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A Medium Access Scheme for Voice, Self-Similar Traffic and Data Integration in DS-CDMA Personal Communication Networks

by

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ABSTRACT: Future CDMA personal communication systems will support a wide range of broadband services exhibiting self-similarity or long-range dependence. The long-tail property of the aggregate self-similar traffic makes it difficult for the system to predict future resource usage from current resource usage. The result is difficulty in efficient management and control of admitted traffic components. To address this problem, we propose a medium access scheme that guarantees Quality-of-Service (QoS) requirements for a DS-CDMA personal communication system that supports voice, delay-insensitive data and self-similar traffic. The proposed scheme controls the data transmission by estimation of traffic load in the next slot. Estimation of self-similar traffic is based on representation by a hyperexponential distribution. The performance of the scheme is analyzed in terms of outage probability, data packet delay and throughput of voice and self-similar traffic. Numerical results are calculated and compared with the performance of a system without control of data access.

I. INTRODUCTION

CDMA is an attractive technique for personal communication networks that offers advantages such as efficient spectrum utilization, soft capacity, soft hand-off, inherent diversity and resistance to multipath fading characteristics. Because of the anticipated proliferation of personal mobile computing and wireless devices for entertainment, future CDMA personal communication networks will support not only voice and data services, but also a wide range of broadband services, such as video and Internet traffic. Recent research has revealed that both

video and Internet traffic exhibit long-range dependence (LRD) or self-similarity [1-3]. This characteristic is different from the traditional short-range dependence (SRD) Markov-related traffic models. Many medium access schemes in the technical literature, for example [4] and [5], control the access of each session using the Markovian property of traffic's on/off periods (or burstiness). For self-similar traffic components, the system can not reliably estimate the future resource usage based on current resource usage. This is because each individual self-similar session has the long-tail property, which implies large variances of the duration of on and off periods. This makes finding an efficient medium access control scheme a challenging problem and complicates the theoretical analysis of system performance. Few papers address the problem of media access control of self-similar traffic at the level of individual session. The performance of a CDMA/PRMA protocol with individual self-similar sessions has been considered in [6] where the performance analysis is done by simulation (instead of theoretical analysis). In this paper, we approach the problem by fitting the long-tail distribution by a hyperexponential distribution.

We consider a wireless CDMA personal communication system that supports three types of traffic: voice, delay-insensitive data and self-similar traffic. It is important to consider how to control the interference caused by multiple access so that QoS requirements can be met. We propose a medium access scheme with this objective.

In Section II of this paper, the system model and models for voice, delay-insensitive data and self-similar traffic models are described. The *outage condition* of the system is established and the motivation for an efficient medium access control is described in Section III. In Section IV, a medium access scheme for efficient management of self-similar traffic is proposed, and its implementation is discussed. Performance of the scheme is analyzed in Section V. Numerical results and conclusions are presented in Sections VI and VII respectively.

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II. SYSTEM DESCPRIPTION AND TRAFFIC MODELS

1. System Description

A CDMA personal communication system consists of many micro-cells. There is a base station (BS) in each cell to provide services to mobile users in its proximity. Here we focus on the reverse link and consider the limitations that it places on system capacity. The definition of outage and interference refer to the reverse link. We assume that in the system, time is divided into slots (each having a duration of τ) and that admitted sessions are synchronized and transmit only within these slots.

2. Voice Traffic

We assume that a voice session consists of alternating talkspurts and silence gaps. The talkspurts and silence gaps have random durations which have negative exponential distributions (ned) with means of $\overline{T}_t$ and $\overline{T}_s$, respectively. Then, the transition intensity from talkspurt to silence gap, μ_v, is $1/\overline{T}_t$, and the transition intensity from silence gap to talkspurt, λ_v, is $1/\overline{T}_s$. During a talkspurt, a user generates voice packets at a constant rate of one packet per slot. No voice packets are generated during a silence gap. The voice traffic is delay-sensitive, so if a voice packet is not transmitted successfully in a slot, it will be lost due to the delay constraint.

Given that N_v voice sessions are admitted to the system, their combined activity can be modeled as a continuous-time Markov chain with $N_v + 1$ states, as shown in Fig. 1. The state index i denotes the number of voice sessions that are in talkspurt mode at any time. Let $p_v(i)$ denote the equilibrium probability of state i, $0 \leq i \leq N_v$. This is identified with the (equilibrium) probability that exactly i of the N_v voice sessions are in talkspurt mode. Using the properties of Markov chains and the representation of Fig. 1, we can derive the following equations for the state probabilities

$$p_v(i) = \left(\frac{N_v}{1} \cdot \frac{\lambda_v}{\mu_v} \right) \left(\frac{N_v - 1}{2} \cdot \frac{\lambda_v}{\mu_v} \right) \cdots \left(\frac{N_v - i + 1}{i} \cdot \frac{\lambda_v}{\mu_v} \right) \cdot p_v(0)$$

$$= \binom{N_v}{i} \cdot \left(\frac{\lambda_v}{\mu_v} \right)^i \cdot p_v(0), \ 0 \le i \le N_v \tag{1}$$

The normalization condition

$$\sum_{i=0}^{N_v} p_v(i) = 1 \tag{2}$$

is used to determine $p_v(0)$. Thus

$$p_v(i) = \binom{N_v}{i} \cdot \left(\frac{\lambda_v}{\mu_v} \right)^i / \sum_{j=0}^{N_v} \binom{N_v}{j} \left(\frac{\lambda_v}{\mu_v} \right)^j, \ 0 \le i \le N_v \tag{3}$$

Because $\overline{T}_t$ and $\overline{T}_s$ are typically much larger than the duration of a slot, τ, the probability that more than one transition event occurs in one slot is very small and is assumed to be negligible. The transition rate from state i to state i-1 is $i \cdot \mu_v$ the transition rate from state i to state i+1 is $(N_v - i) \cdot \lambda_v$. Because the system that we consider is a slotted system, the continuous-time model has to be adapted to a discrete-time time model and the transition rates in the continuous-time model have to be adapted to transition probabilities in the discrete-time time model. The discrete-time model is shown in Fig. 2. Let N_{vc} and N_{vn} define the numbers of active voice sessions in the current slot and in the next slot respectively. Using Fig. 1 and 2, we find that the probability that there is no change at state i in the next slot, $P_v(N_{vn} = i \mid N_{vc} = i)$, is given by

$$P_v(N_{vn} = i \mid N_{vc} = i) = e^{-((N-i) \cdot \lambda_v + i \cdot \mu_v) \tau}, \ 0 \le i \le N_v. \tag{4}$$

The probabilities of a transition from state i to state i-1 and state i+1 are given respectively by

$$P_v(N_{vn} = i-1 \mid N_{vc} = i) = [i \cdot \mu_v / ((N_v - i) \cdot \lambda_v + i \cdot \mu_v)] \cdot (1 - e^{-((N-i) \lambda_v + i \mu_v) \tau}), \ 1 \le i \le N_v \tag{5}$$

$$P_v(N_{vn} = i+1 \mid N_{vc} = i) = [(N_v - i) \cdot \lambda_v / ((N_v - i) \cdot \lambda_v + i \cdot \mu_v)] \cdot (1 - e^{-((N-i) \lambda_v + i \mu_v) \tau}), \ 0 \le i \le N_v - 1 \tag{6}$$

3. Self-Similar Traffic

Traffic, such as video-on-demand, that exhibits timescale-invariant burstiness can be described by the notion of self-similarity. In stochastic traffic modeling, self-similarity means that the traffic's structure is the same regardless of the timescale over which the traffic is observed. The mathematics of self-similarity is briefly described in Appendix A.

As shown in [1], the superposition of many i.i.d. copies of renewal reward processes with long-tail inter-renewal time exhibits self-similarity. Readers are referred to details in Appendix B. Thus, we take a renewal reward process with long-tail inter-renewal time as an adequate traffic model for an *individual* self-similar session. We assume that the rewards in the renewal reward process of a self-similar session take only the values 1 and 0. For a renewal with a reward of 1, it is supposed that during the interval between this renewal and the next renewal, the self-similar session generates a packet every time unit (slot). That is, the self-similar session is in an "on" period. For a renewal with a reward of 0, it is supposed that during the interval between this renewal and the next renewal, the self-similar session generates nothing. That is, the self-similar session is in an "off" period. Modeled in this way, an individual self-similar session is equivalent to an ON/OFF source. We assume that on-time and off-time of self-similar sessions have different distributions. Let T_{on} denote the duration of an on period and T_{off} denote the duration of an off period. Let $F_1(t)$ and $F_2(t)$ respectively denote the (cumulative distribution functions) *cdf*'s of the on-time and off-time. Because durations of both on-time and off-time are long-tail distributed [1], we have

$$1 - F_1(t) = P\{T_{on} \geq t\} \sim t^{-\alpha_1} \cdot u_1(t), \text{ as } t \to \infty, \ 1 < \alpha_1 < 2 \tag{7}$$

$$1 - F_2(t) = P\{T_{off} \geq t\} \sim t^{-\alpha_2} \cdot u_2(t), \text{ as } t \to \infty, \ 1 < \alpha_2 < 2 \tag{8}$$

where $u_1(t)$ and $u_2(t)$ vary slowly at the infinity. For simplicity of illustration, we assume that the self-similar traffic discussed in the paper is delay-sensitive, so no retransmission of self-similar packets is allowed.

4. Delay-Insensitive Data Traffic

One way to control the data transmission is for the BS to determine (and control) the maximum number of data sessions that can transmit in each slot. Another way is for the BS to determine at each time slot an access probability of data traffic and send this probability back to the data sessions. The data sessions then transmit (or not) according to this probability. In this paper, we consider the latter approach. As in [7], we assume that in any slot there is a data packet ready for transmission for any data session that has been admitted. We assume that there are N_d data sessions admitted to the system. In every slot, the BS computes the data access probability, p_d, for the next slot. Then in the next slot, the data sessions will transmit with the computed access probability. If a data packet is either not transmitted or not transmitted successfully (due to multiple access interference), it will be stored in the sender's buffer and will be retransmitted until it succeeds. As in [8], we assume that the BS returns an acknowledgment to the mobile terminal for each packet that is received correctly. No new packet is generated by the data session until this packet succeeds in its (re)transmission.

III. OUTAGE PROBABILITY

CDMA systems are interference-limited and require effective power control of each user in order to deal with the near-far problem. It is usually assumed that there are enough codes in each BS so that when an admitted session wants to use a code to transmit there are always some codes available. We assume that the system uses a call admission scheme to control the number of admitted sessions. Details of the call admission scheme are not important in the context of this paper. The reception quality of a session is affected by the transmission powers of other sessions that are transmitting at the same time. The transmission power of each session is assigned by the BS. For simplicity, we consider a CDMA system with perfect power control, so that all sessions in the coverage range are received with the same power at the BS.

Suppose that in a single cell there are i voice sessions, j self-similar sessions and d data sessions that are transmitting in the same slot. Let E_{bv}, E_{bd} and E_{bs} denote the energy per bit for

voice, delay-insensitive data and self-similar sessions respectively. Let R_v, R_d and R_s denote the required bit rate for voice, delay-insensitive data and self-similar sessions respectively. Let N_0 denote the background noise. The total noise-plus-interference power, denoted by I_0W, is given by

$$I_0W = i \cdot E_{bv} \cdot R_v + j \cdot E_{bs} \cdot R_s + d \cdot E_{bd} \cdot R_d + N_0W \tag{9}$$

It is required to limit the ratio I_0W / N_0W because of the dynamic range limitations on the BS's multiple access receiver [9]. Thus, we require

$$I_0W / N_0W < 1/\eta, \quad \eta < 1 \tag{10}$$

where η, called the noise-to-interference threshold, typically takes value from 0.1 to 0.25. From (9) and (10), we have

$$i \cdot E_{bv} \cdot R_v + j \cdot E_{bs} \cdot R_s + d \cdot E_{bd} \cdot R_d = (I_0 - N_0)W < I_0W (1-\eta) \tag{11}$$

If we let $\alpha_v = \left(\dfrac{E_{bv}R_v}{I_0W} \right)$, $\alpha_d = \left(\dfrac{E_{bd}R_d}{I_0W} \right)$ and $\alpha_s = \left(\dfrac{E_{bs}R_s}{I_0W} \right)$, equation (11) can be written as

$$i \cdot \alpha_v + j \cdot \alpha_s + d \cdot \alpha_d < (1-\eta) \tag{12}$$

A feasible power assignment for a voice-only CDMA system exists only when $I_0W / N_0W < 1/\eta$ [9]. Similarly, for the CDMA system that we discuss, a feasible power assignment exists only when condition (12) is met. If the condition (12) is not met, the system is in the *outage* condition. We take θ as the requirement of outage probability to provide acceptable QoS. We assume pessimistically that if an outage condition occurs in a slot then all packets transmitted in the slot will be corrupted. If no outage occurs in a slot then all packets transmitted in this slot will be received correctly by the BS. If the outage probability of the system is high, voice and self-similar traffic will suffer high packet loss and data traffic will suffer high packet delay. To keep the outage probability below the requirement θ, an appropriate medium access scheme that controls the transmission of admitted traffic components is necessary. This is the motivation for the medium access control.

IV. MEDIUM ACCESS SCHEME

The basic idea of the medium access scheme is to allow more data sessions to transmit when the voice and self-similar traffic load is low, and allow less data sessions to transmit when voice and self-similar traffic load is heavy. This is done by the BS's control of the access probability of data traffic based on the estimation of the voice and self-similar traffic load in the next slot. In our scheme, the BS controls the data access probability to meet a specified outage probability requirement.

1. Hyperexponential Approximation

The BS can estimate the voice traffic load by using the Markov property of the combined voice sessions' activity. However, the on-time and off-time of self-similar session are long-tail distributed in form of (7) and (8). Let $E[T_{on}]$ and $E[T_{off}]$ denote the mean of the on-time and off-time respectively. Then their variances $V[T_{on}]$ and $V[T_{off}]$ are given by

$$V[T_{on}] = E[(T_{on} - E[T_{on}])^2] \tag{13}$$

$$V[T_{off}] = E[(T_{off} - E[T_{off}])^2] \tag{14}$$

Since a long-tail distribution, such as a Pareto or Weibull distribution, weighs values that are far away from the mean significantly, the variance is usually very large. This makes it very difficult for the BS to reliably estimate the self-similar traffic load. The data access probability should be determined by the estimation of the total voice and self-similar traffic in the next slot. If the BS can not estimate the self-similar traffic load in the next slot, efficient control on the access probability of the data traffic can not be exerted. We circumvent this problem by casting the long-tail property of the inter-renewal time in a renewal-reward process model into a Markovian framework.

In [10], it has been shown that a wide range of long-tail distributions, including Pareto and Weibull distributions, can be approximated by an hyperexponential distribution with appropriate parameters. The on-time and off-time cdf's $F_1(t)$ and $F_2(t)$ in the renewal reward

process model of self-similar session can then be approximated in a certain time interval $[t_1, t_2]$ and expressed as

$$1 - F_1(t) = \sum_{i=1}^{k} p_i e^{-\lambda_i t}, \ t \in [t_1, t_2], \ \sum_{i=1}^{k} p_i = 1 \tag{15}$$

$$1 - F_2(t) = \sum_{j=1}^{m} q_j e^{-\mu_j t}, \ t \in [t_1, t_2], \ \sum_{j=1}^{m} p_j = 1 \tag{16}$$

Parameters k and m are the number of exponential components in the models that are used to fit the long-tail distributions. Typically, k and m take values between 4-20, [10]. The larger k and m are, the better the fitting result is. Parameters p_i's, λ_i's, q_j's and μ_j's are obtained by using the fitting algorithm in [10]. Readers are referred to [10] for details of the fitting algorithm. Since self-similarity is observed only on a finite timescale [1-3], in the network performance analysis, a long-tail distribution only matters through its values in some finite interval $[t_1, t_2]$. If t_1 is sufficiently small and t_2 is sufficiently large, the values of the distribution outside the interval $[t_1, t_2]$ are not important and the approximation will be good enough for the purpose of performance analysis. For example, in the algorithm we can choose t_1 to be 0.01 sec (duration of a slot) and t_2 to be 10^6 sec (11 days).

An individual self-similar session can be represented as a continuous-time Markov chain with $k+m$ states as shown in Fig. 3 [10]. State i, $1 \leq i \leq k$, corresponds to the session in the on period with the component exponential having parameter λ_i; state j, $k+1 \leq j \leq k+m$, corresponds to the session in the off period with the component exponential having parameter μ_{j-k}. Packets are generated at a constant rate of one packet per slot only when the session is in the on period. The transition intensity from state i ($1 \leq i \leq k$) to state $k+j$ ($1 \leq j \leq m$) is $\lambda_i q_j$, the transition intensity from state $k+j$ ($1 \leq j \leq m$) to state i ($1 \leq i \leq k$) is $\mu_j p_i$, and all other transition intensities are 0. Let $p_s(l)$ denote the steady state probability of state l ($l=1, 2, \ldots, k+m$). Since Fig. 3 depicts a Markovian process, we have the following balance equations for the state probabilities

$$p_s(i) \cdot \lambda_i = p_i \sum_{j=1}^{m} p_s(k+j) \cdot \mu_j, \ 1 \leq i \leq k \tag{17}$$

$$p_s(k+j) \cdot \mu_j = q_j \sum_{i=1}^{k} p_s(i) \cdot \lambda_i \, , \ 1 \le j \le m \tag{18}$$

$$\sum_{i=1}^{k} p_s(i) + \sum_{j=1}^{m} p_s(k+j) = 1 \tag{19}$$

$$p_s(i) = \frac{p_i}{\lambda_i} \cdot \frac{\lambda_1}{p_1} \cdot p_s(1), \ 1 \le i \le k \tag{20}$$

$$p_s(k+j) = \frac{q_i}{\mu_i} \cdot \frac{\mu_1}{q_1} \cdot p_s(k+1), \ 1 \le j \le m \tag{21}$$

Finally, we obtain

$$p_s(i) = \left(\frac{p_i}{\lambda_i} \right) \bigg/ \left(\sum_{i=1}^{k} \frac{p_i}{\lambda_i} + \sum_{j=1}^{m} \frac{q_j}{\mu_j} \right), \ 1 \le i \le k \tag{22}$$

$$p_s(k+j) = \left(\frac{q_j}{\mu_j} \right) \bigg/ \left(\sum_{i=1}^{k} \frac{p_i}{\lambda_i} + \sum_{j=1}^{m} \frac{q_j}{\mu_j} \right), \ 1 \le j \le m \tag{23}$$

The probability that a self-similar session is in the on period or the off period is given respectively by

$$p_s(on) = \sum_{i=1}^{k} p_s(i) \tag{24}$$

and

$$p_s(off) = \sum_{j=1}^{m} p_s(k+j) \tag{25}$$

We assume that self-similar sessions are independent of each other. If there are N_s self-similar sessions admitted to the system, the probability that there are exactly j self-similar sessions in the on period among these N_s sessions, is given by

$$P_s(j) = \binom{N_s}{j} \cdot p_s(on)^j \cdot p_s(off)^{N_s - j} \tag{26}$$

We take the duration of a slot, τ, to be 10 msec. It is seen in [10] that the fitting of a typical long-tail distribution, such as Pareto or Weibull distribution, usually generates parameters $1/\lambda_i$ ($1 \le i \le k$) and $1/\mu_j$ ($1 \le j \le m$) which are much larger than the duration of a slot, τ.

Thus, the probability that more than one self-similar session among the N_s admitted sessions make a transition between the on and off period during the same slot is very small and is assumed to be negligible. This simplification is valid for normal traffic load in a cell, for which the number of *admitted* self-similar sessions (only part of the total *admitted* sessions) is less than 100. Even if this small probability event occurs, it will only degrade the outage performance, but will not affect the operation of the medium access scheme. If j self-similar sessions are on in the current slot, then the number of on sessions in the next slot can only be $j-1$, j or $j+1$.

Suppose that there are j self-similar sessions that are currently on. For a self-similar session that is on, there are k possible states in the hyperexponential approximation model; for a session that is off, there are m possible states. Let $\vec{l}$ denote the vector $(l_1, l_2, ..., l_{N_s})$, where l_i is the state of the ith self-similar session. Then, the probability of $\vec{l}$ is given by

$$\phi_s(\vec{l}) = \prod_{i=1}^{N_s} p_s(l_i) \tag{27}$$

Let $\Omega(j)$ denote the subspace of vector $\vec{l}$ when there are j sessions in the on period among N_s self-similar sessions. Let $\phi_s(\vec{l} \mid j)$ denote the conditional probability of the vector $\vec{l}$ given the number of on sessions is j. Then

$$\phi_s(\vec{l} \mid j) = \phi_s(\vec{l}) / P_s(j) \tag{28}$$

In order to estimate the self-similar traffic load, we need to know the probabilities that there will be $j-1$, j and $j+1$ on sessions in the next slot given that there are j on sessions in the current slot. Let $\vec{l}_+$ denote the set of all possible vectors resulting from $\vec{l}$ when one off session in $\vec{l}$ transits to on and no other session changes its states. Let $\vec{l}_-$ denote the set of all possible vectors resulting from $\vec{l}$ when one on session in $\vec{l}$ transits to off and no other session changes its states. In vector $\vec{l}$, the i-th self-similar session will change its state with a transition intensity of λ_{l_i} if $l_i \leq k$ (or μ_{l_i-k} if $l_i > k$). Let $\lambda(\vec{l})$ denote $\sum_{\substack{i=1 \\ l_i \leq k}}^{N_s} \lambda_{l_i}$, and let $\mu(\vec{l})$ denote $\sum_{\substack{i=1 \\ l_i > k}}^{N_s} \mu_{l_i}$. Thus, the vector $\vec{l}$ will transit to a vector either in $\vec{l}_+$ or $\vec{l}_-$ with a transition rate of $\lambda(\vec{l}) + \mu(\vec{l})$. The

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following equations adapt the continuous-time state-transition model to the slotted-time model under consideration here.

$$\phi_s(\dot{i} \mid \dot{i}) = e^{-[\lambda(\dot{i})+\mu(\dot{i})]\tau} \tag{29}$$

$$\phi_s(\dot{i}_- \mid \dot{i}) = \frac{\lambda(\dot{i})}{\lambda(\dot{i}) + \mu(\dot{i})} (1 - e^{-[\lambda(\dot{i})+\mu(\dot{i})]\tau}) \tag{30}$$

$$\phi_s(\dot{i}_+ \mid \dot{i}) = \frac{\mu(\dot{i})}{\lambda(\dot{i}) + \mu(\dot{i})} (1 - e^{-[\lambda(\dot{i})+\mu(\dot{i})]\tau}) \tag{31}$$

Let N_{sc} and N_{sn} define the numbers of self-similar sessions that are on in the current slot and in the next slot respectively. Let $P_s(j-1 \mid j)$ denote the probability that there will be j-1 on sessions in the next slot given there are j on sessions in the current slot. It can be expressed as

$$P_s(N_{sn} = j-1 \mid N_{sc} = j) = \sum_{\dot{i} \in \Omega(j)} \phi_s(\dot{i}_- \mid \dot{i}) \cdot \phi_s(\dot{i} \mid j) \tag{32}$$

Similarly, let $P_s(N_{sn} = j \mid N_{sc} = j)$ and $P_s(N_{sn} = j+1 \mid N_{sc} = j)$ denote the probabilities that there will be j and $j+1$ on sessions respectively in the next slot given there are j on sessions in the current slot. They are given as

$$P_s(N_{sn} = j \mid N_{sc} = j) = \sum_{\dot{i} \in \Omega(j)} \phi_s(\dot{i} \mid \dot{i}) \cdot \phi_s(\dot{i} \mid j) \tag{33}$$

$$P_s(N_{sn} = j+1 \mid N_{sc} = j) = \sum_{\dot{i} \in \Omega(j)} \phi_s(\dot{i}_+ \mid \dot{i}) \cdot \phi_s(\dot{i} \mid j) \tag{34}$$

As we can see, the hyperexponential approximation allows the BS to estimate the self-similar traffic load in the next slot by using the transition probabilities in (32), (33) and (34). The estimate is used to determine the access probability of data traffic.

2. Medium Access Scheme

Based on the number of transmitting voice and self-similar sessions, the BS will estimate the maximum data access probability with the specified guaranteed outage probability. Let $\lfloor x \rfloor$ denote the least integer that is not smaller than x. Let $d(i, j)$ denote the minimum number of

transmitting data sessions that will cause outage when there are i voice sessions and j self-similar sessions transmitting. From equation (12), $d(i,j)$ is given by

$$d(i,j)=\lfloor((1-\eta)-i\cdot\alpha_v - j\cdot\alpha_s)/\alpha_d\rfloor \tag{35}$$

Let $P_{out}(i,j,p_d)$ denote the outage probability when there are i voice sessions and j self-similar sessions transmitting in a slot and all data sessions are transmitting with an access probability p_d in the same slot. If $d(i,j)$ is even larger than N_d, then $P_{out}(i,j,p_d)$ is 0. Otherwise, it is given as the average probability that data transmission causes outage, i.e. average probability that the number of transmitting data sessions is at least $d(i,j)$.

$$P_{out}(i,j,p_d)= \sum_{h=d(i,j)}^{N_d} \binom{N_d}{h} \cdot (p_d)^h \cdot (1-p_d)^{N_d-h} \tag{36}$$

As in [4], we assume that each packet has a preamble, which is always received by the BS correctly. This is made possible by controlling the data rate of the preamble. Readers are referred to [4] for details. Upon receiving all the preambles in the current slot, the BS knows the respective numbers of transmitting voice, self-similar and data sessions in this slot. For the self-similar sessions, the BS knows only the number of sessions that are on, but does not know which state i ($i=1, 2, ..., k$) that a particular session is in. This is because the on-time and off-time are modeled by the hyperexponential approximation only for the convenience of the characterization of traffic load and performance analysis. The states do not have physical meaning. Thus, the BS must estimate the self-similar traffic load in the next slot based only on the self-similar traffic load in the current slot.

Suppose that there are i voice sessions and j self-similar sessions transmitting in the current slot. Based on the current traffic load, the BS estimates all the possible voice and self-similar traffic load in the next slot with corresponding probabilities using equations (4)-(6) and (37)-(39). Then, the BS must determine the data access probability in the next slot. For a probability p_d, if there are h voice sessions and k self-similar sessions transmitting in the next slot the outage probability will be $P_{out}(h,k,p_d)$ as determined in (41). Let $h_{max}(i)$ and $h_{min}(i)$ denote the maximum and minimum values of the number of active voice sessions in

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next/last slot given the number of active voice sessions in the current slot is i. We have $h_{\max}(i) = \min(i+1, N_v)$ and $h_{\min}(i) = \max(i-1, 0)$. Similarly, let $k_{\max}(j)$ and $k_{\min}(j)$ denote the maximum and minimum values of the number of on self-similar sessions in next/last slot given the number of on self-similar sessions in the current slot is j. We have $k_{\max}(j) = \min(j+1, N_s)$ and $k_{\min}(j) = \max(j-1, 0)$. Let $p_{d\max}(i, j)$ denote the maximum data access probability allowed in the next slot in order to meet the outage probability requirement given that there are i voice sessions and j self-similar sessions in the current slot. This is the maximum p_d that makes the average outage probability over all possible traffic loads in the next slot meet the requirement θ. Using (33) and (34) this is calculated by

$$p_{d\max}(i,j) = \max\{p_d : \sum_{h_{\min}(i)}^{h_{\max}(i)} P_v(N_{vn} = h \mid N_{vc} = i) \sum_{k_{\min}(j)}^{k_{\max}(j)} P_s(N_{sn} = k \mid N_{sc} = j) \cdot P_{out}(h, k, p_d) = \theta\} \quad (37)$$

The base station broadcasts data access probability for the next slot for the use by data sessions at the mobile terminals. Before the end of each slot, each data sessions knows the data access probability for the next slot and get adjusted to the probability for transmission.

If the data access probabilities for all the possible states (i, j) in (37) are computed beforehand and stored in the BS, the BS does not need to compute the data access probability in each slot. However, upon the new call or hand-off call arrival, call completion and hand-off departure, the numbers of admitted voice sessions, self-similar sessions and data sessions are changed. This means that the models of combined voice traffic in equations (4)-(6), combined self-similar traffic in equations in (32)-(34) and combined data traffic in equation (36) are changed. Then, data access probabilities for all the possible states in equation (37) have to be recomputed. Because the changes of admitted traffic models occur over a much larger time scale than the duration of a slot, the recomputation will not add much complexity to the medium access scheme.

V. PERFORMANCE ANALYSIS

Because both voice and self-similar traffic are delay-sensitive, no retransmission of corrupted packets is allowed. So, if an outage occurs, all the voice and self-similar packets

transmitted in this slot are lost. While all the data packets transmitted in this slot are also corrupted but will be retransmitted in subsequent slots until they succeed. We define the total voice and self-similar traffic throughput as the average total number of voice and self-similar packets that are transmitted *successfully* per slot. We define the throughput of data traffic as the average number of data packets that are transmitted *successfully* per slot and the average data traffic delay as the average of the time between a data packet's generation and its successful transmission. Recall that outage probability is defined as the probability that condition (12) is violated. Throughput of voice, self-similar and data traffic, delay of data traffic and outage probability are the major performance metrics of interest. We compare the performance of the system with data access control and the system without access control.

1. System with Access Control Based on Estimation

Let $P_v(N_{vc} = h \mid N_{vn} = i)$ denote the probability that the number of active voice sessions in the current slot was h given the number of active voice sessions in the next slot is i. Let $P_v(N_{vc} = h, N_{vn} = i)$ denote the joint probability that the number of active voice sessions in the current slot and the next slot are h and i respectively. We have the following equations:

$$P_v(N_{vc} = h, N_{vn} = i) = P_v(N_{vc} = h \mid N_{vn} = i) \cdot p_v(i)$$

$$= P_v(N_{vn} = i \mid N_{vc} = h) \cdot p_v(h) \tag{38}$$

So, the conditional probability that the number of active voice sessions in the current slot is h given the number of active voice sessions in the next slot is i can be expressed as

$$P_v(N_{vc} = h \mid N_{vn} = i) = P_v(N_{vn} = i \mid N_{vc} = h) \cdot p_v(h) / p_v(i) \tag{39}$$

Similarly, let $P_s(N_{sc} = k \mid N_{sn} = j)$ denote the probability that the number of on self-similar sessions in the current slot was k given the number of on self-similar sessions in the next slot is j. Let $P_s(N_{sc} = k, N_{sn} = j)$ denote the joint probability that the number of on self-similar sessions in the current slot and the next slot are k and j respectively. We have the following equations:

$$P_s(N_{sc} = k, N_{sn} = j) = P_s(N_{sc} = k \mid N_{sn} = j) \cdot P_s(j)$$

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$$\doteq P_s(N_{sn} = j \mid N_{sc} = k) \cdot P_s(k) \tag{40}$$

So, the conditional probability that the number of on self-similar sessions in the current slot is k given the number of on self-similar sessions in the next slot is j can be expressed as

$$P_s(N_{sc} = k \mid N_{sn} = j) = P_s(N_{sn} = j \mid N_{sc} = k) \cdot P_s(k) / P_s(j) \tag{41}$$

The combined voice and self-similar traffic activity is modeled as a 2-dimensional Markov chain. The state (i, j) is the number of active voice and self-similar sessions respectively. According to the traffic model of data sessions, at any state the number of ready data packets is N_d. Thus, the average length for the data packet queue, $\overline{L}_d$, is also N_d. The data access probability at state (i, j) is determined by its predecessor state (h, k). Let $((i, j), (h, k))$ denote the coupled states of (i, j) and its predecessor state (h, k). Thus, each coupled states $((i, j), (h, k))$ has a data access probability $p_{d\max}(h, k)$ that is determined in (37). If $i \cdot \alpha_v + j \cdot \alpha_s \geq (1 - \eta)$, an outage will definitely occur. In this case, the throughput of data traffic is obviously zero. Otherwise, the data throughput will be the average of throughput whenever data packets do not cause outage. The throughput of data packet at coupled states $((i, j), (h, k))$ is given by

$$T_d((i, j), (h, k)) = \begin{cases} 0 & \text{if } i \cdot \alpha_v + j \cdot \alpha_s \geq (1 - \eta) \\ \sum_{m=1}^{d(i,j)-1} m \cdot \binom{N_d}{m} p_{d\max}(h,k)^m \cdot (1 - p_{d\max}(h,k))^{N_d - m} & \text{otherwise} \end{cases} \tag{42}$$

The throughput of data packet at state (i, j) is the average throughput over all possible coupled states $((i, j), (h, k))$. It can be expressed as

$$T_d(i, j) = \sum_{h_{\min}(i)}^{h_{\max}(i)} P_v(N_{vc} = h \mid N_{vn} = i) \sum_{k_{\min}(j)}^{k_{\max}(j)} P_s(N_{sc} = k \mid N_{sn} = j) \cdot T_d((i,j),(h,k)) \tag{43}$$

The average throughput of data traffic is the average over all possible states (i, j).

$$\overline{T}_d = \sum_{i=0}^{N_v} p_v(i) \sum_{j=0}^{N_s} P_s(j) \cdot T_d(i, j) \tag{44}$$

Using Little's law [11], the average delay of data packet can be expressed as

$$\overline{D}_d = \overline{L}_d / \overline{T}_d \tag{45}$$

The throughput of voice and self-similar traffic at state (i, j) will be $i+j$, if no outage occurs in this slot. For coupled states $((i, j),(h,k))$, the throughput of voice and self-similar traffic, $T_{vs}((i,j),(h,k))$, can be expressed as

$$T_{vs}((i,j),(h,k)) = (i+j) \cdot (1 - P_{out}(i, j, p_{d\max}(h,k)))$$

(46)

Thus, the throughput of voice and self-similar traffic at state (i, j) is the average throughput over all possible coupled states $((i, j),(h, k))$. It can be expressed as

$$T_{vs}(i, j) = \sum_{h_{\min}(i)}^{h_{\max}(i)} P_v(N_{vc} = h \mid N_{vn} = i) \sum_{k_{\min}(j)}^{k_{\max}(j)} P_s(N_{sc} = k \mid N_{sn} = j) \cdot T_{vs}((i,j),(h,k))$$

(47)

The average throughput of voice and self-similar traffic is the average throughput over all states (i, j).

$$\overline{T}_{vs} = \sum_{i=0}^{N_v} p_v(i) \sum_{j=0}^{N_s} P_s(j) \cdot T_{vs}(i, j)$$

(48)

Recall that all voice and self-similar packets transmitted in a slot are lost if an outage occurs. Then, the outage probability of the system corresponds to the packet loss probability of voice and self-similar traffic. For coupled states $((i, j),(h, k))$, the outage probability, $P_{out}((i, j),(h, k))$, is equivalent to the outage probability given that i voice sessions and j self-similar sessions are transmitting. That is

$$P_{out}((i, j),(h, k)) = P_{out}(i, j, p_{d\max}(h, k))$$

(49)

The outage probability at state (i, j), $P_{out}(i, j)$, can be expressed as

$$P_{out}(i, j) = \sum_{h_{\min}(i)}^{h_{\max}(i)} P_v(N_{vc} = h \mid N_{vn} = i) \sum_{k_{\min}(j)}^{k_{\max}(j)} P_s(N_{sc} = k \mid N_{sn} = j) \cdot P_{out}((i,j),(h,k))$$

(50)

Thus, the outage probability of the system, P_{out}, can be expressed as

$$P_{out} = \sum_{i=0}^{N_v} p_v(i) \sum_{j=0}^{N_s} P_s(j) \cdot P_{out}(i, j)$$

(51)

2. System without Data Access Control

If the system can not estimate the self-similar traffic load in the next slot, the system has no control on the access probability of data traffic at all. In each slot every data session transmits with an access probability of one, that is, there are N_d data sessions transmitting in every slot. Suppose that at state (i, j), there are i voice sessions, j self-similar sessions and N_d data sessions transmitting in the same slot. Let $\delta(i \cdot \alpha_v + j \cdot \alpha_s + N_d \cdot \alpha_d)$ be the indication function of whether outage occurs or not. If no outage occurs, $\delta(i \cdot \alpha_v + j \cdot \alpha_s + N_d \cdot \alpha_d)$ is one; otherwise, it is zero. It can be expressed as

$$\delta(i \cdot \alpha_v + j \cdot \alpha_s + N_d \cdot \alpha_d) = \begin{cases} 0 & i \cdot \alpha_v + j \cdot \alpha_s + N_d \cdot \alpha_d \geq 1 - \eta \\ 1 & otherwise \end{cases} \tag{52}$$

Then, the throughput of data packet in a state (i, j) can be expressed as

$$T_d^{'}(i, j) = N_d \cdot \delta(i \cdot \alpha_v + j \cdot \alpha_s + N_d \cdot \alpha_d) \tag{53}$$

The average throughput of data traffic is the average of the throughput in each state (i, j), i=1, 2, ..., N_v, j=1, 2, ..., N_s. It can be expressed as

$$T_d^{'} = \sum_{i=0}^{N_v} p_v(i) \sum_{j=0}^{N_s} P_s(j) \cdot T_d^{'}(i, j) \tag{54}$$

The average length of data packet queue, $\overline{L_d}^{'}$, is N_d. Using Little's law [11] as before, the average delay of data traffic can be expressed as

$$\overline{D_d}^{'} = \overline{L_d}^{'} / \overline{T_d}^{'} \tag{55}$$

The throughput of voice and self-similar traffic in a state (i, j) can be expressed as

$$T_{vs}^{'}(i, j) = (i + j) \cdot \delta(i \cdot \alpha_v + j \cdot \alpha_s + N_d \cdot \alpha_d) \tag{56}$$

The average throughput of voice and self-similar traffic is the average of the throughput in each state (i, j), i=1, 2, ..., N_v, j=1, 2, ..., N_s. It can be expressed as

$$\overline{T}_{vs}^{'} = \sum_{i=0}^{N_v} p_v(i) \sum_{j=0}^{N_s} P_s(j) \cdot T_{vs}^{'}(i, j) \tag{57}$$

Let $P_{out}(i, j)$ denote the outage probability in a state (i, j). It is the complement of the outage indication function. It can be expressed as

$$P_{out}(i, j) = (1 - \delta(i \cdot \alpha_v + j \cdot \alpha_s + N_d \cdot \alpha_d)) \tag{58}$$

The average outage probability of the system can be expressed as

$$P_{out} = \sum_{i=0}^{N_v} p_v(i) \sum_{j=0}^{N_s} P_s(j) \cdot P_{out}(i, j) \tag{59}$$

VI. NUMERICAL RESULTS

The parameters chosen for the purpose of attaining example numerical results are shown in Table I. These parameters are chosen for the purpose of demonstrating the numerical results only. The distributions of on-time and off-time for self-similar traffic are taken to be Pareto distributions with the following form

$$1 - F(t) = (1 + bt)^{-a} \tag{60}$$

where $F(t)$ is the *cdf* of on-time or off-time distribution. For the on-time distribution, we took a to be 2.2 and b to be 5. For the off-time distribution, we took a to be 1.2 and b to be 5. In the hyperexponential approximation, we took both k and m to be 8. We applied the algorithm in [10] to fit the two distributions. The results of the fitting algorithm are shown in the Table II.

Performance characteristics for different numbers of admitted voice, delay-insensitive data and self-similar sessions were calculated. The average delay of data traffic in the system with data access control and the system without data access control under system scenarios, i.e. different number of admitted voice, delay-insensitive data and self-similar session are plotted in Fig. 4 and 5 respectively. The average throughput of voice and self-similar traffic under different system scenarios in the system with data access control and the system without data access control are plotted in Fig. 6 and 7 respectively. The outage probabilities of the system with data access control and the system without data access control under different system scenarios are plotted in Fig. 8 and 9 respectively.

From Figures 4 and 5, we can see that although in the system with access control data packets are sometimes withheld from transmitting, once permitted to transmit, their probability of successful transmission is high. So the average delay of data traffic in the system with access control is low. In the system without access control, the data packets are permitted to transmit at any slot but have a low probability of successful transmission. Thus, data packets have to be retransmitted over and over, which causes much higher average delay than the system with access control.

From Figures 6 and 7, we can see that because the data access probability is controlled on the basis of the voice and self-similar traffic load, the total throughput of voice and self-similar traffic is almost kept as a constant value over different number of admitted data sessions in the system with access control. In the system without access control, because the data packets are permitted to transmit at any slot without any coordination with voice and self-similar traffic load, the total throughput of voice and self-similar traffic gets worse when the number of admitted data sessions increases.

From Figures 8 and 9, we find that the outage probabilities in both systems increase as the number of admitted data sessions increases. The outage probability in the system with access control finally saturate around 0.1% because the outage probability is guaranteed at the cost of delaying data transmission. The outage probability in the system without access control finally reaches 100%, which means throughput of the system is zero.

As seen in Figures 4-9, the medium access scheme provides guaranteed outage probability, much smaller data packet delay and much higher and constant throughput of voice and self-similar traffic compared with the system without access control.

VII. CONCLUSION

In the paper, we proposed a medium access scheme to manage traffic efficiently in a DS-CDMA personal communication system that supports voice, delay-insensitive data and self-similar traffic. Because the on-time and off-time for self-similar sessions are long-tail

distributed, it is very difficult to estimate the self-similar traffic load in the next slot. We resolved this difficulty by casting the long-tail distribution into a Markovian framework using a hyperexponential approximation. The base station estimates the voice and self-similar traffic load in the next slot, and based on the estimation it controls the data access probability to guarantee the outage probability requirement. In this way, the data transmission is coordinated with the traffic load of delay-sensitive traffic, i.e. voice and self-similar traffic. The performance metrics including delay of data packets, throughput of voice and self-similar traffic and outage probability of the system were developed to evaluate the medium access scheme. The numerical results have shown that this scheme provides much better system performance than the system that can not estimate the self-similar traffic load, i.e. the system without access control.

APPENDIX

A. The Stochastic Property of Self-Similarity

Let X ($X_t : t = 0, 1, 2, ...$) denote a discrete-time wide-sense stationary stochastic process with mean μ, variance σ, and autocorrelation function ρ. The autocorrelation function is of the form

$$\rho(k) \sim k^{-\beta} L(k), \, as \, k \to \infty \tag{61}$$

where $0 < \beta < 1$ and $L(k)$ is slowly varying at infinity. That is, $\lim_{k \to \infty} L(\tau k) / L(k) = 1$ for all $\tau > 0$ [1]. If the original series X is observed at a timescale that is m times larger, we get a new process $X^{(m)}$. Suppose that the original series X is divided into nonoverlapping subblocks of size m. The kth element of the new process $X^{(m)}$, $X_k^{(m)}$, is the arithmetic average of series X in the kth subblock. Then for each $m=1, 2, 3, ...$, the kth element of $X^{(m)}$ (that is $X_k^{(m)}$) is given by

$$X_k^{(m)} = (X_{km-m+1} + X_{km-m+2} + ... + X_{km}) / m, \, k=1, 2, 3, ... \tag{62}$$

Each process $X^{(m)}$ is a wide-sense stationary process with an autocorrelation function $\rho^{(m)}$. Self-similarity parameter H is defined as the self-similarity measure of a self-similar process. It usually takes values between ½ to 1. The process X is called second-order self-similar with self-

similarity parameter $H = 1 - \beta / 2$ if the aggregated processes $X^{(m)}$ have the same correlation structure as X, that is

$$\rho^{(m)}(k) = \rho(k), \text{ for } m=1, 2, 3, \dots \tag{63}$$

In other words, X is exactly second-order self-similar if the aggregated processes $X^{(m)}$ are indistinguishable from X with respect to their second-order properties. The essential property of a self-similar process is that its structure remains unchanged over a wide range of timescales, m.

B. The Modeling of Self-Similar Traffic

At first, we briefly introduce the concept of the renewal process and renewal reward process. Consider a sequence of renewals. If the inter-renewal time distribution follows a general distribution, the resulting counting process is a renewal process. Let T_n denote the inter-renewal time between the $(n-1)$st and the nth renewals, and S_n denote the time of the nth renewal. If we let $S_0=0$, the total time that elapses from $t=0$ to the nth renewal is

$$S_n = \sum_{i=1}^{n} T_i \ , n=1, 2, \dots \tag{64}$$

Define $N(t) = max\{n \mid S_n \leq t, n = 1, 2, \dots\}$ [12]. Then, $N(t)$ represents the number of renewals in $(0, t]$. The process $N(t)$, is a renewal process. Suppose that at the nth ($n=1$, 2, …) renewal a reward of value W_n is earned. The renewal reward process, $W(t)$, is the total reward earned by the $N(t)$ renewals in $(0, t]$. It is given by

$$W(t) = \sum_{i=1}^{N(t)} W_i \tag{65}$$

Suppose that the inter-renewal time of the renewal reward process W satisfies the long-tail distribution

$$P\{T_n \geq t\} \sim t^{-\alpha} \cdot u(t), \text{ as } t \to \infty, \ 1 < \alpha < 2, \text{ for } n=1, 2, \dots \tag{66}$$

where $u(t)$ varies slowly at infinity. We obtain a new process ω by aggregating M i.i.d. copies $W^{(1)}$, $W^{(2)}$, …, $W^{(M)}$ of process W in such a way

$$\omega(T, M) = \sum_{t=1}^{T} \sum_{m=1}^{M} W^{(m)}(t) \tag{67}$$

According to [13], the resulting superposition process ω is a fractional Brownian motion process, that is, a self-similar Gaussian process. This means that the aggregate self-similar traffic can be decomposed as a collection of simple renewal reward processes with long-tailed inter-renewal time.

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Table I: Parameters Choice for the Numerical Results

Parameter	Symbol	Value
Voice bit rate	R_v	9.64 kbps
Self-similar traffic bit rate	R_s	9.64 kbps
Delay-insensitive data bit rate	R_d	9.64 kbps
System bandwidth	W	1.25 MHz
Voice's E_b / I_0 level	E_{bv} / I_0	7 dB
Self-similar traffic's E_b / I_0 level	E_{bs} / I_0	7 dB
Delay-insensitive data's E_b / I_0 level	E_{bd} / I_0	8 dB
Voice mean talkspurt duration	$\overline{T}_t$	1.0 sec
Voice mean silence gap duration	$\overline{T}_s$	1.35 sec
Duration of a slot	τ	10 msec
Noise-to-interference threshold	η	0.2
Outage probability	θ	0.1%

Table II: Parameters of the hyperexponential approximation of on-time distribution.

i	On-time distribution		Off-time distribution	
	λ_i	p_i	μ_i	q_i
1	0.000083176	0.0000052778	0.000090108	0.0000019171
2	0.000415858	0.0000364047	0.000450513	0.0000155329
3	0.002415113	0.0002602843	0.002535532	0.0001306811
4	0.012544923	0.0018165113	0.012994464	0.0010669561
5	0.063131158	0.0123455894	0.065115965	0.0084993608
6	0.309043963	0.0770551741	0.317520895	0.0625261319
7	1.383948615	0.3596328194	1.407287845	0.3315570226
8	3.345185230	0.5480975954	3.616488403	0.5962023970
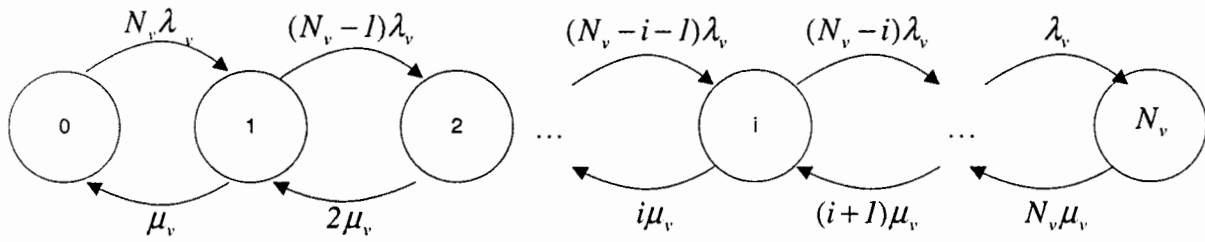
Fig. 1: Continuous-time model of N_v admitted voice sessions' combined activity.
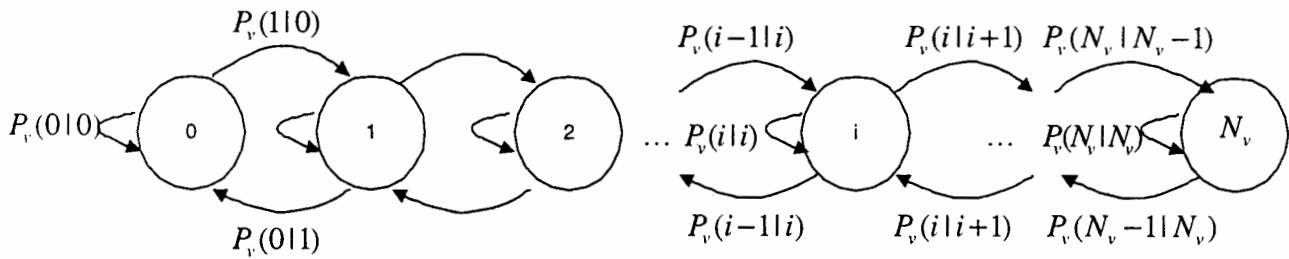

Fig. 2: Discrete-time model of the N_v admitted voice sessions' combined activity.
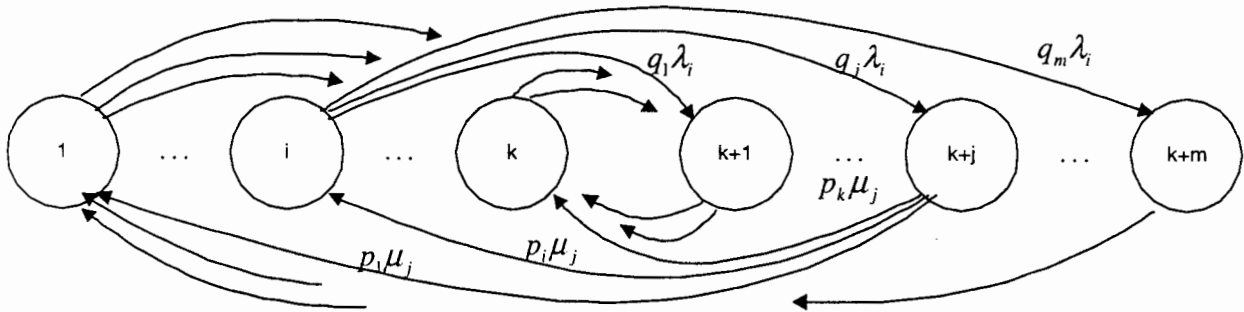

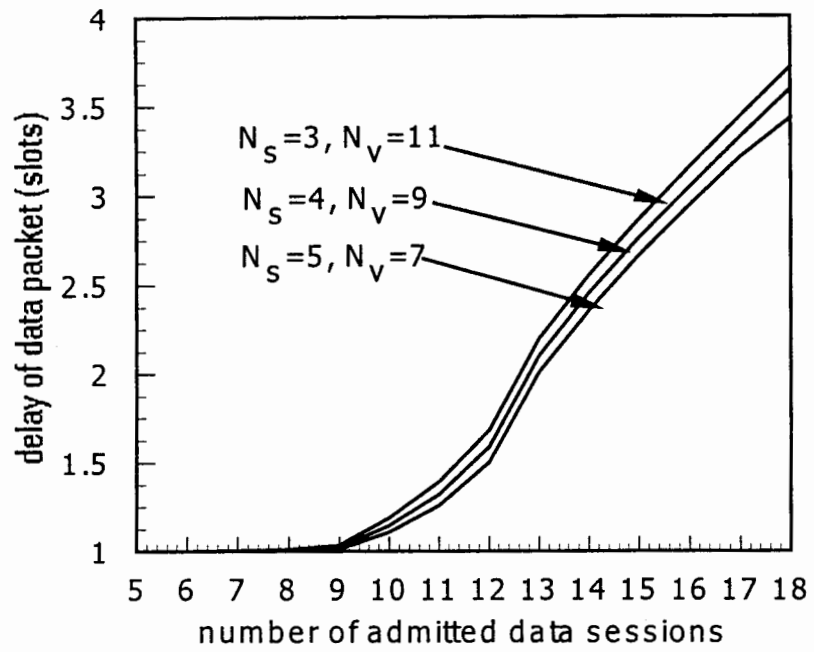Fig. 3: Hyperexponential approximation model of a self-similar session.

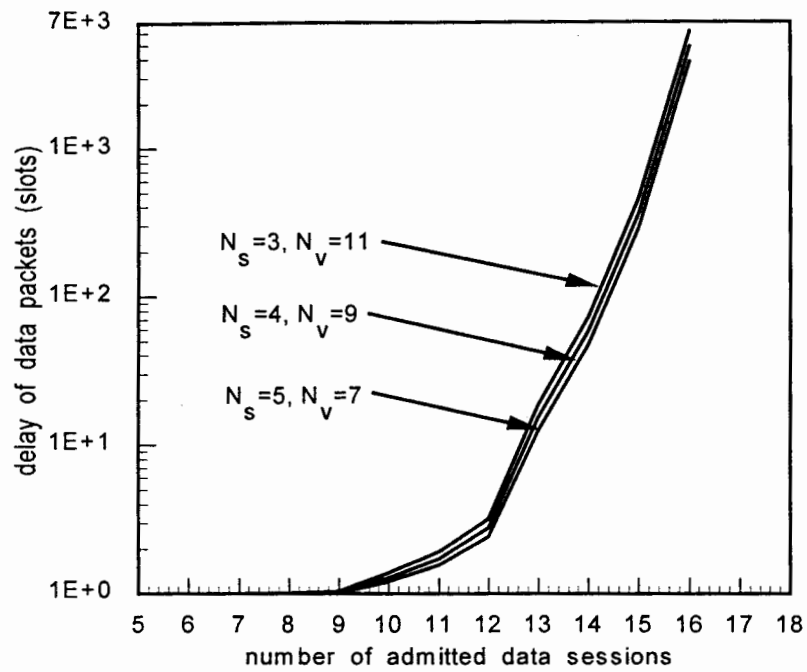Fig. 4: Delay of data packets in the system with medium access control under different scenarios.

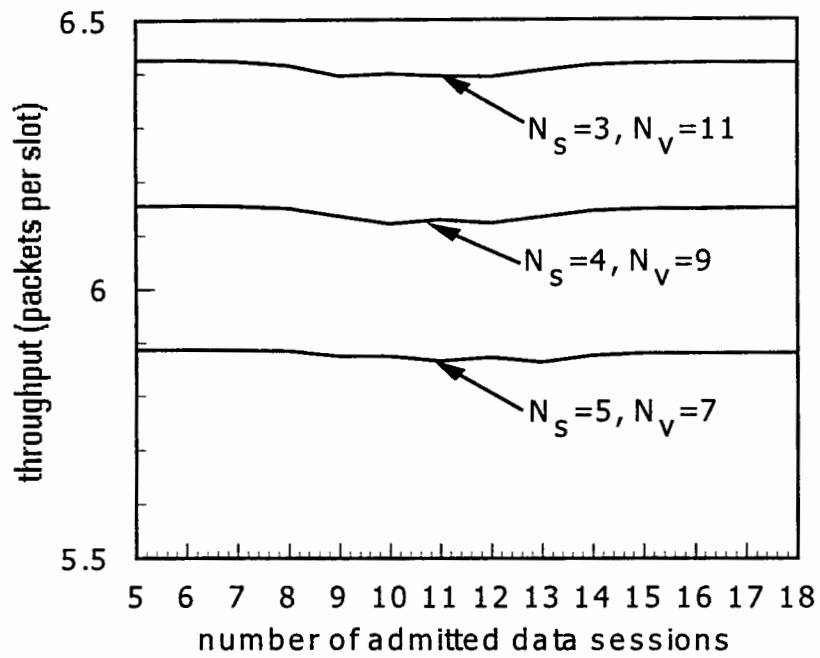Fig. 5: Delay of data packets in the system without access control under different scenarios.

Fig. 6: Total throughput of voice and self-similar traffic in the system with medium access control under different scenarios.
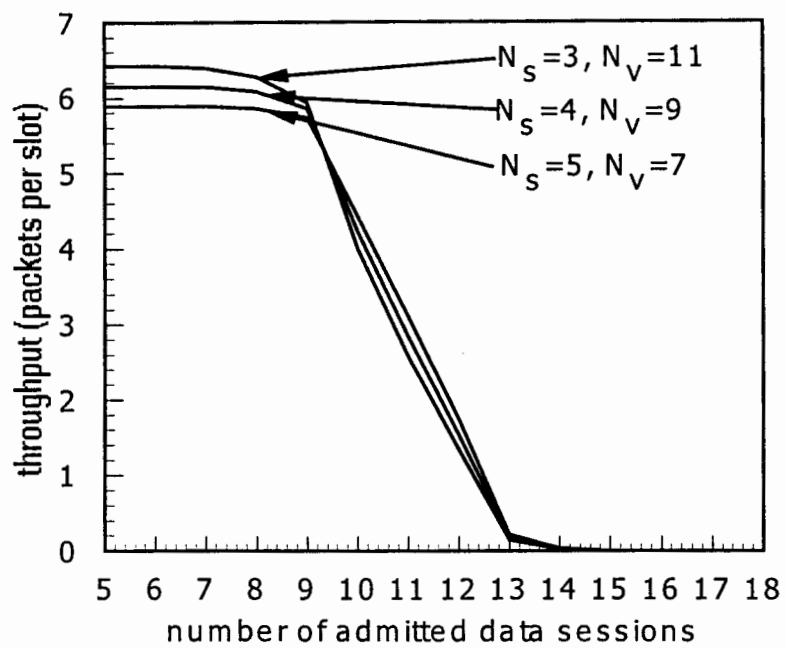
Fig. 7: Total throughput of voice and self-similar traffic in the system without access control under different scenarios.
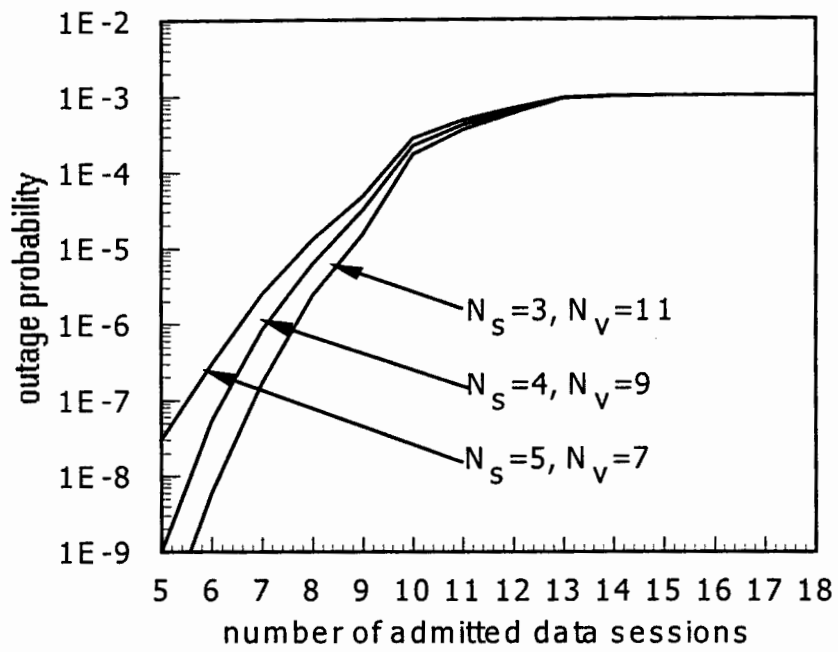
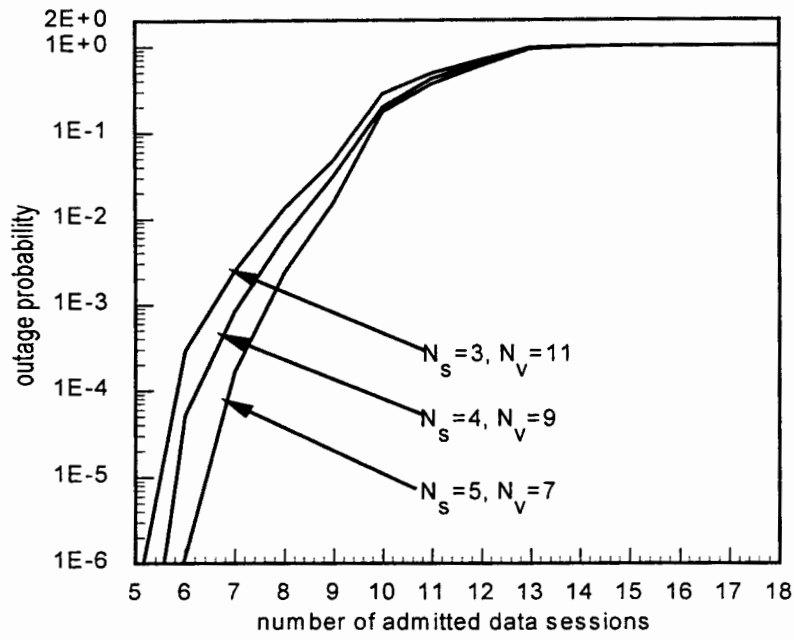Fig. 8: Outage probability of the systems with medium access control under different scenarios.

Fig 9: Outage probability of the systems without access control under different scenarios.