

VARIABLE QUALITY OF SERVICE IN CDMA SYSTEMS BY STATISTICAL POWER CONTROL

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ABSTRACT

The low bandwidth and high error rates of the wireless channel make joint source-channel coding desirable for optimizing resource usage. We argue that a mechanism for providing variable quality of service (QOS) is essential for joint source-channel coding, and show that its implementation by way of power control is a natural choice for CDMA. Present-day power control techniques focus on controlling interference. In this work, we present a power control algorithm which simultaneously minimizes interference and provides variable QOS contracts for different traffic types in a CDMA system. The algorithm accommodates different QOS requirements by assigning different power levels to each traffic type, and can add or drop connections dynamically while ensuring that QOS specifications are satisfied. Both the uplink and downlink are analyzed, and the scheme is statistically formulated to handle variable-rate traffic.

1 INTRODUCTION

Power control can substantially impact the capacity and perceived quality of service of a CDMA system. Regardless of the mode of multiple access, power control is necessary in cellular systems to mitigate the intercell interference that arises from frequency reuse. In direct sequence CDMA systems, power control is further employed to minimize the intracell interference; it is especially crucial on the DS/CDMA uplink for mitigating the near-far effect. This need for power control to combat interference has been recognized and is the subject of much research ([1]-[6]).

We now motivate a less conventional use of power control. We start by considering how an application may specify its QOS needs to the network. The three components of an application's QOS are bandwidth, delay and reliability. For packet networks, we may further distinguish between corruption (errors in the packet payload) versus loss (errors in the packet header, causing the entire packet to be lost). The Internet Protocol defines flow headers [7] to support variable QOS across different applications. In this paper, we

ask how variable QOS can be provisioned on wireless access links so as to support flows, or similar concepts in other protocols.

Specifying variable QOS for different traffic types gives the network an opportunity to fine-tune resource allocation through joint source-channel coding. This is particularly desirable on the wireless channel, with its low bandwidth and high error rates. To carry out joint source-channel coding, we break up an information source into multiple *substreams* [8]. A substream is characterized by its own QOS specification, like an Internet flow. It may consist of one media type (e.g. an audio source) or one component of a media type (e.g. the coarse resolution portion of a multiresolution video signal [17]). The substream concept enhances network efficiency by only appropriating more resources - for example, lower latency and stronger 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.

The concept of substreams is illustrated by the CDMA system under study, shown in Fig. 1. The substreams are

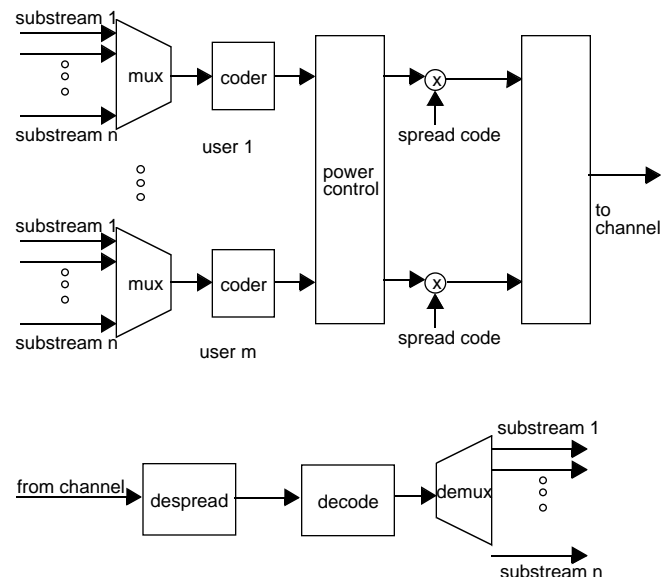


Figure 1. schematic of CDMA downlink with power control and joint source channel coding. Top figure - transmitter; bottom figure - receiver for one user.

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variable-rate and statistically multiplexed into one aggregate *stream* for each user. How the statistical multiplexing impacts the delay aspect of each substream's QOS will not be discussed in this paper; instead, we concentrate our efforts on the loss and corruption aspects of QOS. We assume flow control is applied, so that the sum of the substream bit rates for any user do not exceed the total bit rate of that user's stream. Each stream then undergoes channel coding, modulation and power control before being assigned a spreading code and transmitted.

Key to joint-source channel coding and higher efficiency on the wireless channel, then, is coding for unequal error protection (UEP) of different substreams. UEP may be required at many levels. At the highest level, some users may demand a more stringent reliability guarantee than others. At the application level, video, audio and data all have different error sensitivities. At the compression level, motion vectors from an interframe video coder requires more protection than do block differences. At a bit level, we may wish to afford greater protection to the most significant bits than to the least significant bits.

Embedded trellis coded modulation for UEP has been suggested [13][14], though its complexity grows quickly with the number of protection levels. Algebraic UEP codes have also been proposed [15]. Both these approaches are better suited towards UEP at the bit level than at higher levels. Recently, punctured convolutional codes have been applied to UEP [16], by which the reliability of a substream is increased through migration from a high rate to a low rate code. However, moving to greater redundancy without altering the source information rate requires bandwidth expansion. On a wireless channel with constrained bandwidth, changing the error protection of a substream dynamically over time becomes difficult.

As noted above, the capacity of CDMA is interference-limited[10][11][12]: the greater the power of one's own signal relative to the aggregate power of other users, the lower the probability of error. This observation suggests that CDMA lends itself to a different approach for UEP. Rather than use a UEP channel coder, which has suboptimal coding gain in comparison with a fixed-rate coder, we utilize a more efficient fixed-rate coder, then vary the degree of error protection by modulating the power level instead. Trellis coding is particularly attractive for the bandlimited radio channel, as it provides redundancy without increasing bandwidth. However, it is difficult to produce the trellis equivalent of a variable-rate convolutional code by varying the constellation size, as virtually all of the coding gain is attained by doubling the alphabet size[9]. A solution is to perform UEP by using a fixed rate trellis code and varying the power. By modulating the power level, we exploit the no-

tion that for a CDMA system it is beneficial to transmit the minimum power necessary to support a given QOS for a substream, as this creates the least interference to other users. Apart from simplicity, fine granularity and the wide range of BERs achievable, a significant advantage to using power control is that UEP is achieved in a manner completely transparent to the receiver. While UEP by power control can be simultaneously applied at the bit level, the compression level and all higher levels, the receiver decoder can perform detection without any knowledge of the hierarchy of UEP coding established by the transmitter. This eliminates the need for special packet framing structures for hierarchical UEP coding.

Present day power-control algorithms focus on controlling interference by keeping the received power constant [5][6] or performing carrier-to-interference ratio (CIR) balancing ([1]-[4]). Instead, we consider the problem of how to achieve different quality of service requirements for different substreams or users, and show that it is possible to *simultaneously achieve variable reliability requirements and minimize interference, by way of power control.*

In [21], we describe a power control scheme that minimizes the total transmit power while providing a *hard* bound on the QOS requirements - i.e. a *deterministic* guarantee that the SNR experienced by every substream meets or exceeds specifications at all times. A deterministic call admission criterion works well when the system is lightly loaded, but may lead to conservative utilization of system capacity. This stems from the very definition of a deterministic guarantee: it must always satisfy the worst case, namely when all the users simultaneously transmit substreams of the highest reliability. In this paper, we extend [21] to a statistical formulation which provides QOS guarantees for variable-rate traffic, improve the underlying wireless CDMA model, and generalize the analysis to include uplink as well as downlink power control.

2 PROBLEM FORMULATION

The measure of reliability in CDMA systems is usually specified by the energy to interference density ratio [10] or by the signal to noise interference ratio (SNR) [1]. As these two quantities differ only by the time-bandwidth product $2BT$, a parameter common to the system, we will keep notation simple and henceforth specify the QOS requirement of an individual substream by its desired SNR.

To maintain independent control of loss and corruption, we treat the packet header and packet payload of a substream as two logically separate substreams. Hence, the packet header may specify a higher reliability requirement than the payload, which the network then provides by as-

signing a higher power level to the header than to the payload in the power control algorithm.

2.1 Uplink power control

Denote the number of users by M , and let N_m be the number of substreams of user m . The SNR experienced by the i -th substream of user m on the uplink is

$$SNR_{\text{experienced}} = \frac{G_m x_{i,m}}{2 + I_m^{\text{intra}}}, \quad (1)$$

where G_m is the path gain ([1]-[3]) from mobile m to the base station; $x_{i,m}$ is the transmit power assigned to substream i ; I_m^{intra} is the intracell interference experienced by mobile m , and 2 is the lump sum of background noise and intercell interference experienced at the base station.

The uplink and downlink path gains are assumed equal, with the latter derived from the pilot strength or the automatic gain control circuit in the mobile. There are several ways to measure 2 . The simplest approach is to simultaneously hold all mobiles silent for a short period. During this interval, the received power at the base station is measured and equals 2 . Synchronization between mobiles is achieved by the base station. Alternatively, the base station knows the power received from each mobile and correspondingly the intracell interference experienced by each user. The information can be relayed to each mobile user, who subtracts this quantity from the total power it measures to obtain 2 . Whereas the ‘‘silent period’’ scheme uses uplink bandwidth, the second method uses the downlink. On an asymmetric wireless channel in which downlink has much greater bandwidth than the uplink [23], the second approach may be preferable.

The intracell interference experienced by a substream of mobile m is

$$I_m^{\text{intra}} = \sum_{n=1}^M \sum_{k=1}^{N_n} f_{m,n} G_n x_{k,n}. \quad (2)$$

$f_{k,n}$ is an indicator function, equalling one if substream k of user n is currently active, zero otherwise. A user may have multiple substreams, but the substreams are statistically multiplexed together onto one user stream, so that

only one of the user’s substreams is active at any time. $f_{m,n}$ is the partial correlation coefficient between codes of users m and n : because signals from different mobiles travel through different multipath channels to reach the receiver, $f_{m,n}$ is usually non-zero. Uplink transmission is inherently asynchronous, so $f_{m,n}$ is well modelled by f , the correlation between *random* signature sequences, with $E[f] = 2/3$ [12][19].

The indicator function of a substream as it evolves over time, $k_{m}(t)$, $t \in [0, \infty)$, is a random process. Let \bar{k}_{m} denote the time-average of $k_{m}(t)$; e.g. $\bar{k}_{m} = 1/4$ if the average bitrate of substream k is 500 kbps and it belongs to a 2 Mbps user stream. We assume the process is ergodic in the mean, so that $E[k_{m}(t)] = \bar{k}_{m}$. This is based on the intuition that at any given time slot, the probability that you receive a packet from substream k equals the average rate of that substream, divided by the aggregate rate of the user stream to which it belongs. The expected value of the total power is then

$$E[P] = E \left[\sum_{n=1}^M \sum_{k=1}^{N_n} k_{m}(t) x_{k,m} \right] \quad (3)$$

$$= \sum_{n=1}^M \sum_{k=1}^{N_n} \bar{k}_{k,n} x_{k,n}. \quad (4)$$

Our objective is to minimize the average overall power $E[P]$, while promising each substream that the *expected value* of the SNR it experiences will meet or exceed the desired SNR:

$$\text{minimize } E[P] = \sum_{n=1}^M \sum_{k=1}^{N_n} \bar{k}_{k,n} x_{k,n} \text{ such that } \quad (5)$$

$$i, m, \frac{G_m x_{i,m}}{2 + E[f] \sum_{n=1}^M \sum_{k=1}^{N_n} \bar{k}_{k,n} x_{k,n}} \geq SNR_{i,m}, \quad (6)$$

$$x_{i,l} \geq 0, SNR_{i,l} > 0 \quad (7)$$

$SNR_{i,m}$ is the signal-to-noise ratio requested by substream i of user m , and the inequality in Eq. 6 implies that the expected value of the SNR achieved at the receiver must equal or exceed the desired SNR.

Eq. 5 - Eq. 7 constitute a linear programming problem and can be solved numerically via the Simplex algorithm [20], but we can obtain a closed-form solution. In the Appendix, we derive that the necessary and sufficient condition for feasibility is

$$\alpha_{i,m} < 1, \quad (8)$$

$$\text{where } \alpha_{i,m} = \frac{M}{m}, \quad (9)$$

$$m = \sum_{k=1}^{N_m} E[f]_{k,m}, \quad (10)$$

$$\text{and } \alpha_{i,m} = \frac{SNR_{i,m}}{1 + \sum_{k=1}^{N_m} SNR_{k,m}}, \quad (11)$$

$$i = 1, \dots, N_m, m = 1, \dots, M.$$

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

$$x_{i,m} = \frac{SNR_{i,m}}{G_m} \frac{1 - \alpha_{i,m}}{1 - \alpha_{i,m}^2}. \quad (12)$$

2.2 Downlink Power Control

On the downlink, all intracell substreams arrive at mobile receiver m via the same multipath channel and thus are attenuated by the same amount, G_m . In contrast, the intercell interference is different for each mobile. Since transmission is synchronous, the downlink code correlation coefficient f_m will be directly proportional to the fraction of the received power which is scattered due to the multipath in user m 's channel [11]. For a practical CDMA system employing time diversity [18], this information is available at the RAKE receiver. In absence of time diversity, we consider the worst case, namely when no line-of-sight power component exists. In this event, the crosscorrelation can be modelled by f , as in the uplink.

The downlink formulation is then

$$\text{minimize } E[P] = \sum_{n=1}^M \sum_{k=1}^{N_n} x_{k,n} \quad \text{such that} \quad (13)$$

$$x_{i,m} \leq \frac{G_m x_{i,m}}{M \sum_{n=1}^{N_n} x_{k,n}} SNR_{i,m}, \quad (14)$$

$$x_{i,m} \geq 0, SNR_{i,m} > 0. \quad (15)$$

The downlink solution is derived along the same line of reasoning as the uplink. The necessary and sufficient condition for downlink feasibility is identical to the uplink case, provided we substitute $E[f_m]$ for $E[f]$ in the expressions for m and $\alpha_{i,m}$ (Eq. 10 and Eq. 11). If feasible, the unique, optimal solution is

$$x_{i,m} = SNR_{i,m} \left(\frac{2}{m} / G_m + E[f_m] (E[P] - E[P_m]) \right),$$

$$\text{with } E[P_m] = \frac{2}{m} \frac{m}{G_m E[f_m]} + E[P]$$

$$\text{and } E[P] = \left(1 - \sum_{n=1}^M \frac{n}{G_n E[f_n]} \right)^{-1}. \quad (16)$$

3 DISCUSSION

Looking at (11), $\alpha_{i,m}$ is a monotonically increasing function of $SNR_{i,m}$; thus, the power assigned to a substream is monotonic in the substream's desired reliability requirement. We can interpret (8), the feasibility criterion, as a measure of *the QOS capacity for an interference-limited CDMA system*. The closer $\alpha_{i,m}$ is to unity, the closer such a system is to operating at capacity in terms of being able to meet QOS requirements for all users and substreams. If the QOS requirements of the substreams in a cell are too stringent, then the intracell interference will be too great and no solution exists, regardless of how much power is pumped into the cell. In addition to a fundamental rate capacity, we have shown for interference-limited CDMA that there is a signal-to-interference, or QOS, capacity as well.

Secondly, the feasibility criterion points to a simple way to perform call admission. To determine if we can add a new substream without violating the QOS guarantees for substreams in-progress, we simply check whether

$$\text{current_system} + E[f]_{\text{new_substream}} < 1. \quad (17)$$

If Eq. 17 holds, we can admit the new substream; otherwise, we will have to renegotiate the QOS contracts of the existing substreams to make room for the new substream.

To better understand what can be gained by using power control, we simulated the system in Fig. 1 for 50 users. Hybrid PN-Walsh codes from the IS-95 standard [24] were chosen to perform the spreading. The channel consisted of an FIR filter followed by an additive Gaussian noise source, to simulate background noise, intercell interference and multipath. The intercell interference noise power that each user experiences is random, uniformly distributed between 0 to 20 dB. So that results can be readily interpreted, we consider the case where each user has only one substream, and all substreams request the same QOS. Plotted in Fig. 2 is a histogram of the number of users versus the bit error rate experienced for 2 cases, power control and no power control. For fairness of comparison, the total transmit power is the same for both. In the case of no power control, power is divided evenly between all 50 users.

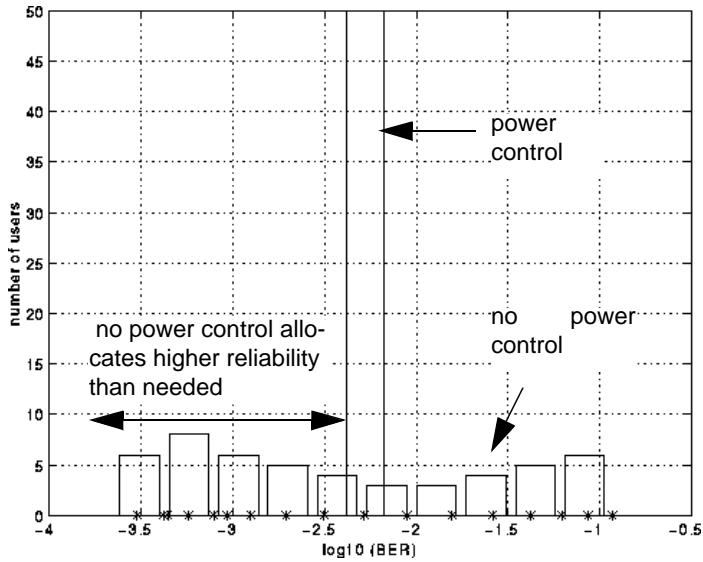


Figure 2. Histogram of the number of users vs. the bit error rate each user receives, with and without power control.

In the absence of power control, higher reliability than needed is allocated to roughly half of the users, at the expense of unacceptable QOS for the rest of the users. By contrast, power control permits the network to utilize the same amount of power resource to satisfy the QOS contracts of all users.

Finally, we consider the variability incurred in the achieved SNRs through usage of a statistical bound. From the solution, we note that the transmit power of user channel m at any instant is a discrete random variable with probabil-

ity mass function

$$\Pr[P_m = x_{k,m}] = \frac{1}{N_m}, \quad k = 1, \dots, N_m,$$

$$\Pr[P_m = 0] = 1 - \frac{1}{N_m}$$

and variance

$$P_m^2 = \frac{1}{N_m} \sum_{k=1}^{N_m} x_{k,m}^2 - \left(\frac{1}{N_m} \sum_{k=1}^{N_m} x_{k,m} \right)^2. \quad (18)$$

Assuming independence of different user traffic, the standard deviation in the total received power is

$$P_{\text{received}} = \sqrt{\sum_{m=1}^M G_m^2 P_m^2} \quad (19)$$

If we now consider the ratio of the standard deviation to the mean for the total received power, it can be shown [22] that this ratio approaches zero as the number of users tends to infinity. Hence, as the number of users grow large, the total received power becomes increasingly deterministic. By applying a statistical guarantee when the system is heavily loaded, the instantaneous intracell interference power will be close to the expected interference power, with the degree of variability in the achieved SNRs becoming ever smaller as the number of users increases. Likewise, the quantity we are minimizing - the expected total transmit power - will closely reflect the instantaneous total power. Thus, a statistical criterion and high system utilization work together to each other's mutual advantage.

In conclusion, we have described how power control can be used simultaneously to provide variable QOS and to combat intracell and intercell interference in a cellular system. UEP by power modulation can be applied at all levels, not just the bit level, and the degree of protection can be varied with fine granularity. The scheme does not require bandwidth expansion and the computations are relatively simple, making it suitable for time-varying error protection on a bandlimited channel.

4 APPENDIX

We now derive the closed-form solution to the uplink optimization problem; the downlink is symmetric. The proof is similar in spirit to [21]. Map substream i of user m

to an index u by $u(i, m) = i + \sum_{n=1}^{m-1} N_n$, and likewise let

$v(j, n)$ be a (substream, user) index. Let K be the total

number of substreams, and define the $K \times K$ matrix

$\mathbf{A} = [a_{u,v}]$ by

$$\begin{aligned} a_{u(i,m),v(j,n)} &= G_m / SNR_{i,m}, \quad u = v, \\ &= -G_n E[f]_{j,n}^{-1}, \quad u \neq v. \end{aligned} \quad (20)$$

Define the $K \times 1$ vectors \mathbf{c} , \mathbf{b} , \mathbf{x} by $c_{u(i,m)} = 1$, $b_{u(i,m)} = G_m^2$, and $x_{u(i,m)} = x_{i,m}$ respectively. The uplink formulation (Eq. 5 - Eq. 7) can then be expressed as

$$\text{minimize } \mathbf{c}^t \mathbf{x} \quad (21)$$

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

We will solve system (21) by first finding the optimal solution to the system of *equalities*

$$\text{minimize } \mathbf{c}^t \mathbf{x} \quad (22)$$

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

In general, the solution set for system (22) is a subset of the solution set for system (21). However, we will prove that (21) and (22) have equal solution spaces for the problem of interest.

Eq. 9 - Eq. 12 can be verified to form a solution to $\mathbf{A}\mathbf{x} = \mathbf{b}$. Moreover, if Eq. 8 holds then $\mathbf{x} \geq 0$ and Eq. 9 - Eq. 12 represent a finite, feasible solution to our problem; otherwise, a finite, feasible solution does not exist. It remains to show that this solution is optimal. From basic algebra, \mathbf{A} is nonsingular if and only if $\mathbf{x} = \mathbf{0}$ is the unique solution to $\mathbf{A}\mathbf{x} = \mathbf{0}$. To use this fact, we manipulate the system $\mathbf{A}\mathbf{x} = \mathbf{0}$ into the following form:

$$x_{u(i,m)} = SNR_{i,m} G_m^{-1} (1 - \sum_{n=1}^{N_n} x_{k,n}) I, \quad u = 1, \dots, K, \quad (23)$$

$$I(1 - \sum_{n=1}^{N_n} x_{k,n}) = 0, \quad (24)$$

$$\text{with } I \text{ defined as } I = E[f]_{k,n}^{-1} G_n \sum_{k=1}^{N_n} x_{k,n}.$$

From Eq. 23 and Eq. 24,

$$1 - \sum_{n=1}^{N_n} x_{k,n} = 0. \quad (25)$$

We have the result that matrix \mathbf{A} will be non-singular if $\sum_{n=1}^{N_n} x_{k,n} < 1$. Hence, if $\sum_{n=1}^{N_n} x_{k,n} < 1$, a positive solution will exist, and

moreover it will be unique and therefore optimal for system (22).

We next prove that solving system (22) is equivalent to solving system (21). We show if a solution to (22) exists, then it is optimal for (21); we then demonstrate if (22) has no solution, neither does (21).

Suppose \mathbf{x} is optimal for (22) for $\{SNR_{i,m}\}$, $i = 1, \dots, N_m$, $m = 1, \dots, M$. Clearly \mathbf{x} is also feasible for (21). Let \mathbf{x} be any feasible solution to (21). Then \mathbf{x} will satisfy system (22) for some set $\{SNR_{i,m}\}$ where, from Eq. 6,

$$SNR_{i,m} = \frac{G_m}{x_{i,m}}, \quad i = 1, \dots, N_m, m = 1, \dots, M. \quad (26)$$

Noting that the function $f(t) = t/(1+t)$ is monotonic in t , we have

$$m = \frac{E[f]_{j,m}^{-1} SNR_{j,m}}{1 + E[f]_{j,m}^{-1} SNR_{j,m}}, \quad (27)$$

$$m = 1, \dots, M,$$

$$\text{and } \sum_{n=1}^{N_n} x_{k,n} < 1. \quad (28)$$

Rewriting Eq. 12 as

$$x_{u(i,m)} = \frac{SNR_{i,m}^2}{G_m} \left(1 + \sum_{n=1}^{N_n} x_{k,n} \right) / (1 - \sum_{n=1}^{N_n} x_{k,n})$$

and applying Eq. 26 - Eq. 28 yields

$$x_{u(i,m)} = x_{i,m}. \quad (29)$$

It follows that any feasible solution \mathbf{x} to (21) will have an objective value greater than or equal to that of the solution \mathbf{x} . Thus, the solution to (22) is optimal for (21).

Finally, suppose no solution to (22) exists for $\{SNR_{i,m}\}$, $i = 1, \dots, N_m$, $m = 1, \dots, M$. We then have $\sum_{n=1}^{N_n} x_{k,n} \geq 1$. Suppose a feasible solution \mathbf{x} to (21) exists.

Again, \mathbf{x} will satisfy system (22) for some set

$\{SNR_{i,m}\}$, with $SNR_{i,m} \leq SNR_{i,m}$ and $m = 1, \dots, M$. But then

$$\sum_{n=1}^M \sum_{n=1}^M \frac{1}{SNR_{i,m}} \leq 1, \quad (30)$$

contradicting the assertion that \mathbf{x} satisfies system (22) for

$\{SNR_{i,m}\}$. Hence, no solution to system (22) implies

no solution to system (21). \square

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