Joint rate and power adaptation for radio resource management in uplink wideband code division multiple access systems

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Abstract: The benefits of adaptive joint power control and rate allocation for uplink transmission in a wideband code division multiple access cellular system are investigated. Closed-loop power control (CLPC), to adaptively adjust the transmit power, has the effect of maintaining a target signal-to-interference ratio and bit error rate (BER) performance. On the other hand, rate adaptation requires less transmit power, although the BER performance may be poorer. The authors differentiate the power update interval from the data rate update interval, analyse and evaluate the performance of two joint rate/power adaptation algorithms in a fading environment: optimal spreading factor-power control (OSF-PC) and greedy rate packing-power control (GRP-PC). Numerical results show that GRP-PC exhibits superior throughput performance compared with other three adaptation schemes. CLPC alone exhibits throughput and BER performances comparable to those of the OSF-PC scheme, but consumes a significantly higher amount of transmit power. Rate adaptation only is not efficient in enhancing throughput, but its power consumption is minimal.

1 Introduction

With the increasing demand for wireless communication services, efficient and effective radio resource management functions that can cope with the time-varying nature of the wireless channel are essential. Two of the main resource management functions in a code division multiple access (CDMA) system are power control and rate allocation. In a time-varying environment, schemes to perform power control and rate allocation need to be adaptive in order to enhance resource utilisation.

In many applications, data transmission uses fixed rate and/or fixed power. Fixed transmission schemes are normally designed to meet the transmission quality requirement under worst-case condition or optimally chosen for long-term average channel conditions. However, a fixed transmission scheme fails to exploit the time-varying nature of the wireless channel and the variation of the interference level. Therefore it may result in a loss in throughput. A more efficient approach is an adaptive transmission scheme that responds to the actual channel condition. In general, the transmitter may adapt its data rate and/or transmission power according to the channel state information (CSI). Typical adaptive techniques include power adaptation to maintain the received power of each mobile at a desired level [1–3], coding adaptation [4, 5], modulation adaptation [6], spreading factor (data rate) adaptation [7] or any combination of these approaches [7–9].

There is a large body of works on rate and power allocation/adaptation reported in the literature. These works can be grossly classified into the following three approaches. (i) Resource allocation under perfect power control, that is, the received power is well controlled at the target level, and the transmission rate and power are optimised by maximising the throughput, for example, [10–14]. (ii) A snap-shot evaluation of the power and rate allocations pertaining to a given realisation of channel gains for each of the users, for example, [15–18]. This approach is based on the assumption that the
adaptation converges much faster compared with the changes in the link gains because of user mobility. The snap-shot analysis provides an upper performance bound for practical adaptation implementations. (iii) Power control based on the distributions of the received signal power and interference power, for example, [19–22]. The work in this category is based on the assumption that adaptation is ‘seamless’ and the CSI is perfectly known at the transmitter. The average system performance involves a manipulation of probability density functions. More recently, the authors in [23] developed a framework of utility-based joint power control (UBPC) and rate allocation scheme for downlink CDMA systems using either matched-filter or blind multiuser receivers. By employing rate allocation together with UBPC and opportunistic fair transmission scheduling, a large number of users can be accommodated in the system, and the instantaneous weighted system throughput could be maximised while guaranteeing long-term fairness among all users. The authors in [24] investigated distributed strategies for joint control of power and data rates by taking into account the network congestion levels. The design is based on a formulation of state-space models with and without uncertain dynamics and the determination of control signals that help to meet certain performance criteria, such as robustness and desired levels of signal-to-interference ratio (SIR).

Unlike the previous works cited above, we consider joint rate and power adaptation with a frame/slot structure in a time-evolution fashion for wideband CDMA (WCDMA) communication systems, where a frame is comprised of a number of slots. Our main contribution lies in the application of joint rate/power adaptation algorithms to a practically implementable system to achieve the best trade-off between system performance and transmit power consumption and in the analysis and evaluation of system performance using the specifications in the UMTS-WCDMA standard [25] that could provide design guidelines.

The purpose of using closed-loop power control (CLPC) is to regulate the received power/SIR to be around a target level, which is determined by optimising the radio resources. CLPC makes the transmit power track the time-varying channel to compensate the channel impairments. The price to pay for the improved tracking is higher than average transmit power [3]. On the other hand, rate adaptation attempts to enhance throughput by changing the transmission rate while keeping the transmit power fixed. A higher data rate or a lower spreading factor will lead to throughput improvement. When the carrier-to-interference ratio (CIR) of the desired user is high, a lower spreading factor should be used to enhance throughput. Furthermore, practical restrictions tend to degrade the throughput performance of rate adaptation [26]. As a result, we expect that joint rate/power adaptation will yield excellent system performance and transmit power consumption tradeoff.

Rate and power adaptations are driven by the variations in the CSI of the desired user and the variation in the multiple access interference. From an adaptive processing point of view, rate adaptation is normally done at the frame level, whereas CLPC adaptation is at the slot level [25], so that the frequency of power adaptation is higher than that of rate adaptation. The complementary roles of power control and rate allocation for system performance enhancement motivate our current work on joint power and rate adaptation, recognising that rate allocation saves transmission power and enhances throughput while power control tunes the received CIR statistics around a target level. In this paper, we analyse implementable joint rate/power adaptation schemes that capture the advantages of the individual rate and power adaptation schemes, that is, enhanced throughput compared to rate adaptation and reduced average transmit power compared with CLPC.

The remainder of the paper is organised as follows. System model and channel model are described in Section 2. In Section 3, the optimal spreading factor (OSF) criterion which maximises the throughput is derived as a function of the CIR. This relation is the basis for rate allocation in optimal spreading factor–power control (OSF-PC). Greedy rate packing (GRP) algorithm, which sequentially allocates data rate as high as possible by sorting the channel gains of the users, is also described in this section. In Section 4, we present joint rate/power adaptation algorithms, OSF-PC and greedy rate packing-power control (GRP-PC), for uplink transmission in a DS-CDMA cellular system. Simulation results of the throughput/bit error rate (BER) performance and power consumption for the joint rate/power adaptation schemes, rate adaptation alone and CLPC alone are presented and discussed in Section 5. Conclusions are given in Section 6.

2 System and channel models

We consider a direct-sequence CDMA (DS-CDMA) cellular system supporting packet services of error-sensitive traffic. The objective of this work is to analyse and evaluate joint CLPC and rate allocation strategies in order to assess the enhancement in effective throughput of packet services in uplink transmissions.

2.1 System model

The system under consideration is shown in Fig. 1, where the left hand side represents functions performed at the mobile station (MS) whereas the right hand side represents those performed at the base station (BS). The source at the MS generates a sequence of fixed-length packets, each $L_p$ bits in length. After error control coding, the bits in each of the packets generated by each source are randomised using an interleaver. The rate controlled symbols are then transmitted at the symbol rate $R_c/N$, where $R_c$ is the chip rate of the spreading function and $N$ is the spreading factor. Assuming a fixed chip rate, the symbol duration is
directly a function of the spreading factor $N$. When power control is applied, the transmit power is updated by a fixed step size and a power control command at the end of each power control interval, $T_p$. Otherwise, the transmit power is kept constant. For the analysis in the sequel, the buffer is assumed non-empty at all times, so that the users are persistently transmitting. Therefore the number of active users in the system is constant.

At the BS, the received signal first goes through a matched filter receiver for despreading. Reproductions of the transmitted information bits are retrieved after deinterleaving and decoding. When power control is applied, the estimated CIR is compared with a target, $\xi^*$, to generate a power control command.

We consider error-sensitive traffic, which is assumed to be error-free by the use of retransmissions. Therefore after decoding the received packet, the BS may request the transmitter to retransmit the packet if it contains errors. The effective throughput, defined as the average information rate successfully received, can be controlled through the selection of the spreading gain, $N$, and the retransmission probability, $P_r$. The estimate of CIR averaged over a frame interval is used to specify if the transmission rate (spreading factor) needs to be updated in the next frame transmission if rate adaptation is applied.

There are three possible feedback variables from the BS to the MS, as illustrated in Fig. 1. The first is the power control command at an interval of $T_p$ (equal to one slot). The second is the CIR estimate at a frame length of $T_f (=15 \, T_p)$, which is used to specify the transmission rate if rate adaptation is applied. The third feedback is an indicator to request retransmission when errors are detected after decoding. A simplified structure of the transmission frame is shown in Fig. 2, where a frame, consisting of 15 slots, is 10 ms in length [25]. For the downlink, the pilot symbols, the transmit power control (TPC) command and the transport format combination indicator (TFCI) are time-multiplexed with the transmitted data. For the uplink, the transmitted data and control information are code multiplexed. The transmit power is updated slot by slot, whereas the transmission rate is updated frame by frame.

![Figure 1: Joint rate/power adaptation system model](image1)

![Figure 2: Frame structure for UMTS/WCDMA](image2)

### 2.2 Channel model

We consider a land mobile radio channel for urban areas, where the direct-line-of-sight component between the mobile and the BS is completely obstructed by high buildings most of the time. The envelope of the received signal is Rayleigh distributed and the phase is uniformly distributed over the interval $[0, 2\pi]$. Furthermore, we consider a mobile user roaming over a large area. Thus, the received signal will experience two types of fading: small-scale fading superimposed on large-scale fading. This statistical property is well modelled by a Suzuki process [27].

The Suzuki process is a statistical model that has been developed for the land mobile radio channel on the assumption that the local mean of the Rayleigh process follows a log-normal statistic and accounts for the effects of shadowing. Thus, the stationary Suzuki process $z(n)$ is a product of a Rayleigh process $\psi(n)$ and a log-normal process $\zeta(n)$ at time instant $n$

$$z(n) = \psi(n) \cdot \zeta(n)$$  \hspace{1cm} (1)

where $\psi(n)$ and $\zeta(n)$ are called the small-scale-fading component and the large-scale-fading component, respectively.

A sample of the composite probability density function of the received signal envelope over time is given by [28]

$$f(z) = \int_0^{\infty} \frac{z}{P_0} \exp\left(-\frac{z^2}{2P_0}\right) \frac{1}{\sqrt{2\pi} \sigma_z P_0} \times \exp\left[-\frac{(\ln(P_0) - m_z)^2}{2\sigma_z^2}\right] dP_0$$  \hspace{1cm} (2)

where $m_z$ and $\sigma_z$ are dB values of the area mean signal power and standard deviation for log-normal process, respectively.

In the simulation presented in Section 5, the Rayleigh fading process $\psi(n)$ is generated by using Jake’s model [29] as

$$\psi(n) = \sqrt{x^2(n) + \gamma^2(n)}$$  \hspace{1cm} (3)

where $x(n)$ and $\gamma(n)$ are independent Gaussian low-pass processes, assumed to have a typical U-shape power spectral
density. When simulating a multi-user environment, we assume that each user’s signal is subject to independent fading, and the average Rayleigh fading power on all user transmissions is normalised to unity.

The lognormal fading process \( \xi(t) \) is generated by using a Gaussian white noise process transformed by an exponential function [27]

\[
\xi(t) = e^{\nu + \mu(t)}
\]

where \( \mu(t) \) is a zero-mean unit variance Gaussian random process. The parameters \( m \) and \( s \) are used to transform the Gaussian process to its actual mean and variance, respectively. In this paper, the parameters are selected as \( s = 0.483 \) and \( m = -0.0259 \). The lognormal process is generated by using the method of equal distance [27]. Other parameters are the same as in [27] except where it is explicitly specified.

Fig. 3 shows the simulated fading envelope functions when the mobile speed is 50 km/h and the carrier frequency is 2 GHz. Fig. 3a shows the simulated Rayleigh fading with unit average power. The solid curve in Fig. 3b shows the simulated large-scale lognormal fading process. Fig. 3c shows the composite envelope function. The dashed curve in Fig. 3c is obtained by averaging the envelope function in Fig. 3c over a window with a length of 15 power control cycles (1 frame).

3 Optimal data rate allocation

System throughput is a function of the spreading factor, \( N \), or equivalently, the applied data rate. An OSF selection method is proposed in [16], where the OSF is obtained under the assumption that \( N \) is a continuous function. On the other hand, an effective rate allocation method, referred to as GRP [17], allocates data rate based on the water filling principle, on the assumption that discrete data rates are available.

In a real CDMA system, the spreading factor \( N \) is normally selected as a power of two. Therefore it is expected that GRP is a more efficient rate allocation method than OSF. In the remaining of this section, the principles of OSF and GRP are reviewed to make the paper self-contained.

3.1 Assumptions

We assume that there are \( K \) users in the system. The index for the desired user is 1, and the indices for the interferers are from 2 to \( K \). The received SIR for the desired user is given by

\[
\Gamma_1 = N_1 \cdot \frac{b_1 P_1}{\sum_{j=2}^{K} b_j P_j + \sigma^2} = N_1 \cdot \xi_1 = \frac{R_c}{R_1} \cdot \xi_1
\]

where \( P_j \) and \( b_j \) are, respectively, the transmit power and the channel gain of user \( j \). The spreading factor for the desired user, \( N_1 \), is the ratio of the chip rate to the data rate (\( N_1 = R_c / R_1 \)). Background noise power is represented by \( \sigma^2 \). The term \( \xi_1 \), representing the CIR of the desired user, is given by

\[
\xi_1 = \frac{b_1 P_1}{\sum_{j=2}^{K} b_j P_j + \sigma^2}
\]

which depends only on the received power vector and the background noise level. The difference between SIR and CIR is the processing gain \( N \) (i.e. \( \Gamma = \xi N \)).

Let \( g(\Gamma) \) denote the relationship between BER and SIR, which depends on the modulation and coding schemes used. We use an exponentially decaying function to model the BER as in [12]

\[
P_b = g(\Gamma) = c_1 \exp(-c_2 \Gamma)
\]

where \( c_1 \) and \( c_2 \) are parameters which can be adjusted to match a particular modulation/coding scheme. With different modulation/coding schemes, the mapping between the SIR and BER may change; but this does not have an effect on the analysis and results of this paper. With interleaving/deinterleaving, we assume that the bit errors are independent. The packet retransmission rate for error-free packet reception is thus

\[
P_r = 1 - (1 - P_b)^{L_p r_c}
\]

where \( r_c \) is the code rate and \( L_p \) is the packet length.
3.2 OSF selection

The OSF algorithm presented in this subsection is based on the assumption that rate adaptation is continuous. However, in practice, each user can only be assigned a discrete rate. Therefore we select the available discrete data rate which is closest to the optimal continuous rate solution, leading to a performance degradation.

The throughput for any specific user is defined as the average number of information bits successfully transmitted per second and is given by

$$\eta = \frac{r_c R_c}{N} (1 - P_e)$$  \hspace{1cm} (9)

where $R_c$ is the chip rate, and $(1 - P_e)$ is the probability of error-free packet reception. Substituting (7) and (8) in (9), the throughput can be expressed as

$$\eta = \frac{r_c R_c}{N} (1 - c_1 \exp(-c_2 \xi N))^{1/r_c}$$  \hspace{1cm} (10)

Let $g(\xi N) = c_1 \exp(-c_2 \xi N)$. The OSF, $N^*$ (in the sense that the throughput is maximised), can be obtained by taking the first derivative of (10) with respect to $N$ and equating the result to zero

$$\frac{d\eta}{dN} = -\frac{r_c R_c}{N^2} [1 - g(\xi N^*)]^{1/r_c}$$

$$\times \left[ \frac{1}{N^2} [1 - g(\xi N^*)] + L_{r_c} \cdot \xi \cdot g'(\xi N^*) \right] = 0$$ \hspace{1cm} (11)

Since the first term is strictly non-zero, $N^*$ can be solved by equating the second term to zero

$$1 - g(\xi N^*) + L_{r_c} \cdot \xi N^* \cdot g'(\xi N^*) = 0$$ \hspace{1cm} (12)

Substituting $g(\xi N^*) = c_1 \exp(-c_2 \xi N^*)$ and $\Gamma^* = \xi N^*$ in (12) yields

$$\exp(c_2 \Gamma^*) = c_1 + L_{r_c} c_1 c_2 \cdot \Gamma^*$$ \hspace{1cm} (13)

Note that the left hand-side is an exponential function, whereas the right hand-side is a linear function of $\Gamma^*$. In this paper, we select the same coefficient values as given in [12]: $c_1 = 1/2$ and $c_2 = 2$, which correspond to an asymptotic coding gain of 3 dB, packet length $L_p = 768$ symbols and code rate $r_c = 1/2$, which corresponds to 48 information bytes per packet. With these parameters, the solution to (13) can be obtained graphically from Fig. 4, where the solid curve represents the left hand-side exponential function and the plus-marked line represents the right hand-side linear function. The dashed curve represents the scaled throughput, $\eta$. The exponential and the linear functions intersect at two points. It is shown in [16] that, with the assumption of an exponential BER function, $\eta$, as a function of the spreading factor, has a local minimum at the smaller solution of $\Gamma^*$ and a local maximum at the larger value of $\Gamma^*$. Therefore with the selected parameters, the solution to (13) is the crossover point when $\Gamma^* \simeq 3.62$. The OSF is selected as

$$N^* = \frac{\Gamma^*}{\xi}$$ \hspace{1cm} (14)

For a given set of system specifications, $\Gamma^*$ can be obtained by solving (13) and treated as a constant. Thus, the OSF is uniquely specified by the CIR, $\xi$.

With the application of more advanced coding schemes, the coding gain (represented by the parameter $c_2$) increases, the slope of the linear function in Fig. 4 increases and the exponential function shifts closer to the y-axis. It is anticipated that the solution of (13) decreases, leading to a smaller applied spreading factor and therefore higher throughput. For practical applications, the value of the applied spreading factor is normally restricted to a set of integer numbers. In this case, the sub-OSF is selected from the available set, which is the closest integer to the optimal solution given by (14).

3.3 Rate selection for GRP

The GRP algorithm [17] applies to a discrete rate situation. A user with a high link gain is assigned as high rate as the feasibility condition allows. This sequential heuristic approach yields high system throughput. Assuming that each user can be assigned a discrete rate from a set $R = \{r^{(1)}, r^{(2)}, \ldots, r^{(k)}\}$, with the condition, $r^{(1)} < r^{(2)} < \ldots < r^{(k)}$, where $k$ is the number of available rates which the users can be assigned. The corresponding set of discrete target CIR is $\Omega = \{\xi^{(1)}, \xi^{(2)}, \ldots, \xi^{(k)}\}$, with the condition $\xi^{(1)} < \xi^{(2)} < \ldots < \xi^{(k)}$.

The relationship between $R$ and the target CIR can be obtained from (5) and shown as

$$\frac{r^{(1)}}{\xi^{(1)}} = \frac{r^{(2)}}{\xi^{(2)}} = \ldots = \frac{r^{(k)}}{\xi^{(k)}} = \frac{R_c}{\Gamma^*}$$  \hspace{1cm} (15)

where $\Gamma^*$ is the common target SIR, which is a tunable parameter. In this paper, we will use the optimal SIR value.
solved from the OSF algorithm given in (13). From (15), we can see that the target CIR, $\xi^{(m)}$, is another mechanism to match the effective data rate. Thus, the rate assignment and target CIR assignment are interchangeable.

In our earlier work [30], detailed analysis of system feasibility conditions and optimal power distribution solutions were provided. For uplink transmission, the necessary and sufficient condition for nonnegative power allocation is

$$\sum_{j=1}^{K} \frac{\xi_j}{1 + \xi_j} \leq 1 - \max_{1 \leq j \leq K} \left[ \frac{\xi_j / (1 + \xi_j)}{h_j P_{\text{max}} / \sigma^2} \right]$$

(16)

where $K$ is the number of users in the system, $\sigma^2$ represents the background noise power, $P_{\text{max}}$ is the maximum allowed transmit power level and $h_j$ is the link gain of the $j$th user.

The GRP algorithm [17] applies the necessary and sufficient condition (16) to allocate the target CIR, $\xi^*$, and the corresponding data rate of the users with the aid of CSI. The principle is to give a higher priority to the users with better channel condition to enhance system throughput. More details of the algorithm will be presented in Section 4 when we discuss the procedures for GRP-PC.

### 3.4 Throughput benchmarks: ideal rate adaptation and non-adaptation

For ideal rate adaptation, it is assumed that the spreading factor is always selected based on (14). The throughput as a function of the instantaneous $\xi$ is

$$\eta(\xi) = \frac{r_i R_i \cdot \xi}{\Gamma_i} \left[ 1 - g(\Gamma_i) \right]_{15}^{\#} = \lambda \cdot \xi$$

(17)

where $\lambda$ is a constant given by $\lambda = r_i R_i \left[ 1 - g(\Gamma_i) \right]_{15}^{\#} / \Gamma_i$. The average throughput is

$$\eta = \int_{0}^{\infty} \eta(\xi) f_\xi(\xi) \, d\xi = \lambda \cdot E[\xi]$$

(18)

where $f_\xi(\xi)$ and $E[\xi]$ denote the probability density function and expectation of $\xi$, respectively.

For non-adaptation, the spreading factor is optimally chosen based on the mean of $\xi$, $E[\xi]$ and is kept fixed. Therefore the applied spreading factor is

$$N^* = \frac{\Gamma_i}{E[\xi]}$$

(19)

leading to the instantaneous throughput

$$\eta(\xi) = \frac{r_i R_i}{N^*} \left[ 1 - g(N^*) \right]_{15}^{\#}$$

(20)

and the average throughput is

$$\eta = \int_{0}^{\infty} \eta(\xi) f_\xi(\xi) \, d\xi$$

(21)

Numerical integration can be applied to obtain the average throughput for the non-adaptation scheme.

### 4 Joint rate and power adaptation

In this section, we analyse the approaches to use CLPC in conjunction with rate adaptation to improve throughput and reduce average transmit power consumption. In contrast to CLPC, which can be regarded as an inner-loop control mechanism, the target CIR allocation, which achieves rate adaptation at the frame level, serves as an outer-loop control mechanism to enhance efficient radio resource management.

#### 4.1 OSF-Power Control

Let $\rho_i$ denote the CIR of the pilot signal of the desired user, which is not power controlled and is specified by the channel fading gains of the users

$$\rho_1 = \frac{b_1}{\sum_{i=2}^{K} b_i}$$

(22)

For rate adaptation, at the end of the $m$th frame, the average pilot CIR is estimated by averaging the pilot CIR over the most recent frame (15 slots in length)

$$\rho_1 = \frac{1}{15} \sum_{i=1}^{15} \rho_i$$

(23)

where the superscript $i$ denotes the index of the slot. The resultant average CIR is used as $\xi$ in (14) to calculate the spreading factor for the next transmission frame and fed back to the MS. This value will be set as the target CIR value for the next frame, $\xi^*[m+1]$, where $([m+1]$ denotes the index of the frame.

In the UMTS WCDMA standard [25], the signalling bandwidth is kept small despite the high update rate by utilising a single-bit signalling. At the $n$th slot, the received data CIR ($\xi$) is estimated at the receiver and compared with the target $\xi^*$ to generate power control command to exercise CLPC. When the CIR value is above the target, the power control command (PCC) sent to the transmitter is $\text{pcc}[n] = -1$; when it is below the target, the PCC sent is $\text{pcc}[n] = +1$. The transmit power at the $(n+1)$th slot, $P[n+1]$, can be computed iteratively at the beginning of this slot using the following steps

$$\text{pcc}[n] = \text{sgn}(\xi^*[m] - \text{CIR}[n])$$

(24)

$$P[n + 1] = P[n] + \Delta \cdot \text{pcc}[n]$$

(25)
where $\Delta$ is the applied step size in dB and $\text{sgn}(\cdot)$ is the signum function. Furthermore, the updated transmit power level is limited by

$$P[n + 1] = \begin{cases} P_{\text{max}} & \text{if } P[n + 1] > P_{\text{max}} \\ P_{\text{min}} & \text{if } P[n + 1] < P_{\text{min}} \end{cases}$$ (26)

where $P_{\text{max}}$ and $P_{\text{min}}$ are the maximum and the minimum allowed transmit powers for desirable signal detection, respectively. The adaptive processing involves (i) the determination of the spreading factor based on the pilot CIR to achieve data rate adaptation and (ii) the estimation of the received data CIR at each slot to implement CLPC. The rationale is that by using CLPC, the resultant CIR is forced to be close to the target within each frame. This is also a consequence of using rate adaptation at the frame level. The second difference is that the CIR target varies, leading to a replacement of the initial power vector at the beginning of each frame, an initial power vector is forced to be close to the target within each frame. This is a consequence of using rate adaptation at the frame level. The second difference is that the CIR target varies, leading to a replacement of (i) the initial power vector at the beginning of each frame, an initial power vector is forced to be close to the target within each frame. This is also a consequence of using rate adaptation at the frame level.

4.2 GRP-Power Control

Power adaptation serves a dual role in CDMA systems: power allocation and CLPC. Power allocation is an important resource management function for multiclass systems and is used to specify the available data rate and target CIR value to each user based on their channel gains, $b_1, b_2, \ldots, b_K$. With a certain target CIR assignment, we can obtain the optimal power vector that supports every user with the required SIR target by solving the linear inequalities

$$\begin{bmatrix} I - F \end{bmatrix} P^* \geq U$$

$$P^* \geq 0$$

(27)

where $P^* = [P^1, P^2, \ldots, P^K]^T$ is the transmission power vector

$$U = \sigma^2 \begin{bmatrix} \xi_1/h_1 & \xi_2/h_2 & \cdots & \xi_K/h_K \end{bmatrix}^T$$

is the normalized noise power vector, $I$ is a $K \times K$ identity matrix and $F$ is the normalized cross-link gain matrix with $(i,j)$th element given by

$$F_{ij} = \begin{cases} \xi_i/h_i & i \neq j \\ 0 & i = j \end{cases}$$ (29)

By manipulating (27) and (28), the feasible minimum power solution of the $i$th user is given by

$$P_i^* = \frac{\sigma^2}{1 - \sum_{j=1}^K \xi_j h_j / (1 + \xi_j)}$$

(30)

After the BS assigns the target $\xi^*$, data rates and initial optimal powers to the users in the system, CLPC is triggered by comparing the received CIR with the target CIR in the same way as that in the OSF-PC algorithm. The GRP-PC algorithm is implemented by the following procedure.

4.3 Assignment procedure

Step 1. Based on the system designed available spreading factor values, specify the available data rate $r^{(i)}$, and the corresponding CIR value, $\xi^{(i)}$.

Step 2. At the end of the $n$th frame, the BS computes the average channel gains of every user and then sorts them in a decreasing order: $h_1 \geq h_2 \geq \cdots \geq h_K$, where the subscript $(k)$ denotes the index of the sorted sequence. Initialise the target CIRs of every user, $\xi^{(i)}$, $i \in [1, K]$ to the minimal value of the CIR set, $\xi^{(1)}$.

Step 3. For $i = 1$ to $K$, do

$$\xi_i^* = \max\{\xi^{(1)*}, \xi^{(2)*}, \ldots, \xi^{(i)*}\}$$

while satisfying the constraint in (16).

Step 4. At the beginning of the $(n+1)$th frame, the BS assigns the transmission rates to the users as below

$$r_i^{(n+1)} = \xi_i^{(n+1)} \frac{R}{T}$$

(31)

Step 5. At the MS, the user’s initial power at the beginning of the frame is assigned using (30). Then CLPC starts based on the target CIR ($\xi^*$) for every time slot.

Step 6. Repeat steps 2–5 for the next adaptation cycle.
From this assignment procedure, we can see that the GRP algorithm allocates the maximum feasible rate to each mobile, starting with the mobile experiencing the best channel condition. As a result, we can have $\xi(1) \geq \xi(2) \geq \ldots \geq \xi(k)$ and $r(1) \geq r(2) \geq \ldots \geq r(k)$. It is clear that the user with the best channel condition (highest channel gain) will be assigned the highest data rate.

Compared with OSF-PC, where the transmission power is reset to 0 dBm at the beginning of each frame, GRP-PC makes use of global CSI to allocate data rate, and assigns a feasible minimum power to users based on their allocated target CIR ($\xi^*$). It is expected that GRP-PC could achieve performance gain over OSF-PC.

5 Simulation results and discussions

In this section, simulation results, obtained using 400 000 frames, are presented to show the throughput, average transmit power consumption, BER performance with OSF-PC, GRP-PC, rate adaptation only and CLPC only. The parameter values used in the calculation are selected as follows: chip rate $R_c = 5$ Mchips/s and available discrete spreading factor set [4, 8, 16, 32, 64, 128, 256, 512]. The carrier frequency is assumed to be 2 GHz, the power control frequency of 1500 Hz (This is the power control frequency specification in UMTS-WCDMA [25]) and the background noise power, $\sigma^2$, is $-10$ dBm, which is 10 dB lower than the default transmit power level. The applied step size is 1 dB for all CLPC. The maximum and minimum transmit powers of the MSs are 50 dBm and $-50$ dBm, respectively. The normalised Doppler frequency, $f_dT_p$, is in the range 0.01–0.1, corresponding to mobile speeds from 8.1 km/h to 81 km/h. Our earlier results [3] show that at very high speeds, the tracking ability of the CLPC deteriorates and we need to seek other compensation approaches.

Assuming that all users in the system are equipped to run the same adaptive protocol, the performance results presented in the sequel are for a typical active user in the system. The performance presented is for one typical user in the system. Except where it is explicitly specified, in all cases, the number of users is 11, which implies that the number of interfering users is 10.

Fig. 5 compares the average throughput for different schemes. The marked curves are the simulated average throughput for rate adaptation, CLPC, OSF-PC and GRP-PC, from the bottom to the top. The solid line and dashed line are, respectively, the numerical results for ideal rate adaptation (rate adaptation only) and non-adaptation. The curves in Fig. 5 show that, as the Doppler frequency increases, the throughput decreases, except for rate adaptation where the Doppler effect does not have a significant impact due to adaptation saturation. This is consistent with our earlier results [26]. For CLPC, even when the spreading factor does not change, because of the increased retransmission, the throughput still decreases as the Doppler frequency increases. It can also be observed that GRP-PC achieves much higher throughput compared with the other three algorithms: an average gain of 37.6% over the second best scheme, OSF-PC, which has another 6.9% gain over CLPC. When the normalised Doppler frequency is $<0.07$, GRP-PC performs even better than the ideal rate adaptation. Therefore rate adaptation alone is not sufficient. By combining rate allocation and power control judiciously, it creates great potential for system performance improvement.

The improvement of GRP-PC over OSF-PC can be explained as follows: global user CSI and available spreading factor set are used in rate allocation for GRP, whereas OSF allocates data rate independently for each user based on its own CIR and each user truncates its data rate inside the available spreading factor set, leading to performance degradation compared with GRP. Furthermore, compared with OSF-PC, GRP-PC exploits power allocation at the beginning of each frame for initial power level setting. OSF-PC resets the initial power level as the default value at the beginning of each adaptation frame.

A comparison of the power consumption for these four adaptation approaches is shown in Fig. 6. It can be seen from Fig. 5 that, using CLPC, the throughput is significantly improved over rate adaptation. However, the price paid is the dramatic increase in the transmit power in order to track and compensate for the signal fluctuation due to fading. Fig. 6 shows that the power consumption for CLPC is significantly higher than other three counterparts. It also shows that the average transmit power of OSF-PC is close to that of adaptive rate only scheme, where the transmit power is kept at the default value, 0 dBm. The average transmission power of GRP-PC is higher than that of OSF-PC. However, if background noise power is lowered, the allocated power level for GRP-PC decreases...
correspondingly. Nevertheless, the average transmit power is not sensitive to background noise level for the other three schemes. With an increase in the Doppler frequency, the average transmit power for CLPC increases, which implies that it is more demanding to track and compensate for the fading effects at higher Doppler frequencies. However, for GRP-PC and OSF-PC, the average transmit power is not sensitive to the changes in Doppler frequency.

Fig. 7 shows the simulation results of average BER. From the top to the bottom, the four curves represent rate adaptation, CLPC, OSF-PC and GRP-PC, respectively. The best BER performance, given by the GRP-PC algorithm, shows that the best control of the received SIR to be the closest to the $G/C_3$ value. When the Doppler frequency is high, the BER performance of OSF-PC is very close to that of GRP-PC. The gain in throughput of GRP-PC comes from its more efficient allocation of the data rate. The BER of CLPC is in the same comparable group of that of joint adaptation schemes.

Fig. 8 shows the average throughput as a function of the number of users for the four adaptation schemes. From the top to the bottom, GRP-PC exhibits the best performance, followed by OSF-PC, CLPC and rate adaptation only. The throughput deteriorates as the number of users increases. When the number of users is $<10$, the gain of GRP-PC is more significant over other adaptation schemes. This can be interpreted as follows: with fewer users, we can expect a more dramatic change in the received CIR values, where GRP-PC has best control capability over the other schemes.

Fig. 9 shows the average throughput as a function of the frame length. The simulated frame length is in the set of $[512 640 768 896 992 1120]$ symbols. It shows that for GRP-PC, the throughput exhibits some fluctuation with the changes of the frame length. There are two factors leading to the fluctuations of the throughput due to the selection of the frame length. The first factor comes from the effect of the exponent in (10). The larger the value of the frame length, the smaller the throughput. The second factor comes from the effect of the spreading factor selection. With the increases in the frame length, the optimal target SIR, $G/C_3$, increases, causing the allocated $N$ to increase. A larger $N$ attempts to reduce BER value but a lower data rate. For GRP-PC, we can see that the positive-
going factor and the negative-going factor have a balanced effect. However, for the other three adaptation schemes, with the increases in the frame size, the throughput decreases. The CLPC scheme, with a fixed spreading factor, has the largest decreasing slope since the frame length only effects the exponent in (10).

6 Conclusions

In this paper, the throughput, average transmit power, and BER performances are investigated for an adaptive DS-CDMA system supporting error-sensitive traffic in a Suzuki fading channel. By deriving the OSF, or equivalently, data rate selection criterion, we note that the OSF is related to the CIR. For discrete data rate allocation, we apply the GRP algorithm, which allocates as high data rate as possible to a user with favorable channel condition. We have investigated four adaptation schemes: rate adaptation only, CLPC only, OSF-PC and GRP-PC. The latter two are joint rate/power adaptation schemes. Rate adaptation only uses the OSF selection criterion to adjust the spreading factor at the beginning of each frame. CLPC, on the other hand, adjusts the transmit power based on the power control command at each slot. The joint rate/power adaptation schemes combine the rate and power adaptation approaches to dynamically adjust the data rate at the frame level and the transmit power at the slot level.

Simulation results show that the throughput of the joint adaptation schemes is superior to that of CLPC and rate adaptation alone. Due to the exploitation of the global CIR information and the application of the available discrete rate set, and the optimal power allocation at the beginning of each frame, the overall performance of GRP-PC is significantly enhanced over the other three adaptation schemes. The average transmit power of the joint adaptation scheme is comparable with that of rate adaptation. CLPC needs to use much larger average transmit power to track and compensate for the fading effect.

As a result, we conclude that the joint adaptation schemes capture the advantages of the two individual adaptation schemes and yield the best tradeoff in terms of system throughput performance and transmit power consumption.

7 Acknowledgment

This work has been supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada under Grant Nos. 293237-04 and RGPIN77779.

8 References


