Selective Power Control with Active Link Protection for Combined Rate and Power Management

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Abstract - In wireless multimedia services, the system can provide a user with multiple data rates. This paper focuses on the combined control of rates and powers for the system, in which a finite number of transmission rates are available. In [6], this problem was first addressed and two distributed power control algorithms were suggested. One of the suggested algorithms there is called *selective power control* (SPC). In this paper, we extend SPC by combining it with the *active link protection* (ALP) scheme [8], [9]. Main purpose of such an extension is trying to guarantee the minimum rate to users and to minimize the number of rate changes by smoothing the realized CIRs. Computational experiments are carried out on a DS-CDMA system. The results indicate that the modified SPC achieves smaller outages and less rate changes while giving the same or slightly higher system throughput, compared with SPC.

I. Introduction

Next-generation cellular radio systems will be able to provide multimedia services. Such services include packet-switched connections transporting e-mails, files, WWW pages, video, etc. Those services may be characterized by different QoS requirements such as minimum transmission rates. For a real time service, users must be guaranteed a tolerable minimum rate. However, non-real time applications (delay insensitive) may temporarily lower their transmission rates even to zero, utilizing any excess capacity in the *best effort fashion*. The transmission rate can vary during a single connection, provided that the minimum rate assigned to the service is assured.

The availability of *variable* transmission rates in a radio network raises the problem of controlling them in the most spectrally efficient way. In the radio channel, transmission rates are closely related to carrier-to-interference ratios (CIRs), and the CIRs can be efficiently controlled by power control. Therefore, it is natural to associate rate control with power control.

There has been a substantial amount of work on efficient power controls for the *fixed* rate system (see [1]-[3] and [9] for some of the latest reviews). However, very few studies have suggested *distributed* power control algorithms that support variable transmission rates efficiently. In [4], maximizing the total transmission rate is considered in the context of a CDMA system, where different rates are represented by varying the processing gain and each user has a minimum rate requirement. The recent paper [5] addresses the problem in terms of joint power control and *adaptive* modulation. The underlying idea is that, by controlling the CIR values, we also maximize the total transmission rate through adaptive modulation techniques. The models in [4] and [5] assume that feasible transmission rates may take any *continuous* value; the number of information bits in a block can be any real number, depending on the channel quality. The continuity assumption in these papers simplifies their problem formulation. However, the resulted formulations have nonlinear terms either in the objective function or in the constrains, which in turn do not lend themselves into distributed power control algorithms. In practice, feasible rates are *discrete*. For example in EDGE (*Enhanced Data rates for GSM Evolution*), there are eight data rates that are supported by the same number of modulation and coding schemes [11]. Very recently, Kim *et al.* [6] considered the practical case in which the feasible transmission rates are limited to a small number of discrete values. In their paper, two distributed multirate power control algorithms are described. The first one is based on *Lagrangian relaxation technique* and the second one, called *selective power control* (SPC), applies the *Generalized DCPC* [7].

The rate selection and power control algorithm suggested here is a modification of SPC by combining it with the *active link protection* (ALP) [8], [9]. We denote the modified SPC by SPC-ALP throughout this paper. The idea behind SPC-ALP is as follows: ALP scheme is used in the admission of new users into the network and also for allowing old users to choose higher rates. SPC is then used to control the transmission rates of the *supported* users. The advantage

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of SPC-ALP over SPC is that it tries to guarantee the minimum rate to users and to minimize the number of rate changes by smoothing the realized CIRs. The latter property is important, since the rapidly varying CIR, caused by the power control dynamics, could result in fluctuating transmission rates to users. At the same time, it will require frequent changes in the modulation and coding scheme to adapt to the CIR, which is undesirable in practice.

Computational experiments are carried out on a DS-CDMA system, in which SPC achieves smaller outages and less rate changes while giving the same or slightly higher throughput, compared with SPC. The organization of this paper is as follows: In the next section, we will provide our system model. Section III introduces SPC-ALP. Numerical results are shown in section IV and finally Section V concludes this paper.

II. System Model

Suppose a cellular radio system, in which M transmitters are accessing a common frequency channel. Each transmitter communicates with exactly one receiver. For the uplink case, the transmitters are the mobiles and the receivers are their corresponding base stations; and for the downlink case, their roles are reversed. We consider a time instant in which the link gain between every receiver i and every transmitter j is stationary and is given by g_{ij}. Without loss of generality, we will assume that transmitter i is communicating with receiver i. In a DS-CDMA system, many mobiles will communicate with the same base station through the same frequency channel. Thus, in our notation below, receivers i and j in the uplink may denote the same physical one if the transmitters (mobiles) i and j are assigned to the same base station. We will denote the power of transmitter i by p_i. In the uplink case, the value p_i means the transmission power of mobile i. However, in the downlink, it denotes the transmission power dedicated to mobile i by the base station to which mobile i is assigned. We assume that the power values are bounded by the interval $0 \le p_i \le \bar{p}_i$.

Let $0 < r_i^{(1)} < r_i^{(2)} < \ldots < r_i^{(K)}$ be the transmission rates that mobile i can utilize. Further let $0 < \gamma_i^{(1)} < \gamma_i^{(2)} < \ldots < \gamma_i^{(K)}$ be the corresponding carrier-to-interference-plus-noise ratio (CIR) targets such that a bit stream sent at rate $r_i^{(k)}$ will be received correctly if the received CIR value is larger than or equal to $\gamma_i^{(k)}$. Thus we have the following CIR constraint on transmitter i transmitting at rate $r_i^{(k)}$:

$$\frac{g_{ii}p_i}{\sum_{\substack{j=1\\ j\neq i}}^{M} g_{ij}\theta_{ij}p_j + \nu_i} \ge \gamma_i^{(k)}, \quad i = 1, 2, \ldots, M \qquad (1)$$

In the above ν_i is the thermal noise at receiver i. The quantity θ_{ij} is the normalized cross-correlation between p_i and p_j at receiver i. If the inequality (1) holds for the current rate, the user i is said to be *supported.* Otherwise the user is said to be *unsupported.*

The problem is how to assign transmission rate and power to each user so that the instantaneous throughput (the sum of the transmission rates of all active users at the given instant) is maximized. In addition to this, we will focus on a way of guaranteeing the minimum rate to users and minimizing the number of rate changing.

III. Selective Power Control with Active Link Protection

In SPC-ALP, each user has three different modes of operation: *standard*, *transition* and *passive* modes. At iteration n, let us denote all the users in the standard mode by the set $\mathcal{A}(n)$, all the users in the transition mode by the set $\mathcal{B}(n)$ and all the users in the passive mode by the set $\mathcal{C}(n)$. Let $p_i(n)$ denotes the power value of user i at iteration n. The standard mode user updates its power using SPC [6] given by

$$p_i(n+1) = \max_k \left\{ \frac{\delta p_i(n)\gamma_i^{(k)}}{\gamma_i(n)} \chi\left(\frac{\delta p_i(n)\gamma_i^{(k)}}{\gamma_i(n)} \le \bar{p}_i \right) \right\}, \qquad (2)$$

where $\chi(E)$ is the indicator function of the event E and $\gamma_i(n)$ denotes the received CIR of user i based on the measurements done during the n^{th} iteration. Note that in the original definition of SPC, the margin δ was set to unity but here we will use $\delta > 1$. In SPC, the target rate for the iteration $n+1$, $r_i(n+1)$ corresponds to the index k that maximizes the above equation (2). In the standard mode, the target CIR of a user is set to be non-increasing as the iteration goes. If $r_i(n) < r_i(n+1)$, the user changes its mode to the transition mode at the iteration $n+1$.

The transition mode user updates its power based on ALP [8], [9] given by

$$p_i(n+1) = \delta p_i(n), \; i \in \mathcal{B}(n) \qquad (3)$$

In this mode, the target rate for the iteration $n+1$ is chosen to be the maximum rate that can be supported with the current power:

$$r_i(n+1) = \max_k \left\{ r_i^{(k)} : \gamma_i^{(k)} \le \gamma_i(n) \right\}, \; i \in \mathcal{B}(n) \qquad (4)$$

The passive mode user temporarily stops its transmission

$$p_i(n+1) = 0, \; i \in \mathcal{C}(n) \qquad (5)$$

and sets the target rate $r_i(n+1) = 0$.

In SPC-ALP, once the user is allowed to transmit, the power control tries to guarantee at least the minimum transmission rate to that user for the rest of the time. This means that the CIR of that user should be kept above the CIR target corresponding to the minimum rate. If there is any excess capacity, the SPC-ALP tries to utilize it in the best effort way by dividing it between the active and the possible new users. In what follows we describe each mode and the mode change conditions, and discuss the convergence of SPC-ALP.

III.a. Standard Mode

In this mode, the target CIR of a user is set to be non-increasing. With this setting, SPC-ALP guarantees that if a supported user belongs to the set $\mathcal{A}(n)$, it will be supported in the future given that there is no upper bound for transmission powers:

Proposition 1 (Proposition 1 in [8]) *Let $\gamma_i^t(n)$ be the target CIR of user i at iteration n and assume that $\gamma_i^t(n) \geq \gamma_i^t(n+1)$. Then, for any fixed $\delta \in (1, \infty)$, we have that for every n and every $i \in \mathcal{A}(n)$*

$$\gamma_i(n) \geq \gamma_i^t(n) \Rightarrow \gamma_i(n+1) \geq \gamma_i^t(n+1) \tag{6}$$

under the SPC-ALP updating algorithm.

In practice, we have an upper bound for the transmission power and therefore the above proposition does not necessarily hold. To remedy this problem, we will apply the concept of the *distress signaling* [9]. The idea behind the distress signaling is that if a supported user notes that utilizing its current transmission rate $r_i(n)$ would cause its power at the next iteration $p_i(n+1)$ to fulfill the inequality (7), then the network prohibits all the users in other sets from increasing their powers. This procedure guarantees that the user broadcasting the distress signal will be supported in the future.

$$p_i(n+1) = \frac{\delta \gamma_i^t(n)}{\gamma(n)} p_i(n) > \frac{\bar{p}_i}{\delta^m} \tag{7}$$

In above, the positive integer m corresponds to the signaling delay of the distress signal. Unfortunately, in practice broadcasting of the distress signal must be limited to some subset of users (e.g., all the users assigned to one particular base station) and therefore the absolute warranty of support cannot be assured.

We suggest that the distress signal is sent only if it seems that the power of a user already using its minimum rate is drifting towards the maximum value. In SPC, if the interference level is too high so that even the smallest of rates cannot be achieved, the user temporarily shuts down its transmission. If several users shut down their transmission simultaneously, some capacity might get wasted, since removing only a subgroup of those users would decrease the interference level enough so that the rest could stay supported. Therefore in order to decrease the number of unnecessary removals, we suggest a stochastic mode change strategy, in which the user changes its mode from standard to passive with a certain probability $\pi_{A \to C}$. This strategy is similar to the *gradual removal* algorithm, GRR-DCPC, suggested in [10]. In summary, if $p_i(n+1)$ becomes zero in (2), then there are two options in SPC-ALP: The user sets $p_i(n+1) = 0$, $r_i(n+1) = 0$ and switches its mode to the passive mode with probability $\pi_{A \to C}$, or sets $p_i(n+1) = \bar{p}_i$, $r_i(n+1) = r_i^{(1)}$ and stays in the standard mode.

Since we want to use the radio resources in the best effort way, there must exist a mechanism for increasing the rates of the standard mode users. To protect the other standard mode users, a user wishing to increase its rate is only allowed to do so if distress signal is not broadcast. In SPC, if $r_i(n) < r_i(n+1)$, the user i expects that a better rate can be achieved and therefore changes its mode to the transition mode, provided that distress signal is not broadcast.

III.b. Transition Mode

Transition mode is used by users wishing to increase their transmission rates. As in (3), they utilize the power control with limited power-up steps. This kind of power control guarantees that the CIR-values are non-decreasing at each iteration and that the power increase does not harm users in the set $\mathcal{A}(n)$ (see also Proposition 1).

Proposition 2 (Proposition 2 in [8]) *For any fixed $\delta \in (1, \infty)$, we have that for every n and every $i \in \mathcal{B}(n)$*

$$\gamma_i(n) \leq \gamma_i(n+1) \tag{8}$$

In order to prohibit the transmission power of transition mode users from blowing up, we should have a mechanism to change mode from transition to either standard or passive mode. We use the following as a decision criteria:

$$r_i^*(n+1) = \max_k \left\{ r_i^{(k)} : \frac{\delta \gamma_i^{(k)}}{\gamma_i(n)} p_i(n) \leq (1 - d_i)\bar{p}_i + d_i p_i(n) \right\}, \tag{9}$$

where $d_i = 1$ if the distress signal is sent, otherwise $d_i = 0$. The $r_i^*(n+1)$ denotes the best possible rate that user i could achieve given that interference and link gains are constant. If $r_i^*(n+1)$ does not exist, then the user expects not to be supported in the future and changes its mode to passive. If on the other hand the CIR-target corresponding to the rate $r_i^*(n+1)$ is less than or equal to the current CIR value $\gamma_i(n)$, then the user expects to be supported with its best possible rate in the future and thus has no need to further increase its power by δ. Therefore the user chooses $r_i(n+1) = r_i^*(n+1)$ and changes its mode to standard mode. The CIR-target of that user is chosen to correspond to the rate $r_i^*(n+1)$.

III.c. Passive Mode

A new user is initially in the passive mode. In addition, a user that cannot be further supported becomes a passive user. To become active a user must choose its initial rate and power, and change its mode to the transition mode. Bambos [9] has suggested an upper bound for the initial power so that Propositions 1 and 2 would still hold in the case when some new users are given admission to the network. In practice, however, the power given by this bound is too small; if it would be used, the number of iterations required to increase the CIR of a new user over even the smallest target would be extremely large. The drawback of larger initial values is, of course, that they can cause some standard mode users to become unsupported. To protect the active users, the initial power should be chosen to be *relatively* small and the number of users simultaneously changing their modes from passive to transition should be limited. We suggest that a passive user changes its mode to the transition mode with certain probability $\pi_{C\rightarrow B}$ given that no distress signal is broadcast. Since the initial power is expected to be small, the user is initially expected to be unsupported. Therefore, for the initial target rate of the user, it is enough to utilize the minimum rate.

III.d. Convergence

The power values of SPC-ALP do not generally converge to any fixed point solution. However, as is in the SPC algorithm, the convergence is guaranteed at least in the special case where all the users can be supported with the maximum rate (proofs can be found in [1]):

Proposition 3 *If all the users can be supported with maximum rate and CIR-margin $\delta > 1$ simultaneously, SPC-ALP converges to that fixed point solution with probability one.*

IV. Numerical Results

The testbed is a DS-CDMA system with 19 omni-bases located in the centers of 19 hexagonal cells (Figure 1). The distance between two nearest base stations is 2 Km. We consider the uplink of the system in which $\theta_{ij} = 1$. The chip rate is taken to be 1.2288 Mcps and it is assumed that the radio link can support four data rates, $r_i^k = 9.6 \cdot \frac{1}{2^{k-1}}$ Kbps ($k = 1,\ 2,\ 3,\ 4$). At any given instance, a total of 190 mobiles are generated and uniformly distributed over the 19 cells. The link gain g_{ij} is modeled as $g_{ij} = s_{ij} \cdot d_{ij}^{-4}$, where s_{ij} is the shadow fading factor and d_{ij} is the distance between base i and mobile j. The log-normally distributed s_{ij} is generated according to the model in [13] (pp. 185-186, $E(s_{ij}) = 0$ dB, and $\sqrt{E(s_{ij}s_{kl})} = 8$ dB if $i = k$; $\sqrt{E(s_{ij}s_{kl})} = 4\sqrt{2}$ dB if $i \neq k$). The base receiver noise is taken to be -120 dB, and the maximum mobile power is set to 0 dB. At each instance, the initial transmission rate and power of each mobile is randomly chosen and each mobile is connected to the base station that provides the lowest attenuation. The tuning parameters are taken to be $p_0 = -40$ dB, $\pi_{A\rightarrow C} = \pi_{C\rightarrow B} = 0.05$ and $\delta = 1.05$.

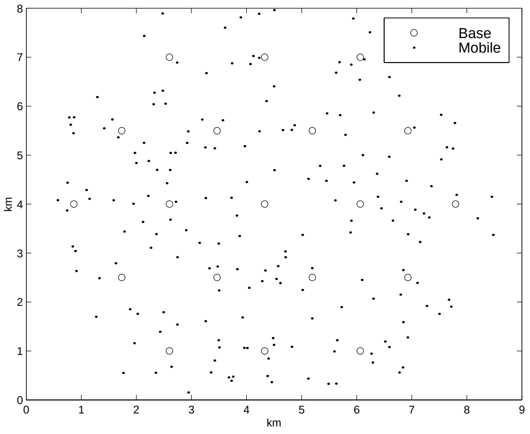

Figure 1: DS-CDMA system with 19 omni-bases.

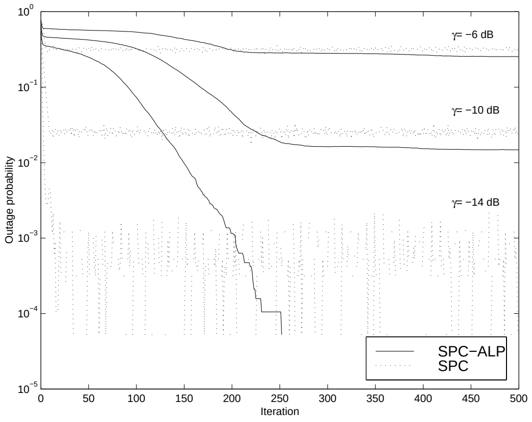

Figure 2: Outage probability.

We consider the *single-code* system in which multiple rates are realized by the variable processing gain that is defined as the ratio of chip rate to the user information bit rate. The required minimum CIR before *despreading* is assumed to be $\gamma_i^k = \gamma \cdot \frac{1}{2^{k-1}}$ for each $9.6 \cdot \frac{1}{2^{k-1}}$ Kbps. Three values, -14 dB, -10 dB and -6 dB are considered for γ, representing light, medium and heavy loads, respectively. The required minimum E_b/I_o, *bit energy-to-interference power spectral density*, is calculated by adding the processing gain to the required minimum CIR value (in dB), which is constant for a given γ, regardless of target rates. For example, when $\gamma = -14$ dB, the required minimum E_b/I_o is about 7 dB. The model used here is adopted from the *variable rate voice calls* in the IS-95 system [12].

The *outage probability*, the *average target rate changing frequency* and the *average throughput per mobile* are used as performance measures. The averages are computed over 190 users in 100 instances. The number of instances is chosen to be small in order to elaborate the oscillatory behavior of SPC. If the CIR value $\gamma_i(n)$, is greater than or equal to the CIR target $\gamma_i^t(n)$ corresponding to the chosen transmission rate $r_i(n)$ then it is assumed that the mobile i successfully transmitted $r_i(n)$ bits at iteration n. Otherwise it is assumed that all the data transmitted by user i

Table 1: Rate changing frequency

State	Algorithm	γ=-6 dB	-10 dB	-14 dB
Transition	SPC-ALP	4.28	2.48	2.02
	SPC	7.75	4.17	1.18
Steady	SPC-ALP	4.27	0.54	0.01
	SPC	6.67	2.90	0.16

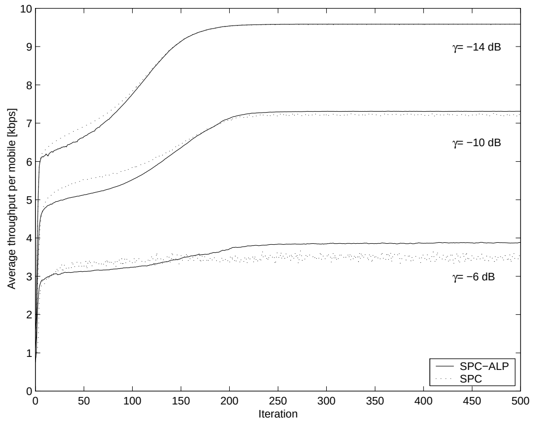

Figure 3: Average throughput per mobile.

at that iteration is lost. The outage at iteration n is defined as the fraction of users that do not get even the minimum rate during the iteration.

Figure 2 indicates that SPC-ALP outperforms SPC in terms of outage probability as the iteration goes. SPC has oscillating CIRs and thus it alternates the set of supported users from iteration to another, resulting in oscillating outage curves. In Table 1, the average number of target rate changes per iteration in the system is shown. The transition state refers to the first 250 iterations during which the throughput of the system is increasing and the steady state refers to the part in which the throughput remains almost constant. From the result we see that SPC-ALP has much smaller changing frequencies than SPC, except at the transition state in the low load case. The reason for the exception is as follows: In Figure 3, it is noticeable that in the low load case, both SPC and SPC-ALP converge, in most of the 100 instances, to the fixed point where all the users are supported with their maximum rate. Since in SPC-ALP the rates are increased gradually, more changes are needed to achieve the maximum rate. In Figure 3, for the medium and the maximum load cases, SPC-ALP gives about 1% and 7% better throughput than SPC respectively, as the system becomes steady. In the low load case the difference is negligible.

V. Conclusions

In this paper, we studied the combined rate and power control for a cellular radio system that can support different transmission rates in a single connection. A new SPC-ALP algorithm applies the SPC algorithm suggested in [6]. Computational experiments carried on a DS-CDMA system indicate that SPC-ALP achieves smaller outages and less rate changes while giving the same or slightly higher system throughput, compared with SPC. The major drawback of SPC-ALP is that the number of tuning parameters that the network operator has to set is rather high.

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