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Optimal Strategies for Admitting Voice and Data Traffic in Networks of Leo Satellites Using CDMA

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OPTIMAL STRATEGIES FOR ADMITTING VOICE AND DATA TRAFFIC IN NETWORKS OF LEO SATELLITES USING CDMA

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Abstract

Efficient policies are derived for admitting voice and data traffic into networks of low-earth-orbit (LEO) satellites using code-division multiple-access (CDMA) with direct-sequence spread-spectrum (DS/SS) signaling. The satellites act as bent-pipes; no on-board processing or inter-satellite links are present. Dual satellite diversity is used to mitigate the effects of shadowing. The policies assume a movable boundary form, allocate optimally the CDMA capacity (PN codes) to voice and data users, and can increase significantly the number of users served while satisfying their bit error rate (BER) requirements. A modified version of our policies can handle two classes of data users: one with high priority which requires real-time delivery and another with low priority that can be queued; the BER requirements of the two data types may differ.

INTRODUCTION

In modern telecommunication networks, there is an increased interest in providing worldwide communications services to mobile or other users via networks of satellites. The primary advantages of LEO satellite networks are the interoperability and the extension of cellular systems, mobile systems, and of terrestrial public switched telephone networks. Earth stations exchanging information may not always be covered by the same satellites. The two ways currently used to overcome this problem is to either to reroute the traffic via terrestrial communication lines, or to retransmit information via an intermediate ground station.

Currently, message transfer in multiple-satellite systems takes place under a circuit-switching method. For instance, in Loral/Qualcomm's Globalstar and in TRW's Odyssey system, a call is set up by assigning a pair of uplink (L-band) /downlink (S-band) frequency subbands and a spread-spectrum code according to its cell location. When a subscriber transmission is received at a satellite, it is transmitted to a gateway within view of the satellite. It is then routed to its destination by means of a connection to terrestrial networks. The control signaling is managed by the Network Control Center (NCC) that communicates with all databases and one or more Network Control Gateways (NCG) via C-band channels. The multiple-access technique used is CDMA/FDM in both the Globalstar and the Odyssey systems. The satellites act as bent-pipes; no on-board processing or intersatellite links are present.

Because of the limited bandwidth of CDMA channels and the quality requirements of voice and data users, the admission requests of new arrivals may not be all accepted. Efficient policies for admitting voice and data traffic must be developed so that the blocking rates are minimized subject to the performance requirements (BER) of the two traffic types. In this paper, we address admission control policies, which manage the admission of voice and data traffic into the LEO satellite network, when a maximum of two satellites are within sight of the mobile users. The performance measures we study involve the average blocking probabilities and the average throughputs for voice and data traffic, as well as the packet error probability for data traffic as functions of the offered voice and data traffic loads.

SYSTEM MODEL

Our system model consists of a satellite cluster, or a constellation of N satellites without intersatellite links. Bent-pipe transponders with no on-board mod/demod processing are employed. DS/CDMA (not hybrid with FDM) is used over the channels between satellites and their earth domains (in both uplinks and downlinks) in order to accommodate several voice calls and data users simultaneously. The frequency bands for uplink and downlink are shared by voice and data traffic. Each user (data or voice node) employs a distinct code for the transmission of its packets. It is assumed that the LEO network provides double coverage, that is, that two satellites are in sight of all users at all times. Of course, shadowing may block one or both links between a mobile user and the two satellites in sight. In an attempt to model the above situation, we classify all voice and data users in the footprints of the two satellites into shadowed and non-shadowed classes as shown in Figure 1. The class of users, who are shadowed for both satellites, must transmit their packets over both satellites to improve their performance. The message of each accepted active user (voice or data) is packetized with the same length. Time is divided into slots of duration equal to the transmission of one packet. In our model, packet transmissions start at common clock instances and packets have constant length. The typical packet length is 1000 to a few thousand bits. The traffic of each voice user is modeled as a three-state discrete-time Markov chain with transition probabilities p_{01}^v, p_{10}^v, p_{12}^v, and p_{21}^v. Each data user is modeled as a two-state (OFF/ON or idle/active) Bernoulli process with transition probabilities p_{01}^d and p_{10}^d. Two priority models are considered. In the first model, voice users have higher priority than data users. In the second model, voice and data users have the same priority.

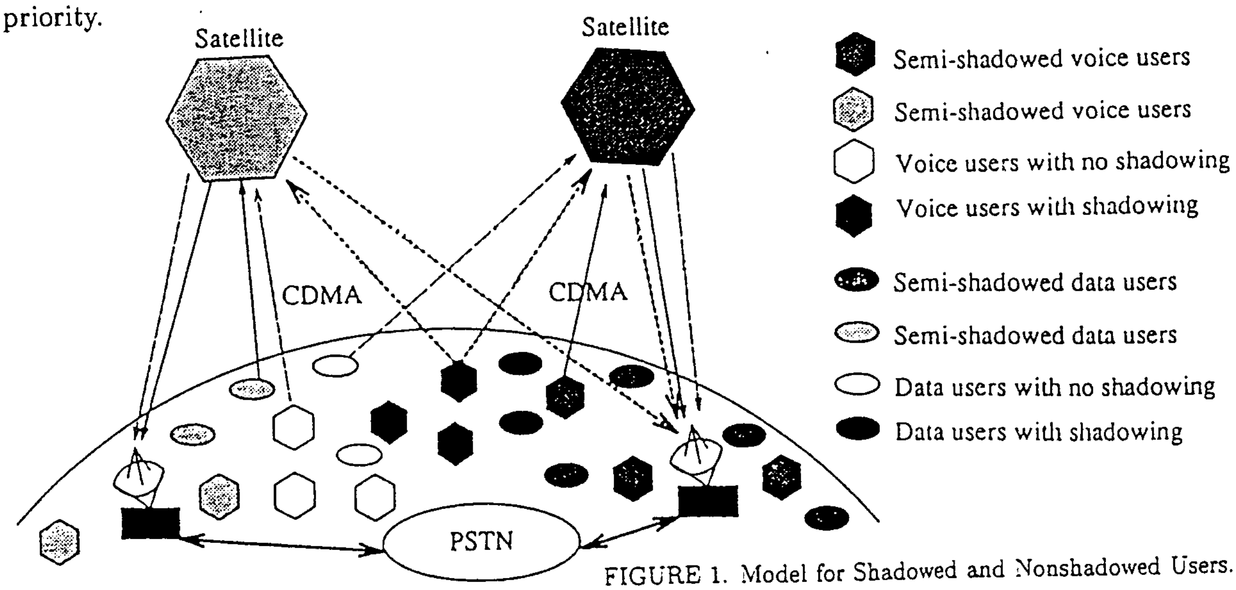

FIGURE 1. Model for Shadowed and Nonshadowed Users.

We define the MAC indices K_v as the number of voice users that can be accommodated simultaneously, such that the expected packet error probability of voice traffic remains below a specified threshold. Similarly, the MAC index K_d for data users is the number of data users that can transmit simultaneously with a tolerable packet error. Thus we have

$$P_E(k) \leq P_E^v, \ \ \forall\ k \leq K_v \tag{1}$$

$$P_E(k) \leq P_E^d, \ \ \forall\ k \leq K_d \tag{2}$$

where P_E^v and P_E^d are the maximum tolerable voice and data packer error probabilities, respectively, and $P_E(k)$ is the packet error probability in the presence of k simultaneous packet transmissions, where k includes both voice and data users. It is assumed that the network operate under perfect power control so that the power of all received signals is the same. In practice, $P_E^v > P_E^d$, and, therefore, $K_v > K_d$.

Actually, each active voice user is either in silence or in talkspurt, alternatively, the number of codes which are assigned to active users can be larger than K_v with the same voice-packet error probability. Given the MAC indices K_v and K_d, we compute the maximum number of acceptable voice calls and data users. Let s^v and s^d be the number of active voice and data users, then the values of s^v and s^d must satisfy the following formulae.

$$0 \leq s^d \leq K_d, \qquad 0 \leq s^v \leq M(s^d) \tag{3}$$

where $M(s^d)$ is the maximum number of active voice calls when the number of active data users is s^d. The value of $M(s^d)$ is obtained by computing that the number of active calls in talkspurt out of $M(s^d)$ is larger than $K_d - s^d$ with prespecified acceptable probability δ.

ADMISSION CONTROL FOR VOICE AND DATA USERS WITH DIFFERENT PRIORITIES

A direct admission policy will accept all voice arrivals if there are available codes for them. That is, if there are i active voice calls and the MAC index is K_v, we accepted only up to $K_v - i$ new voice arrivals; thus, if there are more than $K_v - i$ new arrivals, the surplus (above $K_v - i$) will be blocked. Consider mobile users with two satellites in sight. By detecting the strength of the pilot signals generated by two satellites, each active user detects the shadowing effect on its links to the two satellites. A threshold may be selected to identify the presence or absence of shadowing. The population of voice traffic is classified into 4 different group: users which experience no shadowing in their satellite links, users with no shadowing in the first satellite link and with shadowing in the second satellite link, users with shadowing the first satellite link and no shadowing in the second satellite link, and users with shadowing in both satellite links. Let the number of newly arrival calls from the four groups be $(l_{nn}^v, l_{ns}^v, l_{sn}^v, l_{ss}^v)$, and the number of active voice calls on the channels of satellite 1, satellite 2, and both satellites be s_1^v, s_2^v, s_{12}^v, then the number of newly accepted voice calls for the direct admission policy is given by

$$\begin{cases} a_{ns,nn}^v = \min(l_{ns}^v + \lfloor \gamma^v l_{nn}^v \rfloor, K_{v1} - s_1^v) \\ a_{sn,nn}^v = \min(l_{sn}^v + l_{nn}^v - \lfloor \gamma^v l_{nn}^v \rfloor, K_{v2} - s_2^v) \\ a_{ss}^v = \min(l_{ss}^v, K_{v1} - s_1^v - a_{ns,nn}^v, K_{v2} - s_2^v - a_{sn,nn}^v) \end{cases} \tag{4}$$

where $\gamma^v = \frac{K_{v1}-s_1^v}{K_{v1}-s_1^v+K_{v2}-s_2^v}$ if $K_{v1} - s_1^v + K_{v2} - s_2^v > 0$, $\gamma^v = 0$ if $K_{v1} - s_1^v + K_{v2} - s_2^v = 0$.

The goal of the optimal call admission policy is to minimize the long-run average cost per unit time. A policy that rejects certain voice calls at some instance of time (which would otherwise be accepted) may admit more calls on the average than a policy that always accepts calls, whenever there are available channels. In order to find an optimal policy (in some practical sense) for the admission control problem, we introduce a semi-Markov decision process (SMDP). A Markov decision process does not suffice here, because the times between consecutive decision epochs are not identical but random.

Let the state space of the CDMA two-satellite network be $\mathbf{x}^v = (s_1^v, s_2^v, s_{12}^v)$ and $\mathbf{l}^v = (l_{nn}^v, l_{ns}^v, l_{sn}^v, l_{ss}^v)$. The action corresponding to the state is given by $\mathbf{a} = (a_{nn1}^v, a_{nn2}^v, a_{ns}^v, a_{sn}^v, a_{ss}^v)$, The cost (the number of rejected calls) is $l_t^v - a_t^v$, where l_t^v and a_t^v are the total numbers of new and accepted voice calls, respectively. The **value-iteration algorithm** (Tijms 1986), which minimizes the cost function, is then applied to derive the optimal admission policy.

Two models for admitting data users can be used. Under the threshold model, data users are assigned the remaining codes not used by voice users till a prespecified level of data packet error performance is reached. Under the graceful degradation model, all active data users are accepted and transmit their packets during the next slot, but they are successful with a certain substantial probability. After the admission policies of voice and data users are obtained, we are able to calculate the steady-state probabilities of current voice calls and current data users. Then, the throughput and the blocking rate of voice calls and the throughput and the average packet error probability of data users can be derived.

ADMISSION CONTROL FOR VOICE AND DATA USERS WITH EQUAL PRIORITY

When voice and data users have the same priority, the admission policy of the two traffic types is a movable boundary scheme, which allocate the available codes dynamically between them. The state space is now $(\mathbf{x}^v, \mathbf{x}^d, \mathbf{l}^v, \mathbf{l}^d) = (s_1^v, s_2^v, s_{12}^v, s_1^d, s_2^d, s_{12}^d, l_{nn}^v, l_{ns}^v, l_{sn}^v, l_{ss}^v, l_{nn}^d, l_{ns}^d, l_{sn}^d, l_{ss}^d)$, where (s_1^d, s_2^d, s_{12}^d) are the number of active data users on the channels of satellite 1, satellite 2 and both satellites, and $(l_{nn}^d, l_{ns}^d, l_{sn}^d, l_{ss}^d)$ are the new arrivals from the four different groups of data users defined similarly as the voice population. The action space is also doubled as $\mathbf{a} = (a_{nn1}^v, a_{nn2}^v, a_{ns}^v, a_{sn}^v, a_{ss}^v, a_{nn1}^d, a_{nn2}^d, a_{ns}^d, a_{sn}^d, a_{ss}^d)$. The value-iteration algorithm is applied to derive the optimal admission policy by minimizing the cost function

$$C(\mathbf{z}, \mathbf{a}) = w_v(l_t^v - a_t^v) + w_d(l_t^d - a_t^d), \tag{5}$$

where w_v and w_d are the relative weighting constants, and l_t^d and a_t^d are the total numbers of new and accepted data calls, respectively. The blocking rates and the throughputs of voice calls and data users are obtained from the steady-state probabilities.

A modified version of this algorithm can accommodate voice and two types of data traffic: one with priority equal to voice and another with lower priority; the former requires real-time delivery (as does voice) while the latter can be buffered. This algorithm is reported in (Geraniotis et al. 1994).

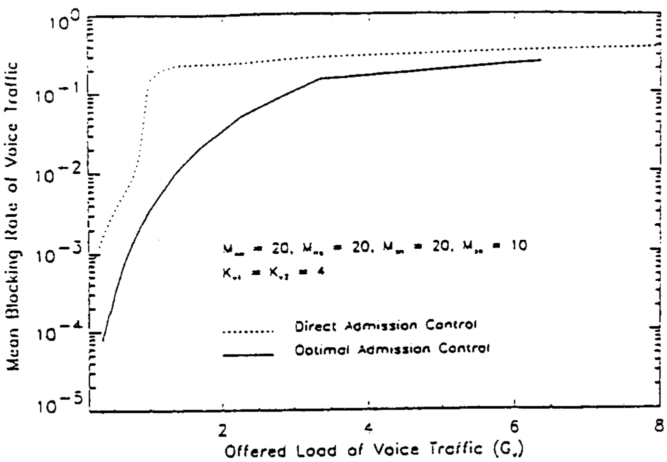

FIGURE 2. Mean Blocking Rate of Voice Traffic with Priority.

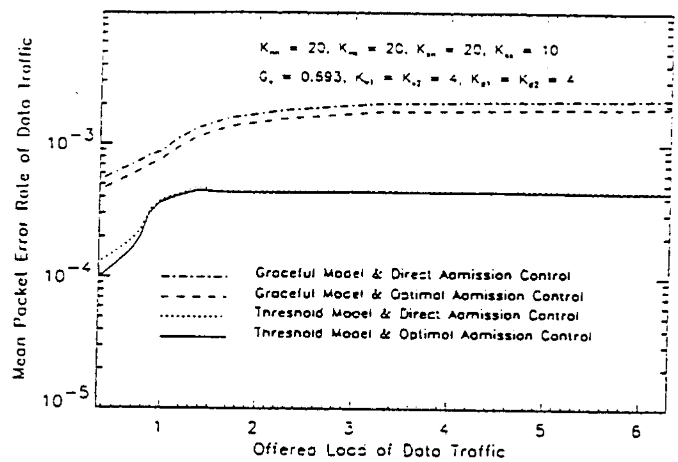

FIGURE 3. Mean Packet Error Rate of Data Traffic.

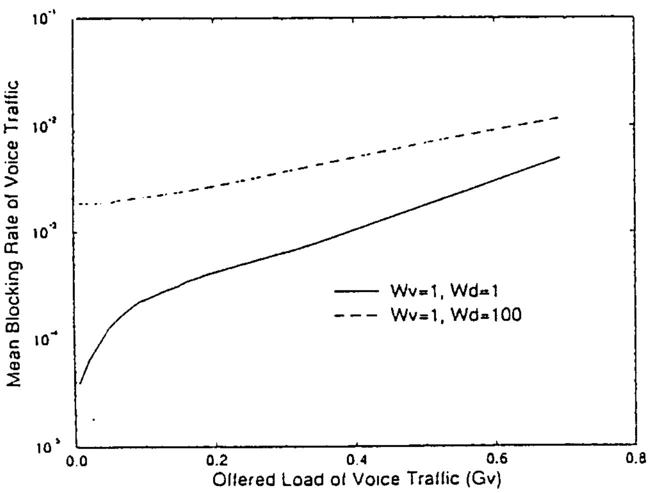

FIGURE 4. Mean Blocking Rate of Voice Traffic vs G_v.

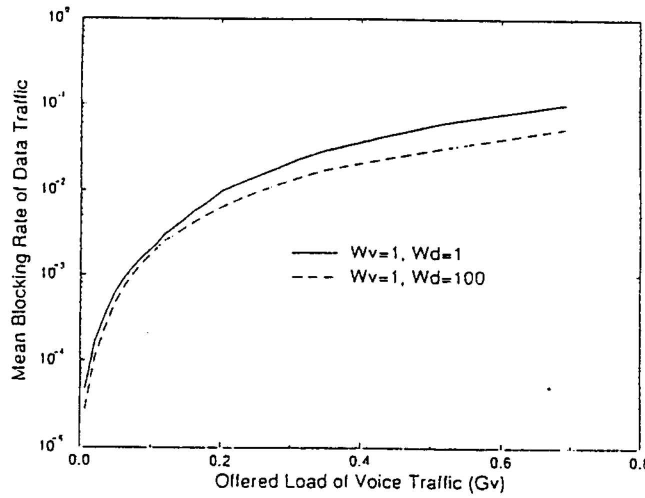

FIGURE 5. Mean Blocking Rate of Data Traffic vs G_v.

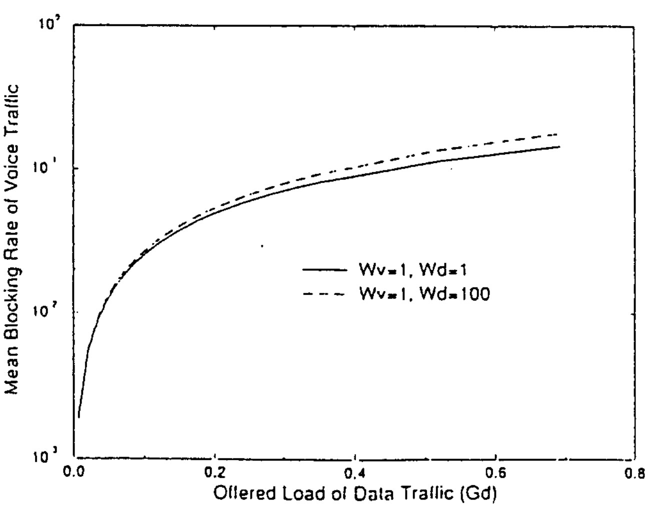

FIGURE 6. Mean Blocking Rate of Voice Traffic vs G_d.

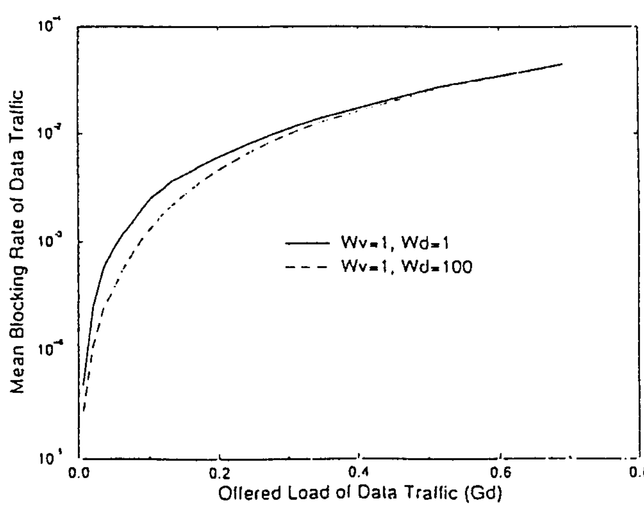

FIGURE 7. Mean Blocking Rate of Data Traffic vs G_d.

NUMERICAL RESULTS

In Figure 2, we present the average blocking probability of voice traffic. The optimal admission control policy has a lower blocking probability than the direct admission control policy. The performance measure of data traffic is shown in Figure 3. The mean packet error rate in the graceful degradation model is worse than the one in threshold model because more data traffic is accepted whenever graceful degradation is employed. In Figures 4 and 5, we present the average blocking rates of voice and data traffic versus the offered loads of voice traffic for two different data weighting factors ($w_d = 1$ and 100). As expected the blocking rates of voice calls and of data traffic increase as the voice load increases. When w_d changes from 1 to 100, the blocking rate of voice calls increases and that of data decreases. In Figures 6 and 7, we present the average blocking rates of voice and data traffic versus the offered loads of data traffic for two different data weighting factors ($w_d = 1$ and 100). As expected the blocking rates of voice calls and of data traffic increase as the data load increases. When w_d changes from 1 to 100, the blocking rate of voice calls increases and that of data decreases.

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