Multi-antenna Pre-Equalization for Single-carrier/TDD System

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***Abstract*— A severe frequency-selective fading, encountered in a broadband wireless mobile communication, significantly degrades the single-carrier (SC) signal transmission performance. In this paper, multi-antenna frequency-domain pre-equalization (called pre-FDE) is presented for spread-spectrum single-carrier (SC) systems. At a transmitter, pre-FDE with transmit power constraint is applied for each transmit antenna; no equalization function is necessary at a receiver. It is shown by computer simulation that pre-FDE transmission can provide significant improvement in the bit error rate (BER) performance in a frequency-selective Rayleigh fading channel and can achieve a BER performance close to that attainable by FDE reception. For a mobile communication system, the pre-FDE transmission for the downlink (base-to-mobile) and FDE reception for the uplink (mobile-to-base) can be implemented at a base station. This allows a simple implementation of mobile transceivers.**

Keywords- *Pre-equalization, spread-spectrum, single-carrier transmission*

I. INTRODUCTION

Demands for broadband services in mobile wireless communications systems are becoming higher and higher. Very high-speed data transmissions capability of far more than few tens of Mbps is required in next generation mobile communications systems, called 4th generation (4G) systems [1]. However, for such high speed data transmissions, wireless channel is composed of many distinct propagation paths with different time delays. As a result, severe frequency-selective multipath fading is produced, which causes inter-path interference (IPI) due to the asynchronism of different propagation paths. This severely degrades the single-carrier (SC) transmission performance. Direct sequence code division multi-access (DS-CDMA) technique, which is a spread-spectrum version of the SC technique, improves the bit error rate (BER) performance by utilizing the well-known rake combining [2]. High-speed data transmissions can be achieved by reducing the spreading factor for the given chip rate. However, the use of small spreading factor cannot sufficiently reduce the IPI and hence, the BER performance degrades. Recently, to avoid the adverse effect of frequency-selective fading, much attention has been paid to the multicarrier (MC) technique, known as MC-CDMA [3], [4], which uses frequency-domain spreading/despreading. MC-CDMA can exploit the channel frequency-selectivity by utilizing simple one-tap frequency-domain equalization (FDE). Quite recently, it has been shown [5], [6], [7] that FDE reception can improve the SC transmission performance as well. Since then, the SC technique has been looked over again as a strong candidate for high-speed wireless data transmissions. To further improve the transmission performance, multi-antenna transmit/receive diversity can be jointly used with FDE. Frequency-domain pre-equalization (called pre-FDE in this paper) is presented for MC-CDMA in [8], [9] and for SC transmission in [10].

In this paper, we consider spread-spectrum SC with time division duplex (TDD) and present multi-antenna pre-FDE transmission using quasi-minimum mean square error (MMSE) criterion under the each antenna transmit power constraint unlike [10]. The achievable BER performance in a frequency-selective fading channel is evaluated by computer simulation and compared with multi-antenna FDE reception. It is confirmed that quasi-MMSE pre-FDE can significantly improve the BER performance and achieve a BER performance close to FDE reception.

II. MULTI-ANTENNA PRE-FDE

The transmitter/receiver structure for pre-FDE transmission is illustrated in Fig. 1. Pre-FDE requires fast Fourier transform (FFT) and inverse FFT (IFFT) operations at the transmitter. Pre-FDE requires the knowledge of transmit channel state information associated with each transmit antenna for computing the equalization weights. Since both transmit and receive links use the same carrier frequency in the TDD system, the receive link channel estimate can be reused for the transmit link. In this paper, however, we assume ideal channel estimation. Below, M-antenna pre-FDE at only the mth antenna (m=0~(M-1)) is presented since it is the same for all antennas.

A block of quadrature phase shift keying (QPSK) modulated symbols $\{d(t);\ t=0\sim(N_c/SF-1)\}$ with $|d(t)|=1$ is to be transmitted, where N_c is the number of data chips in one block and SF is the spreading factor. The spread-spectrum SC signal at the t-th chip time instance can be expressed, using the equivalent lowpass representation, as

$$s(t)=c(t)d\left(\left\lfloor\frac{t}{SF}\right\rfloor\right),\ (1)$$

where $c(t)$ is the t-th spreading chip with $|c(t)|=1$. N_c-point FFT is applied to decompose $s(t)$ into N_c frequency components $\{S(n);\ n=0\sim(N_c-1)\}$. After multiplying by the complex-valued pre-FDE weights $\{w_m(n);\ n=0\sim(N_c-1)\}$, N_c-point IFFT is applied to obtain the pre-equalized signal $s_m(t)$ to be transmitted from the mth antenna. $s_m(t)$ can be expressed as

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$$s_m(t)=\sqrt{\frac{2E_c}{T_c}}\sum_{n=0}^{N_c-1}\left\{w_m(n)\frac{S(n)}{N_c}\right\}\exp\left(j2\pi t\frac{n}{N_c}\right)\ ,\ (2)$$

where E_c and T_c denote the transmit chip energy per antenna and the chip period, respectively, and $S(n)$ is given by

$$S(n)=\sum_{t=0}^{N_c-1}d(t)\exp\left(-j2\pi n\frac{t}{N_c}\right).\ (3)$$

The channel gain associated with the mth transmit antenna at the n-th frequency is denoted by $H_m(n)$. The pre-FDE weight $w_m(n)$ that maximizes the received signal-to-noise power ratio (SNR) at the receiver is given by $w_m(n)=C_mH_m^*(n)$, which is called the maximal ratio combining (MRC) weight. C_m is the power normalization factor under the total transmit power constraint represented by $\sum_{n=0}^{N_c-1}\left|w_m(n)S(n)/N_c\right|^2=1$ (i.e., the transmit power after pre-FDE is kept the same as before pre-FDE). But, the use of MRC weight enhances the channel frequency-selectivity seen at the receiver and accordingly, enhances the IPI. On the other hand, the use of zero forcing (ZF) weight $w_m(n)=C_mH_m^*(n)/|H_m(n)|^2$ can restore the frequency-nonselective channel and hence, remove the IPI, but under the transmit power constraint, most of the transmit power is allocated to frequency components which experience deep fade. Hence, a large power loss is produced in the received signal, thereby degrading the BER performance due to the additive white Gaussian noise (AWGN). In order to avoid the IPI enhancement while exploiting the channel frequency-selectivity, we take a heuristic approach and use the following weight, which is between MRC and ZF:

$$w_m(n)=C_m\frac{H_m^*(n)}{\left|H_m(n)\right|^2+\lambda}\ ,\ (4)$$

where λ is the controlling parameter which is the same for all antennas; $\lambda\rightarrow 0$ gives the ZF weight, while $\lambda\rightarrow\infty$ gives the MRC weight. In this paper, optimum λ is found by the computer simulation. Since Eq. (4) is similar to the weight for MMSE-FDE reception, the weight of Eq. (4) is called the quasi-MMSE weight. C_m is now given by

$$C_m=\frac{N_c}{\sqrt{\sum_{n=0}^{N_c-1}\left|\frac{S(n)H_m^*(n)}{\left|H_m(n)\right|^2+\lambda}\right|^2}}\ .\ (5)$$

When pre-FDE is applied, a cyclic prefix needs to be inserted into the guard interval (GI) as in FDE reception. The GI-inserted pre-equalized signal $\{s_m(t);\ t=-N_g\sim N_c-1\}$, shown in Fig. 2, is transmitted from the mth antenna, where N_g is the GI length in chip.

The superposition of M transmitted signals is received via a frequency-selective fading channel at the receiver. Assuming a chip-spaced L-path frequency-selective channel and denoting the complex-valued path gain and the time delay of the l-th propagation path by $h_{l,m}$ and τ_l (in chips), respectively, $H_m(n)$ can be expressed as

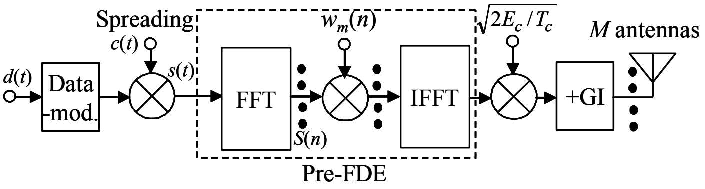
$$H_m(n)=\sum_{l=0}^{L-1}h_{l,m}\exp\left(-j2\pi n\frac{\tau_l}{N_c}\right).\ (6)$$

For simplicity, we have assumed a block fading, where the path gains remain constant over an (N_c+N_g)-chip block. The received signal can be represented as

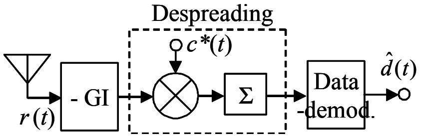
$$r(t)=\sum_{m=0}^{M-1}\sum_{l=0}^{L-1}h_{l,m}s_m(t-\tau_l)+\eta(t)\ ,\ (7)$$

where $\eta(t)$ is the zero-mean complex noise process having a variance of $2N_0/T$ with N_0 being the AWGN one-sided power spectrum density. At the receiver, after removal of GI, simple despreading is applied to obtain the decision variable for the i-th symbol $d(i)$:

$$\hat{d}(i)=\sum_{t=iSF}^{(i+1)SF-1}r(t)c^*(t)\ .\ (8)$$



(a) transmitter



(b) receiver

Fig. 1 Transmitter/receiver structure for pre-FDE transmission.

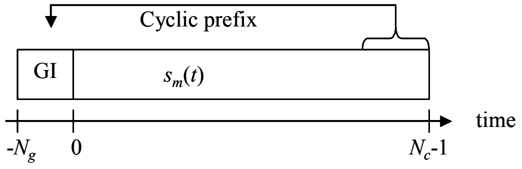


Fig. 2 Chip block structure.

III. COMPUTER SIMULATION RESULTS

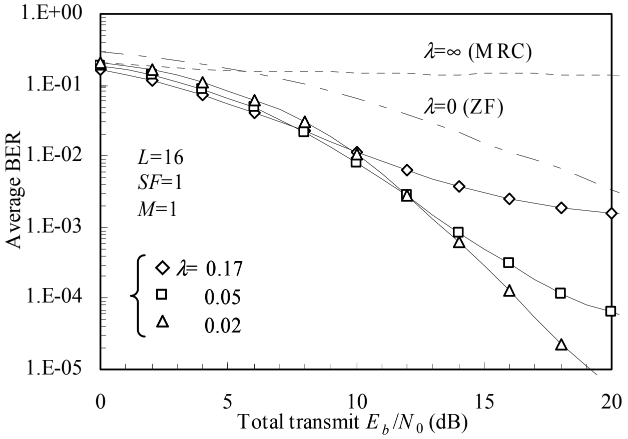
The BER performance achievable with pre-FDE transmission in a chip-spaced L=16-path block Rayleigh fading channel is evaluated by the computer simulation. We assume an M-sequence of 4095 chips as the spreading chip sequence, N_c=256, N_g=32, QPSK data-modulation, and the uniform power delay profile of the channel (the ensemble average of $|h_{l,m}|^2$ is $1/L$ for all l and m). Pre-FDE transmission requires accurate channel estimation. In the computer simulation, however, ideal channel estimation is assumed as in Sect. II.

TABLE 1 SIMULATION CONDITION

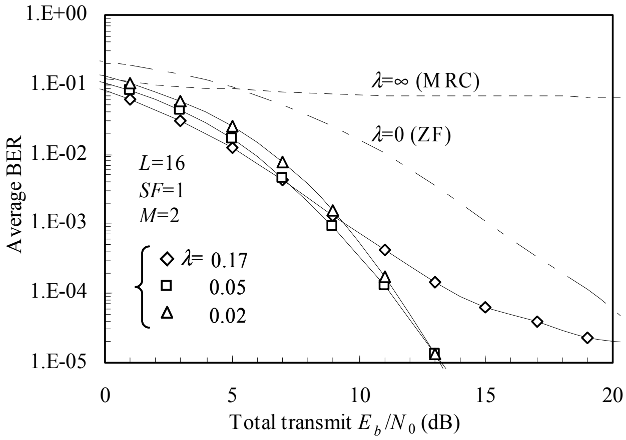
Transmitter	Data modulation	QPSK
	Spreading sequence	M-sequence of 4095 chips
	Spreading factor	SF=1 and 8
	Number of FFT points	N_c=256
	GI	N_g=32 (chips)
Channel	Fading	Frequency-selective block Rayleigh fading
	Power delay profile	L=16-path uniform power delay profile

A. Effect of λ

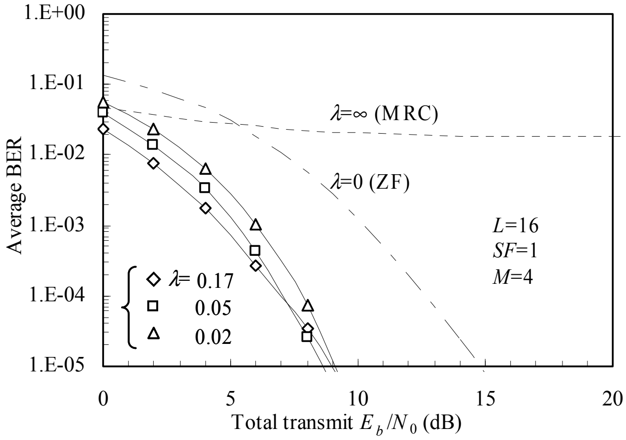
The BER performance using pre-FDE transmission is plotted as a function of transmit signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0 for SF=1 and 8 in Figs. 3 and 4, respectively, where $E_b/N_0=0.5SF(E_c/N_0)(1+N_g/N_c)$ for QPSK data-modulation. The use of λ=0 (ZF weight) produces the noise enhancement while the use of $\lambda\rightarrow\infty$ (MRC weight) enhances the IPI and therefore, as was expected, an optimum λ exists that minimizes the average BER for the given total transmit E_b/N_0. The optimum λ is found to be λ=0.17 (1.4), 0.06 (0.45), and 0.02 (0.12) for the transmit E_b/N_0 per antenna =5, 10, and 15 dB for SF=1 (8), respectively. With the optimum λ, pre-FDE significantly improves the BER performance than with ZF and MRC. It is interesting to note that the BER performance is not that much sensitive to the selection of λ.



(a) M=1

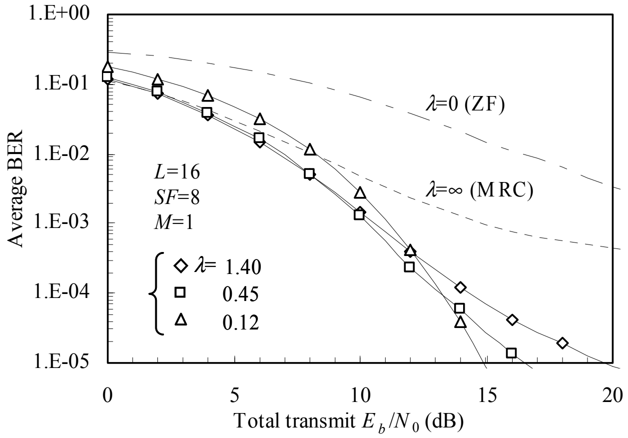


(b) M=2

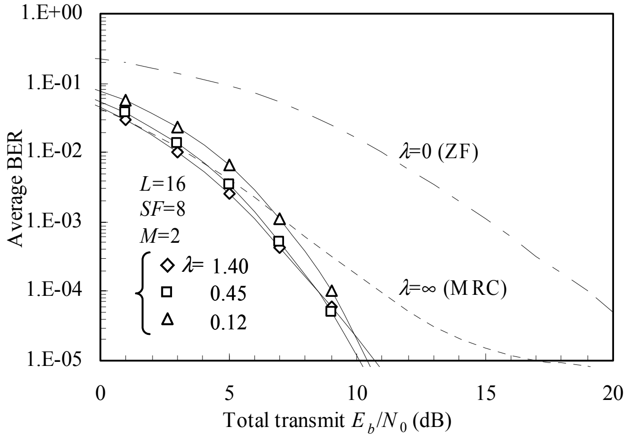


(c) M=4

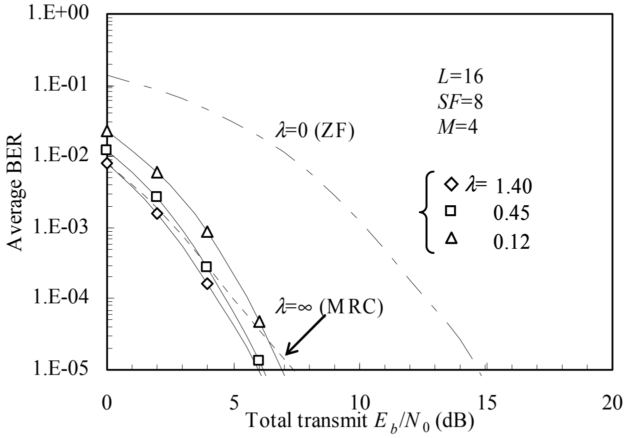
Fig. 3 Effect of λ on BER performance for SF=1.



(a) M=1



(b) M=2

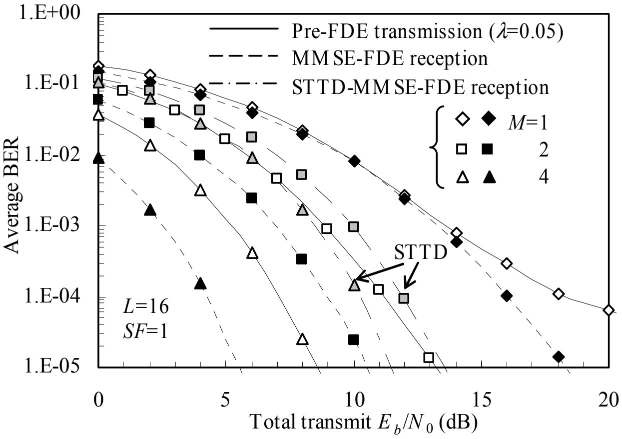


(c) M=4

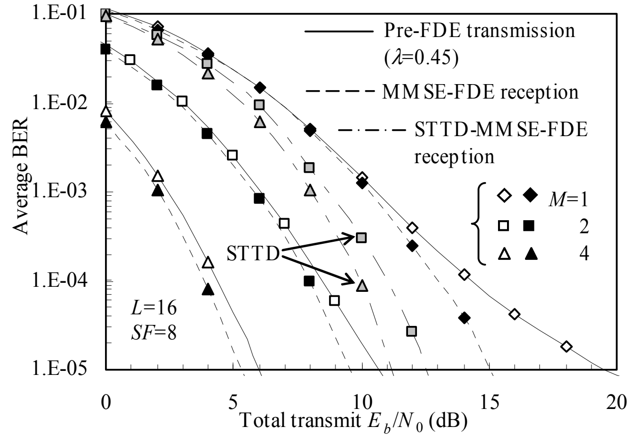
Fig. 4 Effect of λ on BER performance for SF=8.

B. Performance comparison between pre-FDE transmission and MMSE-FDE reception

Figure 5 shows the performance comparison between quasi-MMSE pre-FDE transmission and MMSE-FDE reception with the number M of antennas as a parameter. λ is optimized at the transmit E_b/N_0 per antenna=10dB. Note that in the case of MMSE-FDE reception, the total transmit E_b/N_0 is equal to the received E_b/N_0 per antenna. When SF=1, quasi-MMSE pre-FDE transmission is worse than MMSE-FDE reception. This is because the pre-FDE transmission gives up the perfect restoration of frequency-nonselective channel in order to avoid a large power loss in the received signal and therefore, larger IPI is produced than the case of MMSE-FDE reception. However, when SF=8, the performance difference between quasi-MMSE pre-FDE transmission and MMSE-FDE reception is only a fraction of dB.



(a) SF=1



(b) SF=8

Fig.5 Performance comparison between quasi-MMSE pre-FDE transmission and MMSE-FDE reception.

Also plotted in Fig. 5 is the BER performance using space-time coded transmit diversity jointly used with MMSE-FDE reception [11]. It is seen that quasi-MMSE pre-FDE transmission can achieve much better performance than STTD since the former pre-equalizes the channel such that the signals transmitted from different antennas arrive in phase at the receive antenna. Note that the full rate coding is possible for STTD when M=2, but the code rate reduces to 3/4 when M=4.

C. Pre-FDE transmission for downlink and MMSE-FDE reception for uplink

For a spread-spectrum SC/TDD mobile communications system, all the frequency-domain processing can be implemented at the base station; downlink (base-to-mobile) pre-FDE transmission and uplink (mobile-to-base) FDE reception. Simple despreading/spreading is required at the mobile station. The base station and mobile station structures are illustrated in Fig. 6. At the base station, channel estimation (CE) is carried out using the uplink received signal for performing joint antenna diversity/FDE reception. The uplink channel estimate is reused for computing the pre-FDE weights for performing pre-FDE transmission. It can be understood from Fig. 5 that both downlink and uplink have almost the same BER performance. In this paper, only the single-user case has been considered. However, pre-FDE transmission can be applied to high speed packet access using multi-user diversity, like DS-CDMA high speed downlink packet access (HSDPA) [12] but replacing rake combining by MMSE-FDE [13]. Using multi-user diversity, whole resources of downlink/uplink can be given to a single user at a time based on the channel quality measurement and QoS requirement. In such packet access, a simple transmitter/receiver structure is possible at the mobile stations at the cost of increased complexity of the base stations.

IV. CONCLUSION

In this paper, multi-antenna quasi-MMSE pre-FDE transmission was presented for spread-spectrum SC/TDD. The achievable BER performance in a frequency-selective Rayleigh fading channel was evaluated by computer simulation to show that quasi-MMSE pre-FDE provides a good BER performance. For a spread-spectrum SC/TDD mobile communications system, all frequency-domain processing can be implemented at the base stations; downlink pre-FDE transmission and uplink FDE reception. This allows simple structure of the mobile stations. The performance difference between the downlink and uplink is only a fraction of dB when *SF*>1. Performance comparison with STTD was also presented to show that quasi-MMSE pre-FDE provides much better BER performance. However, with pre-FDE transmission, the instantaneous power varies and this increases the peak-to-average power ratio (PAPR), similar to MC-CDMA or OFDM. Reducing the PAPR is an interesting future study.

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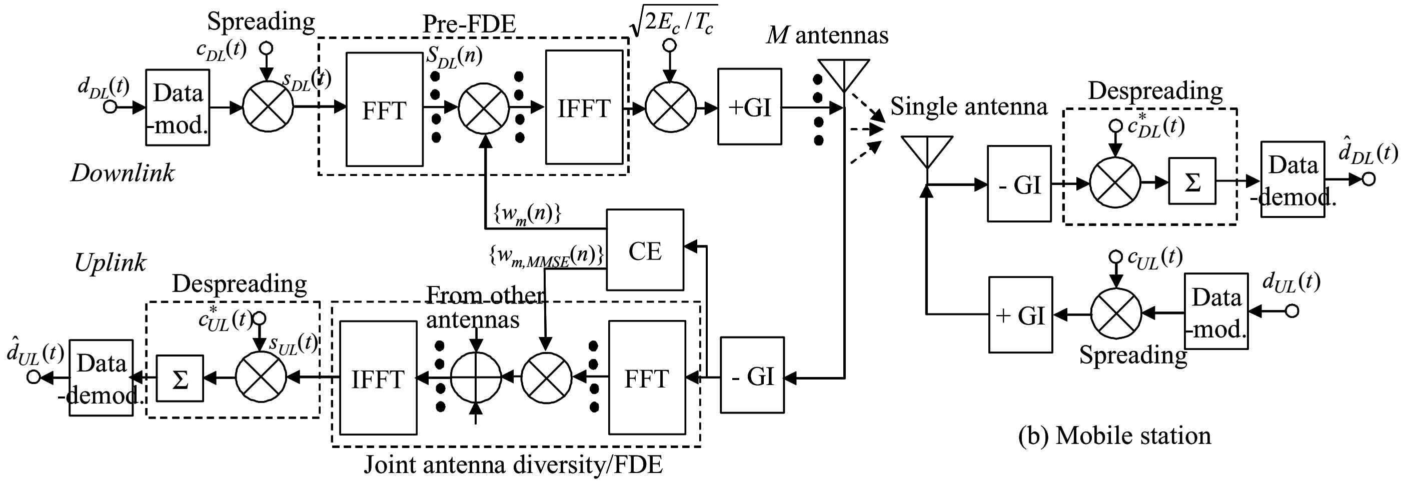

(b) Mobile station

(a) Base station

Fig. 5 Downlink/uplink transceiver structure for spread-spectrum SC/TDD.