Outage-Based Admission Region in Multi-Class Cellular Systems

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***Abstract*— We present an approach to defining probability of outage as a system-wide QoS measure for cellular systems. We describe how to use this approach to define an admission region where the requirements on probability of outage are satisfied. We illustrate the approach by constructing the aforementioned admission region for a few examples.**

I. Introduction

Outage probability is an important performance measure in cellular networks. In a cellular scenario low signal to noise plus interference ratios (SNIR) can increase bit error rate (BER), but more importantly if this ratio remains low for a long enough duration, it can cause an outage in an ongoing service (due to loss of synchronization, etc). This will result in disconnection of an admitted call. In most common scenarios, this is considered a more severe form of low performance than blocking (which occurs when a new call is denied admission to the cell, hence the network). As a result, outage probability is considered a main performance measure for traditional cellular networks. We believe that outage probability together with average bit error rate and throughput can form a reasonable set of performance criteria or quality of service (QoS) requirements for certain types of traffic (e.g. voice and data streams in pre-third-generation CDMA systems). In this work we provide a procedure to determining the admission region of a cellular system where the probability of outage for each user cannot exceed a prespecified threshold (depending on the class of the user).

We describe an outage by two parameters: (i) the SNIR threshold γ; and (ii) a minimum duration τ. An outage occurs when the SNIR remains below the threshold γ for a period longer than or equal to τ.

In most of the currently available literature (e.g. see [3], [5], and [7]), an outage is assumed to occur when the SNIR falls below a threshold γ^*. We believe that this is not sufficient to capture the essence of an outage, since it ignores statistical correlation or burstiness in the incoming traffic stream. It is intuitively expected that traffic streams with high level of burstiness are more probable to cause an outage than non-bursty or iid streams with the same level of instantaneous intereference. Similarly, the memory present in fading channels directly affects how long the impairment will last, hence it affects the occurance of an outage. In other words, the drop in the SNIR below γ does not result in an outage instantaneously; an outage results in when the SNIR is low for an extended period of time, i.e. a time period that exceeds a minimum duration τ. With this definition, the occurance of outage events strictly depend on the second order statitics of the interference and/or fading. A characterization of outage both in terms of the threshold γ and the time duration τ has appeared only in [4] and [10]. One key feature of [4] and [10] is that the effect of other users on the outage probability is not taken into account. That is, the effect of the (random) number of active users and the statistical variation of their channels on the probability of outage is ignored. Attention in both [4] and [10] is restricted on one user and on the effect of its physical channel on the outage probability.

In general, the performance of a wireless system critically depends on two factors: (i) the condition of the physical channel; and (ii) the interference created by other users. The approach to outage that we propose captures both of the aforementioned factors. By incorporating the effect of multiple access interference into our approach, we are able to relate the probability of outage to the number and type of users present in the system and, therefore, to determine an admission region associated with the maximum acceptable outage probability for each type of user.

The salient features of our approach are the following: $(F1)$ We model the statistical variation of the physical channel by a Markov Chain (as in [10]). $(F2)$ We consider several types of users in terms of their statistical activity, and QoS requirements. $(F3)$ We fix the total number of users admitted by the system, and we assume that the status of each user switches between "active" and "inactive" according to a Markov rule (independent of $(F1)$). The status of a particular user is not necessarily independent of that of another user.

As a result of the aforementioned features, we can construct a model which allows us to define, for any multiple access scheme, the SNIR and hence, determine for any parameters γ and τ the probability of outage as a function of the fixed number of users present in the system. This in turn allows us to analytically determine the capacity of the system associated with maximum acceptable probability of outage.

Therefore, the contribution of this paper is twofold: (i) the development of an approximate statistical model for outage; and (ii) the analytic determination of an admission region where under any admission strategy the desired performance of the system with regard to outage is guaranteed.

The paper is organized as follows: In Section II, we construct a stochastic model and analytically calculate the problem of probability of outage. In Section III we present examples illustrating the modeling and results in Section II. In Section IV we conclude the paper.

II. Outage-based Admission Region for Multiuser Systems with Markov Channels

A. Philosophy of Our Approach

We address the issue of outage probability within the context of QoS requirements. A user in the system encounters an outage event when its received SNIR at the base station falls below a threshold for an extended period of time. Hence, an outage is experienced by each user individually. Therefore, the key conceptual issue is how to formulate probability of outage as a system-wide QoS criterion. We address this issue by introducing a fictitious observer/user and by defining the system-wide outage measure as the probability of outage for this user. To guarantee that probability of outage meets the requirements for every type of user that may be admitted by the system we proceed as follows: We consider a separate fictitious observer/user for each type of traffic. Such a user is always active and is identical to the actual users of the same type in terms of the statistics of the physical channel, SNIR threshold, and minimum outage duration. Each fictitious observer/user does not create any interference in the system, hence has no effect on the performance of the system. The probability of outage for such a user is a conservative bound on the outage probability of each user of the same type. Hence, the system-wide QoS requirement in terms of probability of outage is met if the probability of outage for each of the aforementioned fictitious users is below a prespecified value (that depends on the type of user) which reflects the QoS requirement.

In this section, we construct the outage-based admission region following the above philosophy. In Section II-B, we formulate the outage problem associated with a fictitious observer/user u_0 whose statistical variation of its channel, the SNIR threshold γ, and the minimum outage duration τ are given. We fix the number of admitted users, and model the effect of channel variations and interference as a super Markov chain (SMC). Then, we identify the states of the SMC where the combination of channel variation and interference causes a SNIR below γ. In Section II-C, we use the formulation of Section II-B to calculate the outage probability associated with u_0 (when the number of admitted users is fixed). In Section II-D, we construct an admission region where the system-wide QoS in terms of outage probability is guaranteed.

B. Outage Formulation for a Given Observer/User in the Presence of a Fixed Number of Users

In this section we fix the number of admitted users, and then formulate the probability of an outage for a fictitious observer/user u_0, whose channel statistics, SNIR threshold γ, and minimum outage duration τ are given.

In a wireless setting the received SNIR of a observer/user u_0 depends on two decoupled factors: 1) the effect of physical channel in the absence of other users; this captures events like additive noise, fading, and/or shadowing (in the presence or absence of power-control mechanisms). 2) the effect of the presence, power, and channel statistics of the other active users admitted in the system. Therefore, to determine the probability of outage, we need (i) to model the channel degradation; (ii) to model the interference of other admitted users; and (iii) to construct a "Super Markov Chain" combining (i), and (ii) in order to describe the the received SNIR of u_0.

It is very common to model the effect of the channel on SNIR in the absence of other users as a Markov chain. The validity of such model has been extensively studied and confirmed in the literature (see [9]). The most commonly used example of this kind is the Gilbert Channel. In general, such a MC is defined by its state-space $H = \{h_1, h_2, \ldots, h_I\}$, and its transition matrix

$$\mathbf{A} = [a_{kl}] = [\mathrm{Prob}\{X(t+1) = h_l | X(t) = h_k\}]. \qquad (1)$$

Note that in case of an ideal power control mechanism H is reduced to a singleton $\{h\}$, and hence $\mathbf{A} = 1$; whereas in case of power control with quantized error $\pm\delta$, we have $H = \{h-\delta, h, h+\delta\}$.

To model the interference of other admitted users, we assume that there are L types of users in terms of QoS requirements, transmission Power, and the activity factor [7], and there are $(M_1, M_2, \cdots, M_L)$ users admitted to the system (not including u_0). At any time slot, each admitted user can be active (on) or inactive (off). Since only active users interfere with the received signal of u_0, we need to find an appropriate model to describe the evolution of the users' "on" periods. In this paper, we assume that active and inactive periods for a user of type l evolve according to a b_l-order Markov chain. Consequently, we can model the activity of user i of type l by a Markov chain of size $B_l = 2^{b_l}$; we denote the states of this Markov chain by an integer $n_l^i \in 1, 2, \ldots, B_l$. In general we assume that the activity of all users can be correlated. Based on the above, we can express the state of users (in terms of being active or inactive) by the following random array:

$$(n_1, \ldots, n_L) = ((n_1^1, \ldots, n_1^{M_1}), \cdots, (n_L^1, \ldots, n_L^{M_L})). \qquad (2)$$

By construction, this array evolves according to a known Markov rule. Let $\mathbf{T}$ be the transition matrix for this Markov chain, i.e.

$$\mathbf{T}_{ij} = \mathrm{Prob}\{(n_1, \cdots, n_L) \mid (m_1, \cdots, m_L)\}. \qquad (3)$$

Note that T is a square matrix of dimension $\prod_{l=1}^{L} B_l^{M_l}$.

To describe the received SNIR of u_0, we construct a "super Markov chain" (SMC) which represents the variation of the physical channel for u_0 the channel variation of other users, and the state of the admitted users. The states of this SMC are arrays of type

$$\mathbf{s} := (h^{u_0}, (h^{1,1}, \cdots, h^{1,M_1}), \cdots, (n_1, \cdots, n_L))$$

where $h^{u_0} \in H_{u_0}$ is the state of the channel between user u_0 and the base-station, $h^{l,k} \in H_l$ for $l = 1, 2, \ldots, L$, and $k =$

$1,1,\cdots,M_l$ is the state of physical channel (in the absence of other users) between user k of type l and the base-station, and n_l for $l=1,2,\ldots,L$ is a vector of length M_l defined in (2). The state-space of this Super Markov Chain (SMC) is $S = H_{u_0} \times \prod_{l=1}^{L} H_l{}^{M_l} \times \prod_{l=1}^{L}\{1,2,\ldots,B_l\}^{M_l}$. Since the state of the physical channel for a user, $h^{i,l}$, is independent of the number of the other users and their channel state the transition probability for this SMC can be easily obtained, using (3). It is

$$\mathbf{P} = \mathbf{T} \otimes \overbrace{\mathbf{A}_L \otimes \cdots \otimes \mathbf{A}_L}^{M_L} \otimes \cdots \otimes \overbrace{\mathbf{A}_1 \otimes \cdots \otimes \mathbf{A}_1}^{M_1} \otimes \mathbf{A}_0 \qquad (4)$$

where $\mathbf{A}_0$ is the transition matrix of the Markov physical channel between observer/user u_0 and the base-station, and $\mathbf{A}_l$ for $l=1,2,\ldots,L$ is the transition matrix of the Markov physical channel between a user of type l and the base-station.

To determine the probability of outage, first we must specify the received SNIR of observer/user u_0 at each state $\mathbf{s} \in S$. This SNIR is a function $f_{u_0} : S \longmapsto \mathbb{R}_+$. The exact form of $f_{u_0}(\cdot)$ depends on the dynamics of multiple access interference, and possibly the power control mechanism. For instance, for a CDMA system where users of the same class have a common transmitted power and there is no power control, the form of function f_{u_0} is:

$$f_{u_0}(\mathbf{s}) = \frac{h^{u_0} P_0 G_0}{\eta + \sum_{l=1}^{L} P_l \sum_{k=1}^{M_l} \psi_{l,k} h^{l,k}}. \qquad (5)$$

where η is the noise power (that includes the expected total interference from the adjacent cells), G_0 is the spreading gain for user u_0, $h^{l,k}$ is the channel gain between k^{th} user of type l and the base, $\psi_{l,k} \in \{0,1\}$ is an indicator function which is equal to one when the k^{th} type l user is active, and P_l is the common transmitted power for all type-l users. This form can extend to CDMA systems with power control where each class of users has a common targeted power, and where $h^{l,k}$ represents the error of the power control mechanism.

After specifying the SNIR of user u_0 at each state, we define the sets of "bad states" B, and "good states" G as

$$B \;:=\; \{\mathbf{s} \in S \,|\, f_{u_0}(\mathbf{s}) < \gamma\}, \qquad (6)$$
$$G \;:=\; S - B \qquad (7)$$

Based on the above classification of states we can now formally define the probability of outage.

Definition 1: An outage is an event where the state of the SMC enters B and stays in B for at least τ units of time.

Definition 2: The probability of an outage is defined to be the probability that a randomly selected time slot belongs to an outage event.

B.1 Worst Case Scenario

In general, the dimension of the matrix $\mathbf{P}$ can be very large. This creates a practical difficulty in the calculation of outage probability. To deal with this difficulty, we can analyze the worst case condition for user/observer u_0, where all the other users are in their best physical channel realization. In other words, we replace H_l with a singleton $\{h^l_{best}\}$ where $h^l_{best} = \max H_l$, and hence $\mathbf{A}_l = 1$. In this situation the SNIR can be expressed as

$$f^w_{u_0}(\mathbf{s}) = \frac{h^u_0 P_0 G_0}{\eta + \sum_{l=1}^{L} h^l_{best} P_l r_l}. \qquad (8)$$

where r_l is the the total number of active users of type l; and as before η is the noise power, G_0 is the spreading gain for user u_0, h^{u_0} is the channel gain between u_0 and the base station, and P_l is the common transmitted power for all type-l users. Equation (8) implies that in this case the effect of other users are like a noise term proportional to the number of active users. A state for the worst case scenario is a vector of the form $(h, r_1, r_2, \cdots, r_L)$. If we denote by I_l (I_{u_0}), the size of set H_l (H_{u_0}), then the dimension of the state space in the worst case problem is $I_{u_0} \times \prod_{l=1}^{L}(M_l+1)$; whereas the state space in the original formulation is of the dimension $I_{u_0} \times \prod_{l=1}^{L} I_l{}^{M_l} \times \prod_{l=1}^{L} B_l^{M_l} = I_{u_0} \times \prod_{l=1}^{L}(I_l \times B_l)^{M_l}$, which in general is much larger. In the worst case problem, the transition matrix of the SMC is

$$\mathbf{P} = \mathbf{T}' \otimes \mathbf{A}_0, \qquad (9)$$

where $\mathbf{T}'$ is defined as

$$\mathbf{T}'_{ij} = \text{Prob}\{(r_1, r_2, \ldots, r_L) = j \mid (r_1, r_2, \ldots, r_L) = i\}. \qquad (10)$$

$\mathbf{T}'$ can always be determined from $\mathbf{T}$, define by (3), but in most cases $\mathbf{T}'$ can also be constructed using the traffic model of each user type directly.

As before, the sets of "bad" and "good" states are

$$B \;:=\; \{\mathbf{s} \in S \,|\, f^w_{u_0}(\mathbf{s}) < \gamma\}, \qquad (11)$$
$$G \;:=\; S - B \qquad (12)$$

And an outage occurs when the state of the Markov chain remains in the set B for at least τ units of time.

C. Outage Analysis for a Given Observer/User in the Presence of a Fixed Number of Users

The probability and frequency of an outage event in the constructed SMC can be studied in the framework of [10].

Consider the constructed SMC and the associated transition matrix $\mathbf{P}$ with it. We follow [1] and [10] to establish the necessary equations and relations that describe the probability of outage. Note that the SMC is mathematically equivalent to the physical Markov Channel studied in [10], even though the SMC, in general, has a much larger state space, and it has a very specific structure due to its construction. Hence, after introducing the appropriate notation and definitions we can use results provided from [10] for the analysis of the probability of outage.

C.1 Definitions

- Let the row-vector π denote the stationary distribution of SMC.
- Define π_G and π_B as

$$\pi_G(\mathbf{s}) = \begin{cases} \pi(\mathbf{s}) & \text{if } \mathbf{s} \in G \\ 0 & \text{otherwise} \end{cases}, \quad (13)$$

$$\pi_B(\mathbf{s}) = \begin{cases} \pi(\mathbf{s}) & \text{if } \mathbf{s} \in B \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

- Define P_B as the matrix with entries

$$P_B(i,j) = \begin{cases} \mathbf{P}(i,j) & \text{if } j \in B \\ 0 & \text{if } j \in G \end{cases} \quad (15)$$

C.2 Results

We establish an analytical expression for probability of outage. For that matter we need the following result from [10].

Fact. 1: The probability of outage is given as

$$P_{outage} = \tau\pi_G P_B{}^{\tau}\mathbf{1} + \pi_G P_B{}^{\tau+1}(I-P_B)^{-1}\mathbf{1} \quad (16)$$

Based on Fact 1 we establish an alternative analytical expression for the probability of outage. The new expression is easier to compute as it involves neither inversion of a matrix nor calculation of vector π_G.

Proposition 1:

$$P_{outage} = \pi P_B{}^{\tau}(\tau I - (\tau-1)P_B)\mathbf{1} \quad (17)$$

Proof: From (16) we have

$$\begin{aligned} &P_{outage} \\ &= \tau\pi_G P_B{}^{\tau}\mathbf{1} + \pi_G P_B{}^{\tau+1}(I-P_B)^{-1}\mathbf{1} \\ &= \pi_G P_B{}^{\tau}\left((\tau-1)I + (I-P_B)^{-1}\right)\mathbf{1} \\ &= (\pi-\pi_B)P_B{}^{\tau}\left((\tau-1)I + (I-P_B)^{-1}\right)\mathbf{1} \\ &= (\pi_B P_B{}^{\tau-1} - \pi_B P_B{}^{\tau})\left((\tau-1)I + (I-P_B)^{-1}\right)\mathbf{1} \\ &= \pi_B P_B{}^{\tau-1}(I-P_B)\left((\tau-1)I + (I-P_B)^{-1}\right)\mathbf{1} \\ &= \pi_B P_B{}^{\tau-1}\left((\tau-1)(I-P_B)+I\right)\mathbf{1} \\ &= \pi_B P_B{}^{\tau-1}(\tau I - (\tau-1)P_B)\mathbf{1} \\ &= \pi P_B{}^{\tau}(\tau I - (\tau-1)P_B)\mathbf{1} \end{aligned}$$

where the third equality holds since $\pi_B = \pi - \pi_G$, and the fourth and the last equality result from the fact that $\pi_B = \pi P_B$. ■

D. Constructing Admission Region

We now discuss how to use the results obtained in Section II-C to construct an admission region when the probability of outage is the QoS requirement under consideration. An admission region is the set of all combinations of admitted users such that if connection admissions are restricted to a subset of its interior, the probability of an outage encountered by each fictitious observer/user of type l is less than a prespecified threshold P^l_{max} for all $l = 1,2,\dots,L$.

The formulation of probability of outage presented in Section II-B and the analysis of Section II-C provide an expression for the probability of outage of a fictitious user of type l ($l = 1,2,\dots,L$) as a function $g_l : \mathbb{Z}^L_+ \longmapsto \mathbb{R}_+$ of the vector of admitted users $\underline{M} = (M_1, M_2, \dots, M_L)$. Therefore, for a fixed type l fictitious user (i.e. $H_{u_0} = H_l$, $\mathbf{A}_0 = \mathbf{A}_l$, $\tau_0 = \tau_l$, $\gamma_0 = \gamma_l$, and $f_{u_0}(\cdot) = f_l(\cdot)$) the region where QoS (expressed by the probability of outage) is guaranteed for that type of user is

$$R_l := g_l^{-1}([0, P^l_{max}]) = \{\underline{M} : g_l(\underline{M}) \leq P^l_{max}\}. \quad (18)$$

Consequently, the region where the QoS is guaranteed for all the users is

$$R := \bigcap_{l=1}^{L} R_l = \bigcap_{l=1}^{L} \{\underline{M} : g_l(\underline{M}) \leq P^l_{max}\}. \quad (19)$$

Since it is not desirable for any admission strategy to terminate an unfinished service, we define the admission region A as the largest coordinate convex subset of R, i.e.

$$A := \sup_{C \subseteq R} \{C : \text{ if } \underline{M} \in C, \underline{M}' \leq \underline{M} \text{ then } \underline{M}' \in C\}. \quad (20)$$

Recall that our analysis is valid for a fixed number of admitted users. In a wireless system the number of users (active and inactive) present in the system varies with time. To establish he validity of our analysis for wireless systems with dynamic number of users present in the system we prove the following theorem.

Theorem 1: The admission region A is a conservative bound on the dynamic number of admitted users (under any admission policy resticted to A) for which the QoS expressed by the probability of outage is met.

Proof: Fix a fictitious observer/user, say of type l. Restrict an admission policy to A. Since A is coordinate convex, $\underline{M}(t) \in A$ for all t, where $\underline{M}(t)$ is the vector indicating the number of users of each type present in the system at time t. Hence $\underline{M}(t) \in R_l$. Pick $\underline{M}_0 = \arg\max_{\underline{M} \in R_l} g_l(\underline{M})$. Since $\underline{M}(t) \in R_l$ for all t, the probability of outage in a system with a dynamic number of admitted users for the aforementioned fictitious observer/user is less than or equal to $g_l(\underline{M}_0)$. On the other hand, as mentioned in Section II-A, the probability of outage of a fictitious user of type l is a conservative upper bound for the probability of outage experienced by a real type-l user. Hence,

$$P^{dynamic}_{out,real} \leq P^{dynamic}_{out} \leq g_l(\underline{M}_0) \leq P^l_{max} \quad (21)$$

where the last inequality is due to the construction of R_l.

Since l is arbitrary, the admission region A, defined by (20), is a conservative bound on the number of users admitted by the dynamic system for which the QoS requirement expressed by the probability of outage is satisfied. ■

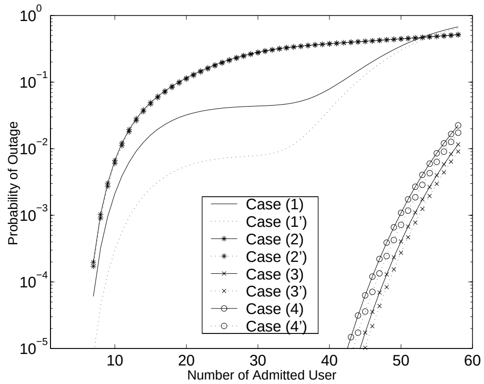

Fig. 1. P_{outage} vs. M for cases in III-A

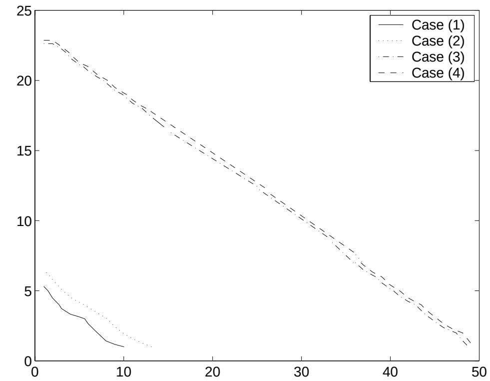

Fig. 2. Admission Regions for cases in III-B

III. Special Cases, Examples, Discussion

In this section we present examples illustrating our approach. In all the examples we consider the outage problem in a CDMA pre-third-generation wireless systems. In such systems, traffic mainly consists of voice, or data streams that are compressed and then treated as voice [8]. This kind of traffic, when the number of users is fixed, can be appropriately modeled by an Engseth birth-death chain (see [1]). Therefore it is appropriate to follow the procedure given in Section II-B.1.

In the remainder of the section we formally introduce the Engseth traffic model. In Sections III-A and III-B we compute the probability of outage, and the resulting admission regions under a variety of power control scenarios and system parameters.

We consider L types of traffic. Let the component M_k of the vector $\underline{M} = (M_1, \ldots, M_L)$ represent the fixed number of users of type k admitted to the system. Let $\underline{N}(t) = (N_1(t), \ldots, N_L(t))$ denote the vector of the number of active users of each type. Then the transition probability for the Engseth model is given as follows:

$$P\{\underline{N}(t+1) = n | \underline{N}(t) = m, \underline{M}\} = \begin{cases} (M_k - m_k)\lambda_k & \text{if } n = m + e_k \\ m_k \mu_k & \text{if } n = m - e_k \\ 1 - \sum_{k \in K_{on}} m_k \mu_k & \\ - \sum_{k \in K_{off}} (M_k - m_k)\lambda_k & \text{if } n = m \\ 0 & \text{otherwise} \end{cases}$$

where e_k is a column vector whose elements are all zero except for the k^{th} element which is 1, λ_k is the activation rate of each inactive user of type k, μ_k is the probability of that an active user becomes inactive, $K_{off} = \{k : m_k < M_k\}$, and $K_{on} = \{k : 0 < m_k\}$. Note that $\frac{\lambda_k}{\lambda_k + \mu_k}$ is the activity factor of each stream. For voice users, this is around 0.4. For data users, it varies with the application, and it depends on the burstiness and information bandwidth of the stream, as well as the compression method employed.

A. Example: Homogeneous Traffic

We study the homogeneous traffic scenario. We first construct the SMC associated with this model. Let M denote the number of admitted users in the system. We construct $\mathbf{T}'_M = [\text{Prob}\{r = i / r = j, M\}]$. For the cases that follow we use different channel models $(\mathcal{H}, \mathbf{A}_0)$. We construct the transition probability $\mathbf{P}$ associated with each $(\mathcal{H}, \mathbf{A}_0)$ pair, using (9).

For all the scenarios under study, we assume that $\frac{\lambda}{\lambda+\mu} = 0.4$, $T = .002\tau_f$ (T is the time slot duration and τ_f is the fading cycle), $\gamma = 3.2$dB, and the spreading gain is $G_0 = 64$.

After identifying the transition matrix, determining the SNIR at each state, and finally labelling "bad" and "good" states according to (11), (12), we calculate the probability of an outage as a function $g_1(M)$. Fig. 1 shows the result of such a calculation for CDMA systems when: 1) the channel follows a Gilbert model with average burst lengths of 4, with steady-state probability of the bad-channel-state equal to 0.1 and $\tau = 7T$ (the value recommended by ITU-T [6]); 1') channel is similar to one of (1), and $\tau = 15T$; 2) the channel is an appropriate approximation to a Rayleigh fading channel with the maximum Doppler frequency of 100 Hz as given by [9] and $\tau = 7T$; 2') the channel is similar to (2) and $\tau = 15T$; 3) an ideal power control mechanism is implemented and $\tau = 7T$; 3') the channel is similar to (3) and $\tau = 15T$; and 4) power control is applied with error of 5% and $\tau = 7T$. 4') the channel is similar to (4) and $\tau = 15T$;

B. Example: Two Types of Traffic

We study the outage problem for the same CDMA system as in Section III-A, when the traffic consists of two classes of users with different activity factors, spreading gains, and outage parameters; these parameters are $\frac{\lambda_1}{\lambda_1+\mu_1} = 0.4$, $\frac{\lambda_2}{\lambda_2+\mu_2} = 0.6$, $G_1 = 64$, $G_2 = 32$, $P_2 = 2P_1$ $\tau_1 = \tau_2$, $\gamma_1 = 3.2$dB, and $\gamma_2 = 3.3$dB. We set the maximum acceptable probability of outage to be equal to 10^{-3}. Under this specification, Fig. 2 shows the admission region, when: 1) the channel is described by a Gilbert model similar to the one in Section III-A and $\tau =$

$7T$; 2) the channel is described by a Gilbert model similar to the one in Section III-A and $\tau = 15T$; and 3) there is an ideal power control mechanism and $\tau = 7T$; and 4) there is an ideal power control mechanism and $\tau = 15T$.

C. Discussion

Fig. 1 illustrates that for all cases discussed in Section III-A $g_1(M)$ is an increasing function of M. Similar plots for other cases, including those mentioned in Section III-B, are provided in [2]. These plots, like Fig. 1, show that $g_l(M_1, M_2)$, $l = 1, 2$, is increasing in M_1 and M_2. This implies that the region $\mathcal{R}$ defined by (19) is coordinate convex, hence $\mathcal{A} = \mathcal{R}$ for the examples studied. Based on these result we propose the following conjecture:

Conjecture 1: In any cellular system, $g_l(\underline{M})$ is increasing in each coordinate for all $l = 1, 2, \ldots, L$; Hence, $\mathcal{A} = \mathcal{R}$.

IV. Conclusion

We have presented an approach to defining probability of outage as a system-wide QoS measure. We have illustrated the approach via examples of Section III.

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