TECHNICAL RESEARCH REPORT

Optimal Policies for Handoff and Channel Assignment in Networks of LEO Satellites Using CDMA

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CSHCN T.R. 96-9
(ISR T.R. 96-27)

CENTER FOR SATELLITE AND HYBRID COMMUNICATION NETWORKS

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Abstract

In this paper, we formulate the combined handoff and channel assignment problems in a CDMA LEO satellite network as a reward/cost optimization problem. The probabilistic properties of signals and traffics in cells are used to formulate a finite-horizon Markov decision process. The optimal policy is obtained by minimizing a cost function consisting of the weighted sum of the switching costs and blocking costs of traffics subject to a bit-error-rate or outage probability constraint. A backward induction algorithm is applied to derive the optimal policy. Performance of the optimal policy and the direct threshold policy are compared.

1 Introduction

LEO satellite networks promise to provide worldwide communication services. The primary advantages of LEO satellite networks are global coverage and the extension of cellular systems, mobile systems, and of terrestrial public switched telephone networks. Because of the limited number of CDMA channels and the call quality requirements, the admission requests of new arrivals may not be all accepted. Efficient policies for admitting traffics must be developed so that blocking rates can be minimized.

Due to the relative movement of satellites with respect to the mobile users, several satellite handoffs are necessary during a voice call. Traditional handoff schemes for terrestrial cellular networks are based on threshold policies, but either severe ping-pong effects or high probability of forced termination will occur. In [3]-[5], the handoff phenomenon is formulated as a reward/cost optimization problem. The received signal is treated as a stochastic process with an associated reward while the handoff is associated with a switching penalty.

For channel assignment in LEO satellite networks an optimal admission policy was derived in [7], which can minimize the long-term blocking rate of newly arrived calls. Handoffs of voice calls between two satellites will change the number of active users in each satellite footprint, and the traffic conditions will also affect the handoff decision (for example, handoff can not be made if the new satellite has no capacity left). Furthermore, the call quality depends on the other user interference in a CDMA network. Therefore, the handoff and channel assignment problems should be considered together to obtain an optimal policy, which will take into account the switching cost, the blocking rate and the call quality in the CDMA satellite system. In [6], an optimal policy was derived for the handoff and channel assignment in terrestrial cellular networks.

The paper is organized as follows. In Section 2, the system models are described. The optimal handoff and channel assignment policy is derived in Section 3. In Section 4, performance of the optimal and traditional policies are analyzed and compared. Numerical results are presented in Sections 5.

2 System Model

Our system model consists of a cluster of LEO satellites. Bent-pipe transponders with no on-board mod/demod processing are employed. DS/CDMA is used over the channels between satellites and their earth domains in order to accommodate several users simultaneously. It is assumed that the LEO network provides double coverage, that is, that two satellites are in sight of all users at all times. Shadowing may occur to block one or both links between a mobile user and the two satellites in sight. Therefore, all users can be classified into four classes according to the shadowing/non-shadowing from the two satellites as in Figure 1.(see also [7]).

Since satellites are traveling along their orbit, the connection of any user to a satellite must be handed over to a new satellite footprint even though the user has never moved during its call session. Soft handoff is employed to improve quality of the call shadowed from both satellites by using maximal ratio diversity combining at the receiver. The class of users, who are shadowed for both satellites, must transmit their packets over both satellites to improve their performance. Handoff request has higher priority over new arrivals.

The message of each active user is packetized with the same length, and time is divided into slots of duration equal to the transmission of one packet. The signal strength from the mobile for handoff decision is measured periodically at these regular time instances. Handoff decision and channel assignments are made after each measurement is made. The traffic of each user is modeled as a two-state discrete-time Markov chain with transition probabilities p_{01} and p_{10} as shown in Figure 2.

The two satellites in sight must have a minimum elevation, θ_{min}, to establish a link with any users. The links between users and a satellite with low elevations are easily shadowed. In [1], the empirical expression for the distribution of the signal fading, P, is represented by a function of the elevation angle of the satellite as follows,

$$f(P,\theta) = \frac{1}{M(\theta)} e^{\frac{N(\theta)-P}{M(\theta)}} \tag{1}$$

where

$$\begin{aligned} M(\theta) &= 3.44 + 0.0975\theta - 0.002\theta^2, \text{ for } \theta < 72^0 \\ N(\theta) &= 34.76 - 0.443\theta \end{aligned} \tag{2}$$

For the range of $\theta > 72^0$, it is assumed that the fading distribution does not change with the variation of satellite elevations since no objects on the ground will block the satellite links.

It is assumed that the variation of the satellite elevation only comes from satellite movements. Movements of mobile users have no effect on the elevation angle. The distances between a satellite and its users are assumed constant. That is, the path loss will not change for different mobile locations.

Let the population be classified into four groups as follows,

M_{nn}: the number of users which experience no shadowing in their satellite links,

M_{ns}: the number of users with no shadowing in the first satellite link and with shadowing in the second satellite link,

M_{sn}: the number of users with shadowing the first satellite link and no shadowing in the second satellite link,

M_{ss}: the number of users with shadowing in both satellite links.

3 Optimal Handoff and Channel Assignment Policy

3.1 Markov Decision Process

A Markov decision process can be used to model the handoff and channel assignment problem. Because of the double coverage of every user and the minimum elevation requirement for the satellites, a finite-horizon problem is considered with initial stage $t = 0$ and final stage $t = N$ defined by

$$\begin{aligned} t = 0: &\quad \text{elevation of satellite } 0 = 90^0, \\ &\quad \text{elevation of satellite } 1 = \theta_{min} \\ t = N: &\quad \text{elevation of satellite } 0 = \theta_{min}, \\ &\quad \text{elevation of satellite } 1 = 90^0 \end{aligned} \tag{3}$$

Let θ_t^0 and θ_t^1, $t = 0, 1, ..., N$ be the elevations of satellite 0 and 1 at the decision epoch t.

Let the state space of the LEO satellite network at time t be

$$\mathbf{Z}_t = (S_t^0, S_t^1, P_t^0, P_t^1, i_t^0, i_t^1, i_t^{01}, l_t^{nn}, l_t^{ns}, l_t^{sn}, l_t^{ss}) \tag{4}$$

where $S_t^{0(1)} = 0$ if the user to be handoffed is not connected to satellite 0(1), $S_t^{0(1)} = 1$ if connected, P_t^i is the fading of received power from satellite i, $i_t^0(i_t^1)$ is the number of active users under satellite 0(1), i_t^{01} is the number of active users under both satellites, and $l_t^{nn}, l_t^{ns}, l_t^{sn}, l_t^{ss}$ are the number of new arrivals from the four shadowing groups.

The action space corresponding to the state $\mathbf{Z}_t$ is given by

$$\mathbf{A}_t = (H_t^0, H_t^1, a_t^{nn0}, a_t^{nn1}, a_t^{ns}, a_t^{sn}, a_t^{ss}) \tag{5}$$

where $H_t^0(H_t^1)$ is the handoff decision with value 0 or 1, representing whether the user is connected to satellite 0(1), and a_t^{nni}, $i = 0, 1$, is the number of accepted new arrivals from the M_{nn} group which transmit through the i-th satellite, a_t^{ns}, a_t^{sn}, and a_t^{ss} are the number of accepted calls from the M_{ns}, M_{sn}, and M_{ss} groups, respectively. Thus, the new accepted calls a_t^0 and a_t^1, which transmits through satellite 0 and 1, and a_t^{01}, which transmits through both satellites, are

$$\begin{cases} a_t^0 = a_t^{nn0} + a_t^{ns} + a_t^{ss} \\ a_t^1 = a_t^{nn1} + a_t^{sn} + a_t^{ss} \\ a_t^{12} = a_t^{ss}. \end{cases}$$

The transition probabilities that at the next epoch $t+1$ the system will be in state $\mathbf{Z}_{t+1}$, if action $\mathbf{A}_t$ is chosen at the present state $\mathbf{Z}_t$, are the following:

$$\begin{aligned} &P_{\mathbf{Z}_{t+1}|\mathbf{Z}_t}(\mathbf{A}_t) = \\ &Pr(S_{t+1}^0, S_{t+1}^1, P_{t+1}^0, P_{t+1}^1, i_{t+1}^0, i_{t+1}^1, i_{t+1}^{01}, l_{t+1}^{nn}, l_{t+1}^{ns}, \\ &l_{t+1}^{sn}, l_{t+1}^{ss} | S_t^0, S_t^1, P_t^0, P_t^1, i_t^0, i_t^1, i_t^{01}, l_t^{nn}, l_t^{ns}, l_t^{sn}, l_t^{ss}, \\ &H_t^0, H_t^1, a_t^{nn0}, a_t^{nn1}, a_t^{ns}, a_t^{sn}, a_t^{ss}) \\ &= Pr(P_{t+1}^0, P_{t+1}^1 | P_t^0, P_t^1) \cdot \mathbf{1}(S_{t+1}^0 = H_t^0, S_{t+1}^1 = H_t^1) \\ &\cdot Pr(i_{t+1}^0, i_{t+1}^1, i_{t+1}^{01}, l_{t+1}^{nn}, l_{t+1}^{ns}, l_{t+1}^{sn}, l_{t+1}^{ss} | i_t^0, i_t^1, i_t^{01}, l_t^{nn}, \\ &l_t^{ns}, l_t^{sn}, l_t^{ss}, S_t^0, S_t^1, H_t^0, H_t^1, a_t^{nn0}, a_t^{nn1}, a_t^{ns}, a_t^{sn}, a_t^{ss}) \quad (6) \end{aligned}$$

where $\mathbf{1}$ is the indicator function.

Since the fading process is exponentially distributed with mean and variance depending upon the elevation angle of the satellite, as shown in (1), the conditional probability is

$$\begin{aligned} &Pr(P_{t+1}^0, P_{t+1}^1 | P_t^0, P_t^1) = \\ &\frac{1}{(1-\rho_0^2)M(\theta_{t+1}^0)} e^{-\frac{1}{(1-\rho_0^2)}\left(\frac{\rho_0^2(P_t^0 - N(\theta_t^0))}{M(\theta_t^0)} + \frac{P_{t+1}^0 - N(\theta_{t+1}^0)}{M(\theta_{t+1}^0)}\right)} \\ &\times I_0\left(\frac{2\rho_0(P_t^0 - N(\theta_t^0))^{1/2}(P_{t+1}^0 - N(\theta_{t+1}^0))^{1/2}}{(1-\rho_0^2)M^{1/2}(\theta_t^0)M^{1/2}(\theta_{t+1}^0)}\right) \\ &\times \frac{1}{(1-\rho_1^2)M(\theta_{t+1}^1)} e^{-\frac{1}{(1-\rho_1^2)}\left(\frac{\rho_1^2(P_t^1 - N(\theta_t^1))}{M(\theta_t^1)} + \frac{P_{t+1}^1 - N(\theta_{t+1}^1)}{M(\theta_{t+1}^1)}\right)} \\ &\times I_0\left(\frac{2\rho_1(P_t^1 - N(\theta_t^1))^{1/2}(P_{t+1}^1 - N(\theta_{t+1}^1))^{1/2}}{(1-\rho_1^2)M^{1/2}(\theta_t^1)M^{1/2}(\theta_{t+1}^1)}\right) \quad (7) \end{aligned}$$

where $I_0(\cdot)$ is the modified Bessel function of order zero, and ρ_i is the correlation coefficient of the two fading measurements from a satellite at two consecutive times.

The traffic transition probability, which is independent of the power measurements, can be represented by

$$\begin{aligned} &Pr(i_{t+1}^0, i_{t+1}^1, i_{t+1}^{01}, l_{t+1}^{nn}, l_{t+1}^{ns}, l_{t+1}^{sn}, l_{t+1}^{ss} | i_t^0, i_t^1, i_t^{01}, l_t^{nn}, \\ &l_t^{ns}, l_t^{sn}, l_t^{ss}, S_t^0, S_t^1, H_t^0, H_t^1, a_t^{nn0}, a_t^{nn1}, a_t^{ns}, a_t^{sn}, a_t^{ss}) \\ &\approx b(i_t^0 - i_t^{01}, i_t^0 - i_t^{01} + a_t^0 - a_t^{01} - i_{t+1}^0 + i_{t+1}^{01} \\ &\qquad + S_t^1 - H_t^1, p_{10}) \\ &\cdot b(i_t^1 - i_t^{01}, i_t^1 - i_t^{01} + a_t^1 - a_t^{01} - i_{t+1}^1 + i_{t+1}^{01} \\ &\qquad + S_t^0 - H_t^0, p_{10}) \\ &\cdot b(i_t^{01}, i_t^{01} + a_t^{ss} - i_{t+1}^{01} - S_t^0 - S_t^1 + H_t^0 + H_t^1, p_{10}) \\ &\cdot b(M_{nn}, l_{t+1}^{nn}, p_{01}) \cdot b(M_{ns}, l_{t+1}^{ns}, p_{01}) \\ &\cdot b(M_{sn}, l_{t+1}^{sn}, p_{01}) \cdot b(M_{ss}, l_{t+1}^{ss}, p_{01}) \quad (8) \end{aligned}$$

where $b(M, m, p)$ denotes the binomial distribution with parameters M and p, $0 \le p \le 1$.

$$b(M, m, p) = \binom{M}{m} p^m (1-p)^{M-m} \quad (9)$$

and the population is assumed to be much larger the satellite capacity.

3.2 Cost Function and Constrained Optimization Formulation

Let C_1 be the set-up cost incurred if a new connection is established between the satellite and the user requesting handoff, and C_{-1} be the disconnection cost if an existing connection is removed at each decision epoch. The blocking cost for the background traffic is the number of rejected newly arrived calls in two satellite footprints, that is,

$$\begin{aligned} &l_{t,total} - a_{t,total} = \\ &l_t^{nn} + l_t^{ns} + l_t^{sn} + l_t^{ss} - a_t^{nn1} - a_t^{nn2} - a_t^{ns} - a_t^{sn} - a_t^{ss} \quad (10) \end{aligned}$$

The objective of the optimal handoff and channel assignment policy is to minimize the total expected weighted sum of the set-up, disconnection and blocking costs,

$$\begin{aligned} E[\sum_{t=0}^{N} r(z_t, a)] = E[\sum_{t=0}^{N} w_1 C_{H_t^0 - S_t^0} \\ + w_2 C_{H_t^1 - S_t^1} + w_3(l_{t,total} - a_{t,total})] \quad (11) \end{aligned}$$

under a BER or outage probability constraint of the handoff call, where $r(z_t, a)$ is the incurred cost when state is z_t and action a is taken at time t. Note that C_0 is defined to be 0.

By adjusting weighting factors w_1, w_2, or w_3, we can obtain different tradeoffs between set-up, disconnection and blocking costs. An alternative of the cost function is adding the outage probability to the cost function, which can improve the call quality at the expense of more handoffs or traffic blocking.

It has been shown that the error probability in a CDMA network can be approximated by [8]

$$\begin{aligned} P_e &\approx Q(\sqrt{SNR}) \\ &= Q\left(\frac{AT}{[\eta_0 T + \frac{A^2}{3}\sigma^2 T_c^2 L(K_0 + K_1 - 1)]^{1/2}}\right) \quad (12) \end{aligned}$$

where A is the signal amplitude with fading, T is the bit duration, L is the processing gain, T_c is the chip duration, σ is the parameter of Rayleigh fading, K_i is the number of users in the footprint of satellite i. Therefore, to ensure the call quality of a mobile, the other user interference has to be limited by setting constraints on the number of active users connected to each satellite.

Because a constraint, say α_1, on the BER is equivalent to the constraint $SNR > [Q^{-1}(\alpha_1)]^2$, we can use the outage probability [9], which is defined below, as an alternative constraint.

$$\begin{aligned} P_{out} &= 1 - Pr(SNR > b) \\ &= E[\int dP_{\theta_2^0} f_{\theta_2^0}(P_{\theta_2^0}) \dots \int dP_{\theta_{K_1}^1} f_{\theta_{K_1}^1}(P_{\theta_{K_1}^1}) \\ &\qquad \cdot \exp(P_1^1 - \sum_{i=2}^{K_0} P_i^0 - \sum_{i=2}^{K_1} P_i^1)] \end{aligned} \quad (13)$$

where $f_{\theta_i^j}$ is the fading distribution with parameter θ_i^j for the i-th user of the j-th satellite, and K_i is the number of active users connected to satellite i.

3.3 Finite-Horizon Dynamic Programming and Optimal Policy

To obtain the optimal policy minimizing the expected total cost, the backward induction algorithm [2], an efficient method for solving finite-horizon discrete-time Markov decision processes, is employed to obtain the optimal actions for every state at $t = 0, \dots, N$.

step 1 : Set $t = N$ and assign boundary cost to $u_N^*(z_N)$ for all the state $z_N \in \mathbf{Z}$,

step 2 : Substitute $t-1$ for t and compute $u_t^*(z_t)$ for each $z_N \in \mathbf{Z}$ by

$$u_t^*(z_t) = \min_{a \in \mathbf{A}_{z_t}} \{r_t(z_t, a) + \sum_{j \in \mathbf{Z}} p_t(j|z_t, a) u_{t+1}^*(j)\} \quad (14)$$

Set

$$A_{z_t,t}^* = \arg\min_{a \in \mathbf{A}_{z_t}} \{r_t(z_t, a) + \sum_{j \in \mathbf{Z}} p_t(j|z_t, a) u_{t+1}^*(j)\} \quad (15)$$

step 3 : If $t = 0$, stop. Otherwise return to step 2.

Thus, the minimized expected total cost is $u_0^*(z_0)$ with z_0 as the initial condition of the state variables. $A_{z_t,t}^*$ is the optimal action to be taken at time t when the state is z_t.

4 Performance Comparison

For the direct handoff and channel assignment policy, the decisions H_t^0 and H_t^1 take values according to the received fading levels,

$$\begin{cases} (H_t^0, H_t^1) = (1,1) \text{ if } P_t^0 > P_{th} \text{ and } P_t^1 > P_{th} \\ (H_t^0, H_t^1) = (1,0) \text{ if } P_t^0 < P_t^1 \text{ and } P_t^0 < P_{th} \\ (H_t^0, H_t^1) = (0,1) \text{ if } P_t^0 > P_t^1 \text{ and } P_t^1 < P_{th} \end{cases} \quad (16)$$

where P_{th} is a fading threshold. For the direct admission policy of new arrivals, users from the groups M_{ns}, M_{sn} are assigned to satellite 0 and 1, respectively, and users from M_{nn} are assigned to either satellite 0 or 1 according to the traffic loads of two satellites. Finally, the remaining channels are assigned to M_{ss}.

$$\begin{cases} a_t^{ns,nn} = \min(l_t^{ns} + \lfloor \gamma l_t^{nn} \rfloor, K_t^0 - i_t^0) \\ a_t^{sn,nn} = \min(l_t^{sn} + l_t^{nn} - \lfloor \gamma l_t^{nn} \rfloor, K_t^1 - i_t^1) \\ a_t^{ss} = \min(l_t^{ss}, K_t^0 - i_t^0 - a_t^{ns,nn}, K_t^1 - i_t^1 - a_t^{sn,nn}) \end{cases} \quad (17)$$

where K_t^i are derived from the outage probability constraint, and

$$\gamma = \begin{cases} \frac{K_t^0 - i_t^0}{K_t^0 - i_t^0 + K_t^1 - i_t^1}, & K_t^0 - i_t^0 + K_t^1 - i_t^1 > 0 \\ 0, & K_t^0 - i_t^0 + K_t^1 - i_t^1 = 0 \end{cases}$$

The numbers of accepted new arrivals through satellite 0 and 1 are

$$\begin{aligned} a_t^0 &= a_t^{ns,nn} + a_t^{ss} \\ a_t^1 &= a_t^{sn,nn} + a_t^{ss} \end{aligned} \quad (18)$$

and the total number of accepted new arrivals is

$$a_{t,total} = a_t^0 + a_t^1 - a_t^{ss} \quad (19)$$

Using the actions defined above, we can also obtain the expected cost function for the direct policy from (14). Besides the expected total cost obtained in the backward induction algorithm, the expected number of channel set-ups, disconnections, and the expected number of blocked users from $t = 0$ to $t = N$ can also be derived by setting

$$r_t(z_t, a) = \mathbf{1}(H_t^0 - S_t^0 = 1) + \mathbf{1}(H_t^1 - S_t^1 = 1) \quad (20)$$

$$r_t(z_t, a) = \mathbf{1}(H_t^0 - S_t^0 = -1) + \mathbf{1}(H_t^1 - S_t^1 = -1) \quad (21)$$

$$r_t(z_t, a) = l_t^{nn} + l_t^{ns} + l_t^{sn} + l_t^{ss} - a_{t,total} \quad (22)$$

respectively, and using (14) to derive different performance measures for the optimal and direct handoff and channel assignment policies.

5 Numerical Results

For the numerical results, we select a model with satellite elevation in the range of 45^0 to 90^0. The correlation coefficients ρ_i are 0.5. The offered traffic load in a cell is defined as

$$G = (M_{nn} + M_{ns} + M_{sn} + M_{ss}) \frac{p_{01}}{p_{01} + p_{10}} \qquad (23)$$

The total population are $M_{nn} = M_{ns} = M_{sn} = 10$, $M_{ss} = 5$.

In Figures 4 to 6 we show the performance measures versus offered traffic load. Figure 4 is the expected cost versus offered traffic load for optimal and direct policies. Both C_1 and C_{-1} are assumed to be 1. As expected the optimal policy has a smaller cost than the direct policy. The difference tends to be larger when more weighting is put on the switching costs(the case $w_1 = w_2 = 0.3w_3$). In all cases, the cost increases as the load increases. In Figure 5 we show the expected number of blocked users versus offered traffic load. The optimal policy performs much better when the load is heavier. In Figure 6 the number of handoffs are compared. The optimal policy has less number of handoffs for all the range of traffic load. When the load is light, the optimal policy performs even better.

In Figures 7 and 8, we show the performance of the optimal policy versus the switching cost C_1, C_{-1}. Figure 7 is the expected number of blocked users versus C_1(C_{-1} in this case is equal to C_1). When switching costs increase, more users will be blocked. In Figure 8, the expected number of handoffs decreases as expected when the switching cost increases.

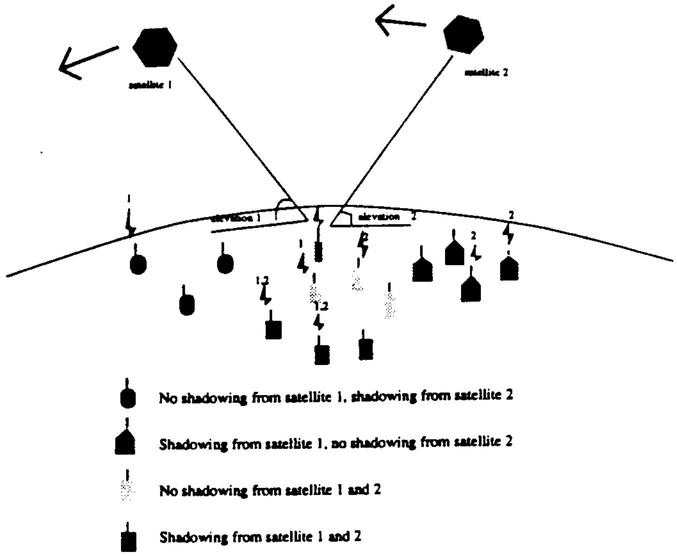

Figure 1: Model for shadowed and nonshadowed users

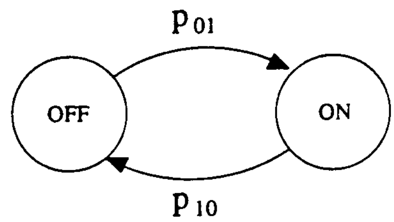

Figure 2: Traffic model: two-state Markov chain

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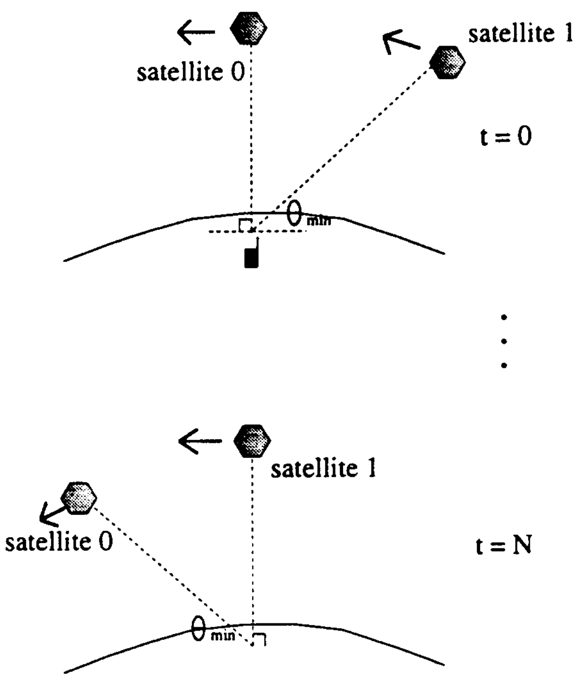

Figure 3: Initial and final stages of finite-horizon MDP

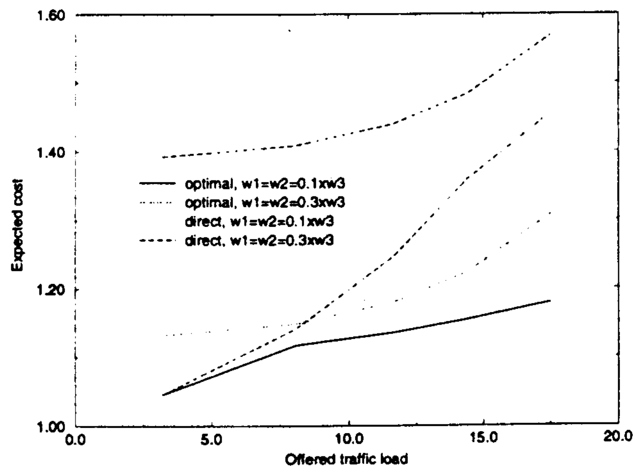

Figure 4: Expected cost vs offered traffic load

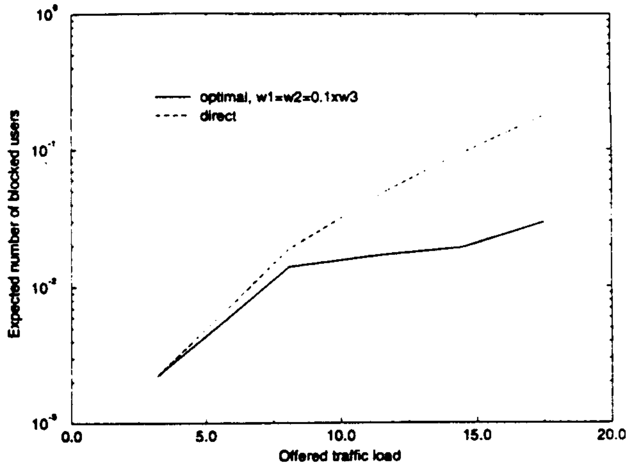

Figure 5: Expected number of blocked users vs offered traffic load

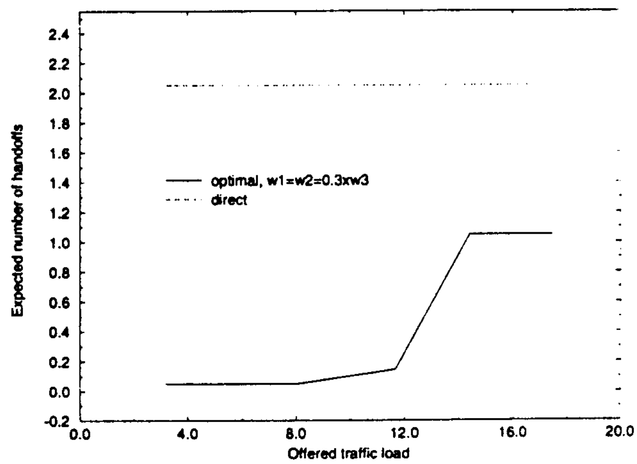

Figure 6: Expected number of handoffs vs offered traffic load

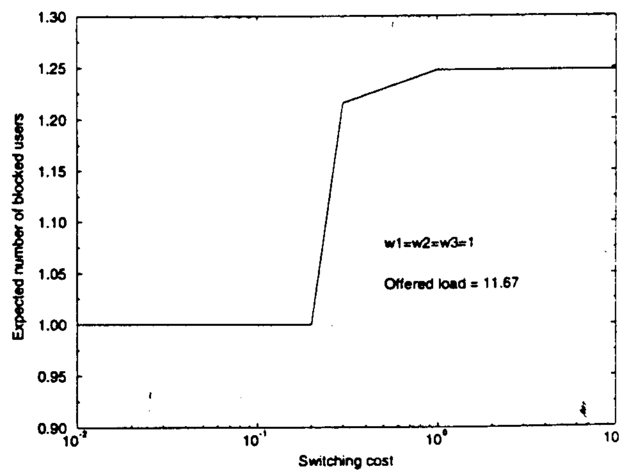

Figure 7: Expected number of blocked users vs switching cost

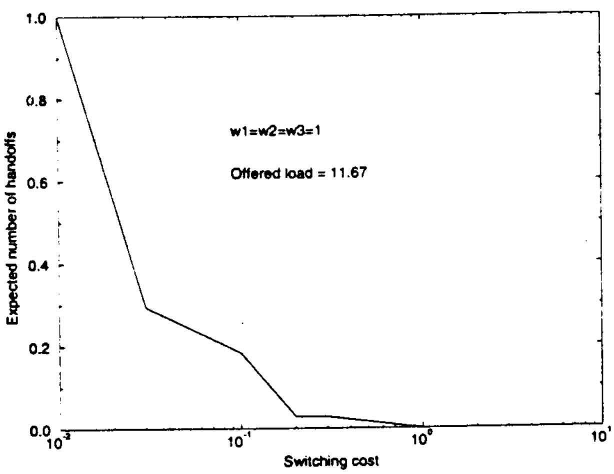

Figure 8: Expected number of handoffs vs switching cost