COMPARISON OF RCPT HARQ THROUGHPUT USING OFDM, MC-CDMA AND DS-CDMA WITH FREQUENCY-DOMAIN EQUALIZATION

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ABSTRACT

OFDM, MC-CDMA and DS-CDMA are being researched vigorously as the prospective signaling technique for the next generation mobile communications systems, which will be characterized by the broadband packet technology. With packet transmission, hybrid ARQ (HARQ) will be inevitable for error control. HARQ with rate compatible punctured turbo (RCPT) codes is one of the promising techniques. Data rate equivalent to OFDM can be attained with MC-CDMA and DS-CDMA by assigning all the available orthogonal codes to the same user, resulting in what is commonly referred to as multicode MC-CDMA and multicode DS-CDMA. In this paper, we introduce RCPT HARQ to DS-CDMA with minimum mean square error frequency-domain equalization (MMSE-FDE) and compare its throughput performance with OFDM, multicode MC-CDMA and multicode DS-CDMA with rake combining. It is found that the throughput of DS-CDMA with MMSE-FDE is the same as or better than that of MC-CDMA. However, with higher level modulation, coded OFDM is better than either MC-CDMA or DS-CDMA.

1. INTRODUCTION

Broadband wireless packet technology is one of the core technologies for the next generation mobile communications systems. Direct sequence code division multiple access (DS-CDMA) has been adopted as the signaling technique for the third generation mobile communications systems [1] and is a likely candidate for the next generation as well. Recently, the combination of multicarrier (MC) modulation based on orthogonal frequency division multiplexing (OFDM) [2] and CDMA, called MC-CDMA [3], has gained a lot of attention because of its ability to allow high data rate transmission in a harsh mobile environment and has emerged as the most promising candidate for the next generation mobile communications systems. Hence, DS-CDMA, OFDM and MC-CDMA are the major contenders for wireless signaling technique. The bit error rate (BER) performances of these signaling techniques have been compared in some recent publications [2, 3]. In [4], the packet error rate (PER) performance of MC/DS-CDMA (DS-CDMA for multiple carriers) is compared with that of MC-CDMA and shown that for downlink, MC-CDMA gives a better performance than MC/DS-CDMA and DS-CDMA. However, in the comparison, it is assumed that rake combining is used for the reception of DS-CDMA signals.

Recently, it is shown [5] that an effective technique to improve the BER performance of DS-CDMA is to apply minimum mean square error frequency-domain equalization (MMSE-FDE). It is shown [5] that DS-CDMA with MMSE-FDE provides a BER performance better than that with rake combining and is comparable to that of MC-CDMA with MMSE-FDE in a frequency-selective fading channel. For packet transmissions, the frequency-selectivity of the channel is not always desirable. With higher frequency-selectivity, the errors are randomized, however, for packet transmissions burst errors are preferable to random errors. Hence, there is a need to evaluate the performance of packet transmissions in a frequency-selective channel. For packet transmission, some form of error control is necessary. To the best of authors' knowledge, the throughput performance of DS-CDMA with MMSE-FDE in the presence of error-control coding has not been evaluated yet. Hybrid ARQ (HARQ) with rate compatible punctured turbo (RCPT) codes [6, 7] is one of the promising error control techniques. In this paper, we introduce RCPT HARQ to DS-CDMA with MMSE-FDE and evaluate the performance improvement over DS-CDMA with rake combining. In addition, the throughput performance of DS-CDMA is compared with OFDM and MC-CDMA.

For a fair comparison, we keep the transmission rate fixed as that attainable with OFDM. Data rate equivalent to OFDM can be realized with DS-CDMA by assigning all the available orthogonal codes, equal to the spreading factor *SF*, to the same user, resulting in what is commonly referred to as multicode DS-CDMA. In MC-CDMA with the same number of subcarriers as in OFDM, when the number of multiplexed codes is the same as *SF*, the transmission rate is the same as in OFDM. MC-CDMA with SF=1 is in fact OFDM.

The rest of the paper is organized as follows. Section 2 presents the transmission system model. The simulation results are presented and discussed in Section 3. Section 4 concludes the paper.

2. TRANSMISSION SYSTEM MODEL

2.1. Overall system model

The transmission system model is shown in Fig. 1. The transmitter consists of a CRC encoder, an RCPT encoder, a bit interleaver, and a data modulator followed by an OFDM, MC-CDMA or DS-CDMA transmitter. The CRC encoder adds the error detection parity check sequence to a binary data sequence to form a CRC encoded sequence $\{u_k\}$ of length K which is input to the RCPT encoder. The rate 1/3 turbo encoder outputs the systematic bit sequence $\{u_k\}$ and the two parity bit sequences $\{p_k^{(1)}\}$ and $\{p_k^{(2)}\}$. The parity bit sequences are punctured according to the puncturing patterns for different RCPT HARQ schemes as described in Section 2.3 and the resulting sequences are buffered together with the systematic sequence for possible retransmissions. The punctured sequence that is to be transmitted is bit interleaved and data-modulated. Let the data-modulated symbol sequence be $\{x(n)\}$ with symbol length T. It is then transmitted as OFDM, MC-CDMA or DS-CDMA signal as described in the next section.

The receiver consists of a data-demodulator, a bit deinterleaver, an RCPT decoder and a CRC decoder in addition to an OFDM, MC-CDMA or DS-CDMA specific receiver. The recovered symbol sequence $\{\hat{x}(n)\}$ is demodulated, deinterleaved and input to the RCPT decoder, where error correction is performed and the CRC coded sequence estimate $\{\hat{u}_k\}$ is obtained. If no error is detected, the CRC decoder outputs the received binary data sequence. In the case of errors being detected by the CRC decoder, a retransmission is requested.

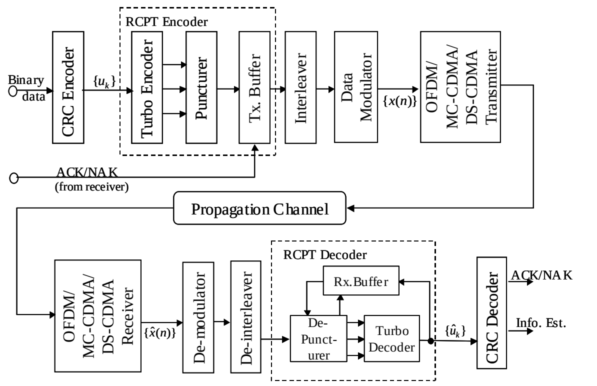


Fig. 1 Transmission system model.

2.2. Signaling techniques

Three signaling techniques - multicode DS-CDMA, multicode MC-CDMA and OFDM - are considered. In OFDM with N_c subcarries, N_c symbols are transmitted in parallel over a duration of N_cT, where T is the data-modulated symbol length. In DS-CDMA and MC-CDMA, N_c data-modulated symbols can be transmitted over a duration of N_cT when the number of multiplexed coded C=SF. However, time, frequency and code utilization differ among the schemes. Figure 2 shows how N_c data-modulated symbols are adjusted in each of the three signaling techniques. SF=N_c is assumed for DS- and MC-CDMA.

The DS-CDMA transmitter/receiver block diagram is shown in Figs. 3(a)~(c). The data-modulated symbol sequence is serial-to-parallel (S/P) converted to C symbol streams and each symbol in the C streams is spread by an orthogonal code with spreading factor SF (C is called the code multiplex order and $C \leq SF$). The C chip sequences are then added, multiplied by the scrambling code and transmitted over a frequency-selective fading channel after the insertion of guard interval (GI); N_g-chip GI is inserted every N_c-chips [5]. DS-CDMA with FDE and rake combing at the receiver are considered. For FDE, N_c-point fast Fourier transform (FFT) is carried out to convert the time-domain signal into N_c frequency components; GI is removed before FFT. After MMSE-FDE, inverse FFT (IFFT) is carried out to get back the time-domain signal that is despread to obtain $\{\hat{x}(n)\}$. For rake combining at the receiver, GI is not needed. The rake combiner consists of a correlator followed by a despreader and coherent detector for each path. The signals for all the paths are combined using the maximal ratio combining (MRC).

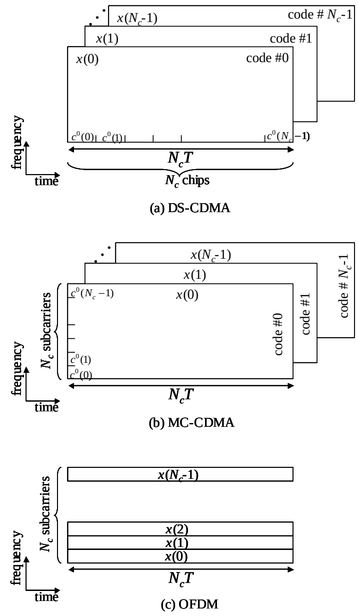


Fig. 2 Time, frequency and code utilization.

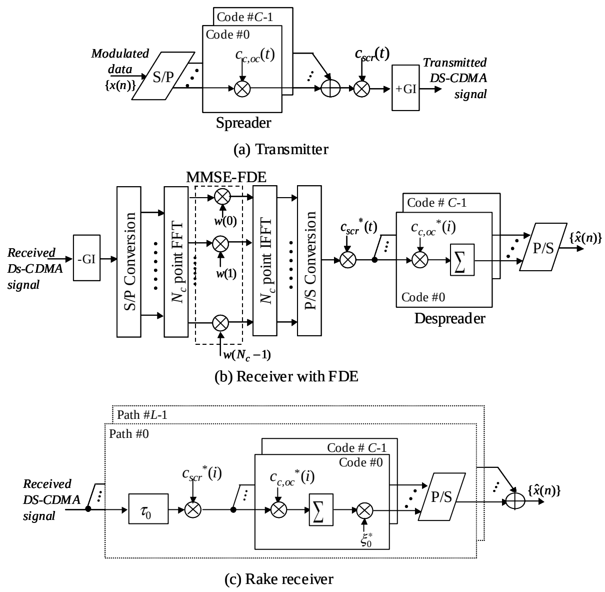


Fig 3 Multicode DS-CDMA transmitter/receiver.

In MC-CDMA, the spread signal is transmitted over a number of subcarriers. This is done by applying IFFT. The MC-CDMA transmitter/receiver is shown in Fig. 4. The code-multiplexing order for MC-CDMA is also taken to be C. For each code, N_c/SF data-modulated symbols are transmitted; a total of N_c symbols are transmitted per MC-CDMA signaling interval if C=SF. The MC-CDMA signal is transmitted over a frequency-selective fading channel after the insertion of GI. The received MC-CDMA signal is decomposed into the N_c orthogonal subcarrier components by applying the FFT. MMSE-FDE is carried out and the signal is despread using the different orthogonal codes to obtain $\{\hat{x}(n)\}$. OFDM is equivalent to MC-CDMA with SF=1.

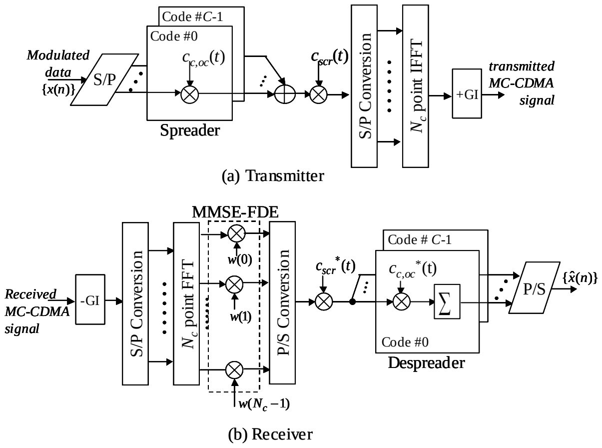


Fig. 4 Multicode MC-CDMA transmitter/receiver.

2.3. RCPT HARQ

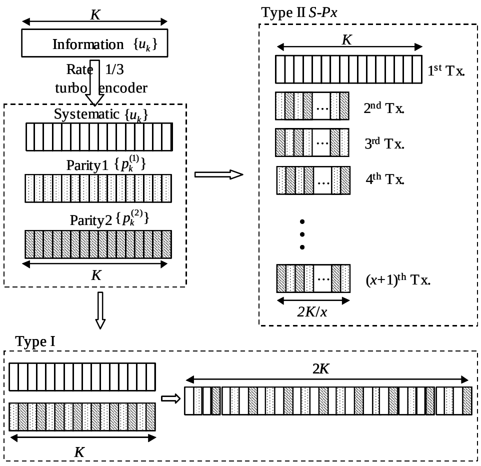


Fig. 5 Different RCPT HARQ schemes.

Two types of HARQ schemes – Type I and Type II – are considered in this paper. The schematic diagrams are shown in Fig. 5. They are obtained by puncturing a rate 1/3 turbo code with different puncturing period P [7].

(1) *Type I*: The two parity bit sequences $\{p_k^{(1)}\}$ and $\{p_k^{(2)}\}$, obtained after rate 1/3 turbo coding, are punctured with P=2 and transmitted along with the systematic (information) sequence. In case a retransmission is requested, the same packet is retransmitted and code combining [8] is employed.

(2) *Type II*: Three type II schemes are considered, represented by *S-Px* (Systematic-Puncture period $P = x$). $\{p_k^{(1)}\}$ and $\{p_k^{(2)}\}$ are punctured with P=x and x different sequences of length $2K/x$ are obtained, where K is the CRC encoded sequence length. In all the schemes, the first transmission consists of transmitting only the systematic bit sequence $\{u_k\}$ of length K. The number of bits transmitted in the second transmission onwards differs depending on the puncturing period. After each retransmission, turbo decoding is performed. As the number of retransmissions increases, the resultant code rate decreases. For *S-P*2, the systematic bit sequence and the two parity bit sequences are received after 3 transmissions, whereas it takes 5 and 9 transmissions for *S-P*4 and *S-P*8, respectively. In all the schemes, incremental redundancy [9] and code combing (in case the same packet is retransmitted) are utilized.

3. RESULTS AND DISCUSSIONS

The turbo encoder with (13, 15) RSC encoders and S-random interleaver is used. The decoder is a log-MAP decoder with 8 iterations. The channel interleaver used in the simulation is a size 2^a x 2^b block interleaver, where a and b are the maximum allowable integers for a given sequence size and are determined so that an interleaver as close as possible to a square interleaver can be obtained. Coherent QPSK data modulation/demodulation is assumed, unless otherwise stated. Walsh-Hadamard codes are used as orthogonal spreading codes and a long pseudo noise (PN) code is used as the scramble sequence.

The number N_c of subcarriers (or the number of FFT points) for MC-CDMA (or DS-CDMA) is taken to be N_c=256 with a GI length of N_g=32. Unless otherwise stated, SF=256 for both DS-CDMA and MC-CDMA. A 16-path Rayleigh faded channel having an exponential power delay profile with decay factor α and time delay τ_l=lT_c, l=0~15, is assumed, with T_c denoting the chip or sample duration. We have assumed block fading, where the path gains stay constant over one block (the block length in time equals T_{blk}=$(N_c+N_g)T_c$). The maximum Doppler frequency f_D normalized by T_{blk} of 0.001 and the decay factor of the power delay profile α=0dB (uniform power delay profile) are assumed unless otherwise stated. f_DT_{blk}=0.001 corresponds to a mobile velocity of about 100km/hr when the carrier frequency is 5GHz and the transmission rate is 100M symbols/sec. Ideal rake combiner with 16 fingers is assumed. For all the schemes, channel estimation is assumed to be ideal. In the following simulations, the information sequence length K=1024bits (CRC encoded sequence length is treated as the information sequence length). Ideal error detection and an error-free reverse channel are assumed. The number of retransmissions is taken to be infinite.

In the paper, for type II HARQ, the parity check packet is shorter than the systematic (information) bit packet. The data to be transmitted is divided into several packets, and they are transmitted using parallel independent stop-and-wait ARQ processes so that the transmission channel can be kept occupied all the time. Analysis of the throughput can be dealt with as a single ARQ process.

The throughput in bits per sec per Hertz (bps/Hz) is defined as the ratio of the number of information bits transmitted successfully to the total number of bits transmitted times the transmission rate normalized by the 3dB bandwidth. The maximum throughput attainable, when GI is inserted, is 1.8bps/Hz, 3.6bps/Hz and 5.3bps/Hz for QPSK, 16QAM and 64QAM, respectively.

3.1. Comparison of different HARQ schemes

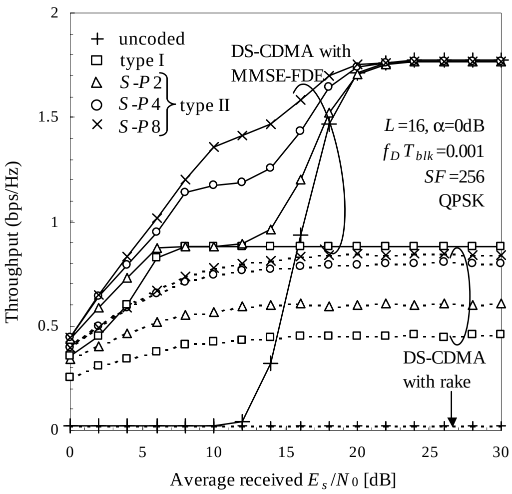
The throughput is plotted for the different HARQ schemes described in Section 2.3 as a function of the average received signal energy per symbol-to-the noise power spectral density ratio E_s/N_0 in Fig. 6(a) and (b) for α=0dB. SF=C=256 is assumed. The throughput of DS-CDMA with rake combining and MMSE-FDE is plotted in Fig. 6(a) and that of MC-CDMA and OFDM is plotted in Fig. 6(b). Type I HARQ scheme has better throughput than when no coding is applied, however as the redundancy bits equal to the number of information bits are always transmitted the throughput is always less than 0.5. Among the type II HARQ schemes, the highest throughput is attained with the type II HARQ *S-P*8 scheme for all the signaling techniques. The number of bits transmitted in the second transmission onwards is less for the *S-P*8 scheme; the transmission of unnecessary redundant bits is avoided and the throughput is seen to be better than either the type II HARQ *S-P*2 or *S-P*4 scheme. It can be observed from Fig. 6(a) that for all types of HARQ, MMSE-FDE provides a higher throughput than rake combining. When multiple codes are multiplexed, the orthogonality is destroyed in a frequency-selective channel. MMSE-FDE can restore the orthogonality to a certain extent. We see from Fig. 6(b) that the throughput of MC-CDMA and that of OFDM is same for type I HARQ. OFDM also benefits from a coding gain as redundancy bits are transmitted together with the information bits, resulting in an improved throughput. For type II HARQ, the MC-CDMA throughput performance is better than that of OFDM. There is no parity bit in the first transmission and hence no coding gain for OFDM; the throughput of type II HARQ OFDM is inferior to that of MC-CDMA. If we compare Figs. 6(a) and (b), we see that the throughput of DS-CDMA with MMSE-FDE is the same as that of MC-CDMA and is better than either OFDM or DS-CDMA with rake combining.

3.2. Effect of spreading factor

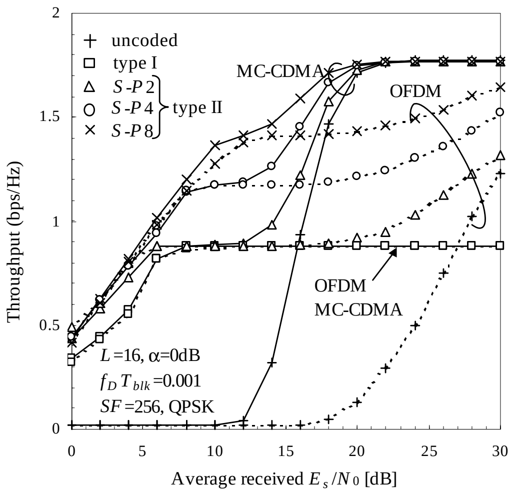
The throughput of DS-CDMA and MC-CDMA when SF<N_c is plotted in Fig. 7 for C=SF. For reference, the throughput of DS-CDMA with rake combining is also plotted. The throughput of uncoded DS-CDMA with rake combing is almost zero for all SF. For uncoded MC-CDMA, it is seen that the throughput increases with the increase in SF due to the increase in the frequency diversity effect and the highest throughput is obtained when SF=N_c=256. SF=1 corresponds to OFDM, and the throughput is almost zero due to no frequency diversity effect. With coding, the throughput is higher but almost independent of SF. For type II HARQ *S-P*8 using MC-CDMA, coding gain owing to better interleaving is obtained even for SF=1 (OFDM), but the throughput when SF=N_c is still the highest. On the other hand, in DS-CDMA, the frequency diversity effect is not a function of SF but the frequency-selectivity of the channel; full diversity gain is obtained for all SF. Hence, with type II HARQ *S-P*8, throughput is the same irrespective of SF for DS-CDMA. The throughput using DS-CDMA with MMSE-FDE is the highest for all SF<N_c but is the same as that of MC-CDMA for SF=N_c.

3.3. Effect of higher level modulation

The number of bits that can be transmitted with each transmission can be increased with the modulation level. With 16QAM and 64QAM, 4 bits and 6 bits can be transmitted over each symbol. However, the BER worsens as the Euclidean distance between the symbols reduces with the increase in the



(a) DS-CDMA (rake and MMSE-FDE)



(b) OFDM and MC-CDMA

Fig. 6 Throughput for different HARQ schemes.

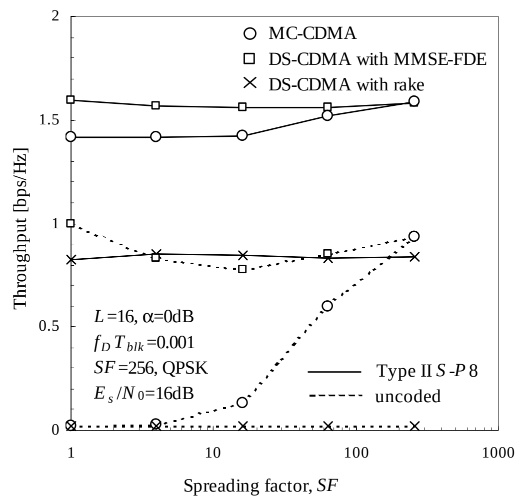


Fig. 7 Throughput for different spreading factor.

modulation level. The effect of modulation level on the throughput is plotted in Figs. 8(a) and (b) for type I HARQ and Type II HARQ *S-P*8, respectively. It is interesting to note two things: first the comparison among the modulation schemes and second the signaling techniques for each modulation level. In Fig. 8(a), it is seen that for lower E_s/N_0 region, which is strongly affected by the AWGN, the highest throughput is given by QPSK modulation. As E_s/N_0 increases, 16QAM gives a better throughput and for E_s/N_0>15dB, 64QAM gives the highest throughput. This is true for OFDM, MC-CDMA and also DS-CDMA with MMSE-FDE. However, if we compare the three signaling techniques, it is seen that for the region where QPSK modulation gives the highest throughput, all the signaling techniques have the same throughput. But for 16QAM and 64QAM, OFDM provides a higher throughput. This is because for higher level modulation, the orthogonality destruction among the codes is severer, and results in the performance degradation of MC-CDMA and DS-CDMA. In OFDM, there is no code multiplexing and a large coding gain can be attained in a frequency-selective channel owing to better interleaving, resulting in better throughput performance than either MC- or DS-CDMA.

Similar result is seen in Fig. 8(b) which plots the throughput of Type II HARQ *S-P*8. However for high E_s/N_0, the MC-CDMA and DS-CDMA throughput performances are seen to be better than that of OFDM. This can be explained as follows. Since no parity bit is transmitted in the first transmission, there is no coding gain for OFDM and a retransmission is requested. However for MC- and DS-CDMA, there is a large frequency diversity gain even without channel coding and hence for very high E_s/N_0 values, retransmission may not be necessary. Thus for all the modulation schemes, MC- and DS-CDMA throughput is higher than OFDM for high E_s/N_0 value.

4. CONCLUSION

The throughput of RCPT HARQ using OFDM, multicode MC-CDMA and multicode DS-CDMA with MMSE-FDE and rake combining was compared. It was found that in a frequency-selective fading channel, the RCPT HARQ throughput using DS-CDMA with MMSE-FDE is much higher than that with rake combining. The throughput using DS-CDMA with MMSE-FDE is same as that of MC-CDMA when $SF=N_c$, but higher than MC-CDMA for $SF<N_c$ including OFDM (SF=1). However with higher level modulation, for type I HARQ OFDM provides the highest throughput due to severe orthogonality destruction in DS-CDMA and MC-CDMA. For the type II HARQ, with no redundancy in the first transmission, DS-CDMA and MC-CDMA ($SF=N_c$) give higher throughput for high E_s/N_0 region where MC-CDMA and DS-CDMA benefit from frequency diversity gain.

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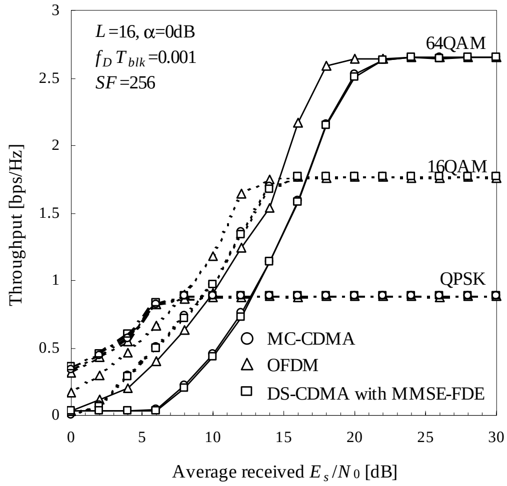
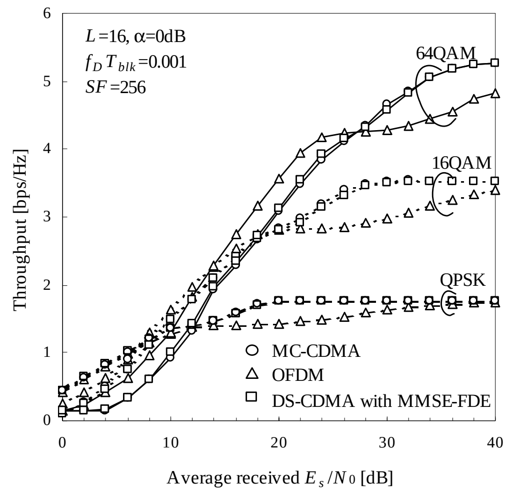


(a) Type I HARQ



(b) Type II *S-P*8 HARQ

Fig. 8 Throughput with higher level modulation.