Turbo-Coded ARQ Schemes for DS-CDMA Data Networks Over Fading and Shadowing Channels

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Abstract— **In this paper modified ARQ (automatic-repeat-request) techniques based on turbo coding are investigated for asynchronous DS-CDMA (direct-sequence code-division multiple-access) data networks under shadowing and frequency selective fading channel conditions. The throughput, delay, and energy efficiency performance of standard ARQ, metric combining, and RCPT (rate compatible punctured turbo) coded ARQ schemes are compared via simulations. The RCPT/ARQ schemes are shown to outperform the other two schemes in terms of both throughput and energy efficiency at the cost of larger delay and complexity. Maximum network throughput is investigated for different ARQ schemes under energy constraints.**

I. Introduction

The growing popularity of transmitting data traffic in wireless communications necessitates the development of ARQ protocols suitable for channels that suffer from severe fading and MAI (multiple access interference). In standard ARQ protocol, if a packet is received containing errors, the packet is discarded and a NAK (negative acknowledgment) is sent to the receiver. This protocol is reasonable under the assumption of small packet error rate (P_e is usually well below 10^{-2} for wired data networks). In severe channel conditions, packets need to be heavily protected with FEC (forward error control) coding in order to maintain an acceptable error rate. However, if the bad channel conditions persist, even very powerful codes such as rate $\frac{1}{3}$ turbo codes could fail repeatedly. More robust and efficient modified ARQ protocols which adapt the code rate according to the channel condition were proposed in [1], [2], [3], [4].

Metric combining is a robust modified ARQ scheme that requires minimal complexity [1], [2]. In metric combining FEC/ARQ schemes, when a decoding error occurs, the packet is retransmitted. The receiver then averages the demodulator output metrics from all received copies of the packet and attempts to decode with the combined packet. The basic idea behind metric combining is to improve the effective channel SNR (signal-to-noise ratio) by combining multiple copies of the received packet. The metric combining algorithms can also be viewed as concatenating a family of repetition codes of rates $\{1, \frac{1}{2}, \frac{1}{3}, \cdots\}$ and a fixed-rate FEC outer code. Instead of using a repetition code, there are usually more flexible ways to construct error correcting codes of varying rate, such as rate compatible FEC codes. A rate compatible FEC code family is a collection of codes such that all coded bits of higher rate codes are contained in lower rate codes. Upon each retransmission, the encoder transmits new parity redundancy so that a more powerful code is formed by combining packets from all transmissions.

In [3], [4] rate compatible FEC codes were investigated in single user communications systems. Thus, no MAI was considered and the performance metric was local throughput. In [5], we investigated the performance of RS-RCPT coded ARQ protocols in asynchronous DS-CDMA data networks over memoryless fading channels. Delay and network throughput performance of different ARQ schemes were investigated. In this paper, we study turbo-coded ARQ protocols over correlated shadowing and fading channels. Energy efficiency metric is also introduced for the study of low energy communications systems.

The remainder of the paper is organized as follows. In section II, the system model is introduced. In section III, the structure of turbo and RCPT codes is briefly described. In section IV, performance of ARQ protocols for DS-CDMA data networks is presented. In section V, we conclude with a discussion of results.

II. System Model

The multiple-access problem addressed in this paper involves K mobile transmitters and K receivers at the base station. The baseband system block diagram of a transmitter-receiver pair is shown in Fig. 1.

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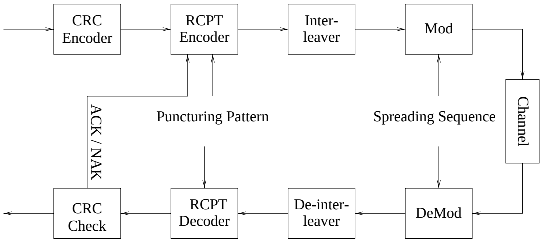

Fig. 1. Block diagram of a RCPT coded FEC/ARQ scheme for a DS-CDMA system

The mobile transmitter is composed of a cyclic redundancy check (CRC) encoder, an RCPT encoder, a bit interleaver, and a spread spectrum BPSK modulator. We model the spreading sequence for each user as an independent and identically distributed binary sequence. We also assume that each user transmits asynchronously. The number of information bits per packet is 424 (the size of a standard ATM cell). The RCPT encoder encodes the information packet and buffers all coded bits for possible retransmissions.

As shown in Fig. 1, the CDMA receiver consists of a demodulator, a bit deinterleaver, an RCPT decoder, and a CRC decoder. The network protocol assumes that the CRC parity check is long enough, hence the probability of undetected errors can be ignored. In simulations, we further assume that the header information can be correctly retrieved due to heavy FEC protection. If decoding errors are detected, a NAK is sent to the transmitter via a feedback channel, which is assumed to be error-free in simulations.

Two fading channel models with different power control assumptions are studied in this paper. In both cases, the fading is assumed to be slow enough (relative to the coded bit rate) that it remains constant over a coded bit duration. Provided the bit interleaving is sufficiently long, the fading can be modeled as independent from bit to bit. Also, hen a large number of users are present in the system, the multiple-access interference can be approximated as Gaussian noise. In the first channel model, we assume that average power control is employed over a frequency-selective fading channel. By average power control, we mean that the power control scheme can compensate for the effect of path loss and shadowing so that the average received power is the same for all users. In a wideband CDMA system, the frequency-selectivity within the bandwidth is usually significant. In this paper, we assume that there are L resolvable and independent equal strength paths for each user's channel. If the receiver has perfect channel side information, i.e., the Rayleigh fading level is known for each path, a RAKE receiver can be used to perform maximum ratio combining.

In the second channel model, we assume that power control is not available. The large-scale fading process is modeled as a shadowing process which has a log-normal distribution, i.e., the logarithm of the received signal strength has a Gaussian distribution. The mean of the shadowing process is the path loss, which is assumed to be constant in our study. Since the shadowing is usually a very slow process compared to the data rate, the shadowing is assumed to be constant over a packet duration. Therefore, the effect of shadowing on reception is analogous to varying the signal-to-interference ratios $\overline{\gamma}$ for each packet. The correlation between the shadowing factors of adjacent packets is modeled as an exponentially decreasing autocorrelation function [6]. Suppose the mobile velocity is v m/s, the correlation $R(T)$ of two packets which are T seconds apart is given by

$$R(T) = \sigma_s^2 \epsilon_D^{vT/D}$$

where σ_s is the standard deviation of the shadowing level, and ϵ_D is the correlation between two points separated by distance D. According to the 1700 MHz measurement in an urban area [6], σ_s was estimated to be 4.3 dB, and the correlation of two points 10 meters apart from each other was estimated to be 0.3, i.e, $\epsilon_{10} = 0.3$. These values are used for the parameters in our simulations. In the rest of this paper, we will refer to the first channel model as the fading channel and the second one as the shadowing channel.

III. RATE COMPATIBLE PUNCTURED TURBO CODES

Since the structure of turbo codes has been described in detail in many papers, only a brief description of turbo codes will be given. Then, the key component of the ARQ protocol, the rate compatible punctured turbo code, will be introduced.

The original turbo codes [7] are parallel concatenated convolutional codes in which the information bits are first encoded by a recursive systematic convolutional (RSC) encoder, and then, after passing through an interleaver, are encoded by a second recursive systematic convolutional encoder. The codewords are composed of the information sequence and the parity check sequences from the two encoders. In our simulations, the pseudo-random interleavers are designed using S-interleaver techniques [8].

The decoding algorithm of turbo codes is a suboptimal iterative algorithm. For each constituent code sequence, a maximum *a posteriori* (MAP) module generates likelihood values for each bit based on the soft-input from the demodulator and other MAP modules. After a number of iterations, a decision for each information bit is made based on the sum of log-likelihood values of that bit from all MAP modules.

A family of RCPT codes can be obtained by puncturing the coded bits of a rate $\frac{1}{n}$ turbo code. Each output bit stream of the turbo code is punctured according to a puncturing pattern, which has period p. The puncturing patterns for n bit streams are represented by an $n \times p$ matrix $\mathbf{P}$, where the ith row of $\mathbf{P}$ denotes the puncturing pattern for the ith bit stream. Detailed description of puncturing patterns can be found in [4], [5]. An efficient selective-repeat ARQ system can be implemented with a reasonable choice of RCPT code for each retransmission[4], [5].

IV. RESULTS

Under the assumption that the number of users in the network is constant and each user has duty factor 1, simulations using 20000 packets obtain the performance of rate $\frac{1}{3}$ turbo-coded standard ARQ, turbo-coded metric combining ARQ, and RCPT/ARQ schemes. In the simulations, we assume that the mobile velocity is 20 m/s, the data rate is 1 Mbps, and the feedback delay is 20 ms. The offered load is defined as $L = \frac{K}{N}$, the normalized network throughput is defined as $\eta(\overline{\gamma}) = \frac{1}{J}\frac{K}{N}$, and the normalized energy efficiency is given by $\lambda(\overline{\gamma}) = \frac{N_0}{E_b}$, where K is the number of users; N is the spreading factor; J is the reciprocal of effective code rate with signal-to-background noise ratio $\overline{\gamma}$.

Two families of RCPT codes are considered. The first code family, RCPT_{P8}, which was proposed in [4], has puncturing period 8. In RCPT_{P8}/ARQ, the transmitter transmits the uncoded information packet in the first transmission and sends incremental parity packets of size one-quarter of the information packet. The second code family with puncturing period 2, RCPT_{P2}, uses one uncoded transmission and two more parity check transmission to reach the code rate $\frac{1}{3}$. Both code families employ a 4-state turbo code with generator polynomial $\frac{5}{7}$. Decoding decisions are made after ten iterations in the turbo decoder.

Fig. 2 demonstrates the throughput performance of the four ARQ schemes that we are considering over the fading channel with $\overline{\gamma} = 4.77$ dB. The RCPT_{P8}/ARQ scheme has slightly better throughput performance than the RCPT_{P2}/ARQ scheme for $L < 3$, while the throughput of both RCPT/ARQ schemes are virtually the same for $L > 3$. The standard ARQ system achieves maximum throughput of 1.05 at $L = 3.4$, then decreases sharply with increasing L. The metric combining ARQ scheme has the same performance as the standard ARQ when the network load is less than 3, but is much more robust under severe interference. Compared with RCPT/ARQ schemes, both standard ARQ and metric combining ARQ schemes fail to achieve comparable throughputs when $L < 1$, which is where most current cellular systems operate.

In Fig. 3, the energy efficiency of the four protocols are compared for the case where $\overline{\gamma} = 4.77$dB. The energy efficiency, in general, decreases with increasing network load (increasing interference level). At $L = 0.4$, the minimum offered load we simulated, RCPT_{P8} has $\lambda = 0.19$, and the energy efficiency of RCPT_{P2}, metric combining, and standard ARQ is 0.17, 0.11, and 0.11, respectively. When $L > 3$, energy efficiency of standard ARQ approaches 0 quickly, while all other three schemes maintain $\lambda > 0.05$. Due to the limits on space, the discussion of energy efficiency performance for other signal-to-background noise levels, which can be quite different from the curves shown in Fig. 3, can be found at URL `http:\\www.eecs.umich.edu\~tji\MILCOM.d`.

In Fig. 4, the average delay of the ARQ schemes over fading channels was demonstrated. We observe that RCPT_{P2} scheme has only about one-third of the delay of RCPT_{P8} scheme. This complies with our intuition that RCPT codes with shorter puncturing periods (and thus larger parity check packet) needs less number of retransmissions to lower the code rate to $\frac{1}{3}$ than the codes with smaller parity check packet size. The delay of standard ARQ scheme diverges to infinity when $L > 3$, and the delay of metric combining scheme is the lowest of all four schemes.

Figs. 5-7 show the simulation results over shadowing channels with $\overline{\gamma} = 4.77$dB. It is demonstrated that all performance curves are smoother than their counterparts over fading only channels due to the SNR averaging effect of the shadowing process. We also notice that the network throughput for all four ARQ schemes is smaller at light traffic loads and larger at heavy network load than their counterparts over the fading channels.

In Figs. 8 and 9, the normalized network throughput maximized over signal-to-background noise ratio and offered load is plotted against the energy efficiency. It is observed that maximum achievable network throughput decreases with increasing energy efficiency requirement. In both plots, RCPT/ARQ can always achieve larger throughput than metric combining and standard ARQ with any energy constraint. We also notice that the optimal throughput is mostly achieved by the lowest signal-to-background noise ratio used in simulation. Note that the dashed curves only indicate lower bounds of the achievable throughput due to the limits on the lowest $\overline{\gamma}$ we can simulate.

V. CONCLUSION

Rate $\frac{1}{3}$ turbo-coded standard ARQ, turbo-coded metric combining ARQ, and RCPT/ARQ schemes are investigated for the uplink traffic of asynchronous DS-CDMA data networks. Multipath fading and shadowing channels with perfect side information are considered. Compared with rate $\frac{1}{3}$ turbo-coded standard ARQ scheme, the RCPT/ARQ schemes provide significant increase in normalized throughput at the cost of additional storage requirements. Shorter puncturing period RCPT/ARQ have similar throughput and energy efficiency performance as longer period RCPT/ARQ but with much smaller average delay. RCPT/ARQ schemes are also shown to be more energy efficient than the standard ARQ and metric combining schemes. It is observed that maximum network throughput is obtained at small energy efficiency and larger energy efficiency leads to smaller network throughput.

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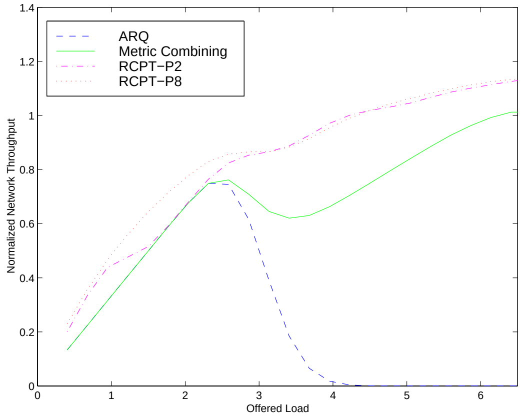

Fig. 2. Throughput comparison of ARQ schemes over fading channel

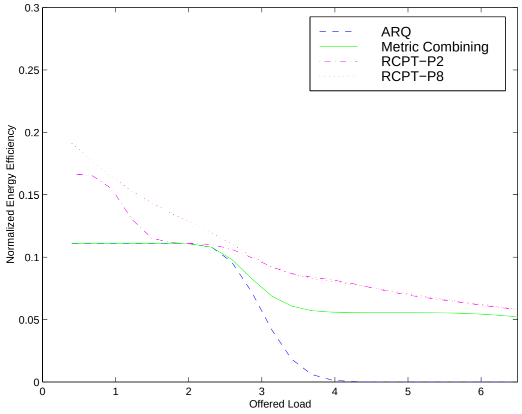

Fig. 3. Energy efficiency comparison of ARQ schemes over fading channel

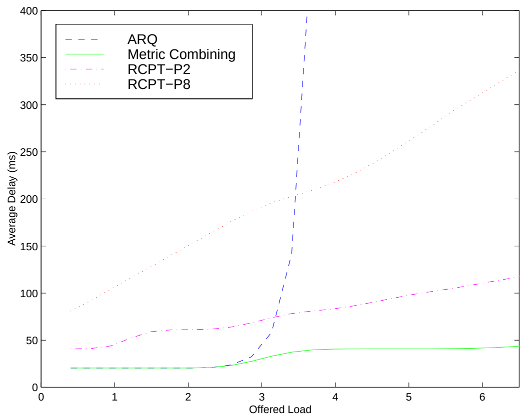

Fig. 4. Delay comparison of ARQ schemes over fading channel

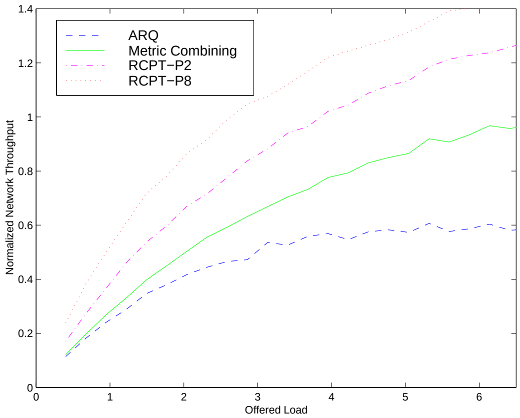

Fig. 5. Throughput comparison of ARQ schemes over shadowing channel

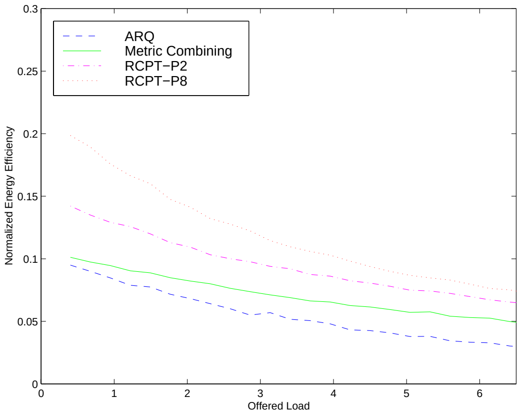

Fig. 6. Energy efficiency comparison of ARQ schemes over shadowing channel

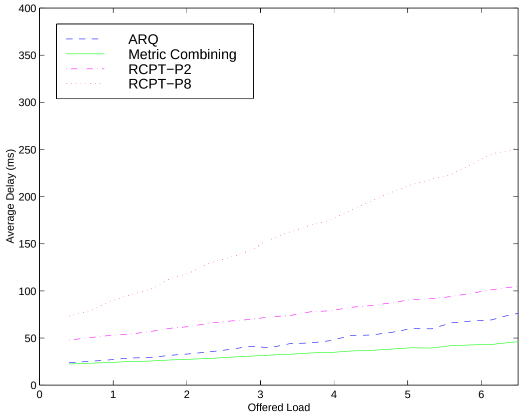

Fig. 7. Delay comparison of ARQ schemes over shadowing channel

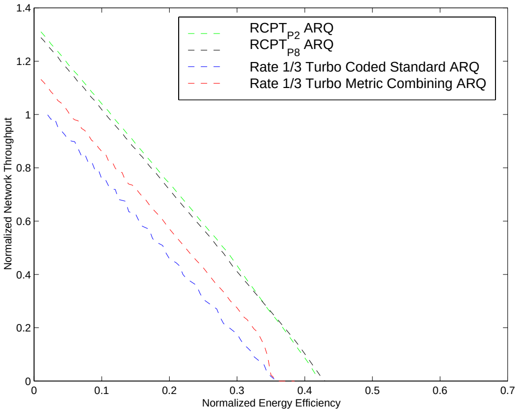

Fig. 8. Maximum network throughput versus energy efficiency over fading channels

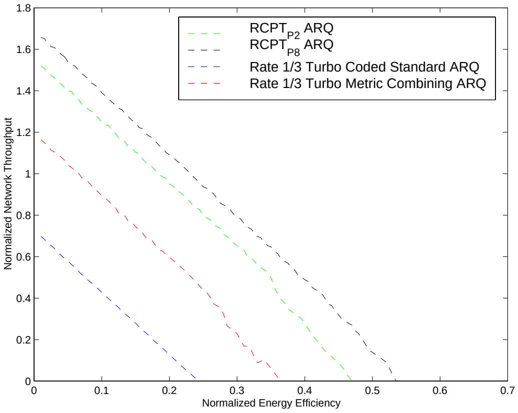

Fig. 9. Maximum network throughput versus energy efficiency over shadowing channels