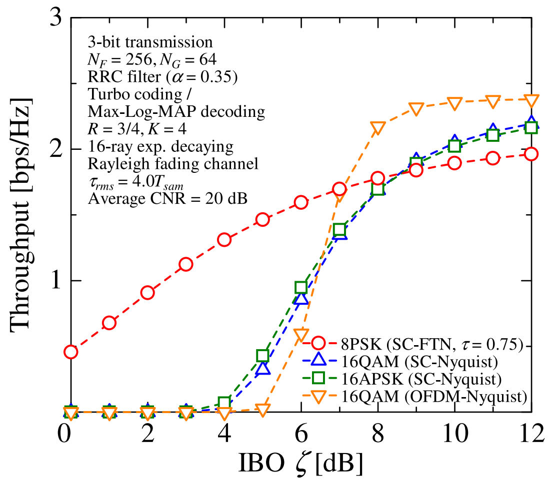


Fig. 5 Throughput versus IBO ζ, where the average CNR = 20 dB.

to the severe effect of nonlinear distortion due to a higher PAPR compared with the case without nonlinear distortion in Fig. 3.

Figure 5 shows the throughput versus IBO, where the average CNR is 20 dB. It can be observed from Fig. 5 that SC-FTN signaling with a lower PAPR outperforms SC-Nyquist and OFDM-Nyquist signaling for $\zeta < 7$ dB. In contrast, the throughput of OFDM-Nyquist signaling, which can yield a higher frequency benefit, exhibits better performance than SC-FTN and SC-Nyquist signaling for $\zeta > 7$ dB.

4. Conclusion

In this study, we investigated the transmission performance of coded FTN signaling using SC-FDE under nonlinear distortion and multipath fading. The aim of this study is to compare FTN signaling and OFDM in coded case at the same transmission rate. In our evaluation, the Rapp model and turbo coding were adopted for PA nonlinearity and channel coding, respectively, and their effects were incorporated into the FER and throughput performances. The numerical results showed that even when the effect of channel coding was considered, the throughput performance of FTN signaling with 8PSK was better than that of OFDM with 16QAM in the lower CNR region. This is because FTN signaling realizes a low PAPR with a lower modulation level while retaining the transmission rate, which improves its performance in the presence of nonlinear distortion. These results lead to the conclusion that FTN signaling is more effective than OFDM in the relatively severe CNR region where a lower modulation level is generally adopted for adaptive bit loading, even in coded cases.

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