DS-CDMA with Frequency-domain Equalization for High Speed Downlink Packet Access

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***Abstract*— The next generation mobile communications system is anticipated to support data rates up to and exceeding 100Mbps. In this paper, we consider a DS-CDMA high-speed downlink packet access (HSDPA) as in 3G W-CDMA systems. Adaptive modulation and coding (AMC), multicode operation and hybrid automatic repeat request (HARQ) will be the enabling technologies. With such high-speed data transmissions, however, multicode operation severely suffers from destruction of orthogonality among the spreading codes since the wireless channel becomes severely frequency-selective. In this paper, we apply frequency-domain equalization (FDE) instead of conventional rake combining for receiving the packet. It is shown that the use of FDE for the reception of multicode signal gives an improved throughput irrespective of the channel's frequency-selectivity.**

Keywords- HSDPA, DS-CDMA, MMSE-FDE, HARQ, AMC, multicode

I. INTRODUCTION

Data services, as anticipated, have become the dominating source of traffic load in the 3G networks based on wideband code division multiple access (W-CDMA). High speed data services will be supported by the high speed downlink packet access (HSDPA) concept [1], which allows peak data rates up to and exceeding 10Mbps. Adaptive modulation and coding (AMC), multicode operation (MC) and hybrid automatic repeat request (HARQ) are the enabling technologies used for HSDPA. The next generation mobile communications system is anticipated to support even higher data rates up to and exceeding 100Mbps. With such high speed data transmissions, the wireless channel becomes severely frequency-selective [2]. AMC, MC and HARQ will still be inevitable. However, in a frequency-selective channel, multicode operation severely suffers from destruction of orthogonality among the spreading codes. Recently, it was shown that DS-CDMA using minimum mean square frequency-domain equalization (MMSE-FDE) partially restores the orthogonality and provides a better bit error rate (BER) performance than conventional coherent rake combining [3, 4]. In this paper, we apply MMSE-FDE for receiving the packet data transmitted as in HSDPA with AMC, MC and HARQ but over a severe frequency-selective channel.

The remainder of the paper is organized as follows. Section II describes the packet access for DS-CDMA with MMSE-FDE. The MMSE weight for packet combining is also introduced. The simulation results are presented and discussed in Sect. III. Section IV concludes the paper.

II. PACKET ACCESS FOR DS-CDMA WITH FDE

The conventional DS-CDMA receivers are equipped with a rake combiner that can take advantage of the path diversity. When the number of propagation paths in the channel increases, the receiver complexity increases due to the increase in the number of rake fingers. Moreover, the orthogonality among the spreading codes is destroyed due to severe inter-path interference and therefore multicode operation cannot guarantee high speed transmissions. The orthogonality can be partially restored with MMSE-FDE and is suitable for multicode operation. In this paper, we propose the use of MMSE-FDE for the reception of multicode packet data.

Similar to HSDPA, we consider the multicode transmission with a spreading factor SF of 16 and assume that error correction coding is done by a rate-1/3 turbo code with the rate R varied between ¼ and ¾ by means of puncturing and repetition. HARQ with incremental redundancy (IR) (each retransmission may use a different redundancy version) [5] or Chase combing (CC) (single redundancy version) [6] may be used. With FDE, the received signal is first converted to frequency components by fast Fourier transform (FFT) and MMSE equalization is performed for each frequency component, after which the signal is transformed back to time-domain signal with inverse FFT (IFFT). However, with FDE, it is essential that the signal be periodic in the FFT window and hence guard interval (GI) in the form of cyclic prefix needs to be inserted [3, 4] in the transmit signal as for multicarrier CDMA (MC-CDMA). At the transmitter, rate matching [1] can be modified so as to allow for GI insertion.

The transmitter and receiver for DS-CDMA packet access with MMSE-FDE are shown in Fig. 1. GI insertion block, which is not present in the current HSDPA standard, is added at the transmitter. The receiver structure is modified to incorporate the FDE; FFT and IFFT blocks are added and the rake combiner is removed.

The information sequence is first turbo coded and punctured according to the channel quality indicator (CQI). It is then interleaved and QPSK or 16QAM modulated according to CQI. The signal is then spread and multicode multiplexing is performed. In this paper, chip-spaced discrete-time represent-

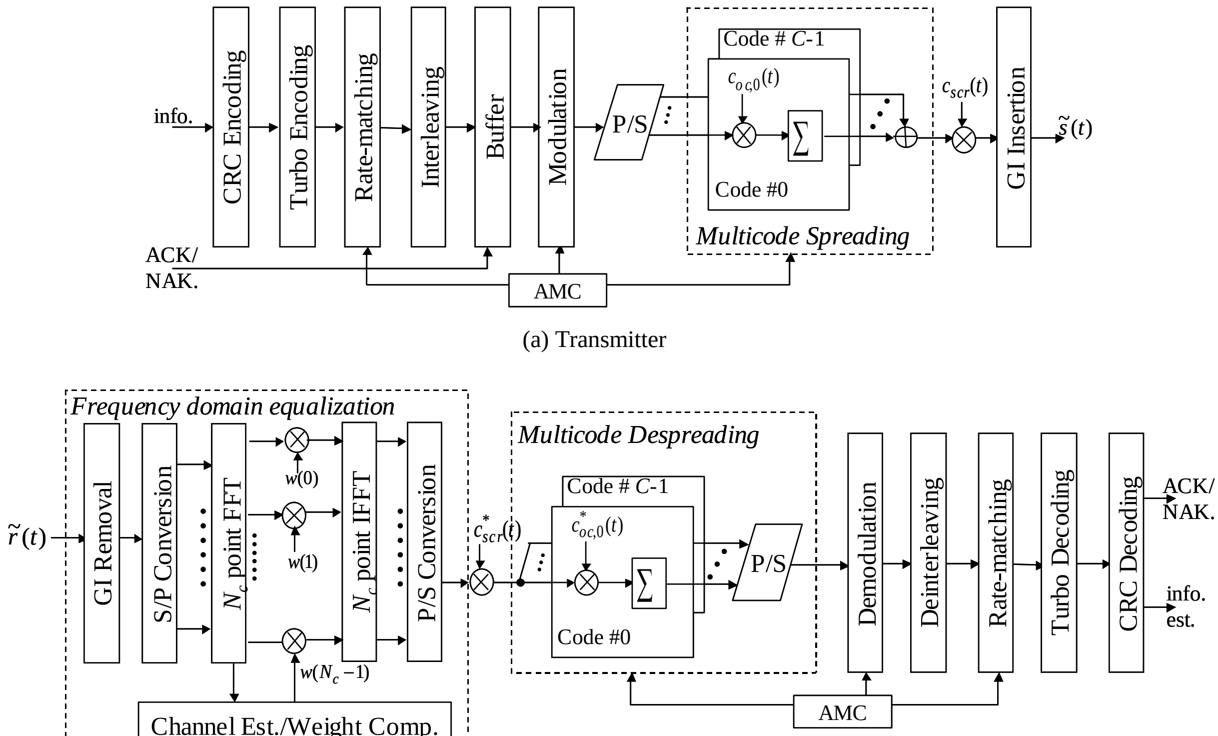


Figure 1 Transmission system model with MMSE-FDE at the receiver

-ation of signals is used. The resulting sequence is

$$s(t)=\sqrt{\frac{2P}{SF}}\sum_{c=0}^{C-1}x_c(\lfloor t/SF \rfloor)c_{oc,c}(t \bmod SF)c_{scr}(t) \tag{1}$$

for $t=0\sim SF\cdot K-1$, where P represents the transmit power per code, C is the number of codes multiplexed, SF is the spreading factor, $\{c_{oc,c}(t),\ c=0\sim C\text{-}1,\ t=0\sim SF\text{-}1\}$ is the channelization code, $\{c_{scr}(t)\}$ is the common scrambling code and $\{x_c(t),\ c=0\sim C\text{-}1,\ t=0\sim K\text{-}1\}$ is the data-modulated symbol of length T_s. N_g-chip GI is inserted for every block of N_c chips; N_c is the number of FFT/IFFT points at the receiver and N_g is a fraction of N_c. The resultant GI-inserted multicode signal $\tilde{s}(t)$ is transmitted over the propagation channel.

The channel is assumed to be composed of L distinct propagation paths with different time delays. The received multicode DS-CDMA signal is sampled at the chip rate to obtain $\{\tilde{r}(t); t=0\sim SF\cdot K(1+N_g/N_c)-1\}$. Ideal sampling timing is assumed. The N_g-sample GI is removed and N_c-point FFT is applied to each block of N_c chips in order to decompose the received DS-CDMA signal into the N_c-frequency components. The kth frequency component for the nth block is

$$R_n(k)=\sum_{t=nN_c}^{(n+1)N_c-1}\tilde{r}(t)\exp(-j2\pi k(t \bmod N_c)/N_c) \tag{2}$$

for $k=0\sim N_c\text{-}1$ and $n=0\sim SF(K/N_c)-1$. The MMSE-FDE weight $w_n(k)$ for $R_n(k)$ is given by [3]

$$w_n(k)=\frac{H_n^*(k)}{|H_n(k)|^2+\left[\frac{C}{SF}\left(\frac{PT_s}{N_0}\right)\right]^{-1}}, \tag{3}$$

where N_0 represents the AWGN power spectrum density, $H_n(k)$ denotes the channel gain at the nth block's kth frequency, which is the FFT of the channel impulse response, and $(.)^*$ denotes the complex conjugate operation. After frequency-domain MMSE equalization, IFFT is carried out to obtain the multicode DS-CDMA signal in the time-domain:

$$\begin{aligned}\hat{s}(t)&=\frac{1}{N_c}\sum_{k=0}^{N_c-1}w_n(k)R_n(k)\exp(j2\pi k(t \bmod N_c)/N_c)\\&=\frac{1}{N_c}\left\{s(t)\sum_{k=0}^{N_c-1}\tilde{H}_n(k)+\sum_{k=0}^{N_c-1}\tilde{H}_n(k)\cdot\right.\\&\left.\sum_{\substack{\tau=0\\ \neq t}}^{N_c-1}s(\tau)\exp\left(j2\pi(t-\tau)\frac{k}{N_c}\right)\right\}+\tilde{\eta}(t)\end{aligned} \tag{4}$$

for $t=nN_c$~$(n+1)N_c$-1, where $\tilde{H}_n(k)=H_n(k)w_n(k)$ and $\tilde{\eta}(t)$ is the noise sample at time t due to the AWGN. IFFT is followed by multicode despreading to obtain

$$\begin{aligned}\hat{x}_c(i) &= \sum_{t=iSF}^{(i+1)SF-1}\hat{s}(t)\{c_{oc,c}(t \bmod SF)c_{scr}(t)\}^* \\ &= \sqrt{\frac{2P}{SF}}\left(\frac{1}{N_c}\sum_{k=0}^{N_c-1}\tilde{H}_n(k)\right)x_c(i)+\mu_{ICI}(i)+\mu_{noise}(i)\end{aligned} \quad (5)$$

for c=0~C-1 and i=0~K–1. The first term represents the desired data symbol component and the second and third terms, $\mu_{ICI}(t)$ and $\mu_{noise}(t)$, are inter-chip interference (ICI) and the noise due to AWGN, respectively, given by

$$\begin{cases}\mu_{ICI}(i)=\dfrac{1}{SF}\displaystyle\sum_{t=iSF}^{(i+1)SF-1}\{c_{oc,c}(t \bmod SF)c_{scr}(t)\}^* \\ \qquad\times\dfrac{1}{N_c}\displaystyle\sum_{k=0}^{N_c-1}\tilde{H}_n(k)\left[\sum_{\substack{\tau=0\\ \neq t}}^{N_c-1}s(\tau)\exp\left(j2\pi k\frac{t-\tau}{N_c}\right)\right]. \\ \mu_{noise}(i)=\dfrac{1}{SF}\displaystyle\sum_{t=iSF}^{(i+1)SF-1}\{c_{oc,c}(t \bmod SF)c_{scr}(t)\}^*\tilde{\eta}(t)\end{cases} \quad (6)$$

It can be understood from Eq. (5) that the equivalent channel gain for all the symbols within an FFT block is $\hat{H}_n(i)=\frac{1}{N_c}\sum_{k=0}^{N_c-1}\tilde{H}_n(k)$ and the frequency diversity gain is a not a function of SF. $\{\hat{x}_c(i);c=0\sim C-1\}$ are parallel-to-serial (P/S) converted for data demodulation. Then, soft decision values for turbo decoding are generated using the log-likelihood (LLR) approximation [7], given by

$$L(b)=\frac{\left|\hat{x}_c(i)-\sqrt{2P/SF}\hat{H}_n(i)\hat{s}_0\right|^2}{2\sigma^2}-\frac{\left|\hat{x}_c(i)-\sqrt{2P/SF}\hat{H}(i)\hat{s}_1\right|^2}{2\sigma^2} \quad (7)$$

for the bth bit in the ith symbol; b=0~1 or 0~3 for QPSK and 16QAM, respectively. Here, $\hat{s}_0$ (or $\hat{s}_1$) is the candidate symbol, with 0 (or 1) in the bth bit position, for which the Euclidean distance from $\hat{x}_c(i)$ is minimum. $2\sigma^2$ is the Gaussian approximated ICI plus noise variance given by [8]

$$\sigma^2=\frac{1}{SF}\frac{N_0}{T_s}\left[\begin{aligned}&\frac{1}{N_c}\sum_{k=0}^{N_c-1}|w(k)|^2 \\ &+\left(\frac{C}{SF}\frac{PT_s}{N_0}\right)\left\{\frac{1}{N_c}\sum_{k=0}^{N_c-1}\left|\tilde{H}(k)\right|^2-\left|\frac{1}{N_c}\sum_{k=0}^{N_c-1}\tilde{H}(k)\right|^2\right\}\end{aligned}\right]. \quad (8)$$

The LLR values are computed for c=0~C-1 and for all the bits in the symbol. Turbo decoding is performed using these LLR values as soft input after rate matching. Then, error detection is performed and retransmission is requested if errors are detected.

In this paper, we introduce MMSE weights for frequency-domain packet combining. When the same packet is retransmitted, time diversity gain is obtained, similar to antenna diversity [4], and hence the weight for frequency-domain packet combining is modified as

$$w_{n,m}(k)=\frac{H_{n,m}^*(k)}{\sum_{m=0}^{M-1}\left|H_{n,m}(k)\right|^2+\left[\frac{C}{SF}\left(\frac{PT_s}{N_0}\right)\right]^{-1}}\ , \quad (9)$$

where M is the number of times the same packet is received and $H_{n,m}(k)$ is the channel gain at the nth block's kth frequency for the mth transmission.

III. Simulation Results

The simulation conditions are summarized in Table 1. For the simulation purpose, we assume a frequency-selective Rayleigh fading channel having a chip-spaced L-path uniform power delay profile and a normalized maximum Doppler frequency f_DT_{blk} of 0.001, where f_D is the maximum Doppler frequency given by traveling speed/carrier wavelength and T_{blk} is the block length with N_c+N_g chips. In the simulation, N_c=256 and N_g=32 are assumed. The Walsh-Hadamard codes with SF=16 are used as short spreading codes. Code multiplexing of C=16 is assumed that provides the same data rate as the non-spread single carrier modulation [9]. In the AMC, a rate-1/3 turbo code having two (13,15) recursive systematic convulutional (RSC) encoders same as in HSDPA, with the rate R varied between ½ and ¾, and QPSK and 16QAM are used as shown in Table 2. Ideal AMC is assumed, i.e., the modulation and coding rate set (MCS) that gives the highest performance at each average received E_s/N_0 is selected and it is assumed that there is no selection error. For Case combining (CC), the same packet with puncturing matrix P_1 is transmitted until a positive acknowledge is received. For incremental

Table 1: Simulation conditions

Turbo coding	R=1/2 and 3/4 (13, 15) RSC encoder Log-MAP decoding with 8 iterations	
Channel Interleaver	Block Interleaver	
Data Modulation	Coherent QPSK and 16QAM	
DS-CDMA	No. of FFT points	N_c=256
	GI	N_g=32
	Spreading factor	SF=16
ARQ	Incremental redundancy/ Chase combining	
Channel model	L-path Rayleigh fading ($\tau_l = l$) f_DT_{blk}=0.001	

Table 2: Modulation and coding rate set

MCS	Modulation	Coding rate
1	QPSK	½
2	QPSK	¾
3	16QAM	½
4	16QAM	¾

Table 3: Puncturing Pattern

R	½	¾
P_1	$\begin{bmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$
P_2	$\begin{bmatrix} 1 & 1 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 \end{bmatrix}$

redundancy (IR), the puncturing matrix P_1 is used for the first transmission and P_2 for the second transmission and the order repeated for further transmissions. Code combining is employed if the same packet is transmitted more than once. The puncturing matrices are shown in Table 3. Ideal chip synchronization and ideal channel estimation are assumed at the receiver. Perfect error detection and an error-free reverse channel are assumed.

Figure 2 plots the throughput in bps/Hz as a function of the average received signal energy per symbol-to-the noise power spectral density ratio (E_s/N_0) for CC and IR with AMC when rake combining is employed at the receiver. C=SF=16 is assumed. This is referred to as AMC. It is seen that IR provides a slightly higher throughput than CC for all channel conditions. In IR, the second retransmission consists of sending the unsent parity bits instead of sending the same bits as in CC. From the result it can be inferred that the additional coding gain due to increased redundancy is more desirable than the increased received power owing to packet combining. For L=1, the throughput gradually increases with the increase in the average received E_s/N_0. However, even for L=2, the throughput attainable with rake combining is drastically reduced due to the destruction of orthogonality among the spreading codes. With the increase in L, the frequency selectivity of the channel increases and the orthogonality destruction is severer. Hence, the throughput decreases with the increase in L.

The throughput with the proposed MMSE-FDE receiver is plotted in Figs. 3(a) and (b) for CC and IR, respectively when 16QAM modulation and rate ½ turbo code is used. The modulation and coding rate is fixed to concentrate on the effect of the number L of paths. For IR, the code rate decreases after the second transmission. With MMSE-FDE, the throughput is almost independent of the channel's frequency selectivity for both CC and IR. The orthogonality destruction is severer for stronger frequency-selectivity, but MMSE-FDE is utilized that restores orthogonality to a certain extent and benefits from the frequency selectivity of the channel [3, 4]. Increased frequency selectivity results in more random errors which are desirable for channel coding but undesirable for packet transmissions. For lower E_s/N_0 regions, the throughput decreases for higher frequency selectivity due to more packet errors but for higher E_s/N_0 regions there are few errors that can be corrected by the

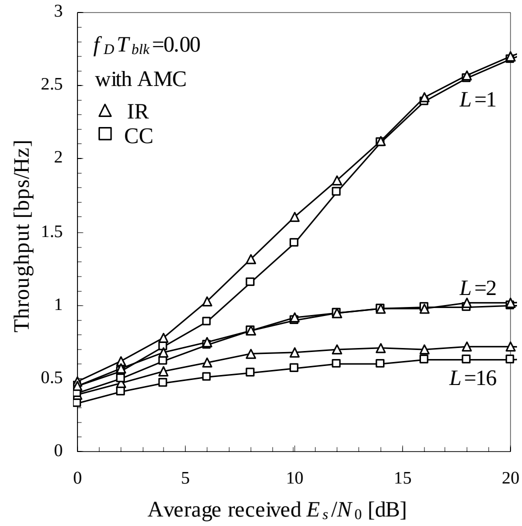
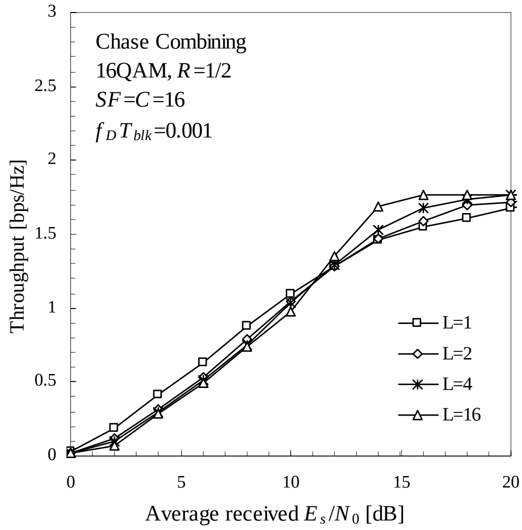
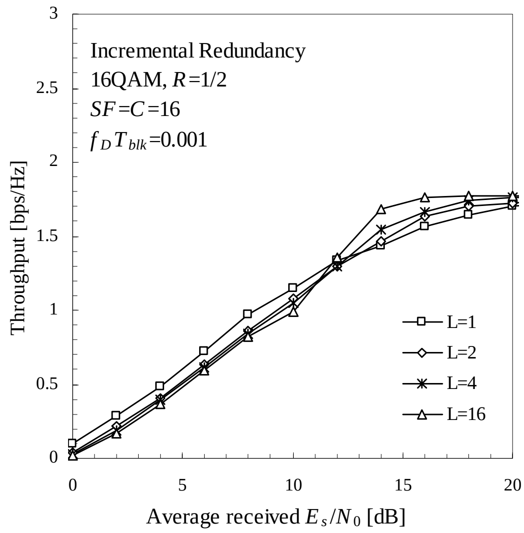


Figure 2. Throughput with rake combining.



(a) Chase Combining



(b) Incremental Redundancy

Figure 3. Throughput with MMSE-FDE.

turbo decoder and the throughput increases.

Figure 4 compares the throughput in bps/Hz with MMSE-FDE and rake combining as a function of the average received E_s/N_0 with AMC when MMSE-FDE is applied for CC and IR. Even with AMC, there is almost no difference in throughput with the increase in L. It can also be noted that there is no advantage of IR over CC employing frequency-domain packet combining. For L=1, the throughput is slightly lower with MMSE-FDE compared to rake combining, due to the GI insertion. However, for L=16, the throughput is much better than that of rake combining. Rake combining is not suitable for channels with many strong paths when MC operation is applied. Some form of orthogonality restoration is needed. The MMSE-FDE provides a good trade-off between orthogonality restoration and noise enhancement [4] and is suitable for channels with high frequency selectivity.

The IR throughput with MMSE-FDE is compared with that of non-spread single carrier transmission [9] in Figure 5 when L=16 and AMC is utilized. The non-spread single carrier transmission is equivalent to DS-CDMA with SF=1. To maintain the data rate fixed, C=16 is assumed. The throughput of DS-CDMA with rake combining is also plotted for reference. The throughput of DS-CDMA with MMSE-FDE is the same as that of non-spread single carrier transmission. As was discussed in Sect. II, the frequency diversity effect in DS-CDMA with MMSE-FDE does not depend on SF. The interference depends on the C/SF ratio as can be seen from Eq. (8). Hence, when C=SF, the DS-CDMA performance is the same irrespective of SF.

IV. CONCLUSION

In this paper, we showed that the use of MMSE-FDE for the reception of multicode packet signal transmitted as in HSDPA gives an improved throughput. When rake combining is used, the throughput degrades drastically with the increase in the frequency-selectivity of the channel due to orthogonality destruction among the spreading codes. However, MMSE-FDE can give improved throughput irrespective of the channel conditions. In addition, MMSE weight for frequency-domain packet combining was introduced. It was found that with adaptive modulation and coding, there was no advantage of incremental redundancy over Chase combining employing frequency-domain packet combining.

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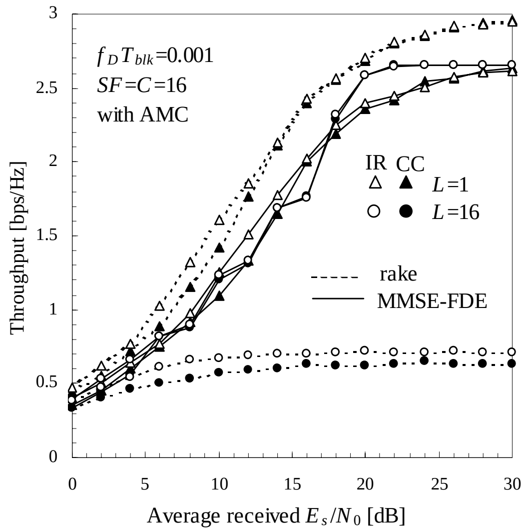

Figure 4. Throughput comparison with rake combining.

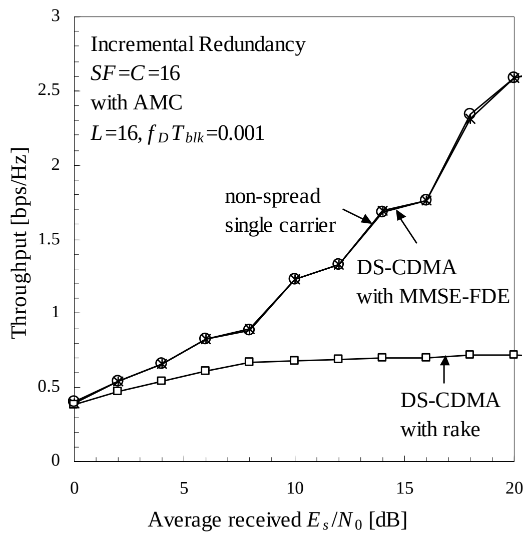

Figure 5. Throughput comparison with non-spread single carrier system.