

# Single-carrier Frequency-Domain CDMA

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**Abstract** Single-carrier (SC) transmission is an appropriate transmission scheme for uplink transmission because of its low peak-to-average power ratio (PAPR). Spread spectrum (SS) transmission achieves higher frequency diversity gain and hence improves the bit error rate (BER) performance. The authors have recently proposed SC with frequency-domain spread spectrum (SC-FDSS) transmission with orthogonal code multiplexing, where spreading and de-spreading are conducted in frequency domain. In this paper, we extend the single-user SC-FDSS to multi-user SC-FDSS called SC with frequency-domain code division multi-access (SC-FD-CDMA). BER and PAPR performances are evaluated and compared to direct-sequence code division multi-access CDMA (DS-CDMA) and SC with frequency division multi-access (SC-FDMA)

**Keyword** Single-carrier (SC) transmission, spread spectrum, code division multi-access (CDMA), uplink transmission

## 1. Introduction

Broadband wireless channel is characterized as a frequency-selective fading channel, in which inter-symbol interference (ISI) degrades system performance in terms of bit-error rate (BER) [1]. Multicarrier transmission, such as orthogonal frequency division multiplexing (OFDM), is robust against frequency-selective fading but its high peak-to-average power ratio (PAPR) of transmit signal is the main drawback [2]. On the other hand, single-carrier (SC) transmission [3] is more attractive for uplink communication in LTE-Advanced (LTE-A) system because of lower PAPR compared to OFDM, while the use of frequency-domain equalization (FDE) can effectively suppress the impact of ISI [4].

SC transmission can be combined with multi-access technique in order to utilize the limited bandwidth in multi-user environment. There exist many multi-access techniques [5-7] providing users' orthogonality in different domain e.g. time-division multiple access (TDMA), frequency-division multiple access (FDMA), and code-division multiple access (CDMA). Among the various combinations of SC transmission and multi-access, SC with FDMA (called SC-FDMA) [8] and direct-sequence CDMA (DS-CDMA) [7] are very attractive for uplink transmission.

In SC-FDMA, users are separated in frequency-domain, and hence there is no multi-user interference (MUI) [9]. However, since the number of available subcarriers is limited, a complicated resource allocation algorithm [10] is mandatory in order to utilize the subcarriers efficiently. On the other hand, DS-CDMA, which is adopted for the third-generation (3G) system [11], allows a user to share the same bandwidth (in the case of DS-CDMA with FDE [7], all users can share all available subcarriers). This implies that the resource allocation is not needed. Frequency diversity gain is also achievable by time-domain spreading; however, strong MUI occurs since

the orthogonality among different spreading codes is severely distorted [9], and consequently degrades the BER performance.

Recently, we have proposed SC with frequency-domain spread spectrum (SC-FDSS) with orthogonal code multiplexing [12, 13], where spreading and de-spreading are conducted in frequency domain with the aid of discrete Fourier transform (DFT) [14]. Performance of SC-FDSS with orthogonal code multiplexing has been evaluated in [12, 13] to find that better BER performance is achieved compared to SC with time-domain spread spectrum (SC-TDSS). The theoretical results in [13] also showed that the inter-chip interference (ICI) in SC-FDSS is lower than SC-TDSS, implying that SC-FDSS is preferable to be used in strong-ICI environment. Note that the performance evaluation in [12, 13] were done only in single-user environment.

In this paper, we extend the single-user SC-FDSS to multi-user SC-FDSS, called SC with frequency-domain CDMA (SC-FD-CDMA). A single-cell multi-user uplink transmission is considered. Performance evaluation of SC-FD-CDMA is done by computer simulation and compared to conventional DS-CDMA [7] and SC-FDMA [8] in terms of BER performance and PAPR performance assuming the same number of users and that of subcarriers. It will be shown that the uplink BER performance of SC-FD-CDMA is better than DS-CDMA. Since any modifications on transmitter leads to changes in PAPR, the PAPR performance will also be discussed.

The rest of this paper is organized as follows. System model, transceiver model, and their signal representations are described in Section 2. Section 3 shows the performance evaluation of BER and PAPR, and Section 4 concludes the paper.



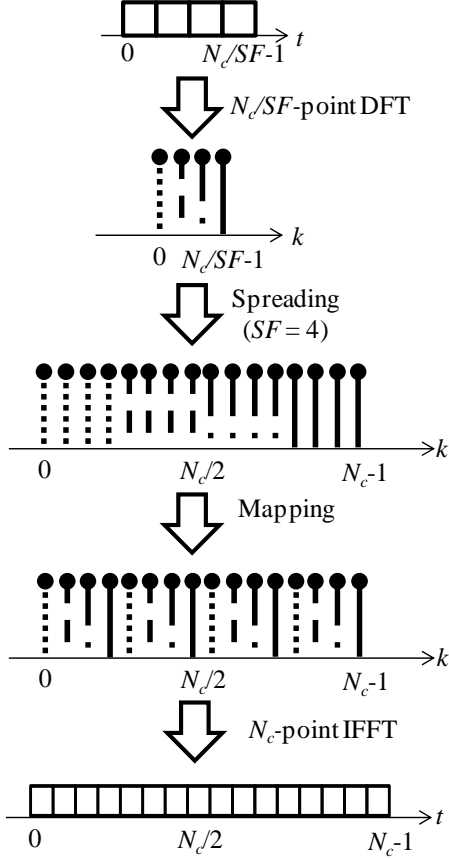


Fig.2 Transmission process.

where  $\mathbf{s}_u$  is obtained from (5), and  $\mathbf{n}_u$  is noise vector in which element is zero-mean additive white Gaussian noise (AWGN) having the variance  $2N_0/T_c$  with  $T_c$  is chip duration and  $N_0$  being the one-sided noise power spectrum density. Channel response matrix  $\mathbf{h}_u$  is a circular matrix representing time-domain channel response between user  $u$  and the base station, which is

$$\mathbf{h}_u = \begin{bmatrix} h_{u,0} & & & h_{u,L-1} & \cdots & h_{u,1} \\ h_{u,1} & \ddots & & & \ddots & \vdots \\ \vdots & & h_{u,0} & \mathbf{0} & & h_{u,L-1} \\ h_{u,L-1} & & h_{u,1} & \ddots & & \\ \mathbf{0} & h_{u,L-1} & \cdots & \cdots & h_{u,0} & \end{bmatrix}. \quad (8)$$

The received signal vector  $\mathbf{r}$  is transformed into frequency domain by  $N_c$ -point FFT, obtaining the frequency-domain received signal  $\mathbf{R}$  as

$$\begin{aligned} \mathbf{R} &= \sum_{u=0}^{U-1} \sqrt{2P_u} \mathbf{F}_{N_c} \mathbf{h}_u \mathbf{s}_u + \mathbf{F}_{N_c} \mathbf{n}_u \\ &= \sum_{u=0}^{U-1} \sqrt{2P_u} \mathbf{F}_{N_c} \mathbf{h}_u \mathbf{F}_{N_c}^H \tilde{\mathbf{S}}_u + \mathbf{F}_{N_c} \mathbf{n}_u, \\ &= \sum_{u=0}^{U-1} \sqrt{2P_u} \mathbf{H}_u \tilde{\mathbf{S}}_u + \mathbf{N}_u \end{aligned} \quad (9)$$

where the frequency-domain channel response  $\mathbf{H}_u$  is

$$\mathbf{F}_{N_c} \mathbf{h}_u \mathbf{F}_{N_c}^H = \text{diag}[H_u(0), \dots, H_u(N_c-1)] \equiv \mathbf{H}_u. \quad (10)$$

FDE based on minimum mean-square error criterion (MMSE-FDE) is introduced for mitigating the ISI occurred by frequency-selective fading channel. The frequency-domain received signal after applying MMSE-FDE of the  $u$ -th user is

$$\hat{\mathbf{R}}_u = \mathbf{W}_u \mathbf{R}, \quad (11)$$

where  $\mathbf{W}_u = \text{diag}\{W_u(0), \dots, W_u(N_c-1)\}$  is a  $N_c \times N_c$  diagonal matrix. In this paper, a conventional MMSE-FDE, which minimize the mean-square error (MSE) between  $\tilde{\mathbf{S}}_u$  and  $\hat{\mathbf{R}}_u$ , is considered for a fair comparison with DS-CDMA and SC-FDMA.  $W_u(k)$  is described in [15] as

$$W_u(k) = \frac{\frac{P_u T_c}{N_0} H_u^*(k)}{\sum_{u=0}^{U-1} \frac{P_u T_c}{N_0} |H_u(k)|^2 + 1}. \quad (12)$$

After that, de-mapping is applied to the received signal after applying MMSE-FDE  $\hat{\mathbf{R}}_u$ , obtaining the frequency-domain signal  $\tilde{\mathbf{R}} = [\tilde{R}(0), \tilde{R}(1), \dots, \tilde{R}(N_c-1)]^T$ . De-mapping can be expressed by

$$\tilde{R}_u(p + (q \times M)) = \hat{R}_u((p \times SF) + q), \quad (13)$$

where  $p=0 \sim M-1$  and  $q=0 \sim SF-1$ . It can be seen that de-mapping in (13) is a simple inverse operation of (4).

De-spreading is also applied in frequency-domain approach by simply multiplying  $\tilde{\mathbf{R}}_u$  by an inverse operation of (3), resulting in frequency-domain vector  $\tilde{\mathbf{D}}_u = [\tilde{D}_u(0), \tilde{D}_u(1), \dots, \tilde{D}_u(M-1)]^T$  as

$$\tilde{\mathbf{D}}_u = \mathbf{C}_u^H \tilde{\mathbf{R}}_u. \quad (14)$$

Note that  $\mathbf{C}_u^H$  has dimension of  $M \times N_c$ . Finally,  $\tilde{\mathbf{D}}_u$  is transformed back into time domain by  $M$ -point inverse DFT (IDFT) matrix, obtaining time-domain received vector of the  $u$ -th user  $\tilde{\mathbf{d}}_u = [\tilde{d}_u(0), \tilde{d}_u(1), \dots, \tilde{d}_u(M-1)]^T$  as

$$\tilde{\mathbf{d}}_u = \mathbf{F}_M^H \tilde{\mathbf{D}}_u. \quad (15)$$

Table 1 Simulation parameters.

Transmitter	Data modulation	QPSK
	FFT/IFFT block size	$N_c = 256$
	Cyclic prefix length	$N_g = 16$
Multiple access	No. of users	$U = 1 \sim 16$
	Multiple access technique	SC-FDMA, DS-CDMA, SC-FD-CDMA
	Spreading factor	$SF = 16, 64$
	Spreading code	Long-PN sequence
Channel	Transmit power control (TPC)	Ideal slow TPC
	Fading	Frequency-selective block Rayleigh
	Power delay profile	Chip-spaced 16-path uniform
Receiver	Equalization	MMSE-FDE
	Channel estimation	Ideal

### 3. Performance Evaluation

Numerical and simulation parameters are summarized in Table 1. We assume a single-cell with  $U$  multi-user uplink transmission. QPSK block transmission is considered with the total number of subcarriers  $N_c=256$  and CP length  $N_g=16$ . A frequency-selective fading channel having chip-spaced  $L=16$  path uniform power delay profile is assumed. For DS-CDMA and the proposed SC-FD-CDMA, long pseudo noise (PN) sequence is used as spreading code  $\{C_u(0), \dots, C_u(SF-1)\}$  for the  $u$ -th user. Path loss, shadowing loss, and channel coding are not considered for simplicity.

#### 3.1 PAPR Performance

PAPR over a block of transmission [16] is defined as

$$PAPR = \frac{\max\{|\tilde{s}(n)|^2\}}{E[|\tilde{s}(n)|^2]}, n=0, \frac{1}{V}, \frac{2}{V}, \dots, N_c-1, \quad (16)$$

where  $V$  represents oversampling factor. We use complementary cumulative distribution function (CCDF) as an indicator of PAPR performance.

Fig. 3 shows the CCDF of PAPR of single-user transmit signal in DS-CDMA, SC-FDMA, and the proposed SC-FD-CDMA. Both localized and interleaved mapping are considered in SC-FDMA transmit signals, where single-user transmit signal of interleaved SC-FDMA is also evaluated at different  $U$  since the transmit waveform depends on number of accessing users. PAPR performance of DS-CDMA and SC-FD-CDMA are evaluated at  $SF=16$  and 64.

It can be seen from Fig. 3 that there is no difference in PAPR performance between localized and interleaved mappings in SC-FDMA, which can be confirmed by [8]. However, it is observed that the PAPR of DS-CDMA and SC-FD-CDMA are slightly lower than SC-FDMA, especially we can achieve 0.5 dB reduction of PAPR at the probability of occurrence of 0.01 (99-percentile) in DS-CDMA with  $SF=16$  and 64, and SC-FD-CDMA with  $SF=16$ . This can be described as a benefit from spreading code since spreading code introduces a pre-determined phase rotation in the transmit signal either in time-domain (for DS-CDMA) or frequency-domain (for SC-FD-CDMA). This benefit is in fact a fundamental of a well-known PAPR reduction technique called selective mapping (SLM) [17]. Moreover, a slight PAPR reduction is further achieved when  $SF=64$  in the proposed SC-FD-CDMA due to more variety of phase rotation in frequency-domain signal as the spreading code becomes longer.

#### 3.2 BER Performance

Fig. 4 shows the uplink BER performance as a function of average received bit energy-to-noise power spectrum density ratio  $E_b/N_0=0.5(P_u T_c/N_0)(SF)(1+N_g/N_c)$  when (a)  $SF=16$  and (b)  $SF=64$ . Ideal slow transmit power control (TPC) (i.e.,  $P_u=P$  for all  $u$ ) is assumed. BER performance of SC-FD-CDMA is compared with DS-CDMA at the same

number of users  $U$ . We also show the BER performance of single-user interleaved SC-FDMA as a reference.

It can be seen from Fig. 4 that the BER performance of SC-FD-CDMA provides better BER than DS-CDMA in every  $U$ . The reasons are well described in [13] as the SC-FD-CDMA can achieve more interference mitigation (ISI and MUI) inherit from mapping in (4), and lower phase error after de-spreading since the de-spreading is done in frequency domain. It can also be observed that the better BER performance is achieved at the low-transmit power region (i.e., average received  $E_b/N_0 \leq 10$  dB) in both DS-CDMA and SC-FD-CDMA compared to interleaved SC-FDMA because of higher frequency diversity. However, at the high-transmit power region, there exists an error floor in both DS-CDMA and SC-FD-CDMA when  $U$  increases due to strong MUI.

In addition, it is seen that the performance gap between SC-FD-CDMA and DS-CDMA is small when  $SF=64$ . This is because all schemes can achieve the similar amount of diversity gain [13]. However, a better PAPR performance is obtained instead.

### 4. Conclusion

In this paper, SC-FDSS with orthogonal code multiplexing was extended to multi-user uplink transmission called SC-FD-CDMA. In SC-FD-CDMA, spreading and de-spreading are done in frequency-domain, providing additional frequency-diversity gain and robustness against ISI and MUI. Simulation results assuming the single-cell environment confirmed that the proposed SC-FD-CDMA improves the BER performance compared to DS-CDMA and is better than interleaved SC-FDMA at the low-transmit power region. It was also shown that the PAPR of SC-FD-CDMA is lower than conventional SC-FDMA and also than DS-CDMA when  $SF=64$ .

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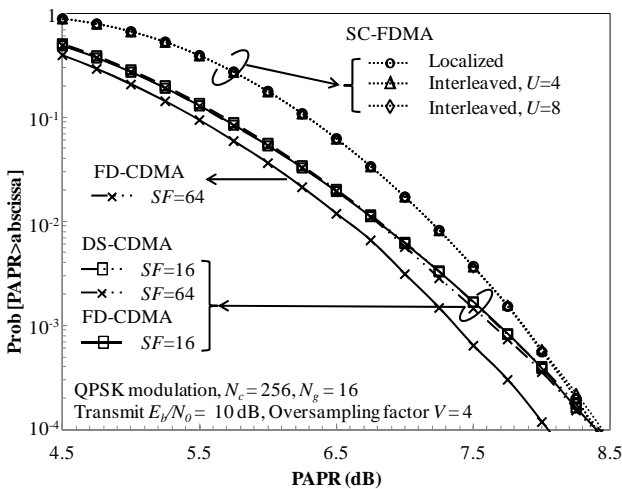
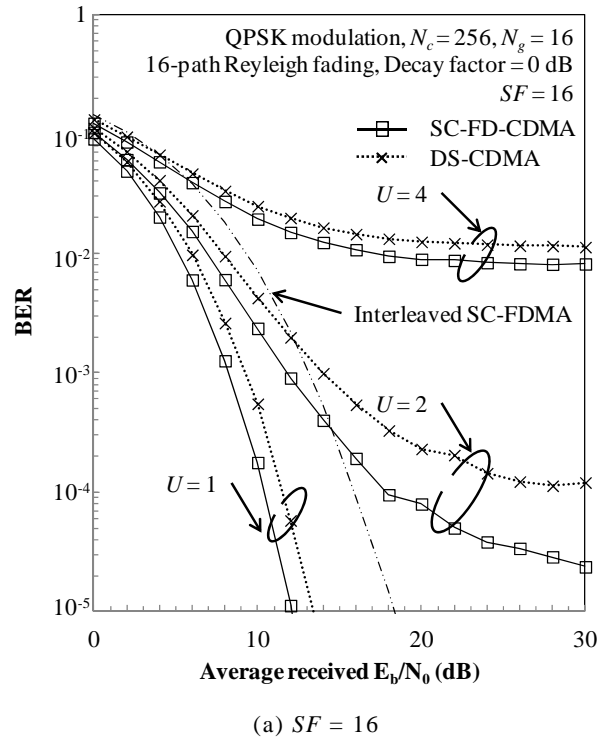
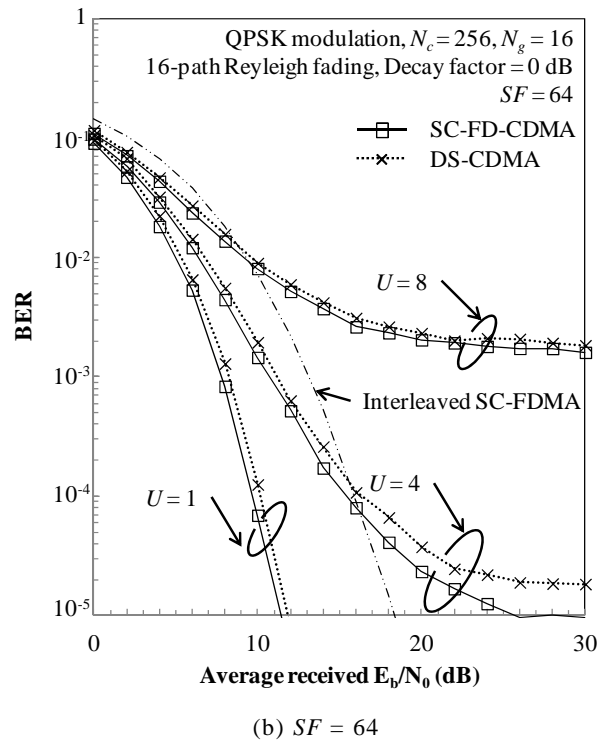


Fig.3 CCDF of PAPR.



(a) SF = 16



(b) SF = 64

Fig.4 BER performance of proposed uplink SC-FD-CDMA.