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Congestion control policies for wireless multimedia CDMA networks

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Abstract. The issues of integrating multimedia traffic in the reverse (mobile to base station) link of wireless CDMA networks are studied. Due to their delay constraint, realtime (voice/video) services are subject to connection-level admission control. In order to maintain the quality of realtime voice/video traffic while fully utilizing the unused channel capacity, non-realtime data traffic follows burst-level congestion control. Two congestion control policies are introduced and their performance under 3 types of feedback information is compared. The impact of various system parameters, such as the traffic parameters (especially video) and the processing gain of the CDMA system are also quantified.

Keywords: CDMA, multimedia, traffic control, quality of service, wireless networks

1. Introduction

As the transmission bit rate increases as a result of the advancement of video compression and wireless technologies, video transport in a wireless link will soon become commercially viable. In order to minimize the delay of realtime services, a connection request for voice or video service must go through the admission control phase, which makes sure that the newly accepted connection will not degrade the quality of realtime service below certain criterion.

In order to make the most of the shared radio bandwidth in a wireless network which supports variable-bit-rate realtime services such as voice and video, data users need to be able to access the shared radio bandwidth only when the realtime traffic sources are not transmitting at their peak rates. Data users can acquire this information from the base station via a broadcast type of feedback channel. This paper looks into the benefits of different forms of feedback information in the context of wireless CDMA networks.

The integration of voice and data services in wireless CDMA networks has been investigated in some depth. Many researchers model the system at the connection level where the voice activity factor is neglected, e.g., [1,2]. There are approximation approaches which incorporate the voice activity factor into the effective multiuser interference, e.g., [3]. Our focus is on the short-term traffic control in the uplink, i.e., burst level congestion control. A multi-code CDMA system (MC-CDMA) [4] for the integration of voice, data, and video services is considered. In MC-CDMA, a code can be used to transmit information at a basic bit rate. Users that need higher transmission rates can use multiple codes simultaneously. The higher data rate generated by multiple codes requires higher transmission power in order to keep the energy per bit (E_b) constant. Therefore, higher rate sources such as video users will generate more interference power compared to lower rate sources such as voice and data users.

In the present work, our objective is to develop and evaluate burst level traffic control schemes for the integrated voice/video/data traffic expected in the future personal communication systems or wireless local area networks. A Markovian model is developed for the integrated voice/video/data traffic for 2 congestion control policies with 3 types of feedback information about the system state. Two performance measures are used for the evaluation

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of these control policies, namely the data throughput and the voice packet error rate (PER). The design goal of an effective control scheme is to maximize the data throughput while maintaining the voice PER below certain threshold, e.g., 10^{-2}.

The rest of the paper is organized as follows. Section 2 introduces the system model for the integrated traffic CDMA network. Component models including the traffic models for voice, video and data users, and the packet error model for the CDMA link are described. A Markovian model is presented and the performance measures of the CDMA system are derived. In Section 3, we develop 2 congestion control policies with 3 types of feedback information, i.e., complete, limited, and no feedback. Numerical results are presented in Section 4 and conclusions are given in Section 5.

2. System model

Since the goal is to evaluate the congestion control policies, the admission control phase is isolated by assuming that there are currently M_{vo} voice, M_{vi} video, and M_d data connections established in the reverse link. The time axis of the CDMA system is fully slotted, with a slot duration equal to the transmission time of a packet which is the same size for all types of users. All users are synchronized at the packet level, i.e., they have to transmit at the beginning of time slots.

2.1. Traffic model for a voice user

The model for a single voice source is the on-off model proposed by Brady [8]. In the on-off model, a voice source alternates between the On-state and the Off-state as shown in Fig. 1. The time durations that the source stays in the On- and Off-states are geometrically distributed with means $1/p_{on-off}$ and $1/p_{off-on}$, respectively. The On-state corresponds to the talkspurt and the Off-state corresponds to the silence period in human speech. In the On-state, a voice source generates voice packets at some constant rate which is equal to the transmission rate of a single CDMA code, whereas a voice source will not generate packets when it is in the Off-state. The parameters p_{on-off} and p_{off-on} are determined by the reciprocals of the expected durations of a talkspurt and a silence period, respectively. The probabilities that a voice source will be in the On- or Off-state are given by $\pi_{on} = p_{off-on}/(p_{on-off} + p_{off-on})$ and $\pi_{off} = p_{on-off}/(p_{on-off} + p_{off-on})$, respectively.

2.2. Traffic model for a video user

With compression, the output rate of a video codec is variable. Most of the time, the codec generates packets with low rates, which corresponds to no scene change in the video being compressed. Occasionally, the output rate will increase abruptly due to a scene change in the video.

Various models have been proposed for variable bit rate video sources in ATM networks, e.g., [5–7]. Most of them model the output rate of a video codec as an autoregressive process [6,7]. To simplify the channel access control of a video source, we assume that the output of a video codec is further buffered such that the buffered video source is either generating packets at a high rate or at a low rate. So the model for a video source is a two-state high-low model shown in Fig. 2. (A two-state approximation for video and indeed different traffic types

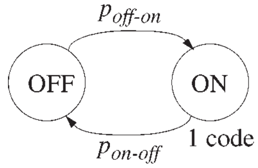

Fig. 1. The on-off model for a voice source.

has been studied [13].) A source will generate video packets at the rates that can be accommodated by C_{hi} and C_{lo} codes, when it is in the High- and Low-state, respectively. Similar to the voice model, the time durations that a video source stays in the High- and Low-states are geometrically distributed with means equal to $1/p_{hi-lo}$ and $1/p_{lo-hi}$, respectively. Thus, the probabilities that a video user is in the High- and Low-state are $\pi_{hi} = p_{lo-hi}/(p_{hi-lo} + p_{lo-hi})$ and $\pi_{lo} = p_{hi-lo}/(p_{hi-lo} + p_{lo-hi})$, respectively. The parameters, p_{hi-lo}, p_{lo-hi}, C_{hi}, and C_{lo}, are functions of the compression scheme, the buffering delay, and the characteristics of the video itself.

2.3. *Traffic model for a data user*

The underlying admission control policy is assumed to accept only M_d data users who have outstanding messages to be transmitted. If there are more than M_d data users who have messages to send, the rest of them will be queued at the base station. After passing the admission control, the M_d data users either are transmitting or have data messages waiting to be transmitted. As soon as a data user finishes transmitting its message, we assume that the base station will accept another data user and therefore keep the number of data users in the system constant-a heavy traffic scenario. The assumption of fixed M_d implies that the arrival process of data messages is isolated from the model, which has 2 implications. First, the data throughput will be maximized since the system is never left idle. Second, the state space of the Markovian model (to be introduced in Section 2.5) is much more tractable than the case where the arrival process is taken into account.

The admitted data users are further subject to the congestion control imposed by the base station, which broadcasts feedback[1] regarding the status of the system on the reverse link. A data user under congestion control is modeled by a 2-state Markov chain as illustrated in Fig. 3. When the user is in the Standby-state, it will transmit with probability p_{try} and enter the Active-state. When in the Active-state, the user will transmit C_d packets in parallel using C_d spreading codes. The data message length is geometrically distributed and has a mean of L packets.[2] If the data user is allowed to finish transmitting its data message without interruption, the message transmission time is approximately geometrically distributed with mean L/C_d, i.e., $p_{quit} = C_d/L$. The setting of p_{try} and p_{quit} based on the feedback is the subject of congestion control which is elaborated in Section 3.

2.4. *Packet error model for CDMA channel*

The signals from users to the central station in a terrestrial wireless environment generally suffer from path loss, shadowing, and multipath fading. Since path loss and shadowing occur in a much slower time scale than for the

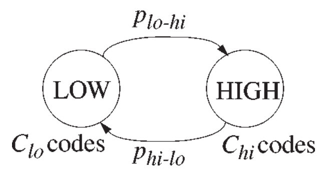

Fig. 2. The high-low model for a video source.

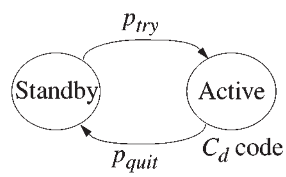

Fig. 3. The state transition diagram for a data user admitted to the system.

[1]The feedback information about the system state can sometimes be obtained by data users themselves, e.g., [9].

[2]Some modeling work on integrated voice/data wireless CDMA networks in the literature assumes $L = 1$ for simplicity, which overlooks the versatile data sources in the future PCS.

fading, we assume that they can be tracked and compensated by power control and will be ignored in the sequel. The fading channel considered here is a slowly time-varying and frequency-nonselective one, the so called flat-flat fading channel. The received signal from a user consists of a direct component and many other non-resolvable scattered components. Hence the amplitude of the received signal follows a Rician distribution with parameter K_R, defined as the ratio of the power of the direct component to that of the scattered components. Due to the difficulty of perfectly tracking the phase of the desired signal, differential PSK modulation (DPSK) is considered as opposed to the coherent BPSK.

The summary of the derivation of bit error rate is given here. Readers are referred to [14] for more details. In order to get a simple closed form expression for the packet error probability, we invoke two Gaussian assumptions typically made in the literature. The conditional *BER* for the desired signal using the Improved Gaussian Approximation is [15]

$$P_b(\Psi,\gamma) = \frac{1}{2}\exp\left(\frac{-\gamma^2}{2\Psi}\right),$$

where γ is the faded amplitude of the desired signal and Ψ is the conditional[3] variance of the total interference. Averaging over γ gives

$$P_b(\Psi) = \frac{\Psi}{2\Psi + 1/(K_R+1)}\exp\left(\frac{-K_R}{2(K_R+1)\Psi+1}\right).$$

With the Standard Gaussian Approximation [16], the average *BER* is given by

$$\mathit{BER} = P_b(E(\Psi)) = \frac{\mu_\Psi}{2\mu_\Psi + 1/(K_R+1)}\exp\left(\frac{-K_R}{2(K_R+1)\mu_\Psi+1}\right),$$

where μ_Ψ is the expected value of Ψ and is given by $\mu_\Psi = N_0/(2E_b) + k/(3G)$ for a rectangular chip pulse shape, in which N_0, E_b, G, and k are the power spectral density of thermal noise (Watts/Hz), the received energy per bit when there is no fading, the processing gain, and the number of interfering CDMA codes, respectively.

Assuming that packets are encoded by BCH forward error correction codes with code word length n and the maximum number of correctable bit errors t, the probability of receiving an uncorrectable packet when there are k simultaneous interfering CDMA codes is given by

$$\mathit{PER}(k) = 1 - \sum_{i=0}^{t}\binom{n}{i}\mathit{BER}^i(1-\mathit{BER})^{n-i}, \tag{1}$$

assuming errors are independent from bit to bit. It should be noted that more complicated packet error models (e.g., [10,11]) can be considered so long as the conditional packet error rate can be represented as a function of k, the number of interfering codes. The following section will use the function *PER*(k) to evaluate the traffic control schemes.

2.5. Markovian model for the integrated voice/video/data traffic

With the Markovian traffic models defined in Sections 2.1–2.3, the CDMA system can be modeled by a 3-dimensional Markov chain with the state variables being the number of voice users in the On-state (N_t^{vo}), the

[3] Conditioning on other interfering signals' amplitudes, phases, and differential delays relative to the desired signal.

number of video users in the Hi-state (N_t^{vi}), and the number of data users in the Active-state (N_t^d), where the subscript t denotes time slot t. In time slot $t+1$, the state variables are given by

$$N_{t+1}^{vo} = N_t^{vo} + B(M_{vo} - N_t^{vo}, p_{off-on}) - B(N_t^{vo}, p_{on-off}),$$
$$N_{t+1}^{vi} = N_t^{vi} + B(M_{vi} - N_t^{vi}, p_{lo-hi}) - B(N_t^{vi}, p_{hi-lo}),$$

and

$$N_{t+1}^{d} = N_t^{d} + B(M_{d} - N_t^{d}, p_{try}) - B(N_t^{d}, p_{quit}),$$

where $B(N,p)$ is a binomial random variable with parameters N and p, the probability of success in an independent Bernoulli trial. Note that the state evolution for voice and video users is independent of other types of traffic sources, whereas the state evolution of data users depends on all of the 3 types of traffic through p_{try} and p_{quit}, since real-time services (voice and video) are subject to admission control only. Once realtime sources are admitted to the system, their behavior depends completely on their traffic models. The 1-step transition probability of the system Markov chain then can be simplified as

$$\Pr\left[N_{t+1}^{vo}, N_{t+1}^{vi}, N_{t+1}^{d} \middle| N_t^{vo}, N_t^{vi}, N_t^{d}\right] = \Pr\left[N_{t+1}^{vo} \middle| N_t^{vo}\right] * \Pr\left[N_{t+1}^{vi} \middle| N_t^{vi}\right] * \Pr\left[N_{t+1}^{d} \middle| N_t^{vo}, N_t^{vi}, N_t^{d}\right].$$

Depending on the congestion control policy used, the transition probabilities of this 3-dimensional Markov chain can be computed and the equilibrium state probabilities, $\Pr[(N^{vo}, N^{vi}, N^d) = (n_1, n_2, n_3)], 0 \leqslant n_1 \leqslant M_{vo}, 0 \leqslant n_2 \leqslant M_{vi}, 0 \leqslant n_3 \leqslant M_d$, can be obtained by solving a system of linear equations [12].

2.6. *Performance measures*

Two performance measures are of interest for the CDMA system with integrated services, namely, the voice *PER* and the data throughput.

With the equilibrium state probabilities and the packet error model given in Section 2.4, the *PER* seen by a particular voice user in the On-state is given by

$$PER = \sum_{n_1=1}^{M_{vo}} \sum_{n_2=0}^{M_{vi}} \sum_{n_3=0}^{M_d} PER\big(f(n_1, n_2, n_3) - 1\big) \frac{(n_1/M_{vo}) \Pr[(N^{vo}, N^{vi}, N^d) = (n_1, n_2, n_3)]}{\pi_{on}},$$

where $((n_1/M_{vo}) \Pr[(N^{vo}, N^{vi}, N^d) = (n_1, n_2, n_3)])/\pi_{on}$ is the conditional probability that the system is in state (n_1, n_2, n_3) given that a particular voice user is in the On-state and $f(.)$ is the number of CDMA codes being used for transmission. $f(.)$ is given by

$$f\big(N_t^{vo}, N_t^{vi}, N_t^d\big) = N_t^{vo} + N_t^{vi} * C_{hi} + \big(M_{vi} - N_t^{vi}\big) * C_{lo} + N_t^d * C_d. \tag{2}$$

The data throughput (packets/slot) of the system is given by

$$S = \sum_{n_1} \sum_{n_2} \sum_{n_3} n_3 C_d \big(1 - PER\big(f(n_1, n_2, n_3) - C_d\big)\big) \Pr\big[(N^{vo}, N^{vi}, N^d) = (n_1, n_2, n_3)\big].$$

3. Congestion control policies

All of the congestion control policies considered in this section are Markovian in the sense that all of the data users receive some form of feedback information about the system state at the end of a slot, which is used to determine the transmission probabilities of data users in the next slot.

The feedback can be either complete (i.e., the number of voice users in the On-state, the number of video users in the Hi-state, and the number of data users in the Active-state are all known) limited (e.g., only some function of the system state is known) or null. In this section, 2 policies are considered for each type of feedback information.

3.1. *The interruptible policy*

The basic idea of this policy is to shut down data transmission when the system is congested, i.e., when the number of active CDMA codes in use exceeds a threshold parameter T_m. Whereas if the system is not congested, transmitting data users continue their transmission and waiting data users transmit with some appropriate probability selected to avoid congestion. The probability of starting transmission for waiting data users is chosen according to the type of feedback available.

3.1.1. *Complete feedback*

In the case of complete feedback, it is assumed that the system state in time slot t, $(N_t^{vo}, N_t^{vi}, N_t^d)$, is known in the beginning of time slot $t+1$. The number of CDMA codes being used for transmission, $f(.)$ defined in (2), can be used as a congestion index. Given the complete feedback in time slot t, the transition probabilities of data users in time slot $t+1$ are given by

$$p_{try} = \begin{cases} \min\left(1, \dfrac{T_m - f(N_t^{vo}, N_t^{vi}, N_t^d)}{C_d(M_d - N_t^d)}\right) & \text{if } f(N_t^{vo}, N_t^{vi}, N_t^d) \leqslant T_m, \\ \min\left(1, \dfrac{T_m - f(N_t^{vo}, N_t^{vi}, 0)}{C_d M_d}\right) & \text{otherwise,} \end{cases}$$

and

$$p_{quit} = \begin{cases} C_d/L & \text{if } f\left(N_t^{vo}, N_t^{vi}, N_t^d\right) \leqslant T_m, \\ 1 & \text{otherwise,} \end{cases}$$

where T_m is the threshold for congestion control and min(x, y) is the minimum of the two arguments. The above says that if the system congestion index does not exceed the threshold T_m, active data users should continue their transmission and waiting data users should try to transmit with a probability selected so as to fill available ‘slots’ on the average. Whereas if the system congestion index exceeds T_m, active data users should stop transmission immediately with probability 1 and all data users can try to transmit with a probability selected to fill available ‘slots’. The rationale behind the selection of p_{try} is that $[T_m - f(N_t^{vo}, N_t^{vi}, N_t^d)]/C_d$ can be thought of as the residual channel capacity, and $(M_d - N_t^d)$ is the number of data users waiting for transmission. By choosing p_{try} equal to the ratio of the above two factors, the expected number of data users that will start to transmit will be equal to the leftover capacity. This policy can be optimized by choosing T_m to maximize the data throughput while guaranteeing *PER* of voice users.

3.1.2. *Limited feedback*

In the case of limited feedback, it is assumed that only the total number of active codes in the CDMA channel in time slot t, $f(N_t^{vo}, N_t^{vi}, N_t^d)$ as defined in (2), is known at the beginning of time slot $t+1$. Compared with the

p_{try} and p_{quit} for the case of complete feedback, p_{quit} under limited feedback is the same whereas p_{try} is given below due to the lack of knowledge of the complete system state.

$$p_{try} = \begin{cases} \min\left(1, \dfrac{T_m - f(N_t^{vo}, N_t^{vi}, N_t^d)}{C_d M_d}\right) & \text{if } f(N_t^{vo}, N_t^{vi}, N_t^d) \leqslant T_m, \\ 0 & \text{otherwise.} \end{cases}$$

The above transmission probability is more conservative than the case with complete feedback. Therefore it is conceivable that the optimal choice of T_m for this case will be greater than that of complete feedback.

3.1.3. NULL feedback

When there is no feedback information, the base station schedules M_d data users to transmit in every slot, i.e., a constant data traffic load.

3.2. The Non-interruptible Policy

Under the Interruptible Policy, an active data user has to stop transmitting when the system is congested. The Non-interruptible Policy is a simplified scheme, which does not force active data users to stop. Some data applications may prefer not to be interrupted in the middle of data burst transmission.

For both complete and limited feedback, p_{quit} is equal to C_d/L exclusively. This policy with null feedback is the same as the Interruptible Policy with null feedback.

4. Numerical results

The numerical results are based on the CDMA system whose system parameters are summarized in Table 1. Given the values of p_{on-off} and p_{off-on}, π_{on} and π_{off} are equal to 0.4359 and 0.5641, respectively.

Table 1
System parameters

Item	Symbol	Value
Number of voice connections established	M_{vo}	variable
Transition probability of a voice source from On-state to Off-state	p_{on-off}	$1/17$
Transition probability of a voice source from Off-state to On-state	p_{off-on}	$1/22$
Number of video connections established	M_{vi}	variable
Transition probability of a video source from High-state to Low-state	p_{hi-lo}	$1/6$
Transition probability of a video source from Low-state to High-state	p_{lo-hi}	$1/30.4$
Slot duration (msec)		20
Number of codes active while a video source is in High-state	C_{hi}	8
Number of codes active while a video source is in Low-state	C_{lo}	2
Average length of data message (packets)	L	variable
Maximum number of data users in the Standby-state	M_d	variable
Number of CDMA codes per data users	C_d	1
Threshold for congestion control	T_m	variable
Packet length (bits)		255
Number of correctable bit errors per packet		4
Bit energy to (1-sided) noise spectral density (dB)	E_b/N_0	13
Processing gain	G	64
Rician factor	K_R	20

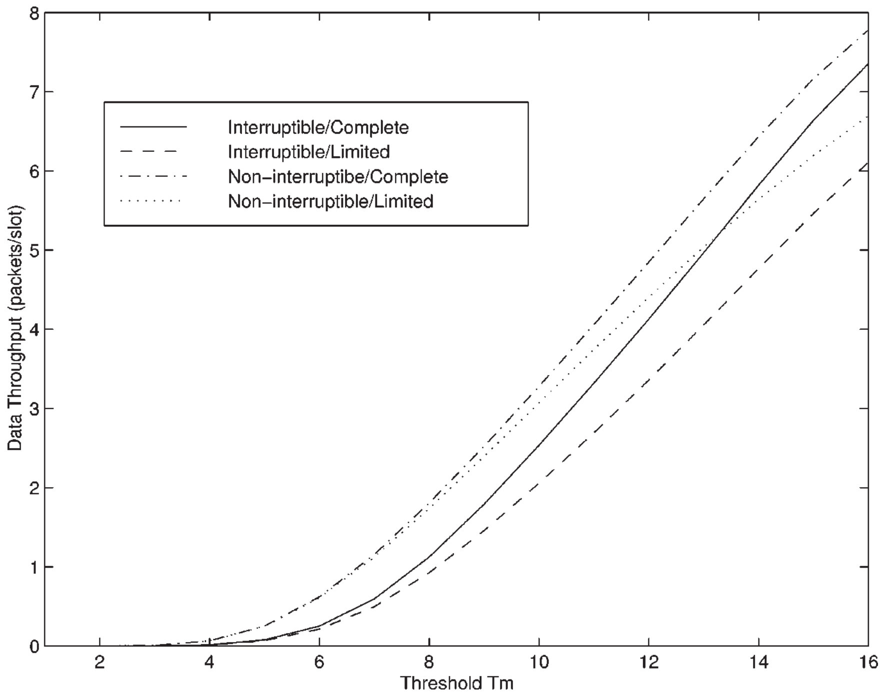

Fig. 4. Data throughput versus congestion control threshold T_m for various control schemes and feedback information. $M_{vo} = 11$, $M_{vi} = 1$, $M_d = 10$, $G = 64$, and $L = 10$.

Figures 4 and 5 show data throughput and voice *PER,* respectively, as a function of the threshold parameter T_m. As expected, both data throughput and voice *PER* increase as T_m increases. Suppose the voice *PER* is targeting at 10^{-2}, for each policy there is an optimal threshold value which maximizes the data throughput. To compare the performance of the 2 policies under the 3 different feedback assumptions, Figs 4 and 5 are combined in Fig. 6 to show the tradeoff between data throughput and voice *PER*. It is observed that the Interruptible Policy performs better than the Non-interruptible Policy. In addition, the complete feedback outperforms limited feedback, which outperforms null feedback. However, the additional information from 'complete feedback' is of little additional benefit, especially for the Non-interruptible Policy.

Figure 7 shows the effect of M_d to the system performance as T_m increases from 1 to 16. For the voice *PER* targeting at 10^{-2}, M_d needs to be sufficiently large (e.g., 7 or 10 in this case) to achieve maximum data throughput.

Figure 8 shows the effect of data message size on the Interruptible Policy with complete feedback. We see that this policy is able to maintain pretty good data throughput for a wide range of message sizes except for single-packet messages. The Non-interruptible Policy with complete feedback, in Fig. 9, is not as robust to different message sizes as the Interruptible Policy. Messages which are too long or too short will make the Non-interruptible Policy approach the case of no feedback information.

Figure 10 compares the performance of the 2 policies with 3 types of feedback for mixed voice/data traffic (no video). It is observed that the difference between various control schemes is less significant due to the smoother nature of voice traffic.

Figure 11 compares the performance of different policies for a larger processing gain (i.e., $G = 128$). Results similar to Fig. 6 (where $G = 64$) are observed. However, if the video traffic parameter C_{lo} is changed from 2 to 4, the performance difference becomes less significant. Again, this is due to the smoother nature of the new video traffic model. From these numerical results, it is conceivable that very large processing gain achieved by wideband CDMA will help to achieve high statistical multiplexing gain in the wireless world.

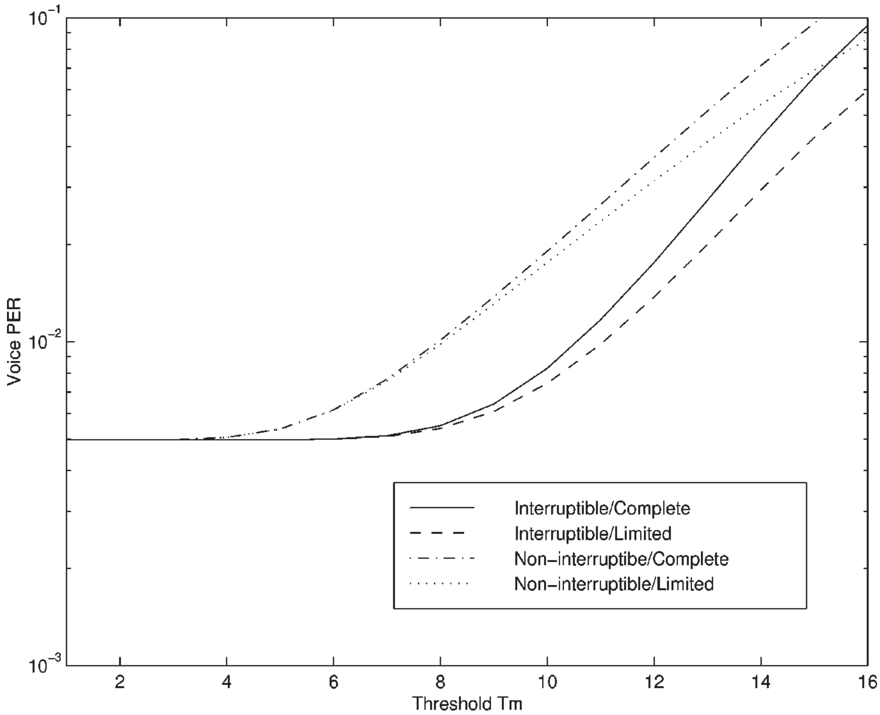

Fig. 5. Voice *PER* versus congestion control threshold T_m for various control schemes and feedback information. $M_{vo} = 11$, $M_{vi} = 1$, $M_d = 10$, $G = 64$, and $L = 10$.

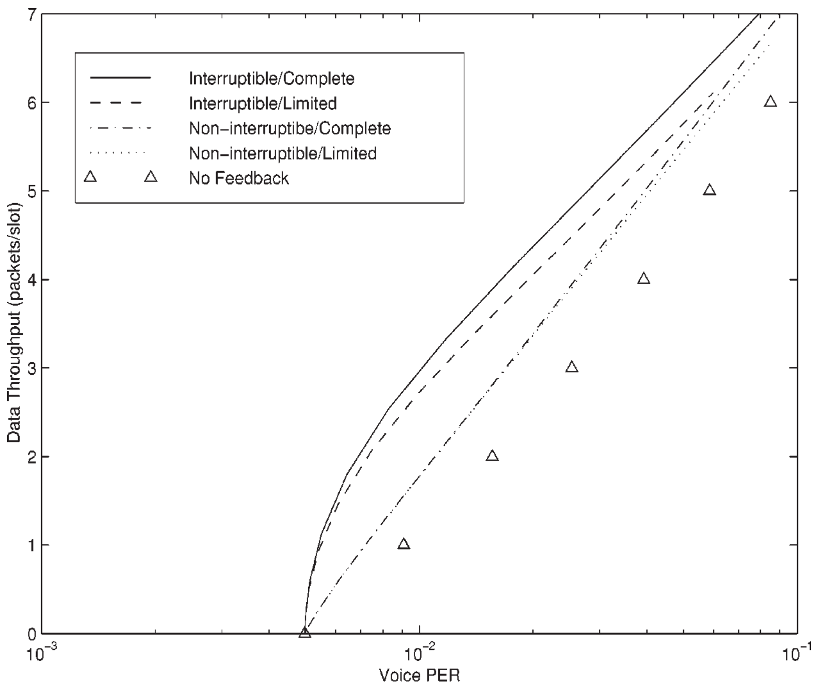

Fig. 6. Data throughput versus voice *PER* for various control schemes. $M_{vo} = 11$, $M_{vi} = 1$, $M_d = 10$, $G = 64$, and $L = 10$.

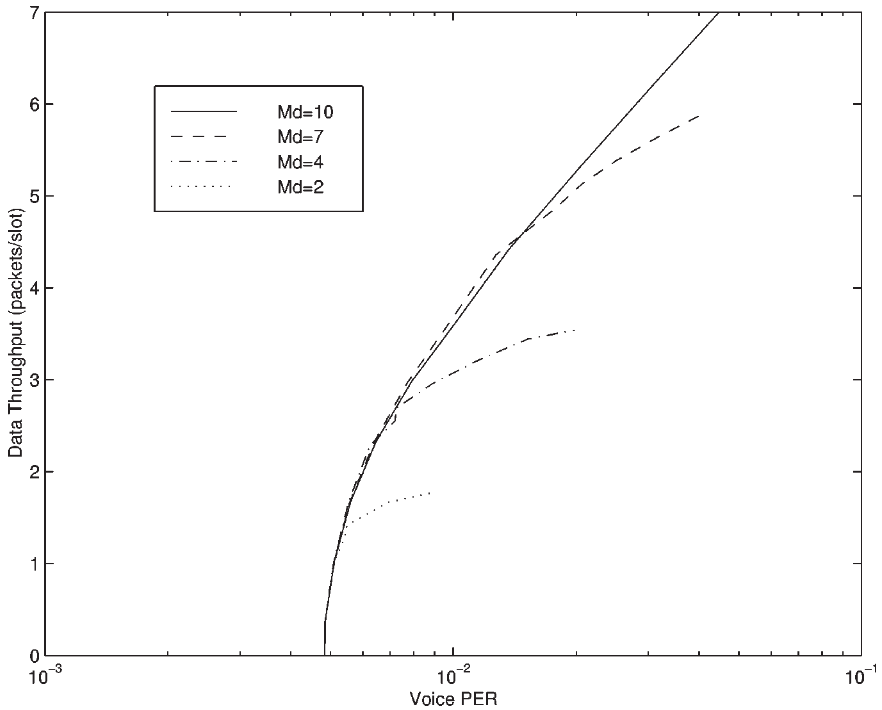

Fig. 7. Data throughput versus voice *PER* for various M_d under the Interruptible Policy with complete feedback. $T_m = 1, \ldots, 16$. $M_{vo} = 11$, $M_{vi} = 1$, $G = 64$, and $L = 10$.

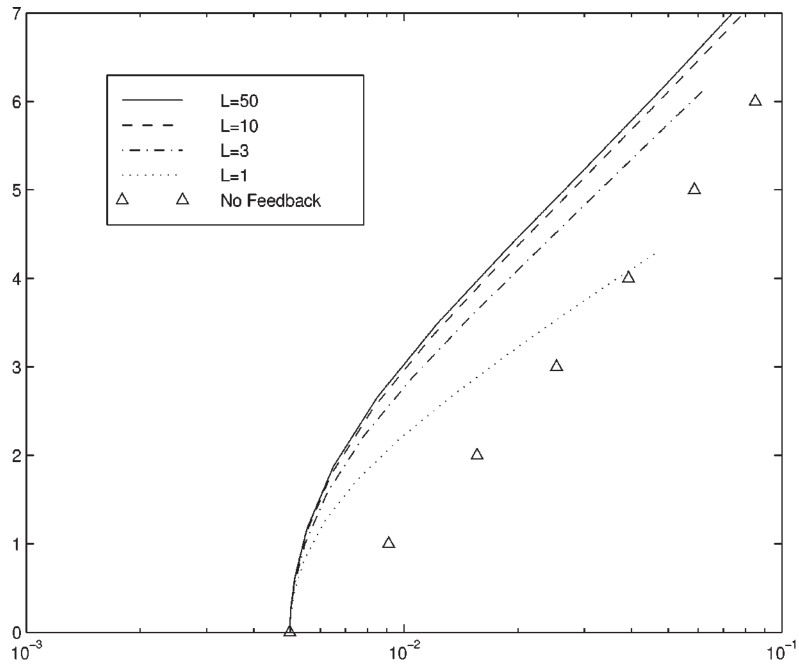

Fig. 8. Data throughput versus voice *PER* for various data message size L under the Interruptible Policy with complete feedback. $T_m = 1, \ldots, 16$. $M_{vo} = 11$, $M_{vi} = 1$, $M_d = 10$, $G = 64$, and $L = 10$.

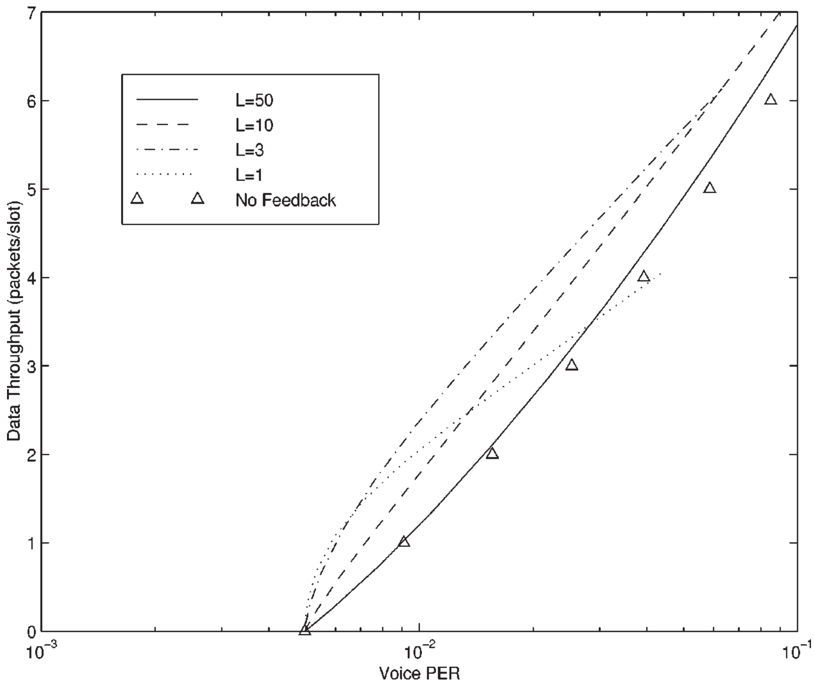

Fig. 9. Data throughput versus voice *PER* for various data message size L under the Non-interruptible Policy with complete feedback. $T_m = 1, \ldots, 16$.

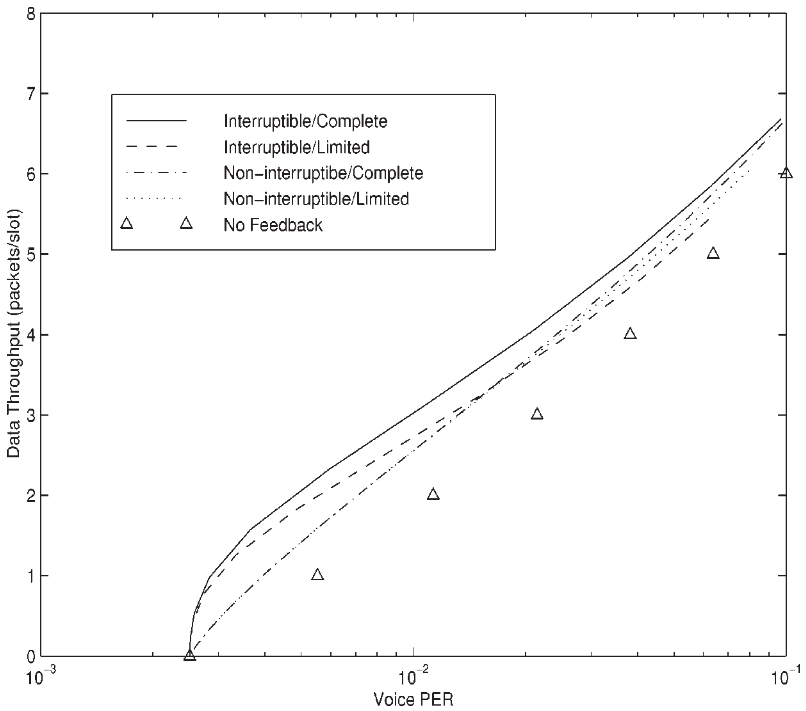

Fig. 10. Performance comparison of various policies with no video traffic. $M_{vo} = 20$, $M_d = 10$, $G = 64$, and $L = 10$. $T_m = 1, \ldots, 16$.

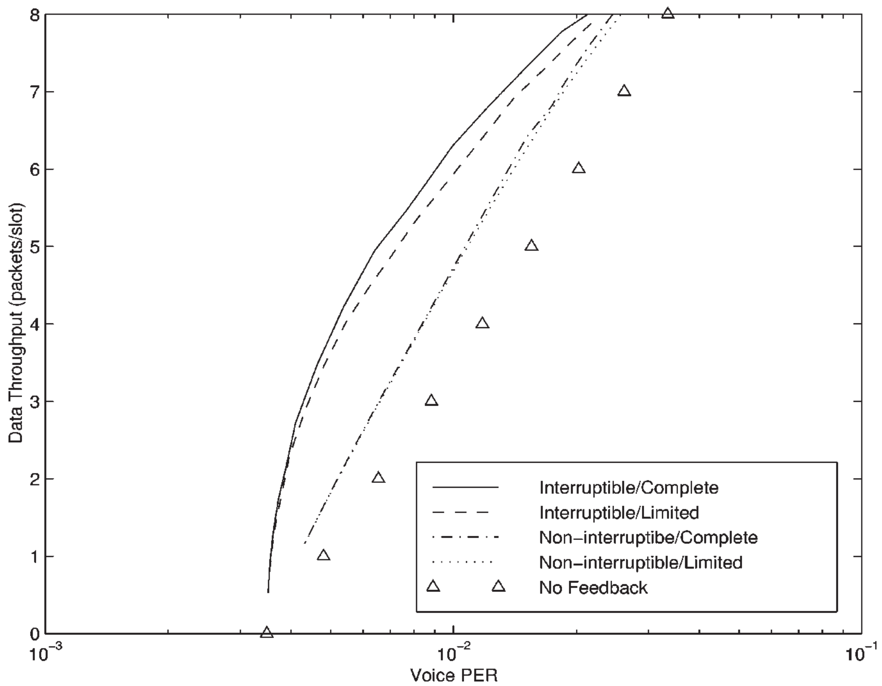

Fig. 11. Effect of larger processing gain. $G = 128$, $M_{vo} = 1$, $M_{vi} = 5$, $M_d = 10$, and $L = 10$. $T_m = 12, \ldots, 30$.

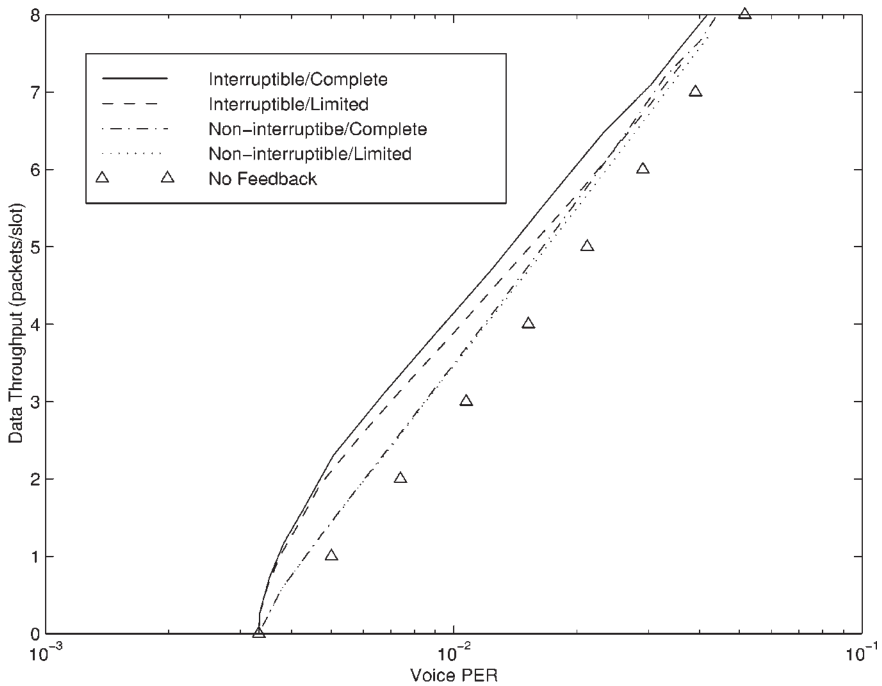

Fig. 12. Effect of larger processing gain with smoother video traffic ($C_{lo} = 4$). $G = 128$, $M_{vo} = 1$, $M_{vi} = 4$, $M_d = 10$, and $L = 10$. $T_m = 16, \ldots, 30$.

5. Conclusion

Analytical models are developed to evaluate the performance of different congestion control policies for the reverse link of packet-based wireless CDMA networks supporting voice/video/data traffic. Two congestion control schemes referred to as the Interruptible Policy and the Non-interruptible Policy with complete, limited, and null feedback information are considered.

Major findings are: (1) Complete feedback is found to give marginal improvement over limited feedback. (2) The Interruptible Policy can effectively handle highly bursty, variable-bit-rate video traffic over a wide range of data message size. (3) With some performance degradation, the Non-interruptible Policy can do reasonably well as long as data message size is not particularly long or short. If data message size is long enough, the performance of Non-interruptible Policy may degrade to be the same as the performance of a policy with no feedback information.

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