INSTITUTE OF POLICY AND PLANNING SCIENCES

Discussion Paper Series

No. 1101

Dynamic Control of the Address Binding Update for Mobile Nodes in a Hierarchical Mobile IP Network

by

Sang-Yong Kim and Hideaki Takagi

December 2004

UNIVERSITY OF TSUKUBA
Tsukuba, Ibaraki 305-8573
JAPAN

Dynamic Control of the Address Binding Update for Mobile Nodes in a Hierarchical Mobile IP Network

Sang-Yong Kim
Doctoral Program in Systems and Information Engineering
University of Tsukuba
e-mail: sykim@sk.tsukuba.ac.jp

and

Hideaki Takagi (Corresponding author)
Graduate School of Systems and Information Engineering
University of Tsukuba
1-1-1 Tennoudai, Tsukuba-shi, Ibaraki 305-8573, Japan
Phone: (029) 853-5003; Fax: (029) 855-3849
e-mail: takagi@sk.tsukuba.ac.jp

Abstract

Hierarchical Mobile Internet Protocol version 6 (HMIPv6) has been proposed by the Internet Engineering Task Force (IETF) as an enhancement of the MIPv6. It is designed to reduce the amount of required signaling and to speed up the hand-off operation for mobile connection by means of hierarchical routing. In the HMIPv6, a router called the Mobile Anchor Point (MAP) serves mobile nodes (MNs) to aid their address binding and update as a local home agent. However, as the number of MNs increases in a MAP domain, the resource of the MAP becomes scarce, which increases the chance of failing in admitting new and hand-off MNs. Therefore some control scheme is needed in order to guarantee the quality of service (QoS) of the network.

In this paper, we propose a dynamic control of the address binding update for the MNs in an HMIPv6 network. We consider three types of MNs entering the MAP domain, namely, a new MN, a hand-off MN in the sleep mode, and a hand-off MN in the active mode. We impose different cost for blocking them, for the forced termination of ongoing communication causes greater pain to a user than blocking a new MN. An optimal admission policy is obtained from a semi-Markov decision process with respect to the number of MNs present in a MAP domain. Based on this optimal policy, we calculate the probabilities of blocking each type of MN. We show numerically that our control reduces the probability of rejecting active-mode hand-off MNs at little expense of blocking new MNs. It is also shown that our dynamic control outperforms the static control based on the guard channel scheme when the arrival rate of new MNs is high.

Keywords: Hierarchical mobile IP network, binding update, guard channel, dynamic admission control, semi-Markov decision process, blocking probability, hand-off termination.

1 Introduction

The continuous growth and sophistication in mobile wireless communication has been demanding successive enhancement of protocol support in networking. First, the Mobile Internet Protocol version 4 (MIPv4) was proposed as a standard by the Internet Engineering Task Force (IETF) in 1996 [1, 2, 3]. It has several functional entities such as a mobile node (MN), a home agent (HA), and a foreign agent (FA). The HA is a router on a MN's home network that delivers packets to the MN by maintaining its location information when it is away from home. The FA is a router on a network visited by the MN that provides routing for the MN while registered. Every MN is assigned an IP address called a home address by the HA on the home network where the MN is registered originally. When the MN is away from the home network, it is assigned a care-of address (CoA) temporarily by the FA on a foreign network. The association of a MN's home address with its CoA, along with the remaining lifetime of their association, is called binding. A MN sends Binding Update (BU) to its HA everytime it moves. The location of the MN is tracked with the binding information while it is away from its home network. When a correspondent node (CN) sends a packet to the MN with its home address, the packet is delivered to the MN at that address. If the MN is away from home, the HA receives the packet and forwards it to the FA on a foreign network which the MN is visiting. This process is called triangle routing.

The triangle routing in MIPv4 causes traffic overhead between the home and foreign networks in a wide area as well as a large latency in the hand-off of MNs locally. To improve these problems, the Mobile IP version 6 (MIPv6) [4] and then the Hierarchical Mobile IP version 6 (HMIPv6) [5] have been proposed. In the MIPv6, a MN sends BUs to its HA as well as all CNs it communicate with. Once a CN has learned the MN's CoA, it may route the packet directly to the MN bypassing the HA. However, it takes time to send the BU to the HA that is typically far away. The HMIPv6 is an enhancement of the MIPv6, which is designed to reduce the amount of required signaling and to speed up the hand-off operation for mobile connection by means of hierarchical routing. In the HMIPv6, there is no FA. Instead, a router called the Mobile Anchor Point (MAP) serves MNs to aid them in binding and updating IP addresses as a local HA. It reduces the hand-off related latency, because MNs can register its bound IP addresses with the MAP more quickly than at a remote HA.

However, as the number of MNs increases in a MAP domain, the MAP suffers from resource starvation. This is caused by the BU operation and the encapsulation/decapsulation of every packet destined to all the MNs present in the MAP domain.

The amount of necessary resource depends on the application running on each MN. Therefore, there is the maximum number of MNs, depending on the application, that can be connected for a router. The quality of service (QoS) in a domain which serves a large number of MNs may not keep up with that in other domains with low density of MNs. Therefore, some control scheme is needed in order to guarantee the same level of QoS throughout the network.

Admission control in a mobile communication network can be static (i.e., independent of the instantaneous traffic condition) or dynamic. For the call admission control of voice traffic in a cellular network, a static control based on the guard channel (also called cutoff priority) scheme was first studied by Hong and Rappaport [6]. In this scheme, a certain number of channels are reserved for exclusive use by the hand-off traffic. Their study for a single cell has been extended to handle the hand-off traffic from neighboring cells in homogeneous and inhomogeneous networks [7, 8]. One-dimensional birth-and-death processes are used to model the stochastic process for the number of calls existing in a cell. Dynamic admission control was proposed by Yang and Geraniotis [9], who employed a semi-Markov decision process with the value iteration algorithm to obtain the optimal policy for the admission of voice and data traffic. We have refined their model for voice calls by taking into account hand-off calls in cellular environment [10]. As for the control of binding update for MNs in a hierarchical mobile IP network, Pack et al. [11] consider a static, guard channel based scheme for the call admission control scheme proposed by Fang and Zhang [12]. Vasilache et al. [13] propose a threshold-based load balancing policy that uses a model of data sharing among multiple HAs in a mobile IP network.

In this paper, we present a dynamic control method of the address binding and updating for the MNs in an HMIPv6 network. We consider three types of MNs entering the MAP domain, namely, a new MN, a hand-off MN in the sleep (not in communication) mode, and a hand-off MN in the active (in communication) mode. We impose different cost for blocking them, because the forced termination of ongoing communication causes greater pain to a user than blocking a new MN. An optimal admission policy is obtained from a semi-Markov decision process with respect to the number of MNs present in a MAP domain. Once the optimal policy is obtained, we calculate the probabilities of blocking each type of MN. The hand-off rates of MNs are computed from the generation rate of new MNs. We show numerically to what extent the control parameters have impact on the admission performance. For comparison purpose, we also analyze the static control method based on the guard channel scheme with a birth-and-death process model.

The rest of the paper is organized as follows. In Section 2, we describe the address binding update operation for MNs in an HMIPv6 network in more detail. We then propose analytic models for studying the performance of the static guard channel scheme with a Markov chain and that of the dynamic admission control of binding update by means of a semi-Markov decision process. In Section 3, we define the performance measures such as the probability of blocking new MNs, the probability of rejecting hand-off MNs, and the resource utilization at the MAP. The calculation of these measures is shown for both static and dynamic control cases. Section 4 presents the numerical results with discussion, including the comparison among dynamic control cases with different parameters and the comparison with the static control case. Concluding remarks are given in Section 5.

2 System Model

As a preliminary, we describe the address binding and update operation for MNs in an HMIPv6 network. We first present a threshold based static control method for the binding update using the guard channel scheme. We then propose a dynamic admission control method for a MAP domain. We assume that our network is homogeneous such that all MAP domains have the same stochastic properties. We keep track of a sequence of events that each MN experiences in the MAP domain. The dynamic admission control method is studied by means of a semi-Markov decision process with the value iteration algorithm for obtaining the optimal policy.

2.1 Binding update in an HMIPv6 network

In a mobile IPv4 network, it is always necessary that every MN registers its location to the HA in the home network. When the MN moves to a foreign network, the location registration takes time, which will result in the deterioration of hand-off quality. To improve such situation, the HMIPv6 has been proposed [5]. In an HMIPv6 network, a MN which is away from its home network is served by a MAP in a local domain. As long as the MN moves within the local domain, the location registration to the home network is omitted. The default router of each MN is its Access Router (AR). An AR belongs to one or more MAP domains. The AR sends out periodically to the MNs the router advertisement (RA) message that includes the information about the MAP domain.

Figure 1 depicts the basic structures of an HMIPv6 network. According to [5],

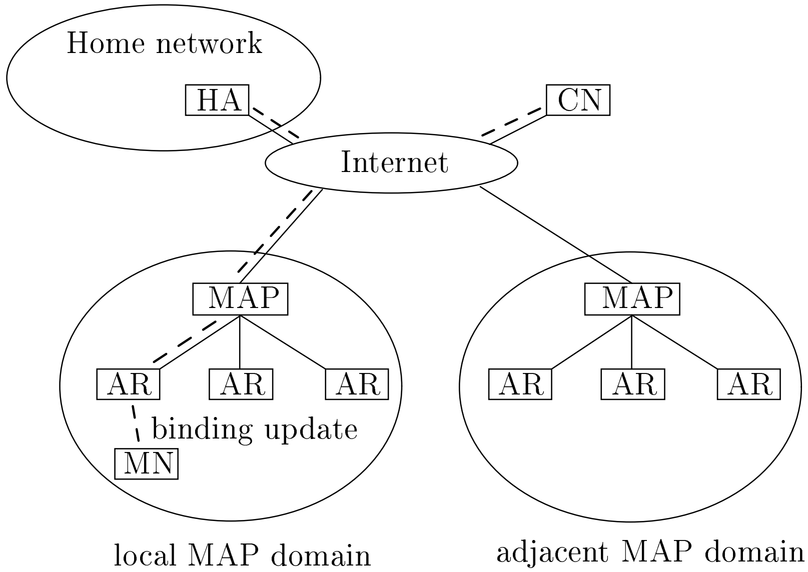

Figure 1: Basic structure of a hierarchical mobile IPv6 network.

when a MN moves into a new MAP domain, it receives the RA message containing the global IP address of the MAP. The MN then configures two care-of addresses: the Regional Care-of Address (RCoA) and the Local Care-of Address (LCoA). The RCoA is an address on the MAP's subnet formed by combining the MN's interface identifier and the subnet prefix of the MAP's global address. The LCoA is the on-link CoA on a MN's interface. The MN sends the binding of RCoA and LCoA to the MAP, and the binding of home address and RCoA to the HA and CNs it communicate with. The BU information along with its lifetime is saved in the binding cache at the MAP, HA and CNs. The lifetime of the BU information is the time interval during which RCoA is valid.

If the MN changes its current address within a local MAP domain, it only needs to register the new address with the MAP. This is called local binding update. Hence, only the RCoA needs to be registered with the HA and the CNs. The RCoA does not change as long as the MN moves within a MAP domain. This makes the MN's mobility transparent to the CNs it is communicating with.

2.2 Threshold based static control (guard channel scheme)

As a static control method, let us consider the guard channel scheme. The critical element in the guard channel scheme is the channel reservation. It reserves a fixed number of channels for MNs with high priority. Let us pay our attention to a single

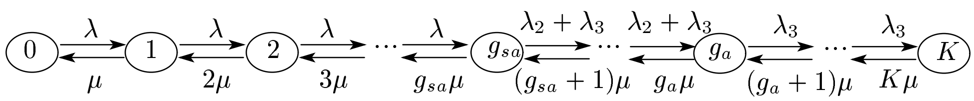

Figure 2: State transition diagram for a Markov chain representing the guard channel scheme.

MAP domain. The MAP can accommodate up to K MNs for binding updates, where K is specified for the router implementing the MAP function. We assume that there are three types of MNs entering the MAP domain, namely, a new MN, a sleep mode hand-off MN, and an active mode hand-off MN. Priority is given to active mode hand-off MNs over sleep mode hand-off MNs, and to sleep mode hand-off MNs over new MNs. In this case, two thresholds are predefined. When the number of MNs exceeds the first threshold, sleep and active mode hand-off MNs are admitted while new MNs are blocked. After the second threshold, only active mode hand-off MNs are admitted; new and sleep mode hand-off MNs are blocked.

BU information has a lifetime in the binding cache at the MAP, and each MN has a residence time in the MAP domain. The residence time of a MN is the time interval during which the MN stays in a MAP domain. The lengths of the lifetime and the residence time may be a few minutes. Their averages are denoted by $1/\mu_1$ and $1/\mu_2$, respectively. Both times are assumed to be exponentially distributed. Let λ_1, λ_2, and λ_3 be the rates at which new, sleep mode hand-off, and active mode hand-off MNs are generated, respectively, according to independent Poisson processes. Then the number of MNs existing in the MAP domain changes as a continuous time Markov chain, more specially as a one-dimensional birth-and-death process. Figure 2 depicts the state transitions in the Markov chain, where $\lambda = \lambda_1 + \lambda_2 + \lambda_3$ and $\mu = \mu_1 + \mu_2$. In addition, K denotes the maximum number of MNs which the MAP can accommodate (the capacity of the MAP), g_{sa} the first threshold, and g_a the second threshold.

Assuming that the chain is ergodic, let p_k be the steady state probability that there are k MNs in the MAP domain, where $0 \leq k \leq K$. Then we have the set of balance equations:

$$\begin{aligned} \lambda \cdot p_k &= (k+1)\mu \cdot p_{k+1} & 0 \leq k \leq g_{sa} - 1 \\ (\lambda_2 + \lambda_3) \cdot p_k &= (k+1)\mu \cdot p_{k+1} & g_{sa} \leq k \leq g_a - 1 \\ \lambda_3 \cdot p_k &= (k+1)\mu \cdot p_{k+1} & g_a \leq k \leq K - 1, \end{aligned} \quad (1)$$

and the normalization condition:

$$\sum_{k=0}^{K} p_k = 1. \tag{2}$$

Hence, the steady state probabilities are given by

$$p_k = \begin{cases} \frac{1}{k!}\left(\frac{\lambda}{\mu}\right)^k \cdot p_0 & 1 \le k \le g_{sa} \\ \frac{\lambda^{g_{sa}}\left(\lambda_2+\lambda_3\right)^{k-g_{sa}}}{k!\mu^k} \cdot p_0 & g_{sa}+1 \le k \le g_a \\ \frac{\lambda^{g_{sa}}\left(\lambda_2+\lambda_3\right)^{g_a-g_{sa}}\lambda_3^{k-g_a}}{k!\mu^k} \cdot p_0 & g_a+1 \le k \le K \end{cases}, \tag{3}$$

where

$$\frac{1}{p_0} = \sum_{k=0}^{g_{sa}} \frac{1}{k!}\left(\frac{\lambda}{\mu}\right)^k + \sum_{k=g_{sa}+1}^{g_a} \frac{\lambda^{g_{sa}}\left(\lambda_2+\lambda_3\right)^{k-g_{sa}}}{k!\mu^k} + \sum_{k=g_a+1}^{K} \frac{\lambda^{g_{sa}}\left(\lambda_2+\lambda_3\right)^{g_a-g_{sa}}\lambda_3^{k-g_a}}{k!\mu^k}. \tag{4}$$

2.3 Dynamic admission control of binding updates

We next consider a dynamic control method for the address binding update of MNs. Let us again focus on a single MAP domain, which can accommodate up to K MNs for binding updates. The model and parameters of the stochastic behavior of MNs in the MAP domain are the same as for the static control method described in Section 2.2. If a new or a sleep/active mode hand-off MN is placed and the number of existing MNs is less than K, the MN is either admitted in the MAP domain or it is blocked according to the dynamic admission control.

Consider an embedded Markov chain in which the state is defined by the pair (k, j), where k is the number of MNs existing in the MAP domain and j denotes how the state is entered. In this model, we identify a set of Markovian decision epochs such that, if we specify the state at a decision epoch and provide information thereafter, we know the state at the next decision epoch. There are five cases of the state transition from state (k, j) at a decision epoch $(0 \le k \le K)$. First, if a new MN is admitted in the MAP domain, the chain moves to state $(k+1, 1)$ $(0 \le k \le K-1)$. Second, if a sleep mode hand-off MN is admitted, the chain moves to state $(k+1, 2)$ $(0 \le k \le K-1)$. Third, if an active mode hand-off MN is admitted, the chain moves to state $(k+1, 3)$ $(0 \le k \le K-1)$. Fourth, if a new, a sleep mode hand-off, or an active mode hand-off MN is placed but rejected, the chain stays in state (k, j) $(0 \le k \le K)$. Fifth, if the lifetime of the BU information expires or if a MN leaves the MAP domain as hand-off,

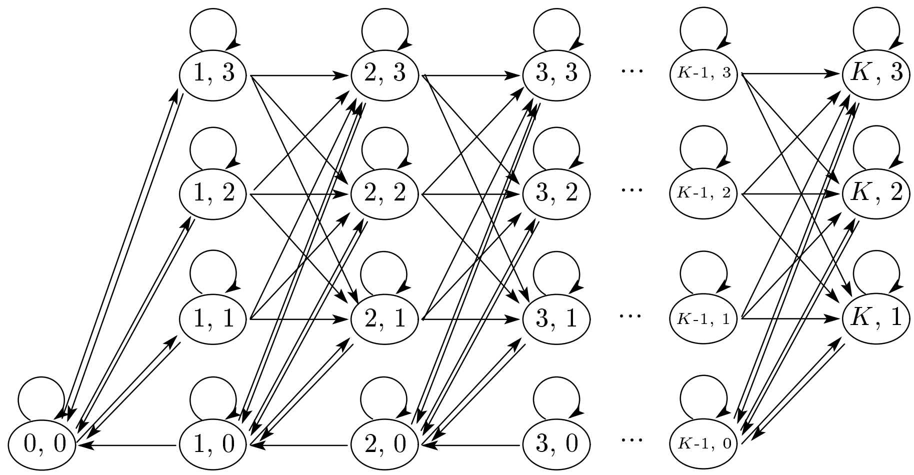

Figure 3: State transition diagram at decision epochs embedded in a Markov chain representing the dynamic admission control.

the chain moves to state $(k-1, 0)$ $(1 \leq k \leq K)$. Note that the last case is a fictitious decision epoch because no decision is made actually. Figure 3 depicts these transitions in the Markov chain embedded at decision epochs.

The probabilities of transition from state (k, j) to state $(k-1, 0)$, $(k+1, 1)$, $(k+1, 2)$, $(k+1, 3)$, and (k, j) are denoted by $q_{k,k-1}$, $q^{(1)}_{k,k+1}$, $q^{(2)}_{k,k+1}$, $q^{(3)}_{k,k+1}$, and $q_{k,k}$, respectively, such that $q_{k,k-1}+q^{(1)}_{k,k+1}+q^{(2)}_{k,k+1}+q^{(3)}_{k,k+1}+q_{k,k} = 1$. They are given in terms of $\mu = \mu_1+\mu_2$, λ_1, λ_2, and λ_3 (let $\lambda = \lambda_1 + \lambda_2 + \lambda_3$) as well as the action parameters $a_{(k,1)}$, $a_{(k,2)}$, and $a_{(k,3)}$ of the dynamic admission control as follows:

$$q_{k,k-1} = \frac{k\mu}{\lambda + k\mu} \qquad 1 \leq k \leq K \tag{5}$$

$$q^{(j)}_{k,k+1} = \frac{\lambda_j \cdot a_{(k,j)}}{\lambda + k\mu} \qquad 1 \leq j \leq 3, \;\; 0 \leq k \leq K-1 \tag{6}$$

$$q_{k,k} = \frac{\lambda_1(1-a_{(k,1)}) + \lambda_2(1-a_{(k,2)}) + \lambda_3(1-a_{(k,3)})}{\lambda + k\mu} \qquad 0 \leq k \leq K, \tag{7}$$

where

$$a_{(k,1)} = \begin{cases} 0 & \text{if a new MN is rejected} \\ 1 & \text{if a new MN is admitted} \end{cases}$$

$$a_{(k,2)} = \begin{cases} 0 & \text{if a sleep mode hand-off MN is rejected} \qquad 0 \leq k \leq K-1 \\ 1 & \text{if a sleep mode hand-off MN is admitted} \end{cases} \tag{8}$$

$$a_{(k,3)} = \begin{cases} 0 & \text{if an active mode hand-off MN is rejected} \\ 1 & \text{if an active mode hand-off MN is admitted} \end{cases}$$

when k MNs are served in the MAP domain, and

$$a_{(K,1)} = a_{(K,2)} = a_{(K,3)} = 0. \tag{9}$$

Note that $q_{k,k'} = q^{(1)}_{k,k'} = q^{(2)}_{k,k'} = q^{(3)}_{k,k'} = 0$ for $|k - k'| > 1$.

Assuming that the chain is ergodic, let $p_{k,j}$; $0 \le k \le K$, $0 \le j \le 3$, be the steady state probability for the chain to be in state (k, j). Then we have the set of balance equations:

$$p_{k,j} = \begin{cases} \left(\sum_{i=0}^{3} p_{k+1,i}\right) \cdot q_{k+1,k} + p_{k,0} \cdot q_{k,k} & j = 0 \\ \left(\sum_{i=0}^{3} p_{k-1,i}\right) \cdot q^{(j)}_{k-1,k} + p_{k,j} \cdot q_{k,k} & 1 \le j \le 3 \end{cases}, \tag{10}$$

and the normalization condition:

$$\sum_{k=0}^{K} \sum_{j=0}^{3} p_{k,j} = 1. \tag{11}$$

Let $\widetilde{p}_{k,j}$ be the probability of state (k, j) at an arbitrary point in the continuous time domain. Then, from the theory of semi-Markov processes [14, Section 9-1], we have

$$\widetilde{p}_{k,j} = \frac{p_{k,j} \cdot \eta_k}{\eta} \qquad 0 \le k \le K,\ 0 \le j \le 3, \tag{12}$$

where

$$\eta_k = \frac{1}{\lambda + k\mu} \tag{13}$$

is the mean sojourn time in state (k, j), and η is the average time interval between the successive points of state transitions, given by

$$\eta = \sum_{k=0}^{K} \sum_{j=0}^{3} p_{k,j} \cdot \eta_k. \tag{14}$$

Furthermore, the marginal probability that there are k MNs in the MAP domain at an arbitrary time is given by

$$p_k = \sum_{j=0}^{3} \widetilde{p}_{k,j}. \tag{15}$$

2.4 Value iteration for the semi-Markov decision process

Situations that ongoing communications are forcibly terminated generally displease the user more than initial registration failures. Thus we impose different rejection cost for new MNs, sleep mode hand-off MNs, and active mode hand-off MNs. We then try to minimize the average cost per unit time over the long term. The cost should quantify the pain that a rejected mobile user feels.

A policy that rejects a new MN even if a capacity of the MAP is not full may reject fewer hand-off MNs on average than another policy that accepts a new MN whenever the MAP is not full. The "policy" means an action to take at every decision epoch. Finding the optimal policy is the goal of our dynamic control policy. That is, the optimal choice of actions (reject or accept a MN) depending on the state at a decision epoch is constructed so as to minimize the average cost.

In order to find the optimal policy, we employ a semi-Markov decision process in a fashion similar to [9, 10]. The process is observed when a binding update message of an MN expires its lifetime, a registered MN goes out of the MAP domain, a new MN is placed, a sleep mode hand-off MN arrives, or an active mode hand-off MN arrives. After observing one of these events, decision is made according to the policy and the corresponding cost is incurred as a consequence. The set of possible states in the process is denoted by

$$\mathcal{I} = \{\boldsymbol{x} = (k,j) \mid 0 \le k \le K, 0 \le j \le 3\} \backslash \{\boldsymbol{x} = (K,0)\}, \tag{16}$$

where state $\boldsymbol{x} = (k,j)$ is defined in Section 2.3.

Suppose that the cost function is given by

$$C_{\boldsymbol{x}}(\boldsymbol{a}_k) = (1 - \boldsymbol{a}_k)\gamma_j \qquad \boldsymbol{x} = (k,j), \tag{17}$$

where $\boldsymbol{a}_k = (a_{(k,1)}, a_{(k,2)}, a_{(k,3)})$ is the action triplet. $C_{\boldsymbol{x}}(\boldsymbol{a}_k)$ represents the instantaneous cost if action $\boldsymbol{a}_k$ is chosen at state $\boldsymbol{x} = (k,j)$. γ_j quantifies the pain which a rejected user feels at state $\boldsymbol{x} = (k,j)$, where we let $\gamma_0 = 0$ and $\gamma_1 \le \gamma_2 \le \gamma_3$.

The expected time until the next decision epoch in state $\boldsymbol{x} = (k,j)$ is given by

$$\tau_{\boldsymbol{x}} = \frac{1}{\lambda + k\mu}. \tag{18}$$

The transition probability from state $\boldsymbol{x} = (k,j)$ to state $\boldsymbol{x'}$ if action $\boldsymbol{a}_k$ is chosen is given by

$$P_{\boldsymbol{x},\boldsymbol{x'}}(\boldsymbol{a}_k) = \begin{cases} q_{k,k-1} & \boldsymbol{x'} = (k-1, 0) \\ q_{k,k+1}^{(j)} & \boldsymbol{x'} = (k+1, j) \qquad 1 \le j \le 3 \\ q_{k,k} & \boldsymbol{x'} = \boldsymbol{x} \\ 0 & \text{otherwise.} \end{cases} \tag{19}$$

The value iteration algorithm is applied to our semi-Markov decision process for determining the optimal policy. To do so, we convert the semi-Markov decision model into a discrete time Markov decision model such that the average costs per unit time over the long term of each stationary policy are the same in both models. This is done by a method called uniformization [15, Section 3.4]. For the conversion, we choose a time unit τ in the discrete time model as

$$0 \le \tau \le \min_{\boldsymbol{x} \in \mathcal{I}} \tau_{\boldsymbol{x}} = \frac{1}{\lambda + K\mu}. \tag{20}$$

Then a decision epoch occurs in time τ with probability $\tau/\tau_{\boldsymbol{x}}$ and it does not with probability $1 - \tau/\tau_{\boldsymbol{x}}$. The transition probabilities in the discrete time model are given by

$$\bar{P}_{\boldsymbol{x},\boldsymbol{x'}}(\boldsymbol{a}_k) = \begin{cases} \dfrac{\tau}{\tau_{\boldsymbol{x}}} P_{\boldsymbol{x},\boldsymbol{x'}}(\boldsymbol{a}_k) & \boldsymbol{x'} \ne \boldsymbol{x} = (k, j) \\ \dfrac{\tau}{\tau_{\boldsymbol{x}}} P_{\boldsymbol{x},\boldsymbol{x}}(\boldsymbol{a}_k) + \left\{1 - \dfrac{\tau}{\tau_{\boldsymbol{x}}}\right\} & \boldsymbol{x'} = \boldsymbol{x} = (k, j) \end{cases}. \tag{21}$$

If the current state is $\boldsymbol{x} = (k, j)$ and action $\boldsymbol{a}_k$ is chosen, the average cost per unit time until the next decision epoch is given by $C_{\boldsymbol{x}}(\boldsymbol{a}_k)/\tau_{\boldsymbol{x}}$. The quantity $V_n(\boldsymbol{x})$ is introduced as the minimal total expected cost with n steps left to the time horizon when the current state is $\boldsymbol{x}$ in the discrete time process. Since the goal is to minimize the average cost per unit time over the long term, we must go backward in the time axis until the one-step difference $V_n(\boldsymbol{x}) - V_{n-1}(\boldsymbol{x})$ converges.

The value iteration algorithm for finding the optimal policy in the discrete time model is described as follows:

1. Choose $V_0(\boldsymbol{x})$ such that $0 \le V_0(\boldsymbol{x}) \le \dfrac{1}{\tau_{\boldsymbol{x}}} \min_{\boldsymbol{a}_k} \{C_{\boldsymbol{x}}(\boldsymbol{a}_k)\}$ for all $\boldsymbol{x} = (k, j) \in \mathcal{I}$. Set $n := 1$.

2. Compute for $\boldsymbol{x} = (k, j) \in \mathcal{I}$

$$V_n(\boldsymbol{x}) = \min_{\boldsymbol{a}_k} \left[\frac{C_{\boldsymbol{x}}(\boldsymbol{a}_k)}{\tau_{\boldsymbol{x}}} + \frac{\tau}{\tau_{\boldsymbol{x}}} \sum_{\boldsymbol{x}' \in \mathcal{I}} P_{\boldsymbol{x},\boldsymbol{x}'}(\boldsymbol{a}_k) V_{n-1}(\boldsymbol{x}') + \left\{ 1 - \frac{\tau}{\tau_{\boldsymbol{x}}} \right\} V_{n-1}(\boldsymbol{x}) \right] \tag{22}$$

   by determining the action $\boldsymbol{a}_k$ that minimizes the quantity in the brackets.

3. Compute the upper and lower bounds of the one-step difference by

$$M_n = \max_{\boldsymbol{x} \in \mathcal{I}} \{V_n(\boldsymbol{x}) - V_{n-1}(\boldsymbol{x})\} \quad \text{and} \quad m_n = \min_{\boldsymbol{x} \in \mathcal{I}} \{V_n(\boldsymbol{x}) - V_{n-1}(\boldsymbol{x})\} \tag{23}$$

4. If $0 \le M_n - m_n \le \epsilon m_n$, then stop the algorithm with the optimal set of actions for all $\boldsymbol{x}$. Otherwise $n := n + 1$ and go to step 2.

Here, ϵ is a prespecified small positive constant (tolerance number) for stopping the iteration. In our numerical experiments, the algorithm had convergence with $\epsilon = 10^{-3}$.

Once the optimal policy $\{\boldsymbol{a}_k = (a_{(k,1)}, a_{(k,2)}, a_{(k,3)}); 0 \le k \le K - 1\}$ is determined, we can obtain the steady state probabilities $p_{k,j}$ and then $\widetilde{p}_{k,j}; 0 \le k \le K, 0 \le j \le 3$, as shown in Section 2.3.

3 Performance Measures

In this section, we define some performance measures to compare the dynamic admission control method with various ratios $\gamma_1 : \gamma_2 : \gamma_3$, the non-admission control model, and the static control method based on the guard channel scheme. We will use the probability of blocking new MNs, the probability of blocking sleep mode hand-off MNs, and the probability of forced termination of active mode hand-off MNs. We also consider the MAP's resource utilization as a measure of effective resource usage for each method.

3.1 Blocking and forced termination probabilities

There are three cases that irritate mobile users. One is that a user who newly tries to enter the network is rejected the binding update by a MAP because the capacity of the MAP is full, which results in the blocking of a new MN. Another is that the binding update of a user who tries to cross the MAP domain while not in communication is rejected, which is the blocking of a sleep mode hand-off MN. The last one is that the ongoing communication is forcibly terminated by the failed binding update of a mobile user who tries to cross the MAP domain during communication, which is the forced termination of an active mode hand-off MN. Therefore, we consider the probability of blocking new MNs, the probability of blocking sleep mode hand-off MNs, and the probability of forced termination of active mode hand-off MNs as performance measures from user's viewpoint.

In the guard channel scheme considered in Section 2.2, if a new MN is placed and there are g_{sa} or more MNs in the MAP domain, it is blocked. Similarly, if a sleep mode hand-off MN arrives when there are g_a or more MNs in the MAP domain, it is blocked. Forced termination of an active mode hand-off MN occurs only if the MAP's capacity is full when it arrives. It is assumed that MNs arrive according to Poisson processes independently. Let P_{bn} and P_{bhs} denote the probabilities of blocking new and sleep mode hand-off MNs, respectively. Let P_{fha} be the probability of forced termination of active mode hand-off MNs. Using the PASTA (Poisson Arrivals See Time Averages) property [14, section 11-2], we have

$$P_{bn} = \sum_{k=g_{sa}}^{K} p_k \tag{24}$$

$$P_{bhs} = \sum_{k=g_a}^{K} p_k \tag{25}$$

$$P_{fha} = p_K, \tag{26}$$

where $p_k; 0 \leq k \leq K$ is the probability that there are k MNs in the MAP domain, given in (3) and (4).

In the dynamic admission control considered in Section 2.3, if a MN is placed in the MAP domain and the action that follows the optimal policy is "reject", it is blocked. Thus the probabilities of blocking three types of MNs, defined above, are given by

$$P_{bn} = \sum_{k=0}^{K} [1 - a_{(k,1)}] p_k \tag{27}$$

$$P_{bhs} = \sum_{k=0}^{K} [1 - a_{(k,2)}] p_k \tag{28}$$

$$P_{fha} = \sum_{k=0}^{K} [1 - a_{(k,3)}] p_k, \tag{29}$$

where $p_k; 0 \leq k \leq K$ is given in (15).

3.2 Resource utilization at mobility anchor point

Another performance measure is the resource utilization U at a MAP. It is given as the ratio of the average number N of MNs present in the MAP domain to the capacity K of the MAP:

$$U = \frac{N}{K}, \tag{30}$$

where

$$N = \sum_{k=1}^{K} k \cdot p_k. \tag{31}$$

From the viewpoint of the efficiency in using the resource at the MAP, it is nice to have high value of U. However, as the utilization U increases, the blocking probabilities usually grow, resulting in the user's dissatisfaction.

4 Numerical Experiments

Numerical experiments have been carried out in order to evaluate the impact of each admission control method on the performance. It has been assumed throughout our experiments that the average lifetime of a binding update is $1/\mu_1 = 3$ (minutes) and that the average residence time in a MAP domain is $1/\mu_2 = 5$ (minutes). The capacity of a MAP is assumed to be $K = 20$. For the static guard channel scheme, it has been assumed that the first threshold g_{sa} is 17 and the second threshold g_a is 19. These values for g_{sa} and g_a have been chosen arbitrarily as there seems no reasonable correspondence between the threshold values in the guard channel scheme and the ratio $\gamma_1 : \gamma_2 : \gamma_3$ in the dynamic control method.

We examine the effectiveness of our dynamic admission control by means of the blocking probability of new MNs, the blocking probability of sleep mode hand-off MNs, and the forced termination probability of active mode hand-off MNs as well as the MAP's resource utilization. In the legend of the figures shown below, "non-AC" means that no admission control is adopted, "HA", "HS", and "New" mean active mode hand-off MNs, sleep mode hand-off MNs, and new MNs, respectively. The "guard channel" means that the static guard channel scheme is adopted.

4.1 Calculation of the hand-off MN arrival rate

In the modeling and performance analysis in Sections 2 and 3, we have assumed that new, sleep mode hand-off, and active mode hand-off MNs arrive in the MAP domain

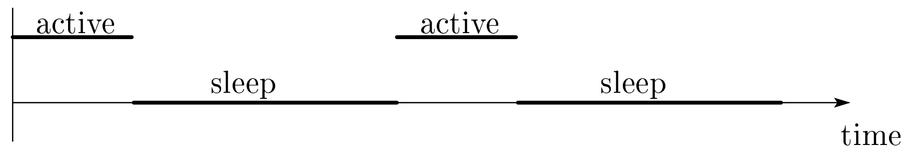

Figure 4: Alternating active and sleep periods of a MN.

independently. However, it is realistic to consider that hand-off MNs are generated when MNs leaving the adjacent domain come in. We present a technique for estimating the arrival rates of sleep and active mode hand-off MNs when the arrival rate of new MNs is given.

Suppose that the network consists of independent and statistically identical MAP domains. Then the inbound hand-off rate can be considered equal to the outbound rate to adjacent MAP domains. Given the steady state probabilities for the number of MNs existing in the MAP domain, the inbound hand-off rate λ_H from neighboring MAP domains can be determined by the fixed-point method [7, 8]. By this method, an iterative algorithm to calculate λ_H is given as follows:

1. Initialize $\lambda_H = 0$.
2. Calculate $p_k; 0 \leq k \leq K$ as shown in Section 2.
3. Compute
$$\lambda_H = \sum_{k=0}^{K} (k\mu_2) \cdot p_k. \tag{32}$$
4. Repeat steps 2 and 3 until λ_H converges.

Next, we obtain the arrival rates λ_2 and λ_3 for the sleep and active mode hand-off MNs. To do so, let us assume that each MN alternates periods of active and sleep modes as shown in Figure 4. The average active and sleep mode times are denoted by $1/\mu_{active}$ and $1/\mu_{sleep}$, respectively. Both times are assumed to be exponentially distributed. The probability p_{active} that a MN is active at an arbitrary point in time is given by the theory of alternating renewal processes [14, section 5-6] as

$$p_{active} = \frac{\frac{1}{\mu_{active}}}{\frac{1}{\mu_{active}} + \frac{1}{\mu_{sleep}}}. \tag{33}$$

Therefore, we get

$$\lambda_2 = (1 - p_{active}) \cdot \lambda_H \tag{34}$$

and

$$\lambda_3 = p_{active} \cdot \lambda_H. \tag{35}$$

In our numerical experiments, we have assumed that the average active period of a MN is $1/\mu_{active} = 2$ (minutes) and that the average sleep period of a MN is $1/\mu_{sleep} = 3$ (minutes). Therefore, the probability that a MN is active at an arbitrary point in time is $p_{active} = 0.4$.

For the dynamic admission control case, step 2 in the above algorithm is conducted with the interim values of λ_2 and λ_3 along with the time unit

$$\tau = \frac{1}{\lambda + 2K\mu} \tag{36}$$

in the value iteration algorithm for the discrete time Markov decision process model.

We omit plotting λ_H as a function of λ_1 as λ_H is proportional to the MAP's resource utilization U shown in Figure 11. From Figure 11 we can say that the hand-off rate λ_H is less for the static guard channel scheme and the dynamic admission control cases with larger ratio $\gamma_1 : \gamma_2 : \gamma_3$. In these cases the arrivals of new and sleep mode hand-off MNs are more likely to be blocked in order to reserve more resource for the benefit of accepting active mode hand-off MNs.

4.2 Performance results and discussion

Figures 5, 6, and 7 show the maximum number of new, sleep mode hand-off, and active mode hand-off MNs that are allowed to be admitted in a MAP domain as a result of optimization. For the dynamic admission control with given ratio $\gamma_1 : \gamma_2 : \gamma_3$, fewer new and sleep mode hand-off MNs can be served as the arrival rate λ_1 of new MNs increases. However, in Figure 6, sleep mode hand-off MNs are not rejected until the MAP's resource is exhausted, because its rejection cost is the same as for active mode hand-off MNs. No rejection of MNs occurs under the MAP's capacity in the non-AC case.

Figure 8 shows the blocking probability P_{bn} of new MNs as a function of the new MN arrival rate λ_1. Since our dynamic admission control restricts new MNs for the benefit of hand-off MNs, it is reasonable that the larger the ratio $\gamma_1 : \gamma_2 : \gamma_3$, the larger the blocking probability of new MNs. For example, at $\lambda_1 = 8$ the values of P_{bn} after implementation of the dynamic admission control with $\gamma_1 : \gamma_2 : \gamma_3 = 1 : 5 : 5$

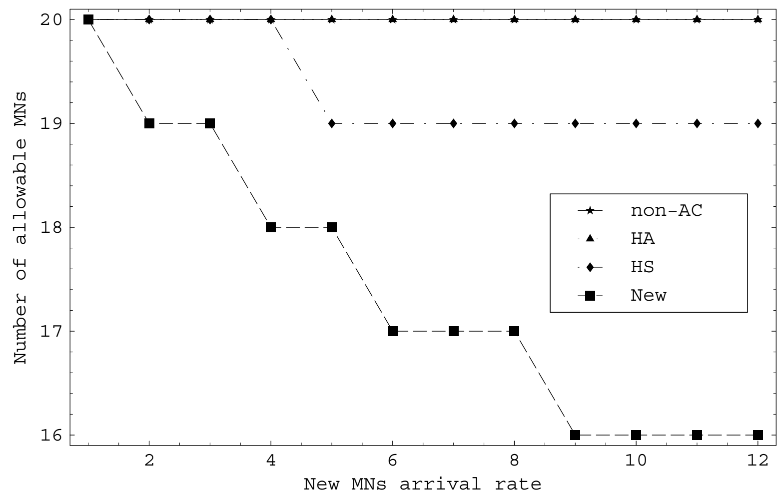

Figure 5: Number of MNs allowed in a MAP domain ($\gamma_1 : \gamma_2 : \gamma_3 = 1 : 1 : 5$).

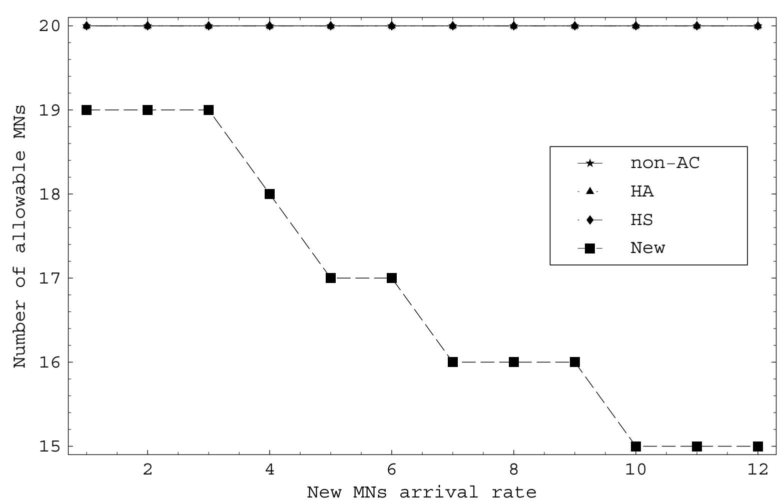

Figure 6: Number of MNs allowed in a MAP domain ($\gamma_1 : \gamma_2 : \gamma_3 = 1 : 5 : 5$).

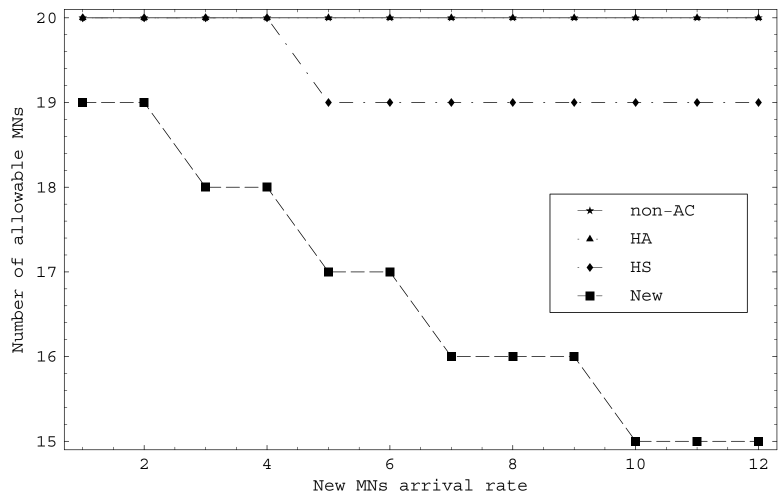

Figure 7: Number of MNs allowed in a MAP domain ($\gamma_1 : \gamma_2 : \gamma_3 = 1 : 2 : 10$).

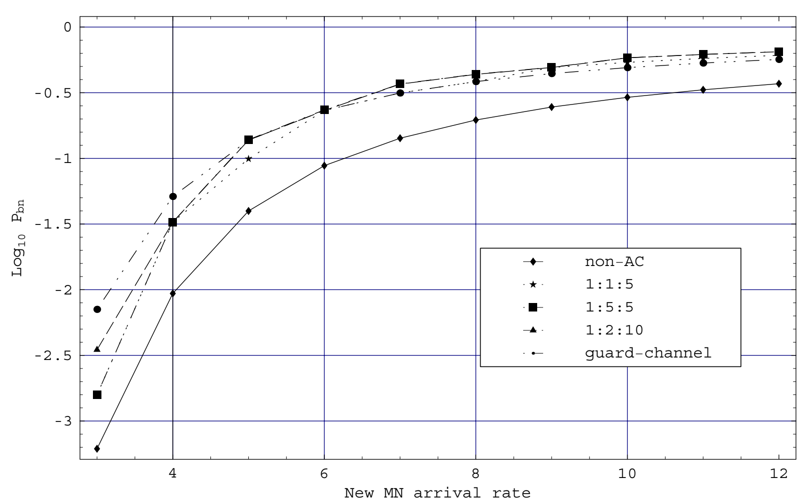

Figure 8: Blocking probability of new MNs.

and 1 : 2 : 10 are 1.9 and 2.2 times larger, respectively, than that under the non-AC. However, the blocking probabilities of new MNs when the static guard channel scheme is adopted can be made very close to those in the case of dynamic admission control by choosing the threshold values properly.

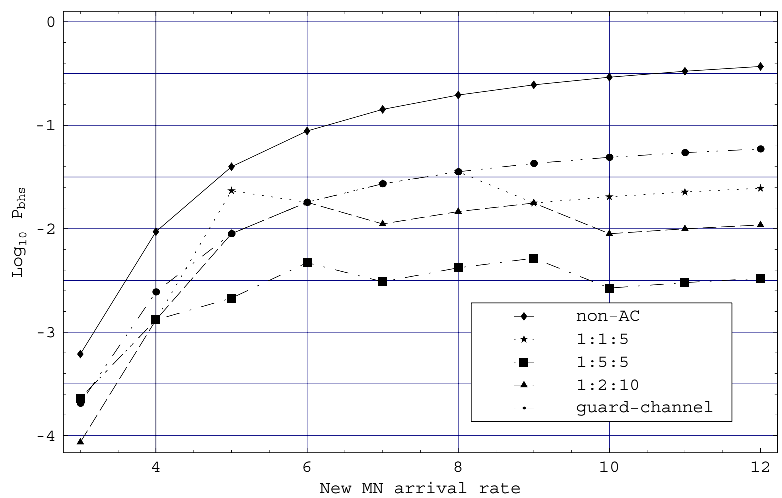

Figure 9: Blocking probability of sleep mode hand-off MNs.

Figure 9 shows the blocking probability P_{bhs} of sleep mode hand-off MNs as a function of the new MN arrival rate λ_1. As sleep mode hand-off MNs have advantage over new MNs, P_{bhs} is smaller under the dynamic admission control with larger ratio $\gamma_1 : \gamma_2 : \gamma_3$. For example, at $\lambda_1 = 10$ the blocking probabilities when the dynamic admission control is adopted with $\gamma_1 : \gamma_2 : \gamma_3 = 1 : 5 : 5$ and $1 : 2 : 10$ are 1/100 and 3/100 times smaller, respectively, than that under the non-AC as well as 5/100 and 18/100 times smaller, respectively, than that under the static guard channel scheme.

In Figure 10, we plot the forced termination probability P_{fha} of active mode hand-off MNs as a function of the new MN arrival rate λ_1. As active mode hand-off MNs have great advantage over new and sleep mode hand-off MNs under the dynamic admission control with large ratio $\gamma_1 : \gamma_2 : \gamma_3$, the forced termination probabilities are significantly smaller at high load conditions. This is the highlight of our dynamic control method. We may remark that the blocking probability in Figure 9 and the forced termination probability in Figure 10 drop abruptly, e.g., at $\lambda_1 = 7$ and $\lambda_1 = 10$ for $\gamma_1 : \gamma_2 : \gamma_3 = 1 : 5 : 5$ and $1 : 2 : 10$. The reason is that the number of MNs allowed in the MAP domain is decremented by one at those arrival rates as observed in Figures 6 and 7.

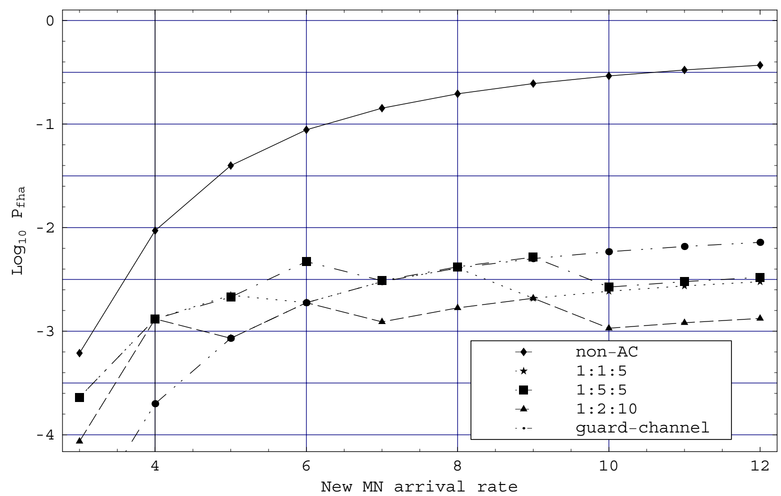

Figure 10: Forced termination probability of active mode hand-off MNs.

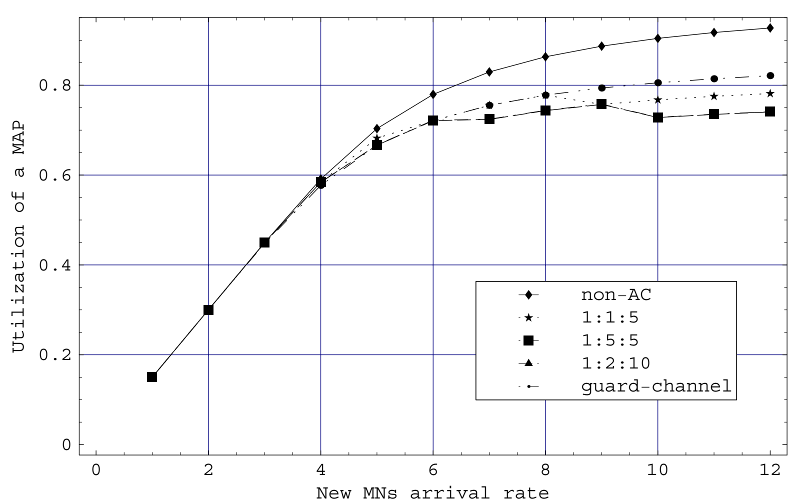

Figure 11: Resource utilization of a MAP.

In addition, Figures 9 and 10 show the static guard channel scheme (with properly chosen threshold values) yield a little better results in comparison with the dynamic admission control method at light load conditions. However, the dynamic admission control method outperforms the static guard channel scheme at heavy load conditions without much difference in the blocking probability of new MNs as shown in Figure 8.

Figure 11 shows the resource utilization of a MAP. The utilization values under the dynamic admission control with $\gamma_1 : \gamma_2 : \gamma_3 = 1 : 1 : 5$, $1 : 5 : 5$, and $1 : 2 : 10$ are 84.3%, 79.9%, and 79.8%, respectively, of the value under the non-AC at $\lambda_1 = 12$. In these cases, although the resource of a MAP is less utilized, the control leads to a certain reduction in the probability of blocking sleep mode hand-off MNs and the probability of forced termination of active mode hand-off MNs as shown in Figure 9 and Figure 10.

5 Concluding Remarks

In this paper, we have proposed static and dynamic admission control methods for the address binding update of MNs and analyzed their performance in terms of the blocking probability for the MAP domain in an HMIPv6 network. We have presented some numerical results leading to the comparison among dynamic control cases with different parameters and the comparison with the static control method based on the guard channel scheme as well as the non-admission control case. We have used various theories for stochastic processes such as a one-dimensional birth-and-death process, a two-dimensional Markov chain, a semi-Markov decision process, an alternating renewal process, and uniformization. According to the numerical experiments, our dynamic admission control reduces the blocking probability of sleep mode hand-off MNs and significantly the forced termination probability of active mode hand-off MNs at little expense of blocking new MNs.

As usual with optimization by Markov decision processes, the computational time may be an obstacle to apply our dynamic admission control method to real systems. However, our results could be used as a benchmark against those by quick approximate optimizing methods.

The mechanism of MAP selection [5] has not been considered in this paper. A MN entering a MAP domain receives router advertisements (RAs) containing information on one or more local MAPs. After receiving the RA, the MN configures its LCoA and RCoA. If the MN receives several RAs, it selects one of MAPs. This procedure is called MAP selection. If a MN can find a MAP which does not suffer from traffic congestion, the performance of the dynamic admission control may be better. Estimate of the performance gain obtained by the MAP selection is one of our future works.

References

[1] C. E. Perkins, “IP mobility support,” *Request for Comments (RFC) 2002*, October 1996.

[2] C. E. Perkins, “Mobile IP,” *IEEE Communications Magazine*, Vol. 35, No. 5, pp. 84–99, May 1997.

[3] C. E. Perkins, *Mobile IP: Design Principles and Practices.* Reading, Massachusetts, Addison-Wesley, 1998.

[4] C. E. Perkins and D. B. Johnson, “Mobility support in IPv6,” *Proceedings of the Second Annual International Conference on Mobile Computing and Networking (MobiCom'96)*, pp. 27–37, Rye, New York, November 10–12, 1996.

[5] H. Soliman, C. Catelluccia, K. E. Malki, and L. Bellier, “Hierarchical mobile IPv6 mobility management (HMIPv6),” *IETF Network Working Group*, October 2004. http://www.ietf.org/internet-drafts/draft-ietf-mipshop-hmipv6-03.txt

[6] D. H. Hong and S. S. Rappaport, “Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and nonprioritized handoff procedures,” *IEEE Transactions on Vehicular Technology*, Vol. VT-35, No. 3, pp. 77–92, August 1986.

[7] K. Sakamaki and H. Takagi, “Evaluation of call loss and forced termination probabilities in cellular communication systems,” *The Transactions of the Institute of Electronics, Information and Communication Engineers B-II*, Vol. J80-B-II, No. 3, pp. 231–238, March 1997 (in Japanese).

[8] H. Takagi, K. Sakamaki, and T. Miyashiro, “Call loss and forced termination probabilities in cellular radio communication networks with non-uniform traffic conditions,” *IEICE Transactions on Communications*, Vol. E82-B, No. 9, pp. 1496–1504, September 1999.

[9] W-B. Yang and E. Geraniotis, “Admission policies for integrated voice and data traffic in CDMA packet radio networks,” *IEEE Journal on Selected Areas in Communications*, Vol. 12, No. 4, pp. 654–664, May 1994.

[10] M. Ohmikawa, H. Takagi, and S.-Y. Kim, "Optimal call admission control for voice traffic in cellular mobile communication networks," Discussion paper No. 1095, Institute of Policy and Planning Sciences, University of Tsukuba, September 2004.

[11] S. Pack, T. Kwon, and Y. Choi, "A mobility-based load control scheme at mobility anchor point in hierarchical mobile IPv6 networks," *IEEE Global Telecommunications Conference (GLOBECOM) 2004*, Dallas, November 2004.

[12] Y. Fang and Y. Zhang, "Call admission control schemes and performance analysis in wireless mobile networks," *IEEE Transactions on Vehicular Technology*, Vol. 51, No. 2, pp. 371–382, March 2002.

[13] A. Vasilache, J. Li, and H. Kameda, "Threshold-based load balancing for multiple home agents in mobile IP networks," *Telecommunication Systems*, Vol. 22, No. 1–4, pp. 11–31, January–April 2003.

[14] D. P. Heymann and M. J. Sobel, *Stochastic Models in Operations Research, Volume I: Stochastic Processes and Operating Characteristics.* McGraw-Hill Book Company, New York, 1982.

[15] H. C. Tijms, *Stochastic Models: An Algorithmic Approach.* John Wiley & Sons, Chichester, England, 1994.