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Generalized Frequency-Domain Filtered Single-Carrier Signal Transmission

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Abstract Single-carrier (SC) transmission is a transmission equipped with frequency-domain equalization (FDE) is suitable for uplink transmission because of its low peak-to-average power ratio (PAPR) property. Square-root Nyquist filtering is widely used, where the filter shape is controlled by the roll-off factor α from 0 to 1. Nyquist filtering with α=1 occupies twice bandwidth of the original signal. SC signal can be generated by inserting discrete Fourier transform (DFT) block in orthogonal frequency division multiplexing (OFDM). This realizes an introduction of various frequency-domain signal processing into SC signal transmission. In this paper, we introduce a generalized frequency-domain transmit filtering to SC transmission equipped with FDE (SC-FDE). The transmitted data is initially transformed to the frequency-domain signal and then copied over the available frequency spectrum before applying filtering. Any transfer function can be used and the filtered signal bandwidth can be arbitrary chosen in order to obtain more frequency diversity gain. The transmit filtering with α>1 is equivalent to spread spectrum technique in the time-domain and frequency-domain. Performance of the proposed generalized filtered SC-FDE is evaluated by computer simulation in aspect of PAPR and bit-error rate (BER), and compared to the time-domain spread spectrum scheme. The advantages and disadvantages of the proposed generalized SC-FDE and the time-domain spread spectrum scheme are also discussed.

Keyword Single-carrier (SC) transmission, transmit filtering, spread spectrum (SS)

1. Introduction

Broadband wireless channel is characterized as a frequency-selective fading channel, in which the inter-symbol interference (ISI) degrades the system performance in terms of bit-error rate (BER) significantly [1]. Orthogonal frequency division multiplexing (OFDM) is robust against frequency-selective fading, but its high peak-to-average power ratio (PAPR) property is the main drawback [2]. On the other hand, single-carrier (SC) transmission [3] has lower PAPR than OFDM, while the use of minimum mean-square error based frequency-domain equalization (MMSE-FDE) [4] can mitigate the impact of ISI. Hence, SC with FDE (SC-FDE) is more attractive for uplink transmission than the downlink transmission.

In conventional SC-FDE, square-root Nyquist filtering [5] is typically claimed as a conventional transmit filtering where the filter shape (or the signal bandwidth) and transmission bandwidth is controlled by changing the filter roll-off factor α between 0 and 1. Increasing the signal bandwidth can improve BER performance as a result from additional frequency diversity gain [6]. However, it is observed from [7] and [8] that when α changes, system performance also changes. This implies the tradeoff among PAPR, BER, and spectrum efficiency.

SC signal can be generated by inserting discrete Fourier transform (DFT) in conventional OFDM transmitter [9], which can introduce the frequency-domain signal processing at the transmitter. In time-domain signal processing, transmit and receive filtering are done as a convolution between signal and filter impulse response [10], which is complicated, while the filtering can be simply done as one-tap multiplication [11] in frequency-domain signal processing.

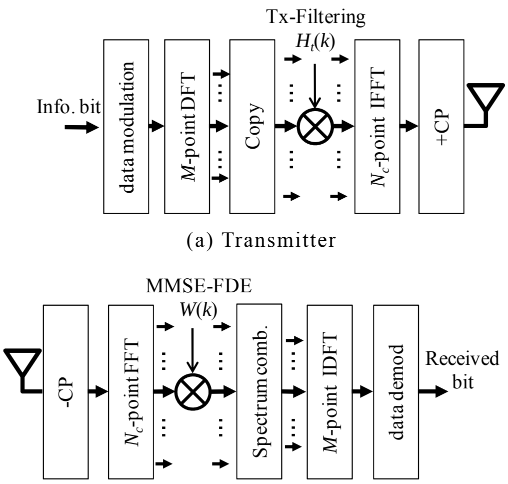
To take advantage of using frequency-domain signal processing, in this paper, we introduce a generalized frequency-domain transmit filtering for SC-FDE. The transmitted data is firstly transformed to the frequency-domain signal and then copied over the available frequency bandwidth before applying filtering. Any filter transfer function can be used and the filtered signal bandwidth can be freely chosen in order to obtain more frequency diversity gain, implying that α can be more than 1. Increasing the signal bandwidth by increasing α to be more than 1 can be considered as the spread spectrum technique (hereinafter, frequency-domain spreading). At the receiver, MMSE-FDE combined with spectrum combining [12] is used for acquiring frequency diversity gain. Even though the concept of spreading the same frequency-domain signal to different subcarriers is similar to multi-carrier code division multiple access (MC-CDMA) [13], the proposed frequency-domain transmit filtering remains the property of SC signal, and consequently, gives lower PAPR. In addition, the proposed filtering technique also does not require spreading code.

Performance of the proposed filtering is evaluated in aspects of PAPR and BER, and also compared with the time-domain spread spectrum technique [14], [15], at the same transmission bandwidth. We provide the mathematical analysis of BER for both conventional and proposed schemes, and the theoretical analysis is confirmed by computer simulation.

The rest of this paper is organized as follows. The proposed transmission system models using frequency-domain spreading is introduced in Sect. 2. Analysis on signal-to-interference plus noise power ratio (SINR) for each transmission scheme is shown in Sect. 3. Sect. 4 shows the simulation results, and Sect. 5 concludes the paper.

2. Transmission System Model

In this paper, we assume single-user block transmission of M symbols over available N_c subcarriers, implying that the spreading factor is N_c/M for both time-domain and frequency-domain approaches. In frequency-domain approach, DFT and its inverse operation are applied. MMSE-FDE equipped with spectrum combining [12] is also used in the receiver. We also mention that the time-domain spreading considered in this paper is the same as [14]. The transmitter and receiver of SC transmission with frequency-domain spreading are illustrated as shown in Fig. 1.



(a) Transmitter

(b) Receiver

Fig.1 SC transmission system model with frequency-domain spreading.

2.1. Transmitter

First, we have a block of M modulated symbol $\mathbf{d}=[d(0), d(1),\ldots,d(M-1)]^T$. The block $\mathbf{d}$ is transformed into frequency domain by M-point DFT. The frequency-domain original transmit signal vector $\mathbf{D}=[D(0),D(1),\ldots,D(M-1)]^T$ is $\mathbf{D}=\mathbf{F}_M\mathbf{d}$, where $\mathbf{F}_M$ is M-point DFT matrix given by

$$\mathbf{F}_M=\begin{bmatrix}1 & 1 & \cdots & 1\\ 1 & e^{\frac{-j2\pi(1)(1)}{M}} & \cdots & e^{\frac{-j2\pi(1)(M-1)}{M}}\\ \vdots & \vdots & \ddots & \vdots\\ 1 & e^{\frac{-j2\pi(M-1)(1)}{M}} & \cdots & e^{\frac{-j2\pi(M-1)(M-1)}{M}}\end{bmatrix}. \quad (1)$$

Next, the frequency-domain vector $\mathbf{D}$ is copied over the entire of N_c available subcarriers. We introduce a spreading matrix $\mathbf{P}$ with the dimension of $N_c \times M$. Spreading matrix is expressed by

$$\mathbf{P}=\begin{bmatrix}\mathbf{I}_M\\ \mathbf{I}_M\\ \vdots\\ \mathbf{I}_M\end{bmatrix}, \quad (2)$$

where $\mathbf{I}_M$ represents the $M \times M$ identity matrix. In other word, $\mathbf{P}$ consists of a repetition of $\mathbf{I}_M$ with (N_c/M)-times, indicating that the spreading factor is $SF = N_c/M$. We can also express the spreading factor in terms of roll-off factor for the general filtering approach as $SF = 1+\alpha$.

In this paper, a matrix $\mathbf{H}_T$ is introduced for transmit filtering operation, which is an $N_c \times N_c$ diagonal matrix where the filter coefficients are in the diagonal. For fair comparison with time-domain approach, we consider equal transmit power allocation by using the ideal rectangular filter whose magnitude is $1/\sqrt{SF}$, and hence, $\mathbf{H}_T = diag\{H_T(0),H_T(1),\ldots,H_T(N_c-1)\}$ is simply expressed by

$$\mathbf{H}_T=\begin{bmatrix}\frac{1}{\sqrt{SF}} & & \mathbf{0}\\ & \ddots & \\ \mathbf{0} & & \frac{1}{\sqrt{SF}}\end{bmatrix}. \quad (3)$$

After that, N_c-point inverse fast Fourier transform (IFFT) is applied for transforming the filtered signal back to time domain. Time-domain transmit signal vector $\mathbf{s}=[s(0),s(1),\ldots,s(N_c-1)]^T$ after passing through all processes in (1), (2), and (3) can be described as

$$\mathbf{s}=\mathbf{F}_{N_c}^H\mathbf{H}_T\mathbf{P}\mathbf{D}=\mathbf{F}_{N_c}^H\mathbf{H}_T\mathbf{P}\mathbf{F}_M\mathbf{d}. \quad (4)$$

In addition, transmission process can also be depicted by Fig. 2. Finally, the last N_g samples of transmit block are copied as a cyclic prefix (CP) and inserted into the guard interval (GI) placed at the beginning of each transmit block and a CP-inserted signal block of N_c+N_g samples is transmitted.

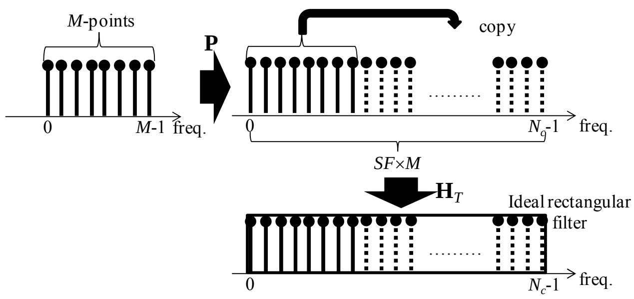


Fig.2 Frequency-domain spreading.

2.2. Receiver

The transmission is conducted under independent L-path block Rayleigh fading channel [1]. In more details, the channel impulse response is

$$h(\tau)=\sum_{l=0}^{L-1}h_l\delta(\tau-\tau_l)\ , \tag{5}$$

where h_l and τ_l are complex-valued path gain and time delay of l-th path, respectively. The received signal vector after CP removal, $\mathbf{r}=[r(0),r(1),...,r(N_c-1)]^T$ can also be expressed as

$$\mathbf{r}=\sqrt{\frac{2E_s}{T_s}}\mathbf{hs}+\mathbf{n}\ , \tag{6}$$

where E_s and T_s represent symbol energy and symbol duration, respectively. Transmit signal vector **s** is obtained from (4). **n** represents noise vector in which each element is the zero-mean additive white Gaussian noise (AWGN) having the variance $2N_0/T_s$ with N_0 being the one-sided noise power spectrum density. In addition, channel response matrix **h** is a circular matrix representing time-domain channel impulse response, which is expressed by

$$\mathbf{h}=\begin{bmatrix} h_0 & & & h_{L-1} & \cdots & h_1 \\ h_1 & \ddots & & & \ddots & \vdots \\ \vdots & & h_0 & \mathbf{0} & & h_{L-1} \\ h_{L-1} & & h_1 & \ddots & & \\ & \ddots & \vdots & & \ddots & \\ \mathbf{0} & & h_{L-1} & \cdots & \cdots & h_0 \end{bmatrix}. \tag{7}$$

The received signal **r** is transformed into frequency domain by using N_c-point FFT, obtaining frequency-domain received signal **R** as

$$\begin{aligned}\mathbf{R} &= \sqrt{\frac{2E_s}{T_s}}\mathbf{F}_{N_c}\mathbf{hs}+\mathbf{F}_{N_c}\mathbf{n} \\ &= \sqrt{\frac{2E_s}{T_s}}\mathbf{F}_{N_c}\mathbf{hF}_{N_c}^H\mathbf{H}_T\mathbf{PD}+\mathbf{F}_{N_c}\mathbf{n} \\ &= \sqrt{\frac{2E_s}{T_s}}\mathbf{H}_c\mathbf{H}_T\mathbf{PD}+\mathbf{N}\end{aligned} \tag{8}$$

Here, we define $\mathbf{H}_c=\mathbf{F}_{N_c}\mathbf{hF}_{N_c}^H$ as a diagonal matrix determining frequency-domain channel response.

MMSE-FDE is applied at the receiver for reducing the effect from frequency-selective fading channel. Spectrum combining [12] is also included in order to recover the original M-point frequency spectrum. Both MMSE-FDE and spectrum combining are introduced by FDE matrix **W** with the dimension of $M\times N_c$, which is

$$\mathbf{W}=\begin{bmatrix}\mathbf{W}_0 & \mathbf{W}_1 & \cdots & \mathbf{W}_{SF-1}\end{bmatrix}, \tag{9}$$

where $\mathbf{W}_n$ is an $M\times M$ matrix expressed by

$$\mathbf{W}_n=diag\begin{bmatrix} W\left(\frac{(nSF)N_c}{SF}\right), W\left(\frac{(nSF)N_c}{SF}+1\right),..., \\ W\left(\frac{((n+1)SF)N_c}{SF}+1\right)\end{bmatrix}. \tag{10}$$

By using MMSE criterion, the MMSE-FDE weight with respect to each frequency index $W(k)$, k=0~N_c−1 is calculated in the same pattern as [9] and [10], which is

$$W(k)=\frac{H_c^*(k)H_T^*(k)}{\sum_{g=0}^{SF-1}\left|H_c(k\bmod M+gM)H_T(k\bmod M+gM)\right|^2+\left(\frac{E_s}{N_0}\right)^{-1}}, \tag{11}$$

where $H_c(k)$ and $H_T(k)$ are the elements in $\mathbf{H}_c$ and $\mathbf{H}_T$ with respect to each frequency index, respectively. The frequency-domain received signal after equalization and spectrum combining $\hat{\mathbf{D}}=\mathbf{WR}$ is finally transformed back into time domain by M-point inverse DFT (IDFT). Therefore, the time-domain received signal vector $\hat{\mathbf{d}}=[\hat{d}(0),\hat{d}(1),...,\hat{d}(M-1)]^T$ is given by

$$\hat{\mathbf{d}}=\mathbf{F}_M^H\hat{\mathbf{D}}=\mathbf{F}_M^H\mathbf{WR}. \tag{12}$$

Spectrum combining can be illustrated as shown in Fig. 3. It can be observed that frequency diversity gain is obtained regarding to copying at the transmitter, i.e., the same frequency spectrum are sent in different frequency index.

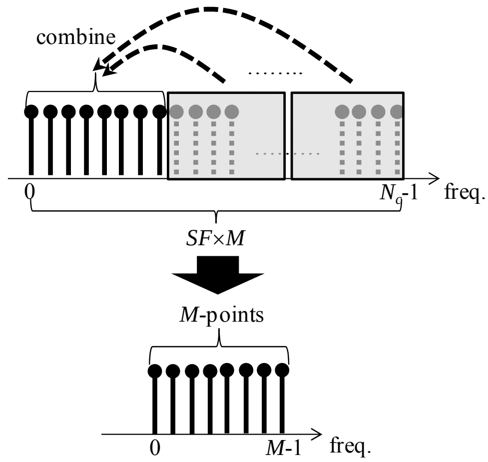


Fig.3 Spectrum combining.

3. SINR Analysis

In conventional time-domain spread spectrum technique [14], diversity gain can be obtained. Similarly, the proposed frequency-domain spreading, as described in the previous section, also provides frequency diversity gain. In this section, mathematical analysis on the SINR of the received signal is derived for both transmission schemes.

3.1 Frequency-Domain Spreading

The SINR for the proposed frequency-domain spreading is derived by firstly beginning from the received symbol $\hat{d}(m)$, which is

$$\begin{aligned}\hat{d}(m) &= \sqrt{\frac{2E_s}{T_s}}\left(\frac{1}{M}\sum_{q=0}^{M-1}\widetilde{H}(q)\right)d(m) \\ &+\sqrt{\frac{2E_s}{T_s}}\left(\frac{1}{M}\sum_{q=0}^{M-1}\widetilde{H}(q)\sum_{\substack{\tau=0\\ \tau\neq t}}^{M-1}d(\tau)\exp(j2\pi q\frac{t-\tau}{M})\right) \\ &+\frac{1}{M}\sum_{q=0}^{M-1}\widetilde{N}(q)\exp(j2\pi q\frac{t}{M})\end{aligned}, \tag{13}$$

where $\widetilde{H}(q)$ and $\widetilde{N}(q)$ are expressed as follows.

$$\begin{cases}\widetilde{H}(q)=\sum_{g=0}^{SF-1}H_c(q+gM)W(q+gM)H_T(q+gM)\\ \widetilde{N}(q)=\sum_{g=0}^{SF-1}W(q+gM)N(q+gM)\end{cases}, \tag{14}$$

From (14), it can be observed that $\widetilde{H}(q)$ is channel response after equalization and combining. The second term and the third term in (13) represent the residual ISI and noise, respectively. By treating the residual ISI and noise as Gaussian distribution, the variance of interference plus noise can be written as

$$2\sigma_u^2=\frac{2N_0}{T_c}\left(\begin{array}{l}\frac{1}{M}\sum_{q=0}^{M-1}\sum_{g=0}^{SF-1}\left|W(q+gM)\right|^2\\ +\frac{E_s}{N_0}\left(\frac{1}{M}\sum_{q=0}^{M-1}\left|\widetilde{H}(q)\right|^2-\left|\frac{1}{M}\sum_{q=0}^{M-1}\widetilde{H}(q)\right|^2\right)\end{array}\right). \tag{15}$$

From (13) and (15), the SINR of SC transmission using frequency-domain spreading in the case that E_s/N_0 and $\mathbf{H}_c$ are given is expressed by

$$\gamma\left(\frac{E_s}{N_0},\mathbf{H}_c\right)=\frac{\frac{2E_s}{T_s}\left|\frac{1}{M}\sum_{q=0}^{M-1}\widetilde{H}(q)\right|^2}{\sigma_u^2}$$
$$=\frac{\frac{2E_s}{N_0}\left|\frac{1}{M}\sum_{q=0}^{M-1}\widetilde{H}(q)\right|^2}{\left(\begin{array}{l}\frac{1}{M}\sum_{q=0}^{M-1}\sum_{g=0}^{SF-1}\left|W(q+gM)\right|^2\\ +\frac{E_s}{N_0}\left(\frac{1}{M}\sum_{q=0}^{M-1}\left|\widetilde{H}(q)\right|^2-\left|\frac{1}{M}\sum_{q=0}^{M-1}\widetilde{H}(q)\right|^2\right)\end{array}\right)}. \tag{16}$$

We also introduce the theoretical error probability [14] which is calculated from conditional BER. Assuming that E_s/N_0 and $\mathbf{H}_c$ are given, conditional BER when QPSK modulation is expressed as

$$p_b\left(\frac{E_s}{N_0},\mathbf{H}_c\right)=\frac{1}{2}erfc\left(\sqrt{\frac{1}{4}\gamma\left(\frac{E_s}{N_0},\{H(k)\}\right)}\right). \tag{17}$$

Here, $erfc(\cdot)$ is complementary error function. The theoretical BER performance is shown in Sect. 4 together with simulation results.

3.2 Time-Domain Spreading

Time-domain spreading approach considered in this paper is the spread spectrum (SS) technique using spreading code, described in [14]. In this transmission scheme, the SINR in the case that E_s/N_0 and $\mathbf{H}_c$ are given is expressed by [15]

$$\gamma\left(\frac{E_s}{N_0},\mathbf{H}_c\right)=\frac{\frac{2E_s}{N_0}\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{H}(k)\right|^2}{\left(\begin{array}{l}\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|W_{MMSE}(k)\right|^2\\ +\frac{1}{SF}\frac{E_s}{N_0}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|\hat{H}(k)\right|^2-\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1}\hat{H}(k)\right|^2\right)\end{array}\right)}. \tag{18}$$

where $\hat{H}(k)=H(k)W_{MMSE}(k)$ and $\hat{N}(k)=N(k)W_{MMSE}(k)$. $H(k)$ and $N(k)$ represent frequency-domain channel response and noise with respect to each frequency index k, respectively. In time-domain spreading, we use the conventional MMSE-FDE weight given by

$$W_{MMSE}(k)=\frac{H^*(k)}{\left|H(k)\right|^2+\left(\frac{E_s}{SFN_0}\right)^{-1}}. \tag{19}$$

We can clearly see that SINR of time-domain approach in (19) and frequency-domain approach in (16) are different. However, to clarify the difference between them, theoretical BER performance is shown in the next section.

4. Simulation Results

Simulation parameters are summarized in Table 1. We assume QPSK block transmission. The number of available subcarrier N_c=256. System performance is evaluated in aspects of BER and PAPR performances, while the BER performance is also compared with the theoretical BER derived from Sect. 3. In this paper, we select the DSSS technique [14], [15] as a representative of time-domain conventional spreading scheme.

Table 1 Simulation parameters

Transmitter	Data modulation	QPSK
	FFT/IFFT block size	N_c = 256
	Cyclic-prefix length	N_g = 32
Time-domain Spreading	Spreading sequence	PN sequence
	Spreading factor	SF = 2, 4, 8
Frequency-domain Spreading	Transmit filtering	Ideal rectangular with magnitude $1/\sqrt{SF}$
	Spreading factor	SF = (1+α) = 2, 4, 8
Channel	Fading	Frequency-selective block Rayleigh fading
	Power delay profile	16-path uniform power delay profile
Receiver	FDE	MMSE, MMSE w/ spectrum combining
	Channel estimation	Ideal

4.1 BER Performance

BER performances of SC transmission using time-domain spreading and frequency-domain spreading are shown in Fig. 4 as a function of average received bit energy-to-noise power spectrum density ratio $E_b/N_0 = 0.5(E_s/N_0)(1+N_g/N_c)$. It is obviously seen that the proposed frequency-domain-based spreading outperforms the conventional time-domain spreading in every spreading factor. Also, simulation results are similar to the theoretical results calculated by using (16), (17), and (18), implying that using frequency-domain spreading together with MMSE-FDE and spectrum combining provides more diversity gain compared to conventional spread spectrum technique. This is because the MMSE-FDE with spectrum combining is calculated so as to minimize the mean-square error (MSE) between the transmit signal before spreading and received signal after combining, while the MMSE-FDE weight in time-domain approach is calculated so as to minimize the MSE of the transmit signal after spreading and received signal before despreading. Even though it is possible to determine the MMSE-FDE weight so as to minimize the MSE of the transmit signal before spreading and received signal after despreading in time-domain approach [16], the MMSE-FDE is not one-tap multiplication (i.e., matrix inversion is required), and hence, leads to high computational complexity. On the other hand, frequency-domain spreading can realize joint equalization and combining with simple one-tap multiplication.

In addition, it can be observed that BER improvement is not much increased when the *SF* is increased from 4 to 8, especially in the frequency-domain approach. This is because of the noise enhancement due to unnecessary bandwidth expansion. It also occurs in the conventional spread spectrum technique at high *SF*.

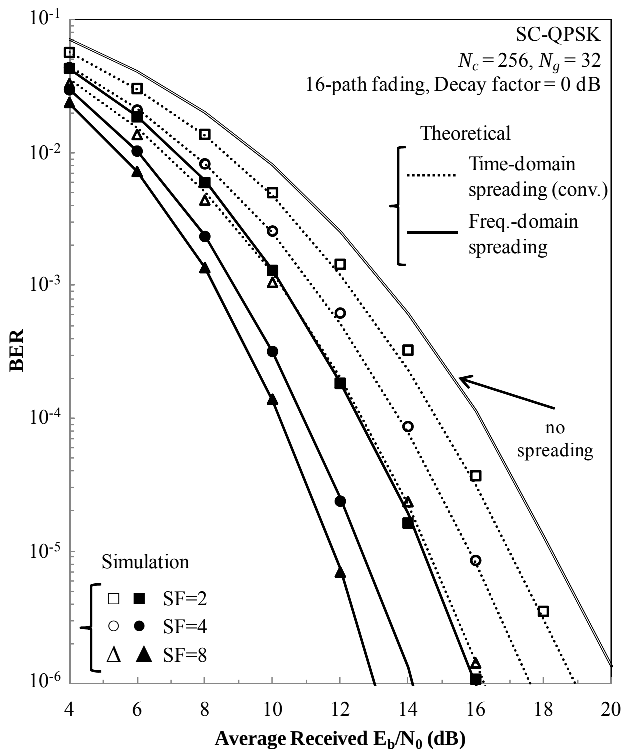


Fig.4 BER performance of SC with various spreading techniques.

4.2 PAPR Performance

PAPR over a block of transmission is defined as

$$PAPR = \frac{\max\{|s(n)|^2\}}{E[|s(n)|^2]}, n = 0,...,N_c - 1. \quad (20)$$

We use the complementary cumulative distribution function (CCDF) as the indicator of PAPR performance. Fig. 5 shows the CCDF of PAPR of both time-domain spreading and frequency-domain spreading, compared to conventional transmission without spreading. It is seen that PAPR performance changes when spreading factor changes in both schemes.

From Fig. 5, we can see that PAPR slightly increases when the spreading factor increases in time-domain approach. However, it is noticed that PAPR is significantly reduced (approximately 1dB) when the spreading factor *SF*=2 in frequency-domain approach, compared to transmission without spreading. Then, PAPR turns to increase again when *SF* increases from 4.

To illustrate the reason of PAPR reduction and increasing in frequency-domain spreading, we observe the time-domain transmit signal $s(n)$, n=0,1,…,N_c-1 for each spreading factor. Fig. 6 is an example of time-domain transmit signal by assuming BPSK modulation. It can be observe that a symbol is transmitted every *SF* period, leads to increasing of distance between each pulse, and also is possible to reduce PAPR. However, if the distance is too high (i.e., *SF* is high), the PAPR turns to increase instead.

We can observe that transmission using frequency-domain spreading with spreading factor is nearly 2 is very attractive since it provides such significant BER improvement with low PAPR compared to the transmission without spreading.

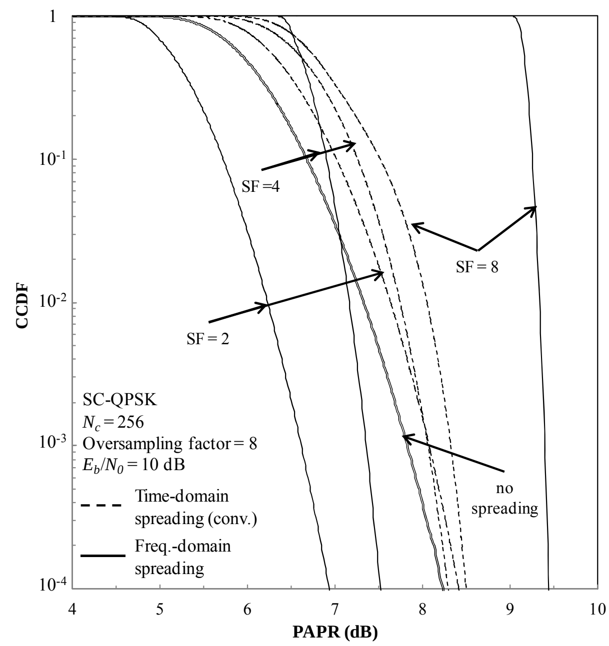


Fig.5 CCDF of PAPR.

5. Conclusion

In this paper, we proposed a generalized frequency-domain transmit filtering for SC-FDE. Transmit data is firstly transformed to frequency domain and then copied over the available frequency bandwidth before applying the transmit filter, which is equivalent to spreading when α is more than 1. Both mathematical analysis on receive SINR and simulation results confirmed that significant BER improvement is achieved compared to both conventional spread spectrum technique and transmission without spreading. The proposed scheme also gave lower PAPR a when the spreading factor SF=2.

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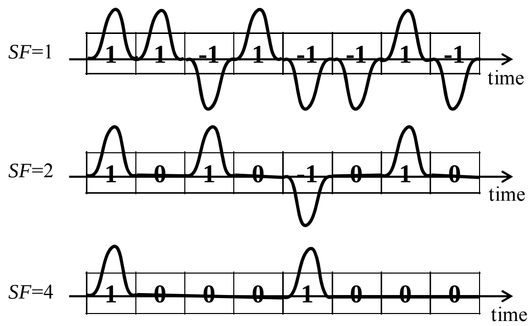

Fig.6 An example of time-domain transmitted signal $s(n)$ of transmission using frequency-domain spreading with BPSK modulation.