Achievable QoS in a Shared Wireless Channel

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Abstract - **In this work, call admission and transmission scheduling policies are studied for a TDMA system servicing Variable Bit Rate (VBR) applications with distinct QoS requirements and traffic characteristics. In this environment, packets which experience excess delays are dropped (due to delay violations) at the source. In addition, packets are dropped at the receiver due to channel induced errors (interference) in the wireless link. The focus of the research is to determine the region of achievable QoS vectors for heterogeneous VBR applications in this shared resource environment and study the impact that channel quality has on the achievable performance. The region of achievable QoS vectors is central to the call admission problem and in this work, it is used to identify a class of scheduling policies capable of delivering any achievable performance.**

I. INTRODUCTION

In *Integrated Services Wireless Networks* resources are shared among geographically disperse applications with diverse traffic characteristics and QoS requirements. The shared transmission resources are defined to be the slots (packet transmission times) of a TDMA frame. This resource structure has been widely considered in both cellular systems [1] and wireless LANs [2], as well as in recent work toward the development of wireless ATM networks [3, 4].

The focus of this work is to determine the region of achievable QoS vectors for heterogeneous VBR applications in a shared wireless environment. The QoS requirements for each application is defined in terms of a maximum tolerable packet delay and dropping probability. Determining the region of achievable QoS vectors is central to the development of a Call Admission Control mechanism. For example, if with the addition of the new source, the new multi-dimensional target QoS vector is in the region of achievable QoS vectors then the call can be admitted. If the call can not be admitted, but more resources can be made available, a precisely defined region of achievable QoS can be used to determine the minimum additional resources required in order for the new call to be admitted. In this work, the region of achievable QoS vectors is also used to identify a class of scheduling policies capable of delivering any achievable performance.

In an error-free channel all transmitted packets are successfully received. In this case, the delivered QoS is shaped by the packet discarding process at the transmitter (source) due to delay violations; the latter occur when the demand exceeds the amount of available resources for a sufficiently long period. Thus, the performance is limited by the amount of available resources (resource limited). The region of achievable QoS vectors in an error-free channel environment has been investigated in [5].

While an optical-fiber based channel may be practically considered to be error-free, this is not the case with wireless channels. Although the necessary resources may become available on time, packets may be corrupted due to channel induced errors and be dropped at the receiver. Under these conditions, the performance is limited by the interference introduced in the wireless channel (interference limited). Such packet discarding may occur with a frequency comparable to that of the packet discards at the transmitter due to resource limitations. As a consequence, the region of achievable QoS vectors is shaped by the packet discarding process at both the transmitter and the receiver due to resource and interference limitations, respectively.

II. DESCRIPTION OF THE SYSTEM MODEL

Consider a system where N VBR (Variable Bit Rate) sources compete for T slots in the up-link channel. T

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represents the number of slots in the TDMA frame available for VBR traffic. At the beginning of each frame n each source i will request a random number of slots denoted by $\lambda_i(n)$. If the aggregate demand in frame n, $\sum_{i=1}^{N} \lambda_i(n)$, exceeds the number of slots available to the VBR traffic (T) - referred to as an overloaded frame - then decisions must be made regarding the amount of service that will be provided to each source. The portion of slots under policy f allocated to source i, $a_i^f(n)$, may be less than what is required by that source, $\lambda_i(n)$, due to resource limitation. Packets from a source which do not receive service over a frame are considered to have excess delay and are dropped at the source.

The above environment could model the sharing of the up-link TDMA frame of a wireless network where request are processed at frame boundaries. Fig. 1 illustrates a typical up-link TDMA frame whose slots are allocated to various classes of services, such as Continuous Bit Rate (CBR), Available Bit Rate (ABR) and Variable Bit Rate (VBR). In this figure $T = 3$ slots are assumed to be available to the VBR applications.

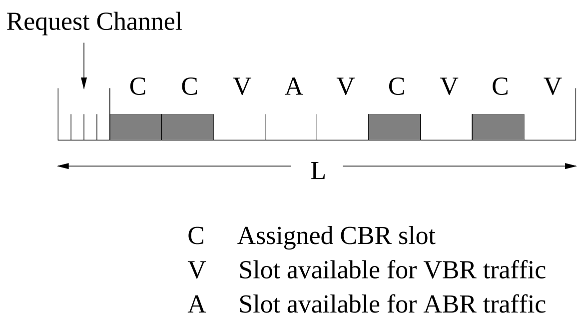

Figure 1. TDMA frame supporting CBR, VBR and ABR traffic classes.

In this paper a transmitted packet will also be discarded at the receiver if the signal to interference ratio (SIR) falls below a threshold b. In a wireless channel, the received signal power may be described by taking into consideration three effects [6]: attenuation due to distance, shadowing - typically described by a log-normal distribution, and fading that causes the instantaneous envelope of the received signal to be Rayleigh distributed and consequently its power is exponentially distributed. An outage is defined as an event that occurs when the SIR falls below a predetermined threshold, b, sometimes called capture ratio. It is assumed that when a source experiences an outage its packet is corrupted, otherwise, it is correctly received. Therefore, the probability that a packet is discarded at the receiver is defined as,

$$P[SIR < b]. \tag{1}$$

Let β be an indicator function of an outage (error event). That is,

$$\beta = \begin{cases} 1 & \text{if } SIR < b \\ 0 & \text{if } SIR \geq b \end{cases}. \tag{2}$$

In this model, it is assumed that outages are independent and identically distributed; with minor modifications, correlation among outages can be easily considered.

Due to the above competition for the resources and the errors induced by the channel, the number of packets from source i dropped in frame n will depend on the policy and is given by,

$$d_i^f(n) = \tag{3}$$

$$\begin{cases} \sum_{k=1}^{\lambda_i(n)} \beta_k & \text{if } \sum_{j=1}^{N} \lambda_j(n) \leq T \\ \lambda_i(n) - a_i^f(n) + \sum_{k=1}^{a_i^f(n)} \beta_k & \text{if } \sum_{j=1}^{N} \lambda_j(n) > T \end{cases}.$$

Let $d_i^f = E\left[d_i^f(n)\right]$, $a_i^f = E\left[a_i^f(n)\right]$ and $\lambda_i = E\left[\lambda_i(n)\right]$ be the (assumed time invariant) expected values of the associated quantities.

Suppose that the QoS requirement of application i is defined in terms of a maximum tolerable average per frame packet dropping rate d_i, $0 \leq i \leq N$. Then the QoS vector associated with the supported applications can be defined in terms of the (performance) packet dropping rate vector $\mathbf{d}$,

$$\mathbf{d} = (d_1, d_2, \ldots, d_N). \tag{4}$$

When the QoS requirement of the application i is defined in terms of a maximum tolerable packet dropping probability p_i, the corresponding packet dropping rate d_i is easily determined by $d_i = \lambda_i \; p_i$.

The first question addressed in the sequel (section III) is whether (under the given channel conditions) a given QoS vectors $\mathbf{d}$ is achievable under any policy f. The second question, addressed in section IV, is concerned with the design of scheduling policies that deliver an achievable target QoS vector $\mathbf{d}$.

III. DETERMINATION OF THE REGION OF ACHIEVABLE QOS VECTORS

The establishment of the region of achievable QoS vectors is based on a set of inequalities and an equality constraint derived by employing work-conserving arguments. A work-conserving policy (denoted as f) does not waste resources (slots) as long as there is work to perform (packets to transmit). Details regarding these derivations may be found in [7].

Let $S = \{1, 2, \ldots, N\}$ be the set of all sources and $d^f_{\{S\}}$ denote the average system packet dropping rate under scheduling policy f, denoted by,

$$d^f_{\{S\}} \triangleq E\left[\sum_{i=1}^{N} d^f_i(n)\right] = \sum_{i=1}^{N} E\left[d^f_i(n)\right] = \sum_{i=1}^{N} d^f_i. \quad (5)$$

Define $\lambda_g(n) = \sum_{i \in g} \lambda_i(n)$ for any $g \subseteq S$.

Under any work-conserving, f, the average system packet dropping rate is,

$$\begin{aligned} d^f_{\{S\}} = E[\beta]\left\{E\left[\lambda_S(n) \,\middle|\, \lambda_S(n) \le T\right]\right\} \quad (6) \\ \cdot Pr\left(\lambda_S(n) \le T\right) \\ + \left\{E\left[\lambda_S(n) \,\middle|\, \lambda_S(n) > T\right] - T(1 - E[\beta])\right\} \\ \cdot Pr\left(\lambda_S(n) > T\right). \end{aligned}$$

As it can be seen from (6), $d^f_{\{S\}}$ is independent of the policy f. Therefore, the system dropping rate, $d^f_{\{S\}}$, is conserved under any policies f and is denoted as $b_{\{S\}}$.

Let $d^f_{\{g\}}$ denote the average subsystem $\{g\}$ packet dropping rate under policy f, defined by,

$$\begin{aligned} d^f_{\{g\}} \triangleq E\left[\sum_{i \in g} d^f_i(n)\right] &= \sum_{i \in g} E\left[d^f_i(n)\right] \quad (7) \\ &= \sum_{i \in g} d^f_i, \quad g \subset S. \end{aligned}$$

That is, $d^f_{\{g\}}$ is equal to the aggregate packet dropping rate associated with sources in group g only, under policy f; all N sources in S are assumed to be present and served under policy f.

Let $b_{\{g\}}$ denote the lower bound for the aggregate packet dropping rate for sources in $\{g\}$, determined to be equal to the packet dropping rate of a system in which only sources in $\{g\}$ are present and served under a work-conserving policy. Sources in set $\{S - g\}$ are considered to be removed. It is given by,

$$\begin{aligned} b_{\{g\}} = E[\beta]\left\{E\left[\lambda_g(n) \,\middle|\, \lambda_g(n) \le T\right]\right\} \quad (8) \\ \cdot Pr\left(\lambda_g(n) \le T\right) \\ + \left\{E\left[\lambda_g(n) \,\middle|\, \lambda_g(n) > T\right] - T(1 - E[\beta])\right\} \\ \cdot Pr\left(\lambda_g(n) > T\right). \end{aligned}$$

It is apparent that no policy can deliver a lower dropping rate to sources in set g than $b_{\{g\}}$, when all sources in S are present. Thus, $b_{\{g\}}$ is a lower bound on the performance induced for the set g under any policy.

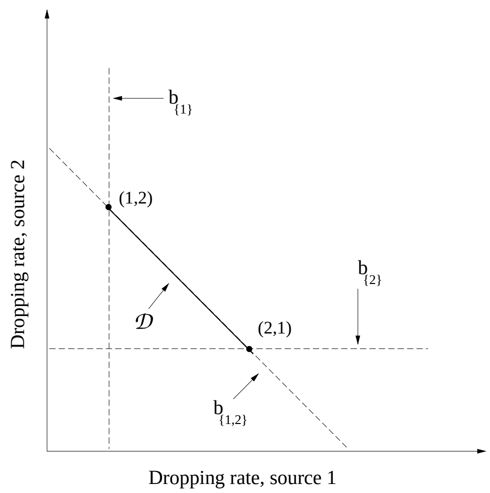

Figure 2. The region (polytope) $\mathcal{D}$ for a system with two sources.

It is shown in [7] that necessary and sufficient conditions for a QoS vector $\mathbf{d} = (d_1, d_2, \ldots, d_N)$ to be achieved by a scheduling policy f are that its components satisfy the following constraints,

$$\begin{aligned} d_{\{g\}} &\ge b_{\{g\}} \quad \forall g \subseteq S \quad (9) \\ d_{\{S\}} &= b_{\{S\}}. \quad (10) \end{aligned}$$

Let $\mathcal{D}$ denote the collection of all vectors $\mathbf{d}$ satisfying (9) and (10). Any vector in the set $\mathcal{D}$ can be expressed as a convex combination of extreme points (vertices) of $\mathcal{D}$; that is, $\mathcal{D}$ may be expressed as the convex hull of its extreme points, $\mathcal{D}$=conv[exp($\mathcal{D}$)], see [7]. It is shown in [7] that $\mathbf{d}^*$ is a vertex of the set $\mathcal{D}$ iff $\mathbf{d}^*$ is a dropping rate vector resulting from an Ordered HoL (O-HoL) priority service policy, $\boldsymbol{\pi}= (\pi_1, \pi_2, \ldots, \pi_N)$; $\pi_i \in \{1, 2, \ldots, N\}$, $\pi_i \ne \pi_j$, $1 \le i,\ j \le N$. The index of π_i indicates the order of the priority given to the π_i source. None of the π_j sources, $j > i$, may be served as long as packets from sources π_k, $k \le i$, are present.

Fig. 2 and Fig. 3 provide a graphical illustration of the region $\mathcal{D}$ for the case of $N = 2$ and $N = 3$ sources, respectively. The extreme points correspond to QoS vectors $\mathbf{d}$ induced by the $N!$ ordered HoL priority policies $\boldsymbol{\pi}= (\pi_1, \pi_2, \ldots, \pi_N)$. Referring to Fig. 2, it may be observed that the policy $(\pi_1, \pi_2) = (1, 2)$ corresponds to the intersection of the line for the lower bound on the packet dropping rate line for source 1, $b_{\{1\}}$, with the system dropping rate line $b_{\{1,2\}}$. Similarly, the second extreme point induced by the policy $(\pi_1, \pi_2) = (2, 1)$ is the intersection of the lower bound on the packet dropping rate for source 2, $b_{\{2\}}$ and $b_{\{1,2\}}$. Similar observations can be made for the region $\mathcal{D}$ for a system of $N = 3$ sources shown in Fig. 3.

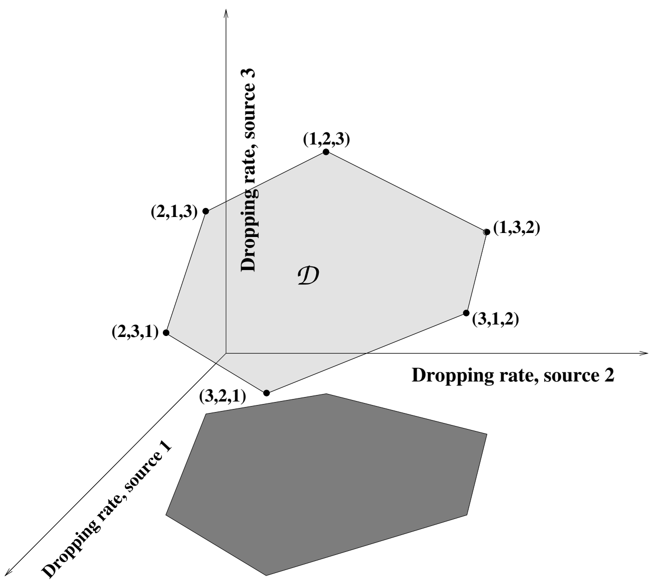

Figure 3. The region (polytope) $\mathcal{D}$ for a system with three sources.

IV. A CLASS OF POLICIES INDUCING ALL QOS VECTOR IN $\mathcal{D}$

Let C_{O-HoL} denote the class of Ordered HoL (O-HoL) priority service policies $\boldsymbol{\pi}$ introduced in section III. A mixing O-HoL priority service policy f_m is defined to be one that at each frame decides to follow the O-HoL priority policy $\boldsymbol{\pi}^i = (\pi_1^i, \pi_2^i, \ldots, \pi_N^i)$ with probability $\alpha_i, \alpha_i \geq 0,\ 1 \leq i \leq N!,\ \sum_{i=1}^{N!} \alpha_i = 1$; decisions over consecutive frames are independent. Clearly, f_m is completely determined by the $N!$ dimensional vector $\boldsymbol{\alpha}$, $\boldsymbol{\alpha} \geq \mathbf{0}$, $\mathbf{1} \cdot \boldsymbol{\alpha} = 1$. Let M_{O-HoL} denote the class of such policies.

For each packet dropping rate vector $\mathbf{d} \in \mathcal{D}$ there exists a policy $f_m \in M_{O-HoL}$ that induces $\mathbf{d}$. The proof follows from the fact that $\mathcal{D}$ can be written as a convex combination of the extreme points (vertices) $\mathbf{d}_{ext-i}$ of $\mathcal{D}$, that is $\mathbf{d} = \sum_{i=1}^{N!} \alpha_i \mathbf{d}_{ext-i}$ for some $\boldsymbol{\alpha} = (\alpha_1, \alpha_2, \ldots, \alpha_{N!})$ where $\alpha_i \geq 0,\ 1 \leq i \leq N!,\ \sum_{i=1}^{N!} \alpha_i = 1$. Since each $\mathbf{d}_{ext-i}$ is induced by some policy in C_{O-HoL}, a mixing policy f_m that selects the HoL priority $\boldsymbol{\pi}^i$ (that induces $\mathbf{d}_{ext-i}$) with probability α_i such that $\alpha_i \geq 0,\ 1 \leq i \leq N!,\ \sum_{i=1}^{N!} \alpha_i = 1$ will have a packet dropping rate vector $\mathbf{d}^{f_m}$ given by,

$$\mathbf{d}^{f_m} = \sum_{i=1}^{N!} \alpha_i \mathbf{d}_{ext-i} \tag{11}$$

and thus f_m induces $\mathbf{d}$.

Let $\mathbf{d} \in \mathcal{D}$ be a target packet dropping rate vector. The mixing policy $f_m \equiv \boldsymbol{\alpha}$ induces $\mathbf{d}$, where $\boldsymbol{\alpha}$ is such that,

$$E_{\boldsymbol{\alpha}}[\mathbf{d}_{ext}] \triangleq \sum_{i=1}^{N!} \alpha_i \mathbf{d}_{ext-i} = \mathbf{d}, \tag{12}$$

$$\boldsymbol{\alpha} \geq \mathbf{0}, \tag{13}$$

$$\mathbf{1} \cdot \boldsymbol{\alpha} = 1, \tag{14}$$

where $E_{\boldsymbol{\alpha}}[.]$ is weighted average of the set of extreme points, $\mathbf{d}_{ext}$, of $\mathcal{D}$ with respect to the Probability Mass Function $\boldsymbol{\alpha}$.

V. NUMERICAL AND SIMULATION RESULTS

In this section, numerical examples and simulations are carried out for a system with two sources competing for 5 slots in a TDMA frame. The source packet arrival processes are assumed to be mutually independent. Each arrival process is described in terms of an underlying finite-state Markov chain embedded at the frame boundaries. The number of packets generated (and requesting service) by a source in the current frame boundary is (probabilistically) determined by the present state of the associated underlying Markov chain.

Consider in this example the typical TDMA frame in which one slot per frame represents a 32 Kbps channel. Let $E^k = \{0, 1, \ldots, M^k - 1\}$ denote the state space of the Markov chain associated with source k, $k = 1, 2$. In this example $M^1 = 6$ and $M^2 = 6$. When in state i, a source generates i packets in the current frame. Source 1 and 2 could be used to model a low rate video transmissions with maximum rate 6 slots/frame = 192 Kbps. Further description of all two sources can found in Table I. The arrival rates are easily computed and are equal to $\lambda_1 = 4.2$ and $\lambda_2 = 3.2$ packets per frame.

State	State Probability	
	Source 1	Source 2
0	0	0.1
1	0.1	0
2	0.1	0.4
3	0.3	0
4	0.2	0.3
5	0.2	0
6	0.1	0.2

Table I
Description of Sources.

With the sources given above, (9) and (10) were evaluated with $T = 5$ slots and under various channel conditions. The impact channel quality has on the region of achievable QoS vectors can be seen in Table II.

The channel quality has a greater relative effect on the lower bounds for the subsets than on the system. This implies that when the system is very diversified, and some sources are requesting service close to their lower bounds, then the channel quality is an important factor in determining whether the target performance is achievable. Simulation results are presented in Table III. The previously described sources in Table I were simulated and service (with $T = 5$ slots per frame) according to various mixing policies. Each mixing policy was given by α, which is the probability of selection of O-HoL policy $\boldsymbol{\pi}$=(1,2) (and therefore $\boldsymbol{\pi}$=(2,1) with probability $(1-\alpha)$), and varied from 0 to 1.

Theoretical Results			
$E[\beta]$	$b_{\{1\}}$	$b_{\{2\}}$	$b_{\{1,2\}}$
0	0.1000	0.2000	2.0700
0.01	0.1350	0.2300	2.1173
0.02	0.1700	0.2600	2.1646

Table II
Impact of channel quality on the region of achievable QoS.

Simulation Results				
$E[\beta]$	α	d_1	d_2	$d_1 + d_2$
0.00	0.00	1.8835	0.1978	2.0814
	0.25	1.4323	0.6490	2.0814
	0.50	0.9837	1.0977	2.0814
	0.75	0.5358	1.5455	2.0814
	1.00	0.0969	1.9844	2.0814
0.01	0.00	1.9007	0.2279	2.1286
	0.25	1.4540	0.6746	2.1286
	0.50	1.0101	1.1184	2.1286
	0.75	0.5668	1.5618	2.1286
	1.00	0.1324	1.9962	2.1286
0.02	0.00	1.9178	0.2586	2.1764
	0.25	1.4756	0.7008	2.1764
	0.50	1.0362	1.1402	2.1764
	0.75	0.5979	1.5784	2.1764
	1.00	0.1677	2.0086	2.1764

Table III
Simulation results displaying the effects of the channel quality on the performance of various mixing policies.

Let d_k denote the target packet dropping probability, for source k, $k = 1, 2$. In this example it is assumed that $d_1 = 1.220$ and $d_2 = 0.900$. Thus, the QoS vector $\mathbf{d}$ is given by $\mathbf{d} = (d_1, d_2) = (1.220, 0.900)$ and the associated system packet dropping rate is equal to $d_{\{S\}} = d_1 + d_2 = 2.120$. By satisfying (9) and (10) (see Table II), it can be established that the performance can be achieved when $E[\beta] \leq 0.01$. When the channel condition are given by $E[\beta] = 0.02$, the system dropping rate can not be satisfied, and there the QoS can not be delivered to applications.

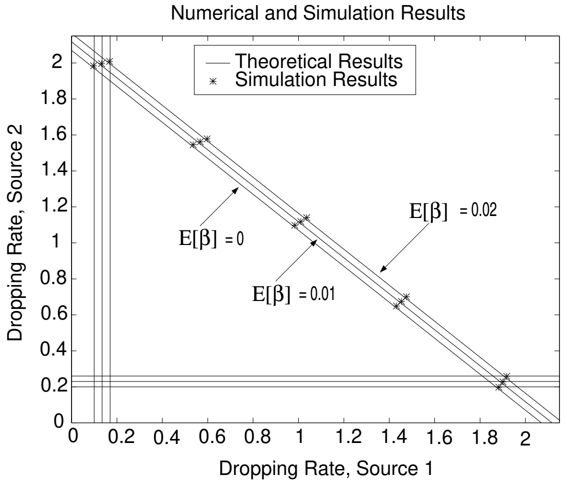

Figure 4. Numerical evaluation of the region of achievable QoS under various channel conditions for the system of sources given in Table 1 ($T = 5$) and simulation results from Table 3.

When $E[\beta] \leq 0.01$, $d_{\{S\}} \geq b_{\{S\}}$ and thus, according to [7], there exists a vector $\mathbf{d}'$ such that $d'_{\{g\}} \leq d_{\{g\}}$, $g \subset S$ and $d'_{\{S\}} = b_{\{S\}}$; $\mathbf{d}'$ is said to have improved performance. Consider the case when $E[\beta] = 0.01$, and let $\mathbf{d}' = (1.218, 0.899)$; $\mathbf{d}' \in \mathcal{D}$ and thus there exists a mixing ordered HoL priority policy $f_m \equiv \boldsymbol{\alpha}$ achieving exactly the QoS vector $\mathbf{d}'$. Any $\boldsymbol{\alpha}$ satisfying the conditions (12), (13) and (14) may be chosen. The following $\boldsymbol{\alpha}_o$ was found by employing linear programming techniques,

$$\boldsymbol{\alpha}_o = \begin{bmatrix} \alpha_1 = 0.3818 \\ \alpha_2 = 0.6181 \end{bmatrix} \tag{15}$$

In this example there exists only one solution, but in systems with greater than 2 sources more than one solution may be found. This allows for the incorporation of additional constraints representing other desirable qualities of the policies. Functions of interest may be minimized subject to the constraints presented in this paper to guarantee the delivery of the target QoS vector. For instance, among all mixing policies inducing $\mathbf{d}'$, the one which minimizes the variance of the service provided to certain sources may be identified.

A simulation was performed using the policy, $\boldsymbol{\alpha}_o$, derived for this example. The sources, as described in Table I, were simulated and generated the service demand. Resources (slots) were allocated according to the prescribed policy and the number of dropped packets per frame from each source was recorded. The simulation time was 50000 frames or 2000 seconds (i.e., 40

Source, i	Theoretical, d_i	Simulation, $\widehat{d_i}(k)$
1	1.218	1.211
2	0.899	0.893

Table IV
Comparison of time-averaged and theoretical steady-state mean packet dropping rate for each source under policy α_o.

ms frame). Throughout the simulation in each frame m, for each source i, the time-averaged mean dropping rate was calculated as,

$$\widehat{d_i}(k) = \frac{1}{k}\sum_{m=1}^{k} d_i^f(m). \qquad (16)$$

The resulting time-averaged mean packet dropping rate for each source under the policy was found and is displayed in table IV. Throughout the progression of the simulation the time-averaged mean packet dropping rates were recorded and are displayed in Fig. 5.Under the policy the objective of mean packet dropping rate d_i for each source i is met, see table IV and Fig. 5.

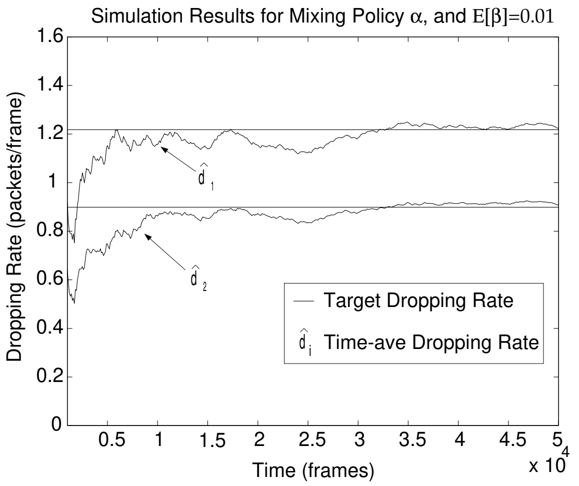

Figure 5. Simulation results obtained with the derived policy α_o.

As it was stated in section 3, satisfying the condition on the system performance, given by (10), is only necessary and not sufficient to guarantee that the target QoS vector is achievable[1]. To illustrate this concept, consider the system given in the previous example with $E[\beta] = 0$ and let $\mathbf{d} = (0.099, 1.971)$ be the target QoS vector. $\mathbf{d}$ satisfies the condition on the system dropping rate, that is $d_{\{S\}} = b_{\{S\}} = 2.07$, but $d_1 < b_1 = 0.100$. Thus, the target QoS vector cannot be achieved under any policy. For this system, the best possible performance source 1 can achieve is if it is given service priority, resulting in dropping rates of 0.100 and 1.970 for sources 1 and 2, respectively. The overall system performance is satisfied, but source 1 is experiencing poorer service than what is desired, while sources 2 is experiencing improved performance.

[1] In the special case of a homogeneous system, such as a cellular voice system, satisfying (10) is sufficient to guarantee that the target QoS vector is achievable. This result has been established in [5].

VI. CONCLUSION

In this work, the region of achievable QoS vectors was established for a system of heterogeneous VBR sources competing for slots of a TDMA frame. The QoS for each application was defined to be the packet dropping rate, which results from the competition for resources (slots may not come available on time and a source is forced to drop the packets with excess delay) as well as channel induced errors (corrupted packets are dropped at the receiver). Knowledge of this region was used to develop a class of scheduling policies that can deliver any achievable performance. Together, the call admission and scheduling functions can ensure the delivery of the target QoS vector under the given channel conditions.

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