Abstract—This paper presents an uplink retransmission control scheme to improve the system throughput based on the active-user estimation capabilities offered by Kalman filtering in a multiuser single CDMA cell. The improvement is achieved by means of selecting the best subset of users with the power-controlled opportunistic retransmission control (PORC) based on the radio resources reservation and a joint PHY-MAC opportunity function, which also takes the channel information and the waiting time into account. Simulation results show that the proposed strategy exhibits significant improvement in terms of throughput and fairness.

I. INTRODUCTION

CDMA random access is a very widely accepted multiple access technique for wireless applications. One striking feature of a CDMA system is to allow the receiver to resolve multiple simultaneously transmitted packets [1]. Due to the variance of wireless channels, in a multiuser packet CDMA system, there is always a very high probability of packet collision. The collisions may occur when the number of concurrent active user is larger than the number of available spreading codes (protocol-collision model) in a overloaded system, or when there is no power control scheme can guarantee the signal-to-interference plus-noise ratio (SINR) for concurrent transmissions (physical-collision model). Because the collided packets that are usually dropped by the receiver and retransmitted later, the system throughput severely degrades. Traditionally, medium access control (MAC) protocols have been designed to deal with the protocol-collision resolution or retransmission control problem [2]-[4].

In the past, some of the earlier research [5] focused on the downlink scheduling. However, the growth of other services like ftp/video-phone have resulted in some researches on the subject of uplink scheduling [6]-[7]. Those uplink applications require high data rates or loss-free transmission so that the retransmission becomes an important issue. Therefore, the wireless systems desire an on-line scheduling and adaptive retransmissions control (ARC) scheme that can change parameters based on the importance of packets and the channel conditions [2]. Specifically, in [6], the uplink throughput maximization was achieved by choosing the “best” $k$ users in terms of their received power. In [4] the favorable channel conditions corresponded to the signal being received at higher SINR than a predefined threshold. Throughput was maximized by choosing the users with “relatively best” channel for transmission/retransmission with a predetermined probability. However, transmission/retransmission probability is actually a random variable of channel condition. Such schemes favored a few strong (power or SINR) users and resulted in the unfairness of resource allocation.

Opportunistic scheduling is usually intended to balance throughput and QoS constraints (e.g. SINR guarantee) [8]. In this paper, we apply adaptive retransmission control in conjunction with power control to opportunistically exploit variations in user channel conditions, then select the best subset of users to retransmission such that maximize throughput. The proposed power-controlled opportunistic retransmission control (PORC) strategy transformed the retransmission problem into the code-time-slot resources utilization efficiency problem to improve resource utilization and the throughput. The number of active-user (including new and existing users) were estimated by means of capabilities offered by Kalman filtering [9]. Then the system performed a joint adaptation processing on the PHY-MAC information such as power control parameter, collision probability, and waiting time, so that the system throughput could be maximized with fairness.

II. SYSTEM MODEL

We consider a TD/CDMA single cell uplink system: there are $N$ available codes for users, and can be viewed as a special case of Multi-Packets Reception (MPR) model [1]. It is allowed to have $M$ registered users that transmit $K_n$ simultaneous packets with size of $L_k$ symbols and at rate $R_k$ in one slot duration. The system uses QPSK with coherent demodulation. A minimum QoS relative SINR threshold $\gamma_k$, [as defined later in (2)] must be met for a user $k$ to transmit on the Rayleigh fading channel. Each user generates Poisson traffic. We assume that the base station (BS) gives the mobile
station (MS) permission to use a particular spreading code, and gets ready to receive packets by tuning a receiver to the spreading code. The BS obtains user or channel state information and then centralized schedule users’ transmission through the control channel.

![Packet Gen](Packet Gen)  
Retran. Packet  
K_r = the best (N - K_s)  
P_R  
CDMA Spreading  
Modulation  
Rayleigh  
N [P_{succ} \leq \text{SINR}_k]  
\frac{1}{\text{succ}}  
\text{De-Mod.}  
\text{De-Spread}  

Fig. 1. Retransmission Control in DS-CDMA

As depicted in Fig. 1, users generate \( K_n \) packets in a slot with probability \( P_g \). The \( K_r \) unsuccessfully transmitted packets are retransmitted in the later time slot with probability \( P_r \). The channel inputs \( K = K_n + K_r \), where \( K_n \) and \( K_r \) are two independent random variables. The system throughput is maximized with respect to total channel input \( K \). The packets are transmitted with probability \( P_i \), and spread by a pre-assigned spreading code with probability \( P_s \) finally. The packet is physical-collided at BS with probability \( P_{coll} \). \( P_{succ} \) is the probability of successful packet receiving. The new packet generation and retransmission of collided packets are considered as two separate issues.

A. Channel and CDMA Physical Layer Model

The transmitters first QPSK modulates the data signal and spreads it with a Gold sequence. The spread data of all users are transmitted to the BS in a noisy Rayleigh fading channel. The BS detects the information data of each user by correlating the received signal with a code sequence allocated to each user.

Consider an uplink synchronous \( M \) users CDMA system with spreading gain \( N \) and \( K \) active users. Let \( \mathbf{S} = [\mathbf{s}_1, \mathbf{s}_2, ..., \mathbf{s}_K]^T \) be the \( K \times 1 \) spreading vector of length \( N \) used by the \( k \)th user, where \((\cdot)^T\) denotes transpose. Assume there are \( K \) active users with \( L \)-size information frames \( \mathbf{b}_k \) as independent identically distributed (i.i.d.) random variables of \( E[|b_k|^2] = 0 \) and \( E[|h_k|^2] = p_k \), \( k = 1, 2, ..., K \). \( \mathbf{B} = [\mathbf{b}_1, \mathbf{b}_2, ..., \mathbf{b}_K] \) be the information data matrix. We correlate with \( \mathbf{S}^H \) to obtain the received data as

\[
\hat{\mathbf{Y}} = \mathbf{RHB} + \mathbf{N} \tag{1}
\]

where \( \hat{\mathbf{Y}} \) is the \( K \times L \) received signal matrix, \( \mathbf{H} \) is the channel response matrix, \( \mathbf{R} = \mathbf{S}^H \mathbf{S} \) is the correlation matrix of spreading code, and \( \mathbf{N} \) is the additive white Gaussian noise (AWGN) noise vector of distribution \( N(0, \sigma^2 I) \).

When the matched filter receiver is used, let \( p_k \) is the received power of the \( k \)th user, the SINR of the \( k \)th user is

\[
\text{SINR}_k = \frac{p_k}{\sum_{l \neq k} p_l |\mathbf{s}_k^H \mathbf{s}_l|^2 + \sigma^2} \geq \gamma_k \tag{2}
\]

B. Traffic Model

All of users are quasi-stationary and randomly distributed in the coverage area of the centrally located base station. Moreover, assume that each user has a saturated infinity first-in and first-out buffer. We consider that users generate a non-real-time Poisson traffic data which is likely to be bursty and randomly arriving, so it is inefficient to assign a mobile-oriented code channel to each MS. Therefore, a MS requests its transmission in a mini-slot; the BS permits the transmission and assigns a code according to the scheduling strategy. This is called "per transmission per code". For the backlogged packet, a retransmission probability is analyzed in the later subsection.

III. POWER-CONTROLLED OPPORTUNISTIC RETRANSMISSION CONTROL STRATEGIES

In the TD/CDMA wireless system, collision increases the probability of retransmission. Now, the problem is, at backlogged time, the wireless channel condition might vary since the last transmission time. Such that, if the backlogged time is larger than the coherent time of the wireless channel, slot-based optimization approach might not be suitable. On the other hand, if there are some available codes in the next slot and the load is not saturated, the slot utilization and throughput will be low. The idea behind the proposed approach is to "opportunistically" retransmit the backlogged users with power control in an earlier time slot under some QoS criteria.

We employ the power control algorithm in [10] to update the power based on the received SINR of user \( k \), \( \text{SINR}_k \), and the acquired SINR target value \( \gamma_k \), called "capture ratio." The optimal power in the \( i \)th iteration could be

\[
p_k(i) = \frac{\gamma_k}{\text{SINR}_k(i-1)} p_k(i-1); \quad k = 1, 2, ..., K \tag{3}
\]

where \( p_k(i-1) \) is the transmitting power of the \( k \)th user in the \( i-1 \)th iteration, and \( \text{SINR}_k(i-1) \) is the received SINR of the \( k \)th MS at the BS in the \( i-1 \)th iteration.

The retransmission control policy is a rule that specifies which collided users are scheduled at the next time-slot for early retransmission. The proposed power-controlled opportunistic retransmission control strategies is to develop a transmission scheduling policy that exploits the time-varying channel condition to maximize the total expected system performance which satisfying both QoS constraints (e.g. SINR guarantee) and the fairness constraint. The problem can be stated formally as follows

\[
\max_{\theta \in \Theta} \left\{ \mathbb{E}\left( \sum_{k=1}^{K} R_k \right) \right\} \tag{4}
\]

s.t.

\[
K = K_n + K_r \leq N; \quad p_k(i) = \frac{\gamma_k}{\text{SINR}_k(i-1)} p_k(i-1); \quad k = 1, 2, ..., K \n\]

\[
\sum_{k=1}^{K} p_k(i) |\mathbf{s}_k^H \mathbf{s}_k|^2 + \sigma^2 \geq \gamma_k; \quad k = 1, 2, 3, ..., K \tag{5}
\]

where \( S(i) = \sum_{k=1}^{K} R_k \) is the system throughput in slot \( i \) and \( \Theta \) is the set of retransmission control policies.

If we assumed that each user has the same rate \( R \) in one slot, the objective function could be transformed as

\[
\max_{\theta \in \Theta} \left\{ \mathbb{E}(K) \right\} \tag{5}
\]
Our goal becomes to maximize slot utilization by increasing the maximum number of simultaneous transmissions.

A joint retransmission control and power control scheme is proposed to achieve the maximum number of simultaneous transmissions in one slot. At each slot, the physical-collided users are backlogged and try to retransmit with adjusted power for anti-fading. For the protocol-collision condition, the retransmission problem is similar to the admission control issue. We use the same criterion as used for physical-collision to choose the best $N$ users to admit their transmission. To be aware of the codes available for retransmission, we must estimate the number of active users (including new and existing users) in the next slot.

Because time is the resource shared among users, a natural fairness criterion is to give each user at least a certain share of the entire resource. Hence, we also take the waiting time into account to our “retransmission admission control” criterion to satisfy fairness requirements.

In summary, the retransmission control strategies can be described briefly as follows.

1) Whenever a user has a message to transmit, each packet will be sent with the spreading code assigned from the BS. If the number of active users at the same slot is larger than the number of available codes, the BS reorders each MS based on the opportunity function $c_{k,i}$. The BS informs the best $N$ users with larger opportunity function to transmit, and the other users are protocol-collided and backlogged.

2) Any received packet with $SINR_k \geq \gamma_k$ would be successfully transmitted. Otherwise, it causes a physical-collision. The physical-collided packets would be retransmitted after power control.

3) The BS calculates the power update based on the received SINR which reflects the channel condition. Also, the BS broadcasts the power update to MS. While the MS receives the closed-loop power control broadcasting, the MS adjusts its transmitting power.

4) To fully utilize the available codes, the BS estimates the number of active users $K_a$ in the next slot, and calculates the number of available codes to be reserved for $N - K_a$ early retransmissions.

5) The BS informs the best $N - K_a$ retransmission in the next slot according to decreasing order of user’s opportunity function.

### A. Retransmission Control Policy

The main idea is to allow users with higher SINR to schedule early retransmission without ignoring fairness. The accumulated collision probability and the waiting time are also considered. If there are more than two users have the same SINR, the one with the lower collision probability retransmits first. The opportunity function at the $i$th slot can be expressed as a function of $SINR_{k,i}$, $P_{c,k}$, and $WT_{k,i}$ as follows

$$c_{k,i} = \frac{SINR_{k,i}}{P_{c,k} \cdot WT_{k,i}}$$

where $P_{c,k}$ is the $k$th user’s accumulated collision probability; $SINR_{k,i}$ is the received SINR of the $k$th user at $i$th slot; $WT_{k,i}$ is the waiting time of the $k$th user at the $i$th slot.

Let $\{c_{k,i}\}$ be a stochastic process associated with user $k$, where $c_{k,i}$ is the value of the opportunity function which measures the “opportunity” of slot $i$ to the user $k$, and is a function of its channel and user condition. One example of $c_{k,i}$ is SINR. We can define the best users as the first $N$ users in the index set $K$. Note that the best users have the larger successful receiving opportunity at the BS. We assume that $c_{m,i} > c_{n,i}; \forall m < n; m, n \in K$.

In summary, retransmission control policy at time slot $i$

1) Order the collided users according to the decreasing order of the quantity $c_{k,i}$.

2) Assign the first $N - K_a$ users with higher value of $c_{k,i}$ to retransmit at the next slot.

### B. Kalman Filter Estimation of Active Users

To estimate the load in the next slot, the Extended Kalman filter [9] is modified to estimate the number of active users in the next slot. We can know how many codes available to support early retransmission for collided users.

In each time slot, the BS measures $P_{c,j}$ of the conditional collision probability which includes two collision condition: saturated slot or received $SINR_k < \gamma$, at each time step $j$. In this paper, we consider the transmission with capture effect.

$$P_{c,j} = \frac{1}{B} \sum_{i=(j-1)B}^{jB-1} C_i$$

where $B$ can be seen as the total number of observed tried to transmission users. For slot $i$, $C_i = 0$ if the slot is empty or the station transmits with a success, while $C_i = 1$ if the user’s $SINR_k < \gamma$. Then $B$ is the summation of the number of users whose $SINR_k < \gamma$ and is $K$ if $K > N$. Being $P_{col}$ the real (unknown) conditional collision probability suffered on the radio channel. For slot $i$, $Prob(C_i = 1) = P_{col} = 1 - (1 - P_T)^{k-1}$, where $P_T$ is the transmission probability during a slot, and $Prob(C_i = 0) = 1 - P_{col}$. Then

$$k = f(P_{col}) = 1 + \frac{\ln(1 - P_{col})}{\ln(1 - P_T)}$$

Therefore, $P_{c,j}$ would be binomial distribution:

$$Prob(P_{c,j} = b) = \binom{B}{b} P_T^b (1 - P_T)^{B-b}; b \in (0, B)$$

The mean value and variance of the measure $P_{c,j}$ are obviously $E[P_{c,j}] = P_{col}$ and $Var[P_{c,j}] = P_{col}(1 - P_{col})/B$.

With the Kalman Filter estimation technique, the system state can be represented by the number $k_j$ of MS in the network at discrete time $j$. The state updating law is $k_j = k_{j-1} + w_j$, where the number of MS $k_j$ in the system at time $j$ is given by the number of MS at time $j-1$ plus a random variable of state noise $w_j$.

Regarding the measurement model, it is the measure of the $P_{col}$ that each MS can carry out via the samples $P_{c,j}$ obtained.
as in equation (7). If, at time \( j \), there are \( k_j \) MS in the system, then the \( P_{c,j} = h(k_j) + v_j \), where \( h(k_j) \) is the inverse function of (8), \( v_j \) is a binomial random variable with zero mean and variance: \( \text{Var}[v_j] = \frac{h(k_j)(1-h(k_j))}{B} \).

Once the state model described by \( k_j \) and \( P_{c,j} \) is given, the definition of the Extended Kalman filter is a straightforward application of basic theory (see e.g. [11]). According to \( k_j = k_{j-1} + w_j \), the estimate \( \hat{k}_j \) of the number of MS at time \( j \) is

\[
\hat{k}_j = \hat{k}_{j-1} + K_j z_j \tag{10}
\]

where \( K_j \) is the Kalman gain. \( z_j = P_{c,j} - h(\hat{k}_{j-1}) \). The other details would refer to [9] and [11].

C. Packet Collision, Retransmission and Success Probability

We provide a theoretical analysis of packet collision probability, retransmission probability and successful transmission probability in the proposed opportunistic retransmission control. For convenience, we use \( c_{k,i} = SINR_{k,i} \) as our opportunity function in the following analysis.

The \( K \) users random access single cell CDMA system, with a maximum of \( N \) spreading codes, consists of newly generated packets and backlogged packets that need to be retransmitted. The probability in which the system have \( K_n \) newly-arrival packets with the arrival rate \( \lambda \) at time \( t \) is often given by

\[
P_g(k = K_n) = \frac{e^{-\lambda t} \cdot (\lambda t)^{K_n}}{K_n!} \tag{11}
\]

We use those notation mentioned before in the following analysis. As depicted in Fig. 1, the backlogged packets with the larger SINR are retransmitted with probability \( P_r \), which is an order statistics [12]. By the generalized Bernoulli theorem, assume that there exist \( M \) retransmission users, and \( K_n \) active users in the next slot. The BS can identify that there are \( N_r = N - K_n \) available codes for retransmission. Let the smallest power-controlled SINR be \( \gamma_r \), \( L = M - (N - K_n) + 1 = M - N_r + 1 \), and denote the random variable SINR as \( \Gamma \). Let \( F_{\gamma_r}^{-1}(\gamma_r) \) be the cumulative distribution function of SINR. \( f_{\Gamma}(y) \) be the probability density function of SINR. Then

\[
P_r = \sum_{j=L}^{M} \binom{M}{j} [\Gamma_r^{j-1}(1-F_{\Gamma}(\gamma_r))(1-F_{\Gamma}(\gamma_r))]^{M-j} \cdot \int_{\gamma_r}^{\gamma_r + d\gamma_r} f_{\Gamma}(y) dy \tag{12}
\]

We approximate SINR by a Gamma distribution \( \sim G(m, \sigma) \) [13], where \( m \) and \( \sigma \) are the mean and standard deviation of SINR. From the multi-packet reception model [1], assume the number of transmission users is \( k \), then the packet success reception probability is

\[
P_{\text{succ}}|k = \sum_{j=1}^{k} \binom{k}{j} P_r^j (1-P_r)^{k-j} (1-P_{\text{coll,i}}) \tag{13}
\]

where \( P_r \) is the success probability after CDMA spreading.

\[
P_T = \begin{cases} \ P_t, & \text{if } k \leq N \\ P_t \cdot P_{\Gamma,N}, & \text{if } k > N \end{cases}
\]

Again, \( P_{\text{coll}} \) is the order statics for the larger \( N \). Let the \( N \)th largest SINR be \( \gamma_N \), \( L = k - N \), then

\[
P_{\text{coll}} = \sum_{j=L}^{k} \binom{k}{j} F_{\Gamma}^{-1}(\gamma_r)[1 - F_{\Gamma}(\gamma_r)]^{k-j} \int_{\gamma_r}^{\gamma_r + d\gamma_r} f_{\Gamma}(y) dy \tag{14}
\]

Given the number of active users \( k \) and SINR threshold \( \gamma \), we have to know the conditional physical-collision probability to find out \( P_{\text{coll}} \) and \( P_{\text{succ}} \). According to [14],

\[
P_{\text{coll}}|k = P(SINR_k < \gamma|k) = 1 - Q\left( \frac{\gamma - m_k}{\sigma_k} \right) \tag{15}
\]

Substituting (15) in (13), we have the success reception probability.

The overall throughput \( S \) can be obtained by adding contributions of the newly arrival packet and the retransmission packet, such that

\[
S = \sum_{p=1}^{\infty} P_{\text{succ}}|k \cdot \frac{e^{-(\lambda t)} \cdot (\lambda t)^p}{p!} + \sum_{q=1}^{K_r} q \cdot P_{\text{succ}}|k \cdot P_r \tag{17}
\]

IV. SIMULATION RESULTS

Computer simulations are conducted to evaluate the performance of the proposed PHY-MAC based power-controlled retransmission control (PORC) scheme (denotes as PHY-MAC_PORC), which is compared with the multi-user TD/CDMA system without PORC scheme (denotes as SINR Only) and SINR-based PORC scheme (similar to [4]) with PROC, denotes as SINR_PORC), in terms of fairness and system throughput which is the average number of successfully received packets per frame time.

The simulation of TD/CDMA network uses QPSK modulation, the channel is assumed to be flat Rayleigh, SINR capture ratio \( \gamma = 10 \text{dB} \), and the Gold code with processing gain \( N = 31 \). Assume that all users’ messages would be split into packets with fixed length \( L = 128 \) symbols, and each MS transmits to BS with the fixed data rate \( R = 512 \) kbps.

A. Case 1: Early Retransmission for Physical-Collided Users

In Fig. 2, the MS population \( M = 50 \). The proposed PORC scheme only applies to the physical-collided users while all protocol-collided users are randomly backlogged. We can observe that the proposed PORC scheme can significantly improve the maximum throughput. For a good channel condition with the transmitted \( Eb/No = 15 \text{dB} \), the performance improvement of SINR-based PORC scheme is limited (approximate 5.5%). In contrast, the proposed PHY-MAC based PORC scheme can achieve performance improvement up to 22%. For a bad channel condition with lower transmitted \( Eb/No = 10 \text{dB} \), the improvement of the SINR-based PORC scheme is still limited, whereas PHY-MAC based PORC scheme still can improve up to 20%.

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B. Case 2: Early Retransmission for both Protocol-Collided and Physical-Collided Users

The MS population $M = 70$. The proposed PORC scheme applies to both protocol-collided users and physical-collided users. Fig. 3 shows that the proposed opportunistic retransmission scheme can achieve significant improvement in comparison with SINR-based PORC scheme and multi-user TD/CDMA system without PORC scheme. For a bad channel condition ($Eb/N0 = 10dB$), when the number of users is 27, the proposed PHY-MAC based PORC scheme achieves the maximum throughput improvement approximate 200% whereas the SINR-based PORC scheme improves approximate 185%. Simultaneously, throughputs of TD/CDMA decrease dramatically when the number exceed 20.

C. Fairness Evaluation

Fig. 4 shows the fairness of the proposed PORC scheme under different $Eb/N0$. Each user transmits packets with different $Eb/N0$: 5, 10, 15, 20, and 25dB. The proposed PHY-MAC based PORC scheme provides almost the same service to each user, especially in the bad channel condition.

V. CONCLUSIONS

A power-controlled opportunistic uplink retransmission control scheme for multiuser CDMA system have been presented. The kernel of the proposed scheme is the adaptive retransmission control which jointly takes the transmission statistics with physical layer SINR and MAC layer waiting time information into account for selecting the best subset of users to efficiently utilize the resource for retransmission.

Aided by the active user estimation offered by Kalman filtering, the adaptive retransmission control scheme with PHY-MAC information can achieve more than 20% throughput improvement in Rayleigh fading channel, while maintaining the long term fairness among the various users despite their varying channel conditions. We also analyzed the throughput and the retransmission probability of the opportunistic uplink retransmission scheme.

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