Power Control for Variable QOS on a CDMA Channel

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Abstract

The scant bandwidth and high error rates of the wireless channel make joint source-channel coding desirable for optimizing resource usage. To this end, we propose a multiple substream abstraction for source traffic, with delay and loss characteristics negotiated between the application and network on a per-substream basis. This model affords flexibility while maintaining network efficiency by only appropriating more resources (e.g. bandwidth and error protection) to more important user information. We describe an algorithm for supporting different quality of service (QOS) requirements for different traffic in an interference-limited cellular CDMA environment. The algorithm accepts QOS specifications for different substreams, accommodates them by assigning different power levels to each signal, and can be used to add or drop substream connections dynamically while ensuring that QOS specifications are not violated. Present-day power control schemes are used to combat the near-far effect; while the proposed algorithm also accomplishes this goal, it is in fact more general: via power modulation, it can provision different QOS levels for different substreams.

1 Introduction

Given the low bandwidth and high error rates on a wireless link, joint source-channel coding is desirable for optimizing network efficiency. This can be done by separating the source traffic into multiple substreams, with each substream's delay and loss characteristics individually negotiated between the application and the network. A substream may consist of one media type (e.g. an audio substream), or one component of a media type (e.g. the coarse resolution portion of a multiresolution video signal). The substream abstraction enhances network efficiency by only appropriating more resources - for example, bandwidth and error protection - to the parts of the user information that are more important. Simultaneously, an application can perform more aggressive source coding on substreams of less importance.

In this paper, we study the problem of how to instantiate different quality of service requirements for different substreams on a wireless CDMA downlink. We show that it is possible to achieve variable reliability requirements by way of power control. Present-day systems primarily use power control on the uplink to combat the near-far effect; however, on the downlink in a cellular environment, mobiles near the cell boundaries will experience greater intercell interference than mobiles closer to the base station. The intercell interference may be estimated by using a pilot tone and providing feedback from mobile to base station. In any event, this deleterious effect must be accounted for by the power control algorithm. While it will become evident that our proposed algorithm counters the near-far effect, it is more general than that: it is a mechanism for providing variable QOS for different types of traffic.

We first consider ways of coding for unequal error protection (UEP) of different substreams. UEP can be performed at many levels. At the highest level, some users may demand and be willing to pay for a more stringent reliability guarantee than required by others. At the application level, errors in video are generally more tolerable than errors in audio, and audio is in turn less error-sensitive than data. At the compression level, the motion vectors in interframe video coding require greater protection than the block differences. At the lowest level, the bit level, the most significant bits may be given greater protection than the least significant bits.

Embedded trellis coded modulation (TCM) constellations have been suggested for the terrestrial broadcast channel, but their implementation grows very complex for more than two different levels of error protection [5]. Algebraic codes for UEP also exist [6][7], although the question of constructing good codes is still an open issue. Both these two approaches are more suited towards UEP at the bit level than at higher levels. More recently, rate-compatible punctured convolutional codes, found by exhaustive computer-search, have been applied towards UEP [8][9]. For a puncturing period of 4, rate 4/5, 4/6, 4/7 and 4/8 codes can be found with coding gains almost equal to that of general convolutional codes, and moreover the bit error rate (BER) can be varied by two orders of magnitude. Using this scheme, we can increase the reliability of a substream by migrating from a high rate to a low rate code for greater error protection. However, moving to a stronger code without altering the source information rate requires bandwidth expansion. Hence, dynamically changing the error protection on a substream with time becomes very difficult on a wireless channel with constrained bandwidth.

On an ideal non-dispersive channel with bandwidth B, it is possible to send $2BT$ waveforms, each of duration T, with zero crosscorrelation between any pair of received waveforms [1]. A wireless channel, however, introduces multipath interference, so that this perfect orthogonality be-

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tween different codes is lost. As a result, the capacity of direct-sequence CDMA is inherently interference limited [2][3][4]: the greater the power of one's own signal relative to the aggregate power of other users (from within the same cell as well as from other cells), the lower the probability of error. This observation suggests that CDMA lends itself to a different approach for UEP. Rather than use a variable-rate channel coder, which has suboptimal coding gain in comparison with a fixed-rate coder, we can utilize a highly efficient fixed rate coder, then vary the degree of error protection by modulating the power level instead. In so doing we exploit the notion that for CDMA it is beneficial to transmit the minimum power necessary to support a given BER for a substream, as this creates the least interference pollution for other users. Such a concept is also applicable to TDMA or FDMA cellular systems with frequency reuse. Apart from simplicity, fine grain control and the wide range of BERs achievable, another advantage to realizing UEP by means of power control is that it can be applied not just at the bit level, but at all levels.

2 Problem formulation

Fig. 1 shows a high level schematic of the system considered. The substreams for each user are statistically mul-

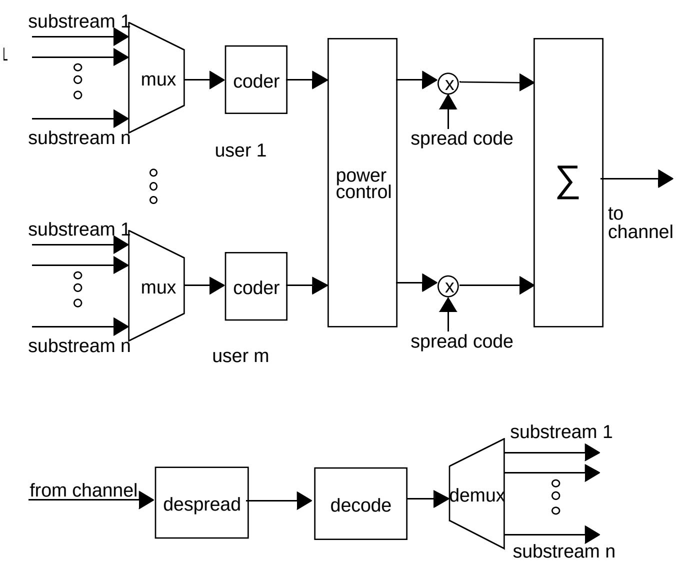

Figure 1. schematic of CDMA with power control and joint source channel coding. Top figure - transmitter; bottom figure - receiver for one user.

tiplexed into one stream (how this is done in accordance with the substreams' different delay bounds will not be described in this paper). The stream then undergoes channel coding, modulation and power control before being assigned a code and transmitted.

2.1 Coding and Modulation for Power Control

In order to provide dynamic time-varying power control, the coding and modulation scheme should be designed such that the power control layer is transparent to the decoder; that is, the decoder should not need to know the amount of signal scaling injected by power control in order to perform detection. A simple modulation scheme satisfying this criterion is M-ary PSK: scaling an MPSK signal constellation also scales the degree of noise immunity, as desired, yet leaves the decision regions invariant.

MPSK is an example of the more general group codes[10]. The points of a group code are generated by a group of orthogonal transformations of an initial vector, and lie on the surface of an N-dimensional sphere. The existence of higher dimension group codes offering greater coding gains over two-dimensional MPSK has long been predicted [11], and it can also be shown that the maximum shaping gain is achieved by a spherical multidimensional constellation [12]. We therefore choose to construct a multidimensional MPSK constellation, consistent with the criterion for transparency of the power control layer to the decoder. Like TCM, this code can be regarded as combined coding and modulation.

We do not generate the code vectors by applying a group of orthogonal transformations, as such a scheme is known to be suboptimal. In fact, an exact solution to the problem of uniformly packing M points on an N-sphere does not exist to date[13]. Instead, we generate the code vectors by a computer simulated relaxation algorithm, as follows: random points lying on the surface of an sphere are initially created. Each point is subjected to a repulsive force from every other point, proportional to the pairwise distance between points. Each point then moves by an elemental amount in the direction of the sum of the forces acting on it on the parametrized N-sphere surface. The entire process is reiterated until convergence within a specified tolerance is achieved.

By this method, we are able to generate to generate higher dimension constellations with coding gains over two-dimensional 8-PSK. Plotted in Fig. 2 is the coding gain over two-dimensional 8-PSK as a function of constellation dimensionality. For fairness of comparison, the average energy per dimension and the spectral efficiency per dimension are kept the same for constellations of different dimension. The coding gain is defined as

$$G = 10\log_{10}[(d^2_{free,\,n-D}/d^2_{free,\,2-D})/(E_{b,\,n-D}/E_{b,\,2-D})] \qquad (1)$$

where $d^2_{free,\,n-D}$, $d^2_{free,\,2-D}$ are the squared free distances, and $E_{b,\,n-D}$, $E_{b,\,2-D}$ are the energy per bit for the two-dimensional and n-dimensional constellations respectively.

2.2 The power control algorithm

Having described a coding and modulation scheme compatible with power control, we turn to the power control

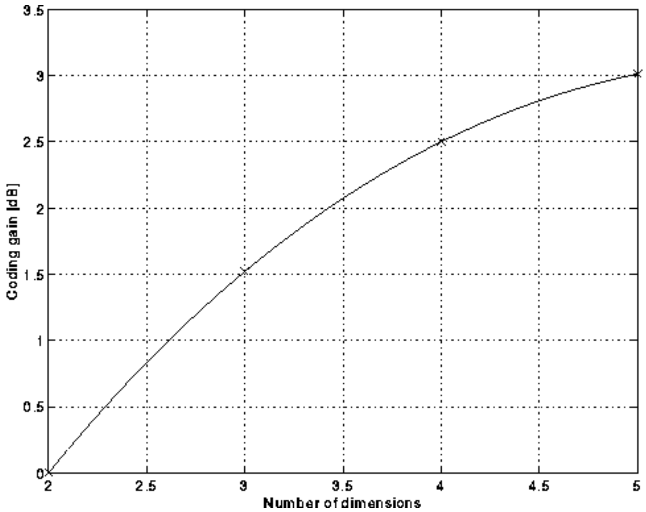

Figure 2. Coding gain versus dimensionality for spherical codes. 2-dimensional 8-PSK is taken as the basis for comparison. The energy per bit and the bit rate per 2 dimensions are the same for all constellations.

algorithm itself. Given a set of substreams, each with its own desired reliability requirement, we wish to address 3 issues:

1. How do we determine if the set of requirements is feasible or infeasible?
2. If feasible, how do we allocate power to each substream?
3. How do we decide if we can admit a new stream without violating the reliability guarantees for streams in-progress?

Before answering these questions, we must first make explicit the notion of a reliability requirement. The reliability requirement in most communications networks is specified as the bit error probability. In CDMA, the sum of the interference from other users and along multiple propagation paths can be approximated as being additive Gaussian noise [15][4][3], and hence the BER can be characterized by the ratio of energy per bit E_b to the interference noise spectral density N_o. A fading channel complicates the analysis, but a monotonic one-to-one mapping between the average BER and the ratio E_b/N_o can still be derived (e.g. see [3]). We will therefore specify the reliability requirement of a substream by its desired energy-to-interference ratio. Let

K = number of substreams

$(E_b/N_o)_i$ = energy-to-interference ratio requested by substream i, i = 1, ..., K.

β_i = 1, if substream i is transmitting during the current time slot
= 0, otherwise

x_i = power assigned to substream i given that it is transmitting during the current time slot

p = total power

N = spreading code processing gain

σ_i^2 = intercell interference experienced by stream i

By a simple extension of the derivation in [2], [3], or [12], the energy-to-interference experienced by substream i is given by the expression

$$Nx_i \Big/ \left(\sigma_i^2 + \sum_{k \neq i} \beta_k x_k\right). \tag{2}$$

We wish to minimize the total power subject to the constraints that the energy-to-interference ratio for every substream is satisfied; i.e.,

$$\text{minimize } p = \sum_{k=1}^{K} \beta_k x_k \tag{3}$$

$$\text{such that } Nx_i \Big/ \left(\sigma_i^2 + \sum_{k \neq i} \beta_k x_k\right) \geq (E_b/N_o)_i \tag{4}$$

$$x_i \geq 0,\ (E_b/N_o)_i > 0 \tag{5}$$

$$\text{for } i = 1, \quad, K.$$

The inequality in Eq. 4 expresses the requirement that the implemented energy-to-interference ratio should equal or exceed the desired E_b/N_o. This system of equations is in fact linear program in non-negative variables. To see this more clearly, let

$$A = \begin{bmatrix} 1/N & -(E_b/N_o)_1\beta_2 & -(E_b/N_o)_1\beta_K \\ -(E_b/N_o)_2\beta_1 & 1/N & -(E_b/N_o)_2\beta_K \\ & & \\ -(E_b/N_o)_K\beta_1 & -(E_b/N_o)_K\beta_2 & 1/N \end{bmatrix},$$

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \\ x_K \end{bmatrix}, \mathbf{b} = \begin{bmatrix} \sigma_1^2(E_b/N_o)_1 \\ \\ \sigma_K^2(E_b/N_o)_K \end{bmatrix}, \ \mathbf{c} = [\beta_1 \quad \beta_K] \tag{6}$$

Eq. 3 - Eq. 5 can then be rewritten as:

$$\text{minimize } \mathbf{cx}$$

$$\text{such that } A\mathbf{x} \geq \mathbf{b},\ \mathbf{x} \geq 0 \tag{7}$$

A linear program can be solved numerically by the Simplex or the interior point algorithm[14]; however, we can exploit the ingrained structure of the problem to obtain a closed-form solution. In the Appendix, we derive that system (7) has a feasible solution if and only if

$$\sum_{k=1}^{K} \beta_k \alpha_k < 1 . \tag{8}$$

Further, if the system is feasible, it has a unique, optimal solution given by

$$x_i = \beta_i \alpha_i (\sigma_i^2 + p) , \tag{9}$$

$$\text{where } \alpha_i = \frac{(E_b/N_o)_i}{N + (E_b/N_o)_i} , \; i = 1, \quad , K , \tag{10}$$

$$\text{with total transmitted power } p = \frac{\sum_{k=1}^{K} \beta_k \alpha_k \sigma_k^2}{1 - \sum_{k=1}^{K} \beta_k \alpha_k} . \tag{11}$$

We can now answer the questions raised at the beginning of this section. Given a set of stream energy- to-interference requirements, we first check if $\sum_{k=1}^{K} \beta_k \alpha_k < 1$ is true. If it is not, no power allocation solution exists. If it is true, then the optimal solution is given by Eq. 9-Eq. 11. The solution also offers an extremely easy way to perform call admission. Suppose the current system has *K* substreams, and we wish to admit one more user (user *K*+1). If we want a hard guarantee on the reliability requirements - i.e. the energy-to-interference ratios must never drop below specifications - we merely set $\beta_i = 1, \quad i$ and check if

$$\alpha_{K+1} + \sum_{k=1}^{K} \alpha_j < 1 . \tag{12}$$

If a soft guarantee is required - i.e. the energy-to-interference ratios meet specifications on average over time - we replaced β_i with $E[\beta_i], \quad i$ in Eq. 19 and Eq. 20. $E[\beta_i]$ is the average duty cycle of substream *i*, and can be directly computed as the ratio of the substream's average rate to the its corresponding user's fixed, aggregate stream rate. We then check if

$$E[\beta_{K+1}]\alpha_{K+1} + \sum_{k=1}^{K} E[\beta_k]\alpha_k < 1. \tag{13}$$

If Eq. 12 or Eq. 13 is satisfied, it is trivial to adjust the power allocation to include the new user. If not, it means we will have to cut back on the other streams' reliability requirements to make room for the new call. How this is done may depend on some economic or fairness criterion.

To summarize, we have described how power modulation can be used to providing unequal error protection for different substreams on a CDMA downlink. It can be applied at all levels, not just the bit level. The scheme does not involve bandwidth expansion and the computations are relatively simple, making it suitable for time-varying error protection as well.

Appendix

We now derive a closed-form solution to the system

$$\text{minimize } \mathbf{cx}$$

$$\text{such that } A\mathbf{x} \geq \mathbf{b}, \; \mathbf{x} \geq 0 . \tag{14}$$

We will do so by first finding the optimal solution to the system of equalities

$$\text{minimize } \mathbf{cx} \tag{15}$$

$$\text{such that } A\mathbf{x} = \mathbf{b}, \; \mathbf{x} \geq 0 . \tag{16}$$

In general, the solution set for Eqn. 15 is a subset of the solution set for Eqn. . However, we will prove that for our problem of interest, solving system Eqn. 15 is equivalent to solving system Eqn. .

A feasible solution to the system $A\mathbf{x} = \mathbf{b}, \; \mathbf{x} \geq 0$, can be readily verified to be

$$x_i = \beta_i \alpha_i (\sigma_i^2 + p) , \tag{17}$$

$$\text{where } \alpha_i = \frac{(E_b/N_o)_i}{N + (E_b/N_o)_i} , \; i = 1, \quad , K , \tag{18}$$

$$\text{and the total transmitted power } p = \frac{\sum_{k=1}^{K} \beta_k \alpha_k \sigma_k^2}{1 - \sum_{k=1}^{K} \beta_k \alpha_k} . \tag{19}$$

From Eq. 19, $0 \leq p < \infty$ if and only if

$$\sum_{k=1}^{K} \beta_k \alpha_k < 1 . \tag{20}$$

If Eq. 20 holds, then $\mathbf{x} \geq \mathbf{0}$ and Eq. 17-Eq. 18 represent a finite, feasible solution to our problem; otherwise, a finite, feasible solution does not exist. We still have to show that this solution is optimal. From basic algebra, **A** is nonsingular if and only if $\mathbf{x} = \mathbf{0}$ is the unique solution to the system $A\mathbf{x} = \mathbf{0}$. This system can be recast in the following form:

$$x_i = \alpha_i \beta_i P, \qquad (21)$$

$$P\left(1 - \sum_{k=1}^{K} \beta_k \alpha_k\right) = 0. \qquad (22)$$

From Eq. 21 and Eq. 22,

$$\mathbf{x} \equiv \mathbf{0} \Leftrightarrow \sum_{k=1}^{K} \beta_k \alpha_k \neq 1. \qquad (23)$$

Hence, A is non-singular if Eq. 20 holds. But from our earlier discussion, this is also the criterion for a finite, feasible solution. Hence, if Eq. 20 holds, a solution will exist, and moreover it will be unique and therefore optimal for system Eqn. 15.

We next show that solving system Eqn. 15 is equivalent to solving system Eqn. . We first show that if a solution to Eqn. 15 exists, then it is an optimal solution for Eqn. ; we then prove that if Eqn. 15 has no solution, neither does Eqn. .

Suppose $\mathbf{x}$ is the optimal solution to Eqn. 15 for $\{(E_b/N_o)_i\}, i = 1, \ldots, K$. Clearly $\mathbf{x}$ is also a feasible solution for Eqn. . Let $\mathbf{x}'$ be any feasible solution to Eqn. . It then follows from Eq. 4 that $\mathbf{x}'$ will satisfy system Eqn. 15 for some set $\{(E_b/N_o)'_i\}$, $i = 1, \ldots, K$, where $(E_b/N_o)'_i \geq (E_b/N_o)_i$, $i = 1, \ldots, K$. Since α_i is a monotonically increasing function of $(E_b/N_o)_i$, it follows that $\alpha_i' = \frac{(E_b/N_o)'_i}{N + (E_b/N_o)'_i} \geq \alpha_i$, $i = 1, \ldots, K$. From Eq. 19, it is clear that

$$p' = \frac{\sum_{k=1}^{K} \beta_k \alpha_k' \sigma_k^2}{1 - \sum_{k=1}^{K} \beta_k \alpha_k'} \geq p \qquad (24)$$

We have shown that any feasible solution $\mathbf{x}'$ to Eqn. will have an objective value greater than or equal to that of the solution x. Hence, The solution to Eqn. 15 is optimal for Eqn. .

Finally, suppose no solution to Eqn. 15 exists for $\{(E_b/N_o)_i\}, i = 1, \ldots, K$. Then from Eq. 20, $\sum_{k=1}^{K} \beta_k \alpha_k \geq 1$. Now suppose a feasible solution $\mathbf{x}'$ to (7) exists. Again, $\mathbf{x}'$ will satisfy system Eqn. 15 for some set $\{(E_b/N_o)'_i\}$, $i = 1, \ldots, K$, where $(E_b/N_o)'_i \geq (E_b/N_o)_i$, $i = 1, \ldots, K$, and $\alpha_i' \geq \alpha_i$. But we would then have

$$\sum_{k=1}^{K} \beta_k \alpha_k' \geq \sum_{k=1}^{K} \beta_k \alpha_k \geq 1, \qquad (25)$$

contradicting the assertion that $\mathbf{x}'$ satisfies system Eqn. 15 for $\{(E_b/N_o)'_i\}, i = 1, \ldots, K$. Hence, no solution to system Eqn. 15 implies no solution to system Eqn. , QED.

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