Analyzing the Performance of Data Users in Packet Switched Wireless Systems with Prioritized Voice Traffic

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Abstract. The integration of wireless telephony and data services in 3G and 4G wireless systems that use packet-switched air interfaces poses new challenges in the management of network resources. Although highly compressed voice traffic is given priority over data traffic, scheduling algorithms which exploit multiuser diversity have been shown to significantly improve the data throughput . In this paper, we quantify the effect of prioritized voice traffic on the performance of data users in the system using a mix of analysis and simulation. We analytically characterize the scheduled rate, delay and packet service times for data in the presence of prioritized voice traffic by using a general scheduling metric that incorporates a measure of the user's channel quality in addition to a delay constraint. The results provide important tools for cellular network operators to evaluate system performance and provision resources for traffic with varying Quality of Service(QoS) requirements.

1 Introduction

The support of real-time services in packet-switched 3G and 4G cellular wireless systems is currently a topic of active research. In particular, there is significant interest in the integration of voice over IP (VoIP) and data traffic. In 1xEV-DO [1,2], if 20 ms speech frames generated by VoIP codecs such as G.729 are to be delivered with minimal delay, 24 voice users can be accomodated, assuming a voice activity factor of 0.5. A higher number of voice users can be served by either using higer compression rates, or by tolerating a larger amount of scheduling delay, both of which can adversely affect voice quality. The simplest technique to support delay-sensitive traffic such as packet voice in a packet-switched cellular data system is to strictly prioritize it over data traffic. 1xEV-DO, for instance, supports QoS by prioritizing delay-sensitive data in the wireline backhaul network as well as over the airlink [3]. The residual bandwidth (time slots) available for data applications can be utilized most efficiently by exploiting multiuser diversity techniques [4,5]. This form of diversity exploits independent fading in a multiuser environment by opportunistically scheduling users at favorable channel instants. However, unfair resource allocation and variability in scheduled rate and delay are natural consequences of such algorithms [6,7].

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This paper focuses on the impact of supporting VoIP services in a time-slotted packet-switched air interface. The system is assumed to use strict prioritization for voice, while data packets are opportunistically scheduled subject to delay constraints. As in 1xEV-DO, mobile users are assumed to report the maximum sustainable downlink rate, $R(t)$ to the base station via a dedicated channel on the uplink in order to support opportunistic scheduling. We consider a general scheduling metric, originally introduced in [8], that combines channel state with delay constraints in the form

$$m(t) = R(t) + \alpha \frac{v(t)}{N_d} = R(t) + \alpha V(t), \tag{1}$$

where $v(t)$ is the scheduling delay for a waiting packet and α is a configurable control weight that allows control of delay at the expense of multiuser diversity gain. While the scheduler is not designed to optimize either throughput or delay constraints, the metric elegantly captures the trade-off between multiuser diversity gain and delay through the control parameter, α. Also, this metric lends itself well to statistical analysis as well as implementation. In order to ensure that the delay does not dominate the scheduler metric as the number of data users N_d increases, we normalize $v(t)$ by N_d. Hereafter, we refer to $V(t)$, the normalized scheduling delay, as *vacation time.*

The original contribution of this paper is an analytical characterization of the effect of prioritized voice users on data users in a cellular wireless system with delay constrained opportunistic scheduling. We quantify the resulting delay and compute the packet service times for data users as a function of the number of voice users in the system when all users have fully loaded queues and the resources of the system are completely utilized. The outline of the paper is as follows. Section 2 discusses related work in this area of research. In the analysis presented in Section 3, we derive expressions for the distribution of scheduling jitter and scheduled rate, which in turn allow computations of the distributions of packet service times. Section 4 contains details of the system model. Simulation results that validate our analysis are presented in Section 5. Finally, we highlight the main ideas in this work and summarize our results in Section 6.

2 Related Work

Wireless networks that were designed to support circuit-switched voice traffic are now migrating to packet-switched networks that support data applications as well [9]. Although QoS support for real-time traffic in wireline networks has been well-studied in the literature, the time-varying wireless channel adds a new dimension to the problem. QoS provisioning for wireless systems that incorporated channel-state dependent scheduling algorithms are outlined in [10] and in in [11]. In the former, the authors propose the Modified - Largest Weighted Delay First (M-LWDF) rule to optimally provide QoS guarantees in terms of predefined guarantees for the probability of loss and minimum long-term throughput for each user. The exponential rule presented in the latter provides an effective way of realizing multiuser diversity gains with a delay constraint. In recent work, the authors in [12] introduce the concept of effective capacity to explicitly guarantee QoS.

Packet-switched wireless networks that primarily support voice calls through prioritization of voice traffic can share unused voice bandwidth among data applications. However, the number of such data users that can be supported is limited by the user experience in terms of delay and throughput. In order to quantify the throughput and delay experienced by data users in the presence of voice traffic, we model the scheduler as a dynamical system. We analyze the performance of the data users at the fixed point as a function of the number of voice users in the system. The results, which are validated by simulations of an actual system provide a network operator useful tools in evaluating system performance for a given mix of voice and data traffic.

3 Delay and Throughput Analysis for Data Users

In this section, we present an analytical framework to evaluate the the throughput and delay of data traffic with prioritized voice traffic. This framework was originally developed in [8] to analyze the trade-off between throughput and delay in opportunistic schedulers. When users have different channel statistics, the scheduler metric in 1 can be modified to ensure resource fairness as follows:

$$m_i(t) = (R_i(t) + \gamma_i) + \alpha V_i(t) \tag{2}$$

where γ_i can be chosen optimally [13] to maximize the total scheduled rate while ensuring temporal fairness without delay constraints ($\alpha = 0$). In order to better understand the interaction of voice and data users, we assume identical channel statistics for all data users. As described in Section 1, we denote the rate requested by data user i at time t by $R_i(t)$. Let $\mathcal{R} = \{r_0, r_1, ..., r_{max}\}$ denote the finite set of rates requested by the users. This set is assumed to have a probability distribution $f_{R_i}(r) = f_R(r) = P(R = r), r \in \mathcal{R}, \forall i$. The delay experienced by data user, i since it was previously scheduled is $v_i(t)$, with $V_i(t) = v_i(t)/N_d$ representing the normalized vacation time.

In every time slot, voice users are served with the highest priority on a first-come first-served (FCFS) basis. If there is no waiting voice packet, the base station transmits to the user with the highest metric as computed from equation 1. In the event that more than one data user has the highest metric, a data user is picked with uniform probability from among the users with the highest metric in order to break the tie. The complexity of the joint state-space resulting from the combinations of scheduling delays and requested rates makes the analysis of the scheduler using Markov models intractable. In [8], we define a permutation of the data user space in which the users are rank-ordered in every slot according to the delay they have experienced since they were last scheduled. Let $\mathbf{U}(t)$ denote the rank-ordering of the N_d data users at time t:

$$\mathbf{U}(t) = \{u_0(t), u_1(t), ..., u_{N_d-1}(t)\} \tag{3}$$

where $u_i(t) \in [0, 1, ..., N_d - 1]$. In this space, $u_i(t)$ denotes the original index of the data user who is ranked in the i^{th} position at time t. By definition,

$$V_{u_0}(t) \leq V_{u_1}(t) \leq ... \leq V_{u_{N_d-1}}(t) \tag{4}$$

where $V_{u_i}(t)$ is the vacation time seen by the data user who is ranked in position i at time t. Naturally, since $u_0(t)$ is the index of the data user who was scheduled in the current slot, $V_{u_0}(t) = 1/N_d$. At time t, if no voice packet is available for transmission, the scheduler selects a data user whose rank-ordered index is given by $S^*(t)$ where

$$S^*(t) = \overset{argmax}{i} \quad m_{u_i}(t) \tag{5}$$

The scheduling decision in one slot affects the rank-ordering at the beginning of the next slot. At time $(t+1)$, the scheduled data user, S^*, at time t now moves to position 0. All data users below the rank of S^* increment their rank by one. However, all data users with rank greater than that of S^* do not change their order in any way. Naturally, if a voice packet is scheduled, the rank-ordering of the data users remains invariant. **U** evolves over time as:

$$u_i(t+1) = \begin{cases} u_{S^*}(t), & i = 0 \\ u_i(t), & i = S^*(t)+1, S^*(t)+2, ..., N_d - 1 \\ u_{i-1}(t), & i = 1, 2, ..., S^*(t) - 1 \end{cases} \tag{6}$$

Similarly, the vacation times seen by the data users change with every packet that is scheduled.

$$V_{u_i}(t+1) = \begin{cases} \frac{1}{N_d}, & i = 0 \\ V_{u_{i-1}}(t) + \frac{1}{N_d}, & 0 < i < S^*(t) \\ V_{u_i}(t) + \frac{1}{N_d}, & i > S^*(t) \end{cases} \quad \text{if data pkt is scheduled} \tag{7}$$

$$V_{u_i}(t+1) = V_{u_i}(t) + \frac{1}{N_d}, 0 \leq i < N_d \quad \text{if voice pkt is scheduled} \tag{8}$$

We define a selection density function, $\pi_{u_i}(t)$ which represents the probability of scheduling the ith rank-ordered data user, u_i at time t.

$$\pi_{u_i}(t) = Pr(S^*(t) = u_i) \tag{9}$$

with the property, $\sum_{i=0}^{N_d} \pi_{u_i}(t) = 1$. We now analyze the dynamical system consisting of the rank-ordered data user space, the corresponding channel conditions and scheduling delays. An iterative computation of $V_u(t)$ and $\pi_u(t)$ converges to the fixed-point, time-invariant solutions of the dynamical system, i.e., V_u and π_u.

3.1 Computation of the Vacation Function, V_u

The vacation function, V_u characterizes the normalized delay expressed by the data users in the system resulting from a choice of the scheduler metric. In the analysis that follows, we assume the existence of a selection density function, $\pi_{u_j}(t)$ which represents the probability of scheduling the jth rank-ordered data user, u_j at time t. Observe from equations 6 and 7 that the vacation function at position i in the rank-ordered space is subject to two transforming forces. The first causes its value to increase by $1/N_d$ when either a voice user is scheduled or a data user with a rank less than i is scheduled. If the probability of scheduling a voice user in any slot is given by p_v, then this event occurs with probability $p_v + (1-p_v)(\sum_{j<i} \pi_{u_j})$. The second transformation causes its value to decrease whenever the rank of the data user scheduled is i or higher. In this event, the value of the vacation-time at position i is replaced by that at position $(i-1)$, augmented by $1/N_d$. The probability of this event is $(1-p_v)(\sum_{j \geq i} \pi_{u_j})$. At equilibrium, the function is invariant to these transforming forces. The potential increase can therefore be equated to the potential decrease.

$$\begin{aligned} &\frac{1}{N_d}(p_v + (1-p_v)(\sum_{j<i} \pi_{u_j})) = \\ &((1-p_v)(\sum_{j \geq i} \pi_{u_j}))(V_{u_i}(t) - (V_{u_{i-1}}(t) + \frac{1}{N_d})) \end{aligned} \tag{10}$$

Dropping the dependence on time and applying the boundary condition, $V_{u_0} = \frac{1}{N_d}$, V_{u_i} may be computed recursively as

$$V_{u_i} = V_{u_{i-1}} + \frac{1}{N_d\,(1-p_v)\left(1 - \sum_{j<i} \pi_{u_j}\right)} \tag{11}$$

3.2 Computation of the Selection Density Function π_u

The data user with rank-ordered index i has a vacation time of V_{u_i}. If R_{u_i} is its requested rate, its scheduling metric is given by

$$m_{u_i} = R_{u_i} + \alpha V_{u_i} \tag{12}$$

The probability of selecting the i^{th} data user is then given by

$$\begin{aligned} \pi_{u_i} &= P(m_{u_i} > m_{u_j} \quad \forall j \neq i) + P(u_i \text{ selected in tie}) \\ &= P(R_i + \alpha V_{u_i} > R_j + \alpha V_{u_j} \quad \forall j \neq i) + P(u_i \text{ selected in tie}) \end{aligned} \tag{13}$$

The computation of the probability of a data user being selected in the event of a tie is given in Appendix A in [8]. This probability is accounted for in all numerical evaluations of the analytical results in Section 5.1. Since the channel rates are i.i.d. random variables with distribution $f_R(r)$, the first term reduces to

$$P(m_{u_i} > m_{u_j}) = \sum_{r=r_0}^{r_{max}} \left(\prod_{j \neq i} F_{R_{u_j}}(r + \alpha(V_{u_i} - V_{u_j})) \right) f_R(r) \tag{14}$$

3.3 Distributions for Vacation Time and Scheduled Rate

The vacation function and the selection density function as computed in Equations 11 and 13 respectively can be composed to calculate the distribution of vacation time at the scheduling instants. Let $\mathcal{V}_{S^*}$ represent the vacation time seen by the *scheduled* data user. The CDF of $\mathcal{V}_{S^*}$ is given by

$$P[\mathcal{V}_{S^*} \leq V_{u_i}] = \sum_{j=0}^{u_i} \pi_{u_j} \tag{15}$$

Apart from delay, the other quantity determining the performance of data traffic is the rate at which it is scheduled, which is related to the multiuser diversity gain. The pdf of the scheduled rate (which is naturally different from that of the requested rate) may be derived as a function of α as

$$\begin{aligned} f_{R_{S^*}}(r) &= \sum_{i=0}^{N_d-1} Pr(R_{u_i} = r, i\text{th rank-ordered data user is selected}) \qquad (16) \\ &= \sum_{i=0}^{N_d-1} f_R(r) \left(\prod_{j \neq i} F_R(r + \alpha(V_{u_i} - V_{u_j})) + Pr(\text{User } i \text{ selected in tie}) \right) \end{aligned}$$

3.4 Packet Service Times

Observe from Figure 1 that the packet service time may be expressed as the sum of scheduling periods and vacation periods. The packet service time, X, is the sum of X_S, the total number of slots required to transmit all the LL segments corresponding to the packet at the head of the queue and X_V, the number of slots where the scheduler goes on vacation. We assume that packets of fixed length, L are served by the base station in the order that they arrive. Furthermore, the packet service times are i.i.d. and independent of the interarrival times. Since

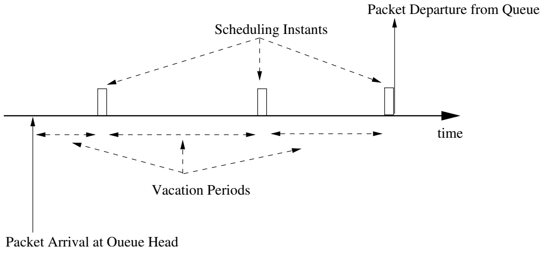

Fig. 1. Illustration of packet service timeline

the scheduling instants are independent of the vacation times, the distribution of service time may be calculated as

$$P(X = n) = \sum_j P(X_V = n - j)P(X_S = j) \tag{17}$$

If the packet completes service in j time slots, then the data user has experienced exactly j vacation periods between the scheduling instants. We represent this sum of j i.i.d. vacations as $V^{(j)}$. Let $R_{S,k}$ represent the scheduled rate corresponding to the k^{th} slot in the transmission of a given packet. The scheduled rates in different slots are assumed to be i.i.d. random variables. The distribution of the packet service times can therefore be computed from the distributions of the scheduled rate and vacation times.

$$P(X = n) = \sum_j P(V^{(j)} = n - j)P(R_S^{(j-1)} < L \leq R_S^{(j)}) \tag{18}$$

4 System Model

In this section, we first outline the model used to describe the wireless channel experienced by mobile users. We then highlight important aspects of the scheduler implementation.

4.1 Wireless Channel Model

Every mobile user is assumed to experience a flat fading channel where the channel response is assumed to be flat for the duration of the slot of K samples. If $x_i(t) \in \mathcal{X}^K$ is the vector of transmitted symbols and $y_i(t) \in \mathcal{X}^K$ is that of the symbols received by user i, then

$$y_i(t) = h_i(t)x(t) + z_i(t) \qquad i = 1, 2, \ldots, N_d \tag{19}$$

where $h_i(t)$ is the time-varying channel attenuation from the base station to the mobile and $z_i(t)$ is i.i.d., zero mean, additive white Gaussian noise with variance σ_i^2. Assuming unit-energy signals, the nominal signal-to-noise ratio (SNR) for data user i is $C_{NOM,i} = \frac{1}{\sigma_i^2}$ with the instantaneous SNR for this data user, $C_i(t)$ given by $C_i(t) = \frac{h_i(t)}{\sigma_i^2}$. We assume a Rayleigh SNR distribution and generate the fading coefficients using the well-known Jakes model [15].

We study the performance of 8 data users ($N_d = 8$), all with a nominal SNR of 2.5 dB and a doppler frequency of 10Hz. A scenario with identical channel statistics for all the data users was selected to enable comparison between analysis and simulation. For the case of i.i.d. channel fades, the distribution of the channel rates is chosen to be identical to the marginal distribution obtained with correlated channel fades at the same nominal SNR.

4.2 Air-Interface Model and Scheduler Implementation

We consider a cellular air-interface with a scheduled downlink and a circuit-switched uplink. Voice and data traffic are scheduled at the base station by the scheduler. Packets streams from voice and data users are assigned separate queues by the BS. Fixed length packets of 512 bytes are then segmented into link-layer (LL) segments of 8 bytes for efficient transmission over the air link. At the beginning of each transmission time slot, the scheduler at the BS computes the metric as defined in equation 1 and selects the data user with the highest metric. If there is no waiting voice packet, the BS transmits one or more LL segments to the selected data user over the airlink in every slot, each of which is a fixed duration of 1.667 ms. The number of segments transmitted in a slot depends on the current SNR of the selected data user. Table 1 lists the transmitted rate in link-layer segments as a function of the SNR. The peak rate of 2.45Mbps achievable in this model is similar to that in systems such as 1xEV-DO. When all the LL segments corresponding to the packet at the head of the queue for a particular data user have been transmitted over the airlink, the packet is deemed to be successfully transmitted. Transmission errors can be simulated by probabilistically delaying packet transmission. Since we assume that the channel state is known to a high degree of accuracy, we assume a negligible loss probability. Every user is always assumed to have data in the queue. This ensures that the scheduling metric is the sole criterion for selecting a user.

Table 1. Transmission rate per slot as a function of SNR

SNR (in dB)	Rate (Kb/s)	SNR (in dB)	Rate (Kb/s)
-12.5	38.4	-1.0	614.4
-9.5	76.8	1.3	921.6
-6.5	153.6	3.0	1228.8
-5.7	204.8	7.2	1843.2
-4	307.2	9.5	2457.6

5 Simulation Results

The effect of admitting prioritized voice users on the throughputs of data users is illustrated in Figure 2, which plots the CDF of the effective throughput experienced by a *packet call*. Our evaluation assumes that the packet call emulates the download of a standard 5KB web page, and is based on standard techniques used in 3GPP [14]. The CDF is obtained by using Monte Carlo simulations to average the effective throughputs of the data call for a number of low-mobility users distributed under different channel conditions in an interference-constrained cell. We plot the packet call throughputs in bits per second with and without voice

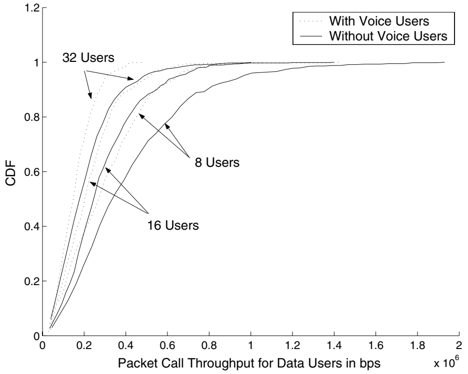

Fig. 2. Impact of 25% voice calls on packet call throughputs of data users

traffic when 8, 16 and 32 data users share 75% of the total voice capacity. Observe from Figure 2 that the performance that the system offers 8 data users in the presence of voice is similar to that obtained by 16 users in the absence of voice. The level of degradation of the data user experience depends not only on the fraction of time slots used by voice users but also on the number of data users sharing the unused voice bandwidth and the type of data traffic.

5.1 Numerical Computation of V_u and π_u

We compare the analytical results in Section 3 with simulations by numerically evaluating the vacation function V_u and the selection density function π_u. Since neither function is known at the outset, we use the following approach to compute the functions iteratively. Let $\pi_u^{(k)}$ and $V_u^{(k)}$ represent the selection density function and the vacation functions estimated in the k^{th} iteration respectively. We start with the Maximum SNR scheduler with $\alpha = 0$ in Equation 1. If the N_d data users have identical channel statistics, this results in a uniform selection function, $\pi_u^{(0)} = \frac{1}{N_d}$. $V_u^{(1)}$ can be therefore be computed using the expression derived in Equation 11. Correspondingly, $\pi_u^{(1)}$ is computed from $V_u^{(1)}$ using the approach outlined in Section 3.2. In subsequent iterations, $V_u^{(k)}$ is computed from $\pi_u^{(k-1)}$, which in turn facilitates computation of $\pi_u^{(k)}$. The convergence of this process has been observed empirically [8].

5.2 Effect of Voice Calls on Vacation Time

The gains from multiuser diversity are maximized by setting $\alpha = 0$ in equation 1. In this case, the selection density function, π_u is uniformly distributed among the data users since the scheduler picks the data user with the best channel without any constraint on delay. Observe from equation 11 that the local slope of the

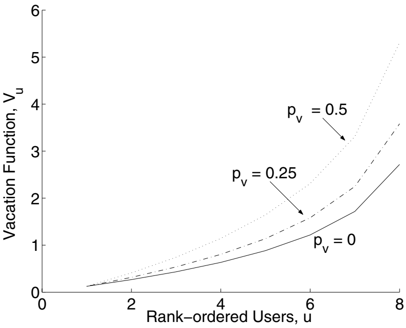

Fig. 3. Impact of voice on vacation function of data users

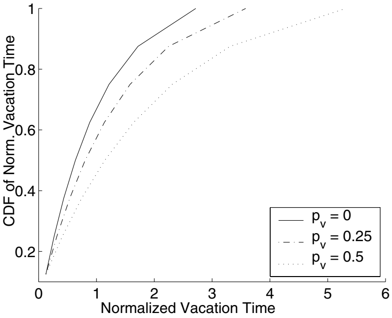

Fig. 4. Impact of voice on CDF of vacation time for data users

vacation function is given by $\frac{1}{N_d(1-p_v)\left(1-\sum_{j<i}\pi_{u_j}\right)}$. For a fixed number of data users and $\pi_u = 1/N_d$, as the number of voice users increases, p_v increases, thereby causing the local slope of the vacation to increase at every point. As expected, we see in Figure 3 that the increase in slope for the higher rank-ordered data users increases with p_v. We see from Fifure 4 that normalized vacation time for data users also increases as they contend for system resources with more voice users.

Multiuser diversity gains are maximized for the data traffic by setting $\alpha = 0$ in the metric defined in Equation 1 for our simulations. It is important to note that a metric with α set to some non-zero positive value will only bias the scheduler to favor data users with higher values of V, i.e., lower scheduling delays at the expense of multiuser diversity gain. These results are not included in this paper for reasons of compactness. Furthermore, increasing the number of voice users will only cause scheduling delay to further dominate the scheduling metric at the expense of overall system throughput and degrade the performance for best-effort data applications even more.

5.3 Packet Service Time Statistics

We see from equations 11 and 18 that the admittance of voice users naturally causes packet service times and delays for data users to increase. Figure 5 illustrates the CDF of packet service times experienced by data users in the absence of any voice calls. The CDF obtained by numerically evaluating the analytical expression from Section 3.4 is compared with simulated results when the channel rates are i.i.d., and shows very close correspondence. In the case of i.i.d. channel fades, the median packet service time is about 20 slots, while the packet service time at the 90th percentile is about 30 slots. In comparison, Figure 6 illustrates the effect on the packet service times when 50% of the time slots are occupied by voice calls. For i.i.d. fades, the median packet service time is about 35 slots,

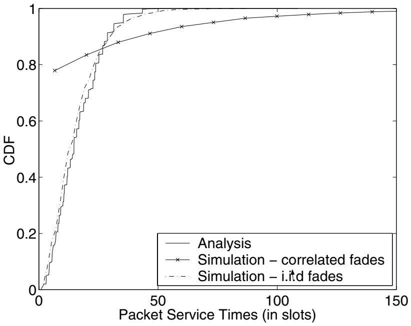

Fig. 5. Packet service time CDF for 8 Data users in the absence of voice

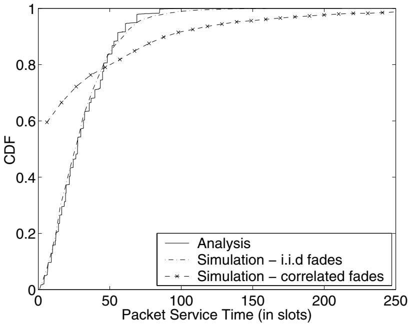

Fig. 6. Packet Service Time CDF for 8 Data Users, 50% Voice Calls

while the packet service time at the 90th percentile increases to 60 slots. The distribution of packet service times in the presence of correlated channel fading, which is obtained through simulation, is also included in these figures. In both cases, the distribution of packet service times for correlated channel fading occupies a much wider dynamic range. This is because a data user may be scheduled repeatedly with lower delays when the channel remains in a good state and higher delays when it remains in a bad state.

6 Conclusions

Cellular wireless systems that traditionally supported voice traffic now see an increasing demand for data services. Packet-switched time-slotted air interfaces such as 1xEV-DO that facilitate wireless data need to incorporate support for the varying QoS requirements of voice and data applications. The stringent delay requirements of compressed voice used in wireless telephony can be met by simply giving voice calls priority over data. While network operators would benefit from allocating system resources unused by voice users to data traffic, prioritized voice naturally limits the bandwidth and time slots available to data users. Data throughput, however, can be significantly improved by using scheduling algorithms that exploit multiuser diversity gain.

The main contribution of this paper is a complete analytical characterization of the scheduled rates, delays and packet service times experienced by data users multiplexed with prioritized voice users in a packet-switched airlink. The analytical results in this paper provide useful tools for a network operator to evaluate whether a given mix of high priority voice users and lower priority data users achieves the desired performance objectives for the data users in terms of throughput and delay.

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