Throughput of RCPT Hybrid ARQ for DS-CDMA with Diversity Reception and Rake Combining

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Abstract*— In this paper, we evaluate by computer simulations the throughput performance of rate compatible punctured turbo coded hybrid ARQ (RCPT HARQ) for direct sequence code division multiple access (DS-CDMA) with antenna diversity reception and rake combining in a frequency selective Rayleigh fading channel. The impact of a range of transmission system parameters and propagation parameters (viz.: the information sequence length, puncturing rate, spreading factor, number of diversity antennas, fading rate, and the power delay profile of the multipath channel) on the throughput is investigated. It is found that RCPT HARQ system has the highest throughput when minimum amount of redundancy bits is transmitted with each retransmission. In addition, the evaluations show that over a frequency selective fading channel, the throughput is almost insensitive to the information sequence length and the fading rate. It is also found that smaller spreading factor (*SF*) for a given chip rate gives a higher throughput in bps/Hz. Furthermore in the multi-user case, when the number of users is equal to *SF*, the total throughput for downlink is higher than that for uplink and is more or less independent of *SF*.

Keywords*— *hybrid ARQ, rate compatible punctured turbo codes, DS-CDMA, mobile communication

I. INTRODUCTION

Wideband DS-CDMA wireless access has been adopted in the 3rd generation mobile communication (3G) systems [1]. Recently, high speed and high quality packet data communication is becoming increasingly important. For packet data communication, hybrid automatic repeat request (HARQ) is the most reliable error control technique. A simple ARQ scheme does not apply channel coding, whereas in HARQ schemes, channel coding for error correction is utilized. In type II HARQ, a subset of HARQ, the redundancy bits transmitted for error correction are adapted to the channel condition to avoid retransmission of unnecessary bits. Rate compatible punctured turbo (RCPT) coding in a HARQ scheme has been shown to achieve enhanced throughput performance over an additive white Gaussian noise (AWGN) channel [2] and over fading and shadowing channels [3]. However, to the best of authors' knowledge, the effect of the various system parameters and propagation parameters on the throughput of type II HARQ has not been fully evaluated. In this paper, we evaluate by computer simulations the throughput performance of RCPT HARQ schemes in DS-CDMA with antenna diversity reception and rake combining for various parameters (viz., the frame length, puncturing rate, spreading factor, number of diversity antennas, fading rate, and the power delay profile of the multipath channel).

II. RCPT ENCODER/DECODER AND RCPT HARQ

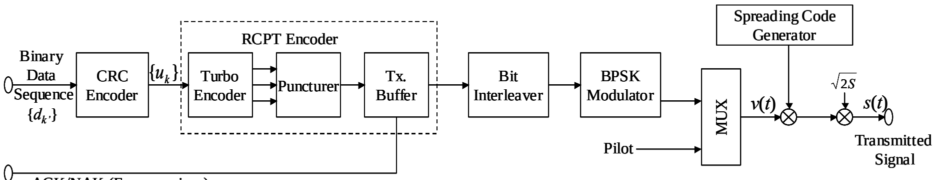
The RCPT encoder and decoder are included as part of the transmission system model (see Fig. 1). The RCPT encoder consists of a turbo encoder, a puncturer and a buffer. The turbo encoder considered in this paper is a rate 1/3 encoder. The turbo encoder/decoder parameters are shown in Table 1. The turbo-encoded sequences are punctured by the puncturer and the different sequences obtained are stored in the transmission buffer for possible retransmissions. With each retransmission request, a new sequence (i.e., previously unsent sequence) from the buffer is transmitted.

TABLE 1: Turbo encoder/decoder Parameters

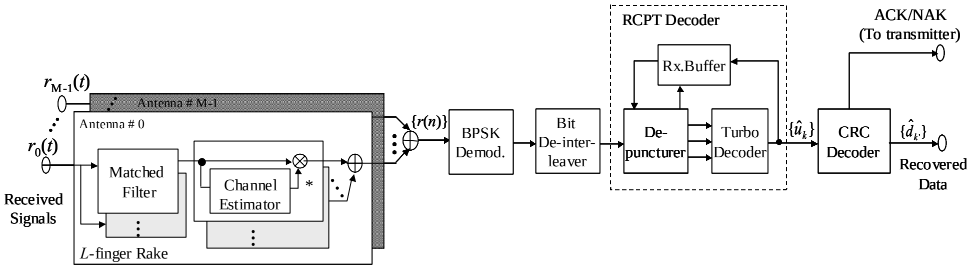
Encoder	Rate	1/3
	Component encoder	(13, 15) RSC
	Interleaver	S-random ($S=K^{1/2}$)
Decoder	Component decoder	Log-MAP
	Number of iterations	8

The RCPT decoder consists of a depuncturer, buffer and a turbo decoder (based on the Log-MAP algorithm). At the RCPT decoder, the newly received punctured sequence is combined with the previously received sequences stored in the receiver buffer. The depuncturer inserts a channel value of 0 for those bits that are not yet received and 3 sequences, each equal to the information sequence length, are input to the turbo decoder where decoding is performed as if all 3 sequences (the systematic bit sequence and the two parity bit sequences) are received.

Different HARQ schemes are obtained by puncturing the parity sequences by different puncturing period P [4]. For type I HARQ, the two parity bit sequences are punctured with P=2 and the punctured bit sequence is transmitted along with the systematic bit sequence. Three different types of type II HARQ schemes are considered, namely S-P2, S-P4 and S-P8, where the puncturing period for the two parity bit sequences are P=2, 4 and 8, respectively. The punctured sequences are of different length for different puncturing periods. In all these schemes, the first transmission consists of transmitting the systematic (information) bit sequence and subsequent transmissions consist of transmitting the punctured bit sequences stored in the buffer. Incremental redundancy and time diversity combining or Chase combining are employed in all the ARQ schemes.



(a) Transmitter



(b) Receiver

Figure 1. System model.

III. TRANSMISSION SYSTEM MODEL

The transmission system model is shown in Fig. 1. A CRC coded sequence of length K bits is input to the RCPT encoder. The RCPT encoder output sequence is interleaved and then transformed into a data modulated symbol sequence having symbol length T. For channel estimation at the receiver, known N_p pilot symbols are time-multiplexed every N_d data symbols. Spreading is implemented by multiplying the pilot-inserted sequence with the long pseudo noise (PN) chip sequence (and also short orthogonal sequence for downlink) having chip period T_c. The spreading factor (SF) is given by the ratio T/T_c.

The DS-CDMA signal is transmitted via an L-path Rayleigh fading channel having an exponential power delay profile with α [dB] as the decay factor. The receiver has M coherent rake combiners, corresponding to M antennas, each having L fingers assumed to be perfectly time synchronized to the corresponding paths. Channel estimation for coherent combining is performed based on the weighted multi-slot averaging (WMSA) algorithm [5]. The M coherent rake combiner outputs are combined and demodulated. The soft decision sample sequence after pilot-extraction is de-interleaved and fed to the RCPT decoder to recover the CRC coded sequence. A retransmission is requested if errors are detected.

IV. PERFORMANCE EVALUATION

The simulation conditions are summarized in Table 2. Unless otherwise stated, the following conditions are assumed. The CRC coded information sequence length is K=1024, the channel interleaver is a 2^a x 2^b block interleaver, where a and b are the maximum allowable integers, and the modulation scheme is BPSK. For channel estimation, N_p=4 and N_d=32. A L=4 path channel with uniform power delay profile (α=0), a difference of 1 chip between adjacent paths and a maximum normalized Doppler frequency $f_D T_c$=1/32000 is assumed. Error detection and the reverse channel are assumed to be ideal throughout the paper.

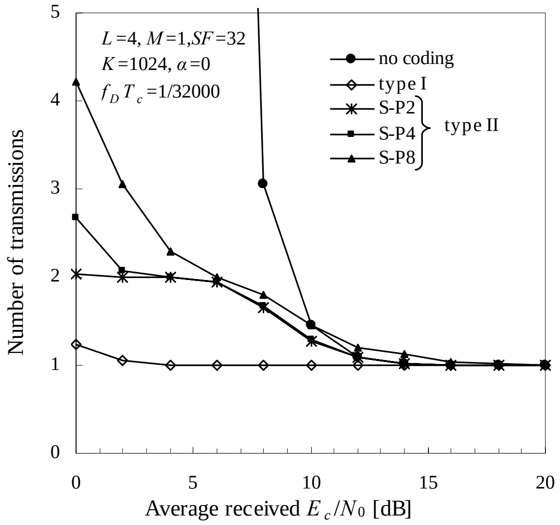
The throughput η (defined as the ratio of bits transmitted successfully to the total number of bits transmitted) of the RCPT HARQ is evaluated by extensive computer simulations. The impact of a range of system and propagation parameters (viz., the frame length, puncturing rate, spreading factor, number of diversity antennas, fading rate, and the power delay profile of the multipath channel) is discussed below.

TABLE 2: Simulation Conditions

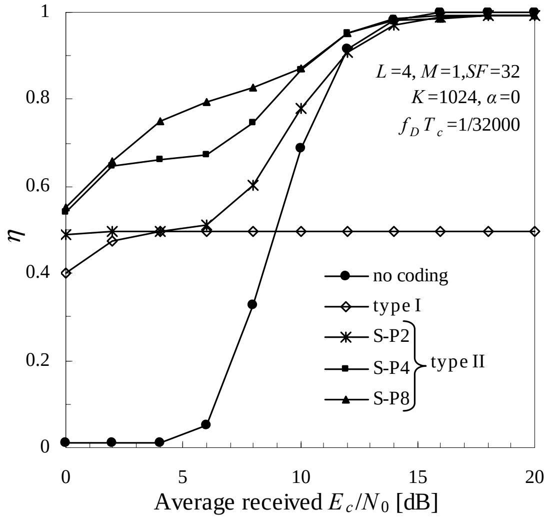
Information sequence length	K=128 ~ 2048 bits	
Channel coding	Turbo coding	
ARQ	Type	Basic, Type I, Type II
	Max. no. of transmissions	∝
Channel interleaver	Block interleaver	
Modulation/ Demodulation	Coherent BPSK	
CDMA	Spreading factor	SF=1 ~ 64
Propagation Channel	Forward	L-path Rayleigh fading (L=1~4) $f_D T$=0.0001~0.1
	Reverse	Ideal

A. Comparison of different HARQ schemes

The average number of transmissions and η for the different hybrid schemes are plotted in Fig. 2(a) and 2(b), respectively, as a function of the average received energy per coded bit per antenna-to-AWGN power spectral density ratio (E_c/N_0). For reference, the throughput and the average number of transmissions for basic ARQ scheme (i.e., no channel coding) are also plotted. From Fig. 2, it is seen that the type I HARQ scheme gives an improved throughput performance, compared to the basic ARQ scheme, at low average received E_c/N_0 values, and the average number of transmissions is almost always 1; however due to the redundancy bits added (1 parity check bit for every information bit), the throughput can never rise beyond 0.5 no matter how good the channel condition is. On the other hand, in the type II HARQ schemes, redundancy bits are transmitted only on request. This ensures that a throughput of 1 may be reached when channel condition is good although the average number of transmissions is higher than the type I HARQ scheme. It can be seen from Fig. 2(b) that among the type II HARQ schemes, the throughput is the best for the *S-P*8 even though the average number of transmissions is the lowest for the *S-P*2 scheme. Since the *S-P*8 scheme was found to give the best throughput performance, it has been used to evaluate the impact of other system parameters in the following evaluations.



(a) Average number of transmissions



(b) Throughput

Figure 2. Comparison of HARQ schemes.

B. *Impact of information sequence length*

Turbo codes are more robust for longer information sequence length; the BER degrades rapidly for shorter information sequence length. On the other hand, since the probability of frame error can be generally reduced according to the decrease in information sequence length, ARQ schemes are better suited for shorter information sequence length. Hence, it is implied that when ARQ is combined with error correction coding, the achievable throughput may be relatively insensitive to the information sequence length. The throughput of type II HARQ *S-P*8 obtained for different average received E_c/N_0 is plotted as a function of the information sequence length in Fig. 3. It is seen that in the case of ideal channel estimation, the throughput is almost insensitive to the information sequence length.

When *k*=2 WMSA channel estimation technique [5] is used, the η decreases owing to the channel estimation error and the addition of pilot symbols; the trend of the throughput performance is the same as for ideal channel estimation.

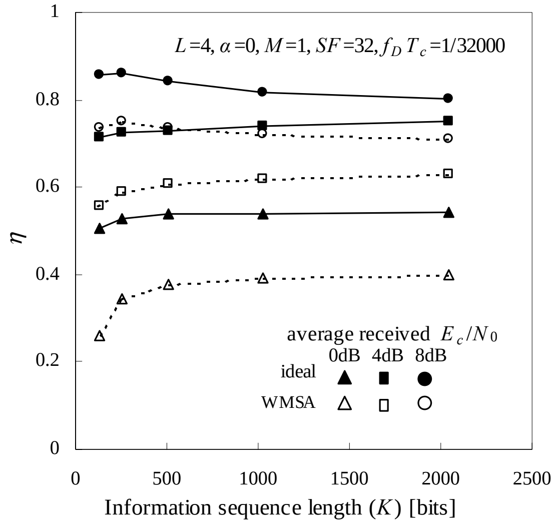


Figure 3.Impact of information sequence length.

C. *Impact of spreading factor*

Figure 4 plots η as a function of *SF* with the average received E_c/N_0 as parameter for the type II *S-P*8. The throughput is more or less independent of *SF* for $SF \geq 8$. For smaller *SF*, the η decreases due to increasing inter-path interference (IPI), however, a throughput of 0.34 can still be achieved at the average received E_c/N_0=4dB for WMSA channel estimation even when *SF*=1 (no spreading).

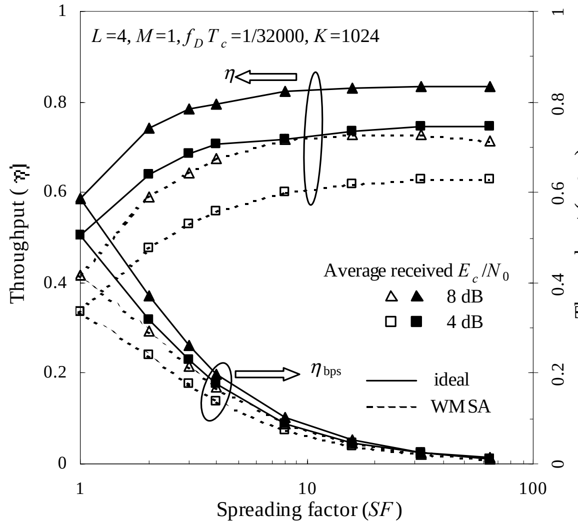


Figure 4. Effect of spreading factor.

For high-speed communications, lowering the *SF* may be advantageous as it allows higher rate data transmission for a fixed chip rate at the cost of retransmissions of few extra bits. The throughput in bps/Hz (η_{bps}) is also plotted in Fig. 4. It is found that η_{bps} increases as the *SF* decreases; the use of *SF*=1 (no spreading) achieves η_{bps} as high as 59% of the chip rate at the average received E_c/N_0 of 8dB. A possible reason for achieving this high throughput in bps is qualitatively explained below. The rake combiner, which has *L* fingers each perfectly synchronized to its corresponding path, can be viewed as a selection combiner that selects the best path having the maximum path gain. If all the channel gains associated with *L* paths are almost equal, large IPI is produced and hence packet error results with a high probability. If this situation occurs, a retransmission is requested; however, the same situation happens quite rarely, resulting in a successful transmission. This stops the throughput from falling to zero despite of *SF*=1. The use of *SF*=1 offers an 8 times faster transmission rate compared to the use of *SF*=8; the consequence is an increased throughput in bps.

D. Impact of the number of receive antennas

Figure 5 plots η as a function of average received E_c/N_0 per antenna with the number *M* of antennas as a parameter. The throughput increases with the increase in the number of antennas. When *M* is increased from 1 to 2, the throughput improves from 0.86 to 1 giving a 16% improvement in throughput for average received E_c/N_0 per antenna =10dB when channel estimation is ideal. However the additional improvement decreases as the number of antennas increases.

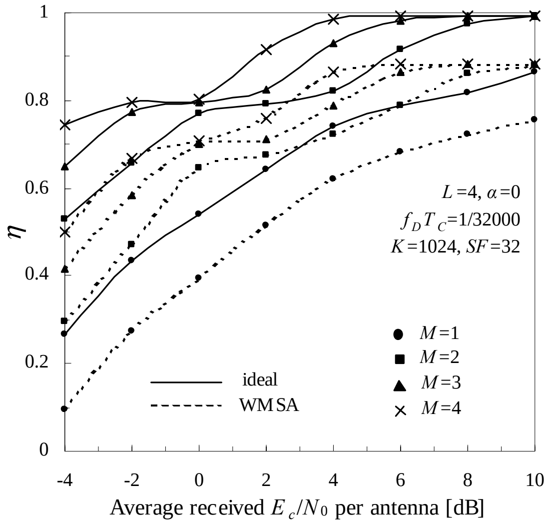


Figure 5. Impact of the number of diversity antennas.

E. Impact of maximum Doppler frequency

Smaller value of the normalized maximum Doppler frequency f_DT corresponds to slow traveling speed of the mobile terminal and vice versa for a given spreading factor and chip rate. Figure 6 plots η for type II HARQ *S-P*8 scheme as a function of f_DT for various average received E_c/N_0 values (here, *M*=1, *L*=4 and *K*=1024). Although the BER performance is dependent on the value of f_DT, the throughput is found to be almost insensitive to the f_DT value. The reason for this is as follows. As f_DT decreases, the coding gain decreases owing to the smaller interleaving effect. However, this is offset by the fewer frame errors owing to the burst error property, which is favorable for ARQ.

As discussed earlier when the WMSA channel estimation scheme is used, the throughput decreases owing to the channel estimation error and the insertion of pilot symbols. It is seen from Fig. 6 that the throughput stays more or less constant for f_DT less than 0.003, however it decreases drastically when f_DT approaches 0.01. In this case, the fading is too fast for the *k*=2 WMSA channel estimation to track.

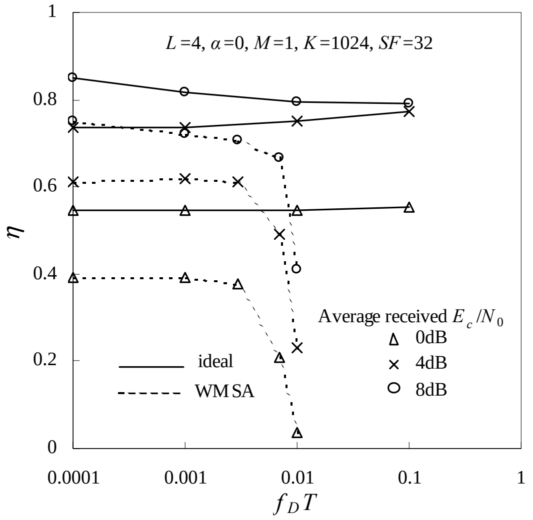


Figure 6. Impact of fading maximum Doppler frequency

F. Effect of the power delay profile shape

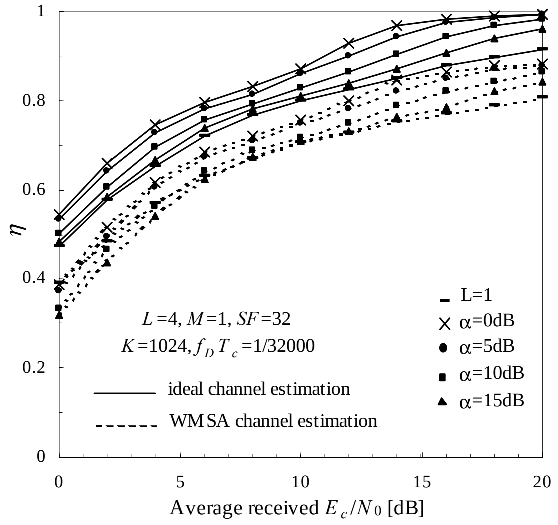


Figure 7. Impact of power delay profile shape

The results presented above are for a uniform power delay profile shape. In this section we discuss the effect of the non-uniform power delay profile shape. Figure 7 plots η as a function of the exponent α of the power delay profile shape. α=0dB corresponds to a uniform power delay profile shape and when α=15dB the profile approaches that of a single path (*L*=1) channel. It is seen that as α increases, the throughput decreases and approaches that of L=1. However for WMSA channel estimation, the throughput becomes even worse than that of L=1 for lower average received E_c/N_0 values. This is because the rake combiner has four fingers at all times irrespective of the strength of the corresponding paths. When the power of a certain path is weak, more channel estimation error occurs resulting in decreased throughput.

G. *Multiuser case*

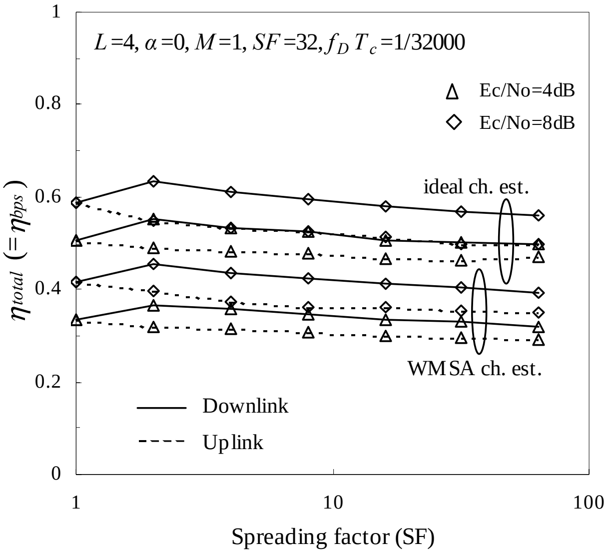


Figure 8. Throughput for multi-user case.

So far, we have considered only the single user case. Figure 8 plots simulation results on the total throughput η_{total} achievable for downlink and uplink with the number of users equal to SF (η_{total} is defined as the ratio of total bits transmitted successfully for all users to the total number of bits transmitted for all users). Hence, $\eta_{total}=\eta_{bps}$. The total transmission rate is equal to the chip rate. We have assumed a slow transmit power control that completely regulates the distance dependent path loss and shadowing for the uplink transmission.

It is observed that the throughput for the downlink case is always higher than that for the uplink case for all values of SF. This is because, on the downlink, no multiuser interference (MUI) is produced in the same propagation path owing to the use of short orthogonal spreading sequences. With larger SF, more users can be multiplexed, but the MUI produced by IPI increases. Therefore, there exits an optimum SF that maximizes the total throughput. The total throughput is seen to be highest when SF=2. However, the result is different in the case of uplink; it is observed in Fig. 8 that the highest total throughput is obtained when SF=1.

It is interesting to note that similar throughput can be achieved for all values of SF and hence, no spreading (SF=1) might be used. When SF=1, CDMA multiple access is not possible and some form of random time division multiple access (TDMA) with scheduling should be utilized. One similar scheme but with SF>1 is found in [6]. When SF=1, only one user is in communication at a time and hence no MUI exists in the time interval assigned to that user. However, note that there exists strong IPI, which cannot be ignored but can be reduced by coherent rake combining and retransmissions. The rake combiner is a channel matched filter that coherently combines the delayed versions of the same BPSK symbol and incoherently adds interference from adjacent symbols, thereby improves the signal-to-IPI power ratio (SIR). It is important to note that rake combining approximately acts to select the best path having the largest instantaneous power. Hence, SIR is always larger than unity. If the selected path is too weak, packet error may occur due to AWGN and IPI even after powerful turbo decoding. However, retransmission follows. In this way, the combined use of rake combining, powerful turbo decoding and ARQ contributes to obtaining a good throughput even when SF=1.

V. CONCLUSION

The throughput performance of the RCPT coded type II HARQ scheme in DS-CDMA was evaluated by computer simulations. The evaluation was done for ideal channel estimation and WMSA channel estimation. From the detailed evaluations presented in this paper, we can draw the following conclusions.

The turbo-coded type II HARQ has the highest throughput when minimum amount of redundancy bits is transmitted with each retransmission. The throughput performance improves with the increase in the number of diversity antennas. However, the additional improvement in performance decreases as the number of antennas increases. The throughput is almost insensitive to the information sequence length and f_DT when channel estimation is perfect; however when practical channel estimation is employed, the performance degrades for fast fading rate. In the single user case, the throughput defined in bps/Hz is higher for lower SF despite of the stronger effect of IPI. In the multi-user case, when the number of users is equal to SF, the total throughput for downlink is higher than that for uplink and is more or less insensitive to SF.

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