Analysis of a Mobility Management Scheme Considering Battery Power Conservation in IP-Based Mobile Networks

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***Abstract*—Mobile hosts (MHs) in all IP-based mobile networks must update their current location to receive incoming packets. The MHs are idle for most of time. Both registration of approximate location information and paging can facilitate efficient power management for the idle MHs. Furthermore, the MHs can be in switch-off state for battery power conservation. Mobile IP, the current standard for IP-based mobility management, needs to be enhanced for use in all IP-based mobile networks. Mobility management in all IP-based mobile networks should consider idle and detached MH states as well as active MH state. A mobility management scheme for all IP-based mobile networks is introduced in this paper. This scheme includes management of communicating, attentive, idle, and detached states. We model MH behavior in the networks when the binding-lifetime-based registrations are utilized as a means of identifying that an MH is switched off. The steady-state probabilities for MH state transitions are derived, and an optimal rate of binding-lifetime-based registrations that results in minimum network cost is derived.**

***Index Terms*—Binding-lifetime-based registrations, communicating state, detached state, idle state, IP-based mobile network, mobile IP, mobility management, paging.**

I. INTRODUCTION

NEXT-GENERATION mobile networks will be envisioned as all IP-based networks. In such networks, mobility management should be based on IETF concept. It has been recognized that Mobile IP [1], [2], the current standard for IP-based mobility management, needs to be enhanced for use in next generation mobile networks. The base Mobile IP specification does not support any form of paging. In the absence of paging support a mobile host (MH) must obtain a local care-of address (CoA) and register the CoA with its mobility agent every time it changes its current subnet, even if it is currently in *idle* or dormant state. This leads to significant waste of an MH's battery power. It is thus important to define some form of paging support in the mobility management scheme. There have been many research efforts on IP paging support [3]–[8]. A functional architecture and requirements for an IP paging protocol have been developed [3]. Reference [5] proposed an extension of Mobile IP with adaptive individual paging. In the scheme, each mobile host computes dynamically its optimal location area size according to its traffic and mobility parameters. Reference [6] proposed an extension to the hierarchical Mobile IPv6 with regional registrations to allow an MH to enter an idle mode. The P-MIP [7] is an extension to Mobile IP that is designed to reduce signaling load in the core Internet and power consumption of mobile nodes.

MHs are usually battery-powered, and they can be in a power-off state in order to save their battery power. It is also important to manage the detached MH state in the mobility management scheme for efficient use of radio and network resources. Many IP-based mobility management schemes [6]–[8] did consider an extension to the base Mobile IP only for paging support for idle MHs and did not consider detached state in addition to active and idle states. When a network supporting an IP paging service does not manage the detached MH state, incoming packets destined to the detached MH result in unsuccessful paging, causing inefficient use of both network and radio resources. There were some investigations for management of the *on/off* state information of mobile terminals in personal communication service environments [9], [10]. In [9] two mobile terminal (MT) power on/off state management schemes based on the level of location registers (LRs) for managing the state information of MTs were introduced. Markoulidakis *et al.* [10] analyzed a periodic attach scheme to detect the off state of a mobile terminal.

There have been some investigations into analytical model design issues for Mobile IP [11]–[15]. Kim and Song [11] proposed a time-based binding update model with a periodic time unit, and analyzed the performance with respect to the processing delay and network load by assuming M/M/1 queuing systems. Zhang *et al.* [12] proposed an IP paging protocol that can be independent of any mobility management protocol, and analyzed the signaling cost which was measured as the product of the signaling rate and weighted distance a signaling message traveled. Khan and Nazir [14] presented a signaling cost analysis of IP-based protocols by varying the paging area size and the velocity of mobile node. To calculate the total signaling costs, a model with a single paging area was considered. Kim and Kim [15] proposed a simulation model and a queuing network model for the performance evaluation of Mobile IP. The suggested queuing network model consisted of two stages of $M/M/1$ queues with priorities.

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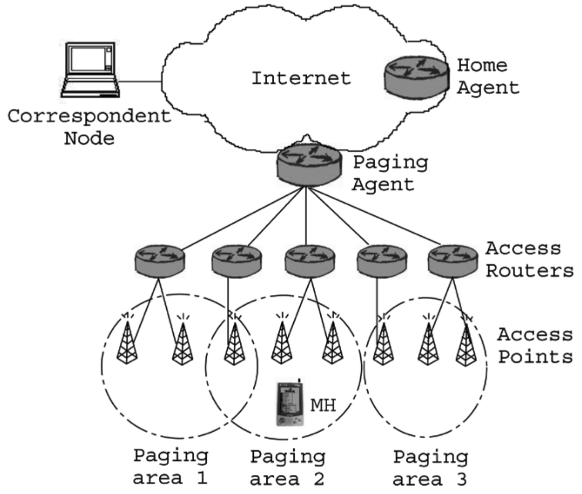

Fig. 1. IP-based cellular network architecture.

In this paper, we introduce an IP-based mobility management scheme for all IP-based mobile networks. The mobility management scheme distinguishes between MHs that are actively communicating, attentive, idle or detached. Power-off actions of MH can be notified to the network explicitly or implicitly. Explicit notification of switch-off actions of the MH is possible by a detachment extension to the base Mobile IP.

In Mobile IP, MH must perform registration whenever binding lifetime expires and we call it *binding-lifetime-based registration* in this paper. This binding-lifetime-based registrations can be utilized as a means that the network identifies that an MH is switched off. We evaluate the characteristics of the IP-based mobility management scheme when the binding-lifetime-based registrations are utilized as a means of identifying that an MH is switched off. The steady-state analysis in this paper is based on the semi-Markov process because the residence time of an MH in each state does not follow an exponential distribution. Analysis based on semi-Markov process was previously performed in [10] and [16]. We formulate the rate of binding-lifetime-based registrations that results in minimum network cost, and compare two probability distributions of the registration intervals.

This paper is organized as follows: An all IP-based cellular network architecture and a mobility management scheme for the network architecture are presented in Section II. MH state transitions are modeled, steady-state probabilities of MH states are analyzed, and the optimal rate for MH registration messages is derived in Section III. Numerical examples are used to investigate the steady-state probabilities of MH states, energy consumption, and network load in Section IV. Conclusions are presented in Section V.

II. MH STATES AND STATE TRANSITION MODEL

Fig. 1 shows an IP-based cellular network architecture. An access point is a layer 2 device providing MHs with wireless link. An access router connects one or more access points and provides MHs with IP connectivity, acting as a default router to the MHs currently served.

Mobile IPv6 is herein considered as a reference mobility protocol. The mobility management scheme we consider manages communicating, attentive, idle, and detached states. Changes in the correspondent node (CN) and home agent (HA) are not necessary. Communicating and attentive MH's behave in the same manner as in Mobile IPv6. Thus, when MH is in communicating or attentive state, a colocated care-of address (CCoA) associated with the MH is registered at the HA, and the paging agent is not involved in the registration procedure. It is assumed that an MH will remain communicating state during a packet train transmission, i.e., a data session. When the data session is completed, the MH enters attentive state and *attention timer* is reset and started. Attention timer is used to determine the instant when the MH enters idle state. As new data session arrives when the MH is in the attentive state, the MH enters communicating state.

Paging agent is used to manage paging-related functionality and the *detached* state. A paging area consists of two or more access routers and has a unique paging area identifier (PAI). As the attention timer expires, the MH enters the idle state by performing an *idle state registration*. Through idle state registration the MH registers the PAI with the paging agent, and the paging agent address is registered at the HA of the MH. When an idle MH moves to a different paging area, it registers a new PAI with the paging agent.

When packets destined for an idle MH arrive at HA, the packets are tunneled to the paging agent, as in Mobile IP. Thus, the HA is unaware of the idle MH state. The paging agent buffers the packet and sends a *paging request* message to all access routers in the paging area. The message is sent to the MH via access points. The idle MH enters the communicating state, sends a *paging reply* message to the paging agent, and simultaneously registers its CCoA with the HA. The paging agent forwards the buffered packets and the MH sends a binding update (BU) to the CN.

An MH in the communicating state can simply send data. An idle MH that is ready to send data reenters the communicating state by restoring the exact routing information. This is achieved in Mobile IPv6 by registering the current CCoA with the paging agent, the home agent, and the corresponding node.

Transition to the detached state is achieved by explicit detachment, unsuccessful paging, or no registration until the binding lifetime of the MH expires. For management of the detached MH state, an explicit notification message of MH switch-off action can be defined as an extension to the base Mobile IP. If the HA puts no limitation on the maximum binding lifetime, the idle MH does not need to refresh the home agent binding. Otherwise, the MH must perform a BU in order to refresh the home agent binding before the lifetime expires. If the home agent or the paging agent puts a limitation on the maximum binding lifetime, binding-lifetime-based registrations can be utilized as a means for identifying that the MH is switched off. In this case, the network considers the MH state to be detached if the network detects silence for more than an agreed time period or if the MH does not respond to paging. In this paper, we neglect the possibilities of paging failure for an MH in the idle state. Thus, we assume that if an MH is in the idle state, the network can always find the MH. Since the switch-off action is not explicitly notified, the MH state remains hidden to the network for a limited time. In this case an MH has the following states.

1) *Communicating state*: When an MH is in the communicating state, there is an ongoing session for the MH and it can send and receive IP packets. The MH performs Mobile IP registration when it changes the serving router. The MH leaves this state by session completion or a switch-off action.
2) *Attentive state*: In this state there is no ongoing session for the MH. The MH performs Mobile IP registration when it changes the serving router or when it enters this state from the *off/attached* or *detached* state. When an incoming or outgoing session arrives, the MH enters communicating state. When an *attention timer* expires, the MH enters idle state by performing an idle state registration. If the MH is switched off, it enters the off/attached state.
3) *Idle state*: The MH in this state performs an idle state registration in order to register a new PAI with the paging agent or to extend the lifetime of the previous idle state registration. The MH leaves this state when it is switched off or when an incoming or outgoing session arrives. This idle MH is not currently involved in an ongoing session and operates in a power conversation mode.
4) *Off/attached state*: When the MH is switched off, the MH does not informed paging agent of this action immediately. When the registration lifetime expires or paging is unsuccessful, the network will detach the MH. When the MH is switched on again, it enters the attentive state by performing Mobile IP registration.
5) *Detached state*: When the network identifies that the MH is in the switch-off state, it detaches the MH. When the MH is switched-off or detached, it neither sends location registration nor responds to paging. When the MH is switched on, it leaves the detached state and enters the attentive state by sending a BU to its HA according to Mobile IP protocol.

III. ANALYSIS OF MH STATE TRANSITIONS

A. Steady-State Probabilities

The steady-state probabilities of MH states are derived. For simplicity, MH movement within a paging area is considered. This assumption is justified when the paging area is large. We make the following assumptions regarding the density functions of random variables.

1) Switch-off actions, incoming and outgoing sessions at an MH occur according to a Poisson process with parameters $\lambda_{\text{off}}, \lambda_t$, and λ_o, respectively.
2) Session holding time is generally distributed with a density function $f_s(t)$ with a mean $1/\mu_s$ and a distribution function $F_s(t)$.
3) The time that an MH remains switched off is exponential with a parameter of μ_{off}.
4) T_r is the interval of binding-lifetime-based registrations with a mean of $1/\lambda_r$, a distribution function $F_r(t)$, and a density function $f_r(t)$.

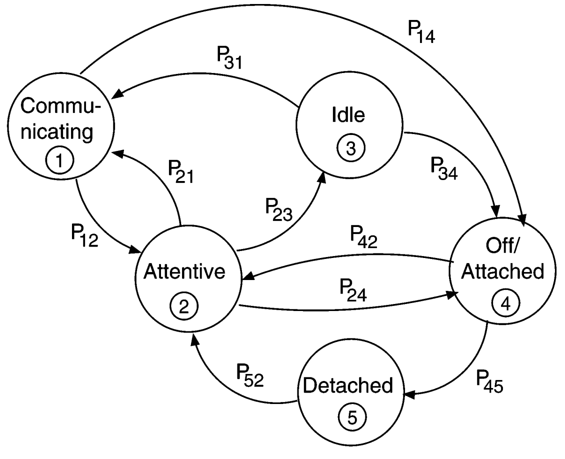

Fig. 2. MH state transition diagram.

Fig. 2 shows an MH state transition diagram. We analyze this diagram using a semi-Markov process because the time spent in each state is not exponential [17]. The stationary probabilities of an embedded Markov chain are obtained by solving the following equations:

$$\pi_j = \sum_{k=1}^{5} \pi_k P_{kj}, \quad j = 1, 2, \ldots, 5 \tag{1a}$$

$$\sum_{k=1}^{5} \pi_k = 1 \tag{1b}$$

where π_i is the stationary probability of state i, and P_{kj} is the state transition probability from states k to j. The state transition probability matrix $P = [P_{kj}]$ of the state transition diagram is given by

$$P = \begin{pmatrix} 0 & P_{12} & 0 & P_{14} & 0 \\ P_{21} & 0 & P_{23} & P_{24} & 0 \\ P_{31} & 0 & 0 & P_{34} & 0 \\ 0 & P_{42} & 0 & 0 & P_{45} \\ 0 & P_{52} & 0 & 0 & 0 \end{pmatrix}. \tag{2}$$

Equations (1a) and (1b) are solved as follows:

$$\pi_1 = \frac{1}{D}[1 - (P_{42} + P_{52}P_{45})(P_{24} + P_{23}P_{34})] \tag{3a}$$

$$\pi_2 = \frac{1}{D}[P_{12} + P_{14}(P_{42} + P_{52}P_{45})] \tag{3b}$$

$$\pi_3 = \frac{P_{23}}{D}[P_{12} + P_{14}(P_{42} + P_{52}P_{45})] \tag{3c}$$

$$\pi_4 = \frac{1}{D}[P_{12}(P_{24} + P_{23}P_{34}) + P_{14}] \tag{3d}$$

$$\pi_5 = \frac{P_{45}}{D}[P_{12}(P_{24} + P_{23}P_{34}) + P_{14}] \tag{3e}$$

where $D = 1 + (1 + P_{23})(P_{42} + P_{52}P_{45})P_{14} + P_{12}(P_{24} + P_{23}P_{34})(1 + P_{45}) + P_{14}(1 + P_{45}) + P_{12}(1 + P_{23}) - (P_{24} + P_{23}P_{34})(P_{42} + P_{52}P_{45})$. To find the state transition probability P_{kj} of the embedded Markov chain shown in Fig. 2, it is necessary to derive the distribution of the time interval T_{kj} from the moment an MH enters state k until the first event corresponding to state j occurs.

Exit from the *communicating* state is caused by either session completion (T_{12}) or a switch-off action (T_{14}). Since switch-off actions follow a Poisson process with parameter λ_{off}, the probability distribution of T_{14} becomes exponential with a mean of $1/\lambda_{\text{off}}$. The probabilities P_{12} and P_{14} are, therefore, obtained as

$$\begin{aligned} P_{12} &= \int_0^\infty f_s(t)\Pr[T_{14} > t]\,dt \\ &= \int_0^\infty f_s(t)e^{-\lambda_{\text{off}}t}\,dt = F_s^*(\lambda_{\text{off}}) \end{aligned} \tag{4a}$$

$$\begin{aligned} P_{14} &= \int_0^\infty f_{T_{14}}(t)\Pr[T_{12} > t]\,dt \\ &= \int_0^\infty \lambda_{\text{off}}e^{-\lambda_{\text{off}}t}[1 - F_s(t)]\,dt \\ &= 1 - F_s^*(\lambda_{\text{off}}) \end{aligned} \tag{4b}$$

where $F_s^*(\theta)$ is the Laplace transform of $f_s(t)$.

Exit from the *attentive* state is caused by any of following events: 1) arrival of an incoming or outgoing session (T_{21}), 2) a switch-off action (T_{24}), and 3) expiration of the attention timer (T_{23}). T_{21} and T_{24} are independent exponential random variables with respective means of $1/(\lambda_o + \lambda_t)$ and $1/\lambda_{\text{off}}$. If ξ denotes the attention timer value, probabilities P_{21}, P_{23}, and P_{24} are derived as follows:

$$\begin{aligned} P_{21} &= \int_0^\infty (\lambda_t + \lambda_o)e^{-(\lambda_t+\lambda_o)t}\Pr[T_{23} > t]\Pr[T_{24} > t]\,dt \\ &= \int_0^\xi (\lambda_t + \lambda_o)e^{-(\lambda_t+\lambda_o)t}e^{-\lambda_{\text{off}}t}\,dt \\ &= \frac{\lambda_t + \lambda_o}{\lambda_t + \lambda_o + \lambda_{\text{off}}}\left(1 - e^{-(\lambda_t+\lambda_o+\lambda_{\text{off}})\xi}\right) \end{aligned} \tag{5a}$$

$$\begin{aligned} P_{23} &= \int_0^\infty f_{T_{23}}(t)\Pr[T_{21} > t]\Pr[T_{24} > t]\,dt \\ &= \int_0^\infty \delta(t - \xi)e^{-(\lambda_t+\lambda_o)t}e^{-\lambda_{\text{off}}t}\,dt \\ &= e^{-(\lambda_t+\lambda_o+\lambda_{\text{off}})\xi} \end{aligned} \tag{5b}$$

$$P_{24} = \int_0^\infty f_{T_{24}}(t)\Pr[T_{23} > t]\Pr[T_{21} > t]\,dt \tag{5b}$$

$$\begin{aligned} &= \int_0^\xi \lambda_{\text{off}}e^{-\lambda_{\text{off}}t}e^{-(\lambda_o+\lambda_t)t}\,dt \\ &= \frac{\lambda_{\text{off}}}{\lambda_t + \lambda_o + \lambda_{\text{off}}}\left(1 - e^{-(\lambda_t+\lambda_o+\lambda_{\text{off}})\xi}\right). \end{aligned} \tag{5c}$$

Exit from the *idle* state is caused by either a switch-off action (T_{34}) or arrival of an incoming or outgoing session (T_{31}). T_{31} and T_{34} are exponential random variables with respective means of $1/(\lambda_o + \lambda_t)$ and $1/\lambda_{\text{off}}$. Therefore

$$\begin{aligned} P_{31} &= \int_0^\infty f_{T_{31}}(t)\Pr[T_{34} > t]\,dt \\ &= \int_0^\infty (\lambda_o + \lambda_t)e^{-(\lambda_t+\lambda_o)t}e^{-\lambda_{\text{off}}t}\,dt \\ &= \frac{\lambda_o + \lambda_t}{\lambda_o + \lambda_t + \lambda_{\text{off}}} \end{aligned} \tag{6a}$$

$$P_{34} = 1 - P_{31} = \frac{\lambda_{\text{off}}}{\lambda_o + \lambda_t + \lambda_{\text{off}}}. \tag{6b}$$

Exit from the *off/attached* state is caused by any of following events: 1) arrival of an incoming session, 2) expiry of the MHs binding lifetime, and 3) a switch-on action (T_{42}).

Let T_{term} be the time from a switch-off action to the arrival of the first incoming session. Since the arrival process of incoming sessions is assumed to be Poisson distributed with parameter $\lambda_t, T_{\text{term}}$ has an exponential probability density $f_{\text{term}}(t)$ with parameter λ_t. Let T_R be the time between the moment of a switch-off action and the moment that the binding lifetime expires. Because T_R is the residual life of T_r, the density function $f_R(t)$ of T_R can be expressed as follows:

$$f_R(t) = \lambda_r \int_{\tau=t}^\infty f_r(\tau)\,d\tau = \lambda_r[1 - F_r(t)]. \tag{7}$$

The probabilities P_{42} and P_{45} are expressed as

$$\begin{aligned} P_{42} &= \int_0^\infty f_{T_{42}}(t)\Pr[T_{\text{term}} > t]\Pr[T_R > t]\,dt \\ &= \int_0^\infty \mu_{\text{off}}e^{-\mu_{\text{off}}t}e^{-\lambda_t t}\left[1 - \lambda_r t + \lambda_r\int_0^t F_r(\tau)\,d\tau\right]dt \\ &= \frac{\mu_{\text{off}}}{\lambda_t + \mu_{\text{off}}}\left\{1 - \frac{\lambda_r}{\lambda_t + \mu_{\text{off}}}[1 - F_r^*(\lambda_t + \mu_{\text{off}})]\right\} \end{aligned} \tag{8a}$$

$$\begin{aligned} P_{45} &= 1 - P_{42} \\ &= \frac{\lambda_t}{\lambda_t + \mu_{\text{off}}} + \frac{\lambda_r\mu_{\text{off}}}{(\lambda_t + \mu_{\text{off}})^2}[1 - F_r^*(\lambda_t + \mu_{\text{off}})] \end{aligned} \tag{8b}$$

where $F_r^*(\theta)$ is the Laplace transform of $f_r(t)$.

Exit from the *detached* state is caused only by a switch-on action. Therefore

$$P_{52} = 1. \tag{9}$$

We have derived the stationary probabilities of the embedded Markov chain. To find the steady-state probability of a semi-Markov process, we calculate the mean sojourn time of the MH in each state. The mean sojourn times of an MH in state $j, \bar{T}_j$, is obtained as follows:

$$\begin{aligned} \bar{T}_1 &= E[T_1] = E[\min(T_{12}, T_{14})] \\ &= \int_0^\infty \Pr[T_{12} > t]\Pr[T_{14} > t]\,dt \\ &= \int_0^\infty [1 - F_s(t)]e^{-\lambda_{\text{off}}t}\,dt = \frac{P_{14}}{\lambda_{\text{off}}} \\ &= \frac{1 - F_s^*(\lambda_{\text{off}})}{\lambda_{\text{off}}} \end{aligned} \tag{10a}$$

$$\begin{aligned} \bar{T}_2 &= E[T_2] = E[\min(T_{21}, T_{23}, T_{24})] \\ &= \int_0^\xi t(\lambda_t + \lambda_o + \lambda_{\text{off}})e^{-(\lambda_t+\lambda_o+\lambda_{\text{off}})t}\,dt \\ &\quad + \xi e^{-(\lambda_t+\lambda_o+\lambda_{\text{off}})\xi} = \frac{1 - e^{-(\lambda_t+\lambda_o+\lambda_{\text{off}})\xi}}{\lambda_t + \lambda_o + \lambda_{\text{off}}} \end{aligned} \tag{10b}$$

$$\bar{T}_3 = \frac{1}{\lambda_t + \lambda_o + \lambda_{\text{off}}} \tag{10c}$$

$$\begin{aligned} \bar{T}_4 &= E[T_4] = E[\min(T_{42}, T_{\text{term}}, T_R)] = \frac{P_{42}}{\mu_{\text{off}}} \\ &= \frac{1}{\lambda_t + \mu_{\text{off}}}\left\{1 - \frac{\lambda_r}{\lambda_t + \mu_{\text{off}}}[1 - F_r^*(\lambda_t + \mu_{\text{off}})]\right\} \end{aligned} \tag{10d}$$

$$\bar{T}_5 = \frac{1}{\mu_{\text{off}}}. \tag{10e}$$

Finally, the steady-state probabilities of a semi-Markov process are obtained using the stationary probabilities of the embedded Markov chain and mean sojourn time in each state, as follows:

$$P_i = \frac{\pi_i \bar{T}_i}{\sum_{j=1}^{5} \pi_j \bar{T}_j}, \quad i = 1, 2, \ldots, 5 \tag{11}$$

$$P_1 = \left[1 - \frac{\lambda_o + \lambda_t}{\lambda_A} F_s^*(\lambda_{\text{off}})\right]^{-1} \times \frac{\mu_{\text{off}}(\lambda_t + \lambda_o)[1 - F_s^*(\lambda_{\text{off}})]}{(\lambda_{\text{off}} + \mu_{\text{off}})\lambda_A} \tag{12a}$$

$$P_2 = \left[1 - \frac{\lambda_o + \lambda_t}{\lambda_A} F_s^*(\lambda_{\text{off}})\right]^{-1} \times \frac{(\lambda_{\text{off}}\mu_{\text{off}})(1 - e^{-\lambda_A \xi})}{(\lambda_{\text{off}} + \mu_{\text{off}})\lambda_A} \tag{12b}$$

$$P_3 = \left[1 - \frac{\lambda_o + \lambda_t}{\lambda_A} F_s^*(\lambda_{\text{off}})\right]^{-1} \times \frac{(\lambda_{\text{off}}\mu_{\text{off}})e^{-\lambda_A \xi}}{(\lambda_{\text{off}} + \mu_{\text{off}})\lambda_A} \tag{12c}$$

$$P_4 = \frac{\lambda_{\text{off}}\mu_{\text{off}}}{(\lambda_{\text{off}} + \mu_{\text{off}})(\lambda_t + \mu_{\text{off}})} \times \left[1 - \frac{\lambda_r}{\lambda_t + \mu_{\text{off}}}(1 - F_r^*(\lambda_t + \mu_{\text{off}}))\right] \tag{12d}$$

$$P_5 = \frac{\lambda_{\text{off}}}{(\lambda_{\text{off}} + \mu_{\text{off}})(\lambda_t + \mu_{\text{off}})} \times \left[\lambda_t + \frac{\lambda_r \mu_{\text{off}}}{\lambda_t + \mu_{\text{off}}}(1 - F_r^*(\lambda_t + \mu_{\text{off}}))\right] \tag{12e}$$

where $\lambda_A = \lambda_t + \lambda_o + \lambda_{\text{off}}$.

Since an idle MH does not have a communicating session, the MH can operate in a power-saving mode, except for the time period when it receives paging and location management related messages. Let c_i be the consumed power in state i. Then, the energy consumed during time t is approximately equal to

$$E = \sum_{i=1}^{3} c_i P_i t. \tag{13}$$

B. Network Load

We analyze the effect of binding-lifetime-based registration messages on the network load. When an MH is in idle or off/attached state, the system will page the MH. If the registration messages are sent frequently by MHs, the network load due to the registration messages increases and the MHs may consume too much power. On the other hand, the network load due to unsuccessful paging decreases because it becomes more likely that the network will detach the powered off MHs before the arrival of incoming sessions. If the messages are sent infrequently, the network load due to binding-lifetime-based registrations decreases, but network load due to unsuccessful paging increases. There is a trade off between the network load due to unsuccessful paging and the rate of binding-lifetime-based registrations. We evaluate an optimal registration interval and consider both fixed registration intervals and exponential registration intervals. Let σ_{MH} and A_{PA} be the density of MHs within a paging area and the size of the paging area, respectively. Then, the rates of paging messages and binding-lifetime-based registrations in the paging area, λ_{pag} and λ_{reg}, are given as follows:

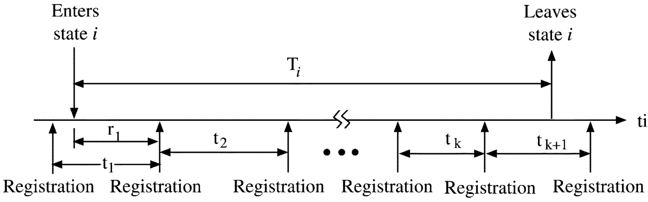

Fig. 3. Timing diagram for k registrations in state i

$$\lambda_{\text{pag}} = \sigma_{\text{MH}} A_{\text{PA}} (n_3 P_3 + n_4 P_4) \lambda_t \tag{14a}$$

$$\lambda_{\text{reg}} = \sigma_{\text{MH}} A_{\text{PA}} (P_1 \lambda_{r,1} + P_2 \lambda_{r,2} + P_3 \lambda_{r,3}) \tag{14b}$$

where $n_j (j = 3, 4)$ is the number of paging repetitions when the MH is in state j. It is assumed that the idle MH immediately responds to the paging, thus n_3 is smaller than n_4. $\lambda_{r,i}$ is the rate of binding-lifetime-based registrations for a mobile host in state i, calculated as follows:

$$\lambda_{r,i} = \frac{\bar{N}_{\text{reg},i}}{\bar{T}_i}, \quad i = 1, 2, 3 \tag{15}$$

where $\bar{N}_{\text{reg},i}$ is the mean number of binding-lifetime-based registrations that occur during the sojourn time of a mobile host in state i. $\Pr[N_{\text{reg},i} = k]$ denotes the probability that an MH performs k binding-lifetime-based registrations during the time interval T_i. Fig. 3 represents the timing diagram for k registrations in state i. Let $t_1, t_2, \ldots, t_{k+1}$ denote the registration intervals and r_1 denote the time interval from the instant that the MH enters state i to the instant that the MH performs the first registration in this state. Let $f_{r1}(t)$ and $f_{T_i}(t)$ be the density functions of r_1 and T_i, respectively. Let $F_{r1}^*(\theta)$ and $F_{T_i}^*$ be the Laplace transforms of $f_{r1}(t)$ and $f_{T_i}(t)$, respectively. Then, we obtain

$$\begin{aligned}
\Pr[N_{\text{reg},i} = 0] &= \Pr[T_i \le r_1] = \int_0^\infty \Pr[r_1 \ge t] f_{T_i}(t)\, dt \\
&= \int_0^\infty \int_t^\infty f_{r1}(\tau)\, d\tau f_{T_i}(t)\, dt \\
&= \frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{1 - F_{r1}^*(\theta)}{\theta} F_{T_i}^*(-\theta)\, d\theta
\end{aligned} \tag{16a}$$

$$\begin{aligned}
\Pr[N_{\text{reg},i} = k] &= \Pr[r_1 + t_2 + \cdots + t_k < T_i \le r_1 + t_2 + \cdots + t_{k+1}] \\
&= \Pr[T_i \ge r_1 + t_2 + \cdots + t_k] \\
&\quad - \Pr[T_i \ge r_1 + t_2 + \cdots + t_{k+1}] \\
&= \frac{1}{2\pi j} \int_{\sigma - j\infty}^{\sigma + j\infty} \frac{F_{r1}^*(\theta)[F_r^*(\theta)]^{k-1}[1 - F_r^*(\theta)]}{\theta} F_{T_i}^*(-\theta)\, d\theta.
\end{aligned} \tag{16b}$$

Equations (16a) and (16b) can be evaluated by using the Residue theorem [18]. For example, consider an idle state. Simultaneously with entering the idle state the MH performs an idle state registration. Therefore, r_1 becomes t_1 in this state. Since the sojourn time in the idle state has an exponential distribution with parameter $\lambda_A (= \lambda_o + \lambda_t + \lambda_{\text{off}})$, (16a) and (16b) are simplified as

$$\Pr[N_{\text{reg},3} = k] = [F_r^*(\lambda_A)]^k [1 - F_r^*(\lambda_A)], \quad k \geq 0. \tag{17}$$

From (10c) and (17), (15) becomes

$$\begin{aligned} \lambda_{r,3} &= \lambda_A [1 - F_r^*(\lambda_A)] \sum_{k=1}^{\infty} k [F_r^*(\lambda_A)]^k \\ &= \begin{cases} \lambda_r & \text{for exponential registration intervals} \\ \dfrac{\lambda_A}{e^{\frac{\lambda_A}{\lambda_r}} - 1} & \text{for a fixed registration interval.} \end{cases} \end{aligned} \tag{18}$$

We define a cost function as the weighted sum of the rate of paging messages and the rate of binding-lifetime-based registrations, as follows:

$$C = w_{\text{pag}} \lambda_{\text{pag}} + w_{\text{reg}} \lambda_{\text{reg}}. \tag{19}$$

In general, paging cost is higher than registration cost $(w_{\text{pag}} \gg w_{\text{reg}})$. Parameter w_{pag} depends on both the number of access routers and access points in a paging area. Let C_{nbr} be the cost when no binding-lifetime-based registration is applied. We define the relative cost function C_0 as the ratio of the cost C to the cost C_{nbr}.

$$\begin{aligned} C_{\text{nbr}} &= \lim_{\lambda_r \to 0} C = w_{\text{pag}} \lim_{\lambda_r \to 0} \lambda_{\text{pag}} + 0 \\ &= w_{\text{pag}} \sigma_{\text{MH}} A_{\text{PA}} \lambda_t (n_3 P_3 + n_4 \lim_{\lambda_r \to 0} P_4) \end{aligned} \tag{20a}$$

$$\begin{aligned} C_0 &= \frac{C}{C_{\text{nbr}}} \\ &= \frac{n_3 P_3 + n_4 P_4}{n_3 P_3 + n_4 \lim_{\lambda_r \to 0} P_4} \\ &\quad + \frac{w_{\text{reg}}}{w_{\text{pag}}} \frac{(P_1 \lambda_{r,1} + P_2 \lambda_{r,2} + P_3 \lambda_{r,3})}{\lambda_t (n_3 P_3 + n_4 \lim_{\lambda_r \to 0} P_4)}. \end{aligned} \tag{20b}$$

An optimal value of λ_r that minimizes C_0 is determined by

$$\frac{dC_0}{d\lambda_r} = 0. \tag{21}$$

Equation (21) has no closed form solution when a fixed registration interval is applied, and the optimal λ_r value can be determined by numerical analysis. If the registration interval and the session holding time have exponential distributions, the optimal λ_r value minimizing C_0 is as follows:

$$\lambda_r = -(\lambda_t + \mu_{\text{off}}) + \sqrt{\frac{w_{\text{pag}} n_4 \lambda_t \lambda_{\text{off}}}{w_{\text{reg}}}}. \tag{22}$$

The optimal rate of binding-lifetime-based registrations is determined by the incoming session rate, the switch-off rate, the time that an MH remains switched off, the number of paging repetitions in off/attached state, and the weighting factors w_{pag} and w_{reg}.

IV. NUMERICAL EXAMPLES

Input parameter values assumed for numerical examples are shown in Table I. The power consumption values $c_i (i = 1, 2, 3)$ are obtained from [19]. Fig. 4 shows that the steady-state probabilities P_1, P_2 and P_3 are constant for varying λ_r values. As the binding-lifetime-based registration rate λ_r increases, the probability P_4 decreases, but the probability P_5 increases.

The mobile host updates the network less frequently in idle state than in communicating and attentive states. Thus, battery power consumption at the mobile host is reduced significantly. Fig. 5 shows the effect of the attention time ξ on energy consumption, which is expressed as the normalized value of the energy consumed when ξ approaches ∞. The ∞ value of ξ indicates that the idle state does not exist to the MH and energy is not saved for the powered-on MH. The value of the attention time ξ affects both P_2 and P_3, as shown in (12b) and (12c). Probability P_3 is a decreasing function of the attention time ξ, whereas

TABLE I
INPUT PARAMETERS

Parameter	Value	Parameter	Value
λ_o	1 [1/hour]	w_{pag}	25
λ_t	1 [1/hour]	w_{reg}	1
λ_{off}	1/4 [1/hour]	c_1	1.50 [W]
μ_s	3600/300 [1/hour]	c_2	1.32 [W]
μ_{off}	1 [1/hour]	c_3	0.18 [W]
ξ	120/3600 [hour]	c_4	0 [W]
n_3	1	c_5	0 [W]
n_4	3		

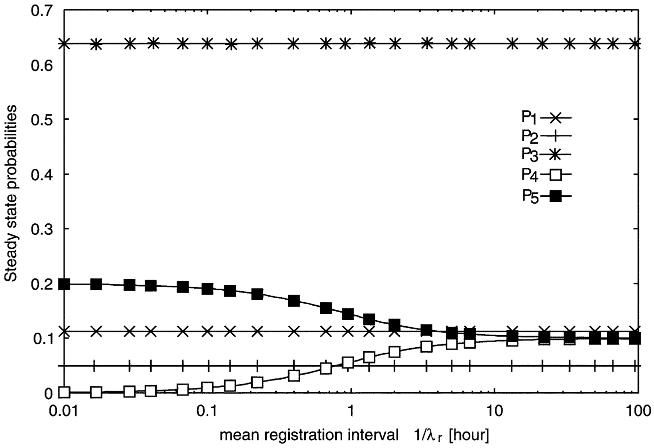

Fig. 4. Steady-state probabilities.

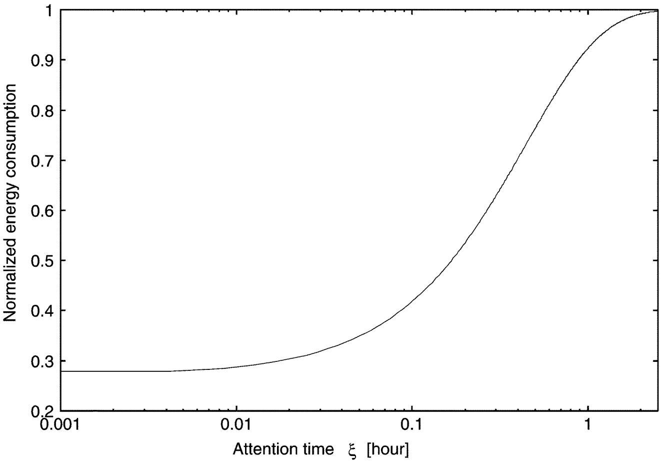

Fig. 5. Effect of the attention time ξ on energy consumption.

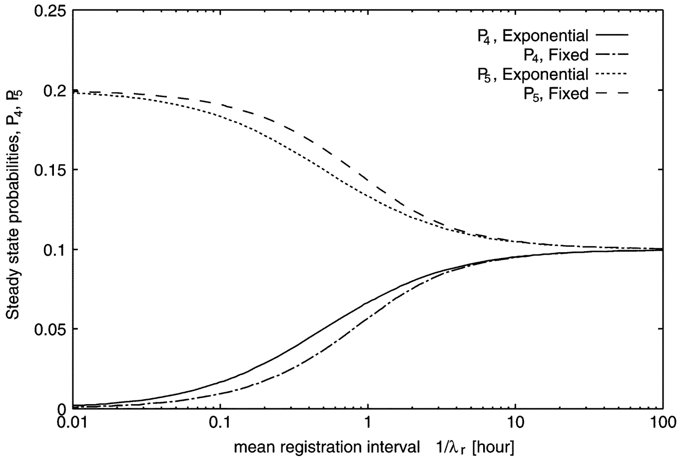

Fig. 6. Steady-state probabilities P_4 and P_5 for fixed and exponential distributions of registration intervals.

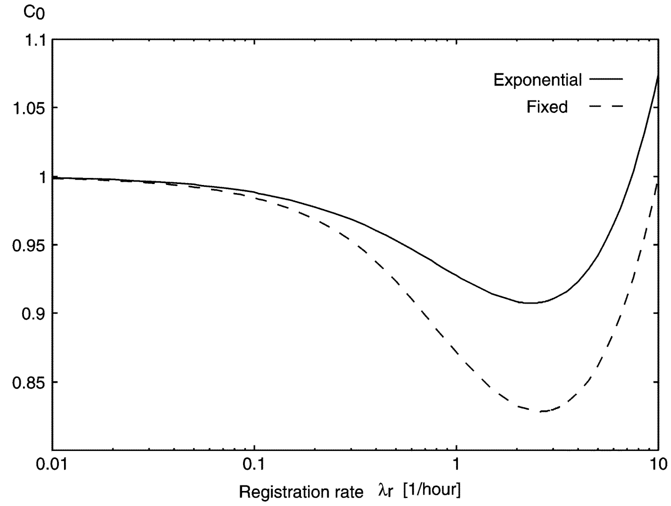

Fig. 7. Relative network cost.

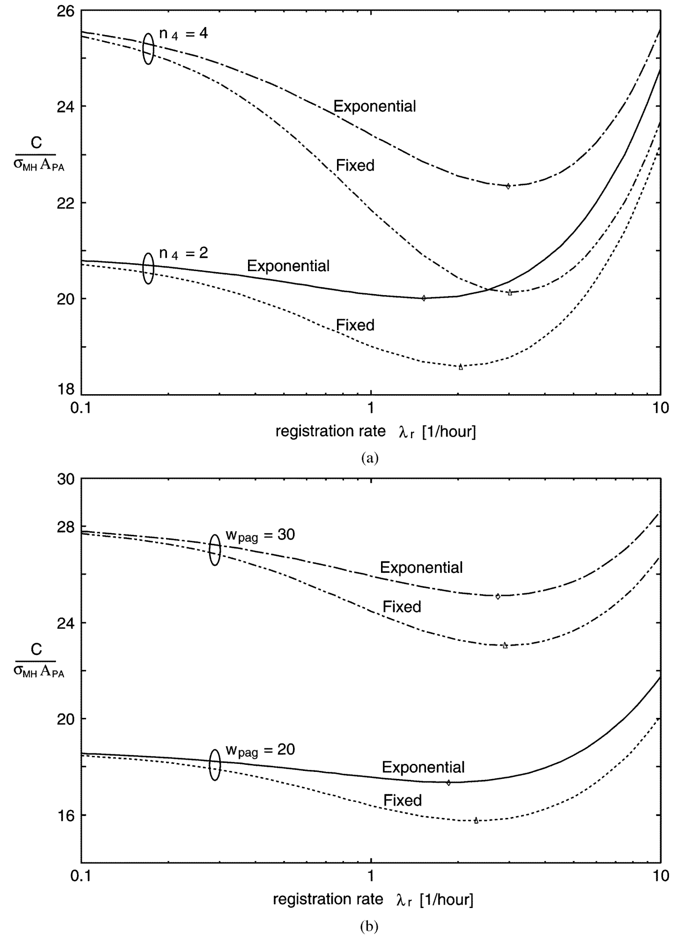

Fig. 8. Influence of n_4 and w_{pag} parameters on the optimal binding rate. (a) n_4. (b) w_{pag}.

probability P_2 is an increasing function of ξ. As ξ increases, the energy consumption also increases. Therefore, energy conservation is reduced. The value of ξ should be determined also considering the incoming session rate and the packet delay.

Fig. 6 shows the effect of the probability distribution of registration intervals on the steady-state probabilities P_4 and P_5. When the registration interval is very small, probability P_4 for both exponential and fixed registration intervals approaches 0. Probability P_4 for exponential registration intervals is higher than for fixed registration intervals. Therefore, fixed registration intervals are preferred.

Fig. 7 shows the relative cost for varying values of λ_r. We choose C_0 instead of C as the cost function in order to judge the effectiveness of binding-lifetime-based registrations. C_0 smaller than 1 means that utilizing binding-lifetime-based registration as a means for identifying that the MH is switched off is effective. The network cost when no binding-lifetime-based registration is applied ($\lambda_r = 0$) is C_{nbr} and thus the relative cost C_0 is 1. As λ_r increases starting from 0 ($0 < \lambda_r < 2.59$ for fixed registration intervals), the cost C_0 is smaller than 1. It means that applying the binding-lifetime-based registration is cheaper than does not applying it ($\lambda_r = 0$). The relative cost is sensitive to the distribution of registration intervals. When fixed registration intervals are used, the relative cost C_0 is a minimum value at $\lambda_r = 2.59$ and the minimum relative cost is 0.89. If exponential registration intervals are applied, the minimum value of the relative cost occurs at $\lambda_r = 2.33$, and the cost C_0 is 0.91. For a specific value of λ_r the relative cost is lower when fixed registration intervals are applied. Therefore, fixed registration intervals are better than exponential registration intervals from the viewpoint of network resource usage. When λ_r is large ($\lambda_r > 2.59$ for fixed registration intervals), the relative cost increases as λ_r increases because the network load due to the registrations increases. As λ_r increases further, the cost C_0 becomes larger than 1 for any registration distributions.

The optimum rate of binding-lifetime-based registrations depends on the many parameters. Fig. 8 shows the influence of n_4 and w_{Pag} on the optimal binding rate. As n_4 or w_{pag} increases, the probabilities in each state is not changed, but the paging cost increases. The paging cost for an incoming session is higher than the cost for a registration because paging message is sent over multiple access routers and access points in paging area. As we can see in Fig. 8 and (22), the optimal binding rate minimizing the network cost increases as n_4 or w_{pag} increases. Fig. 9 shows the influence of $\lambda_{\mathrm{off}}, \mu_{\mathrm{off}}$, and λ_t on the optimal binding rate. As λ_{off} increases, the MH is more likely in the *off/attached* or *detached* state. So, the probabilities P_4 and

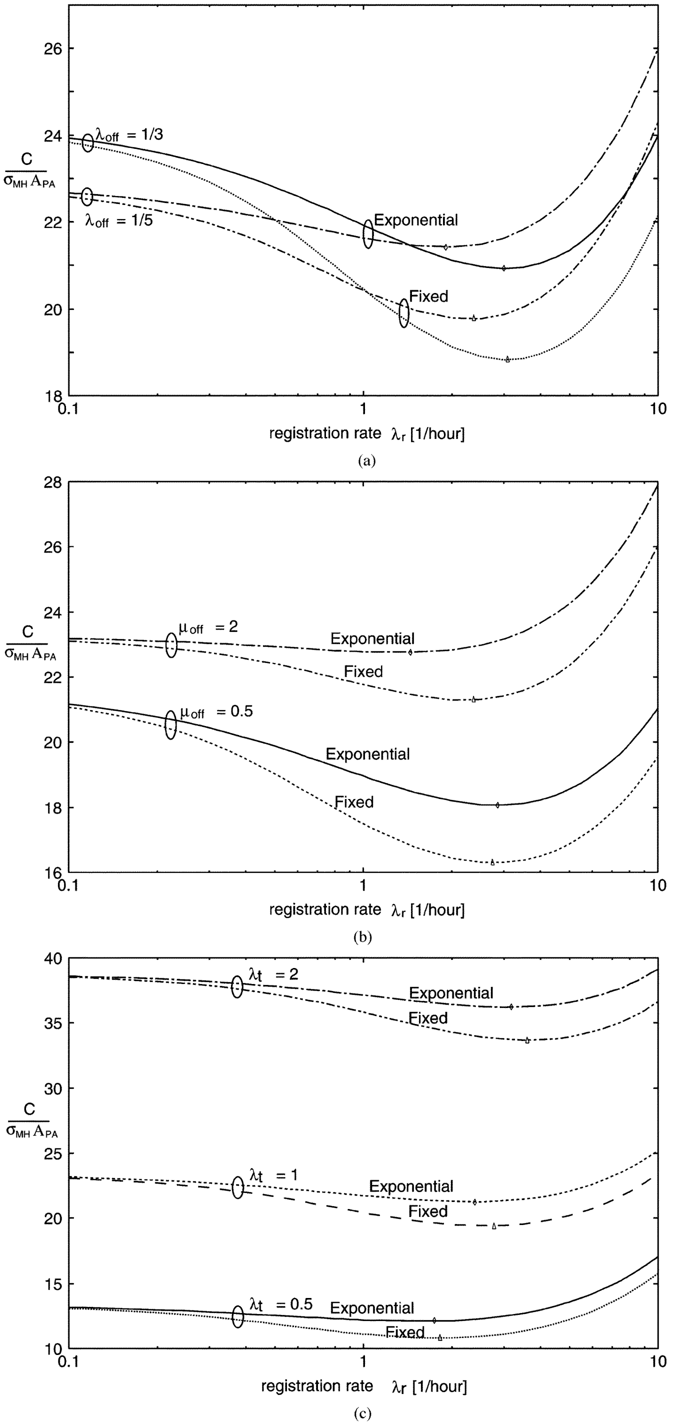

Fig. 9. Influence of λ_{off}, μ_{off}, and λ_t parameters on the optimal binding rate. (a) λ_{off}. (b) μ_{off}. (c) λ_t.

P_5 increase whereas P_1, P_2, P_3 decrease. Optimal binding rate λ_r should be increased to reduce unsuccessful paging cost as λ_{off} increases. As μ_{off} increases, the time that the MH remains switched off decreases and the MH is more like in the active, attentive, or idle state. So, P_4 and P_5 decrease. Therefore, the optimal binding rate decreases when the μ_{off} increases. As the incoming session rate λ_t increases, the paging attempts should be done more frequently with the consequence that the unsuccessful paging load increases. So, the optimal binding rate increases when the value of λ_t increases.

V. CONCLUSION

A mobile host is idle for most of time. Furthermore, it can be in a switch-off state for battery power conservation. A mobility management scheme considering conservation of MH battery power in all IP-based mobile networks is introduced. This mobility management scheme manages communicating, attentive, idle, and detached states. The mobile host updates the network less frequently in idle state than in communicating and attentive states. Thus, battery power consumption at the mobile host is significantly reduced. Furthermore, benefit of managing the detached state is efficient use of radio and network resources. We analyze the mobility management scheme when the binding-lifetime-based registrations are utilized as a means of identifying that an MH is switched off. In this case, the *off/attached* state should be additionally considered. Steady-state probabilities for mobile host state transitions are derived. Then, the optimal rate of binding-lifetime-based registrations that results in minimum cost is derived. The results show that the battery power of MH is more conserved when the attention timer value is small, but the timer value should be determined considering the delay for packet delivery to idle MH as well as battery power conservation. When the binding-lifetime-based registrations are utilized as a means of identifying that an MH is switched off, the fixed registration intervals are preferable to the exponential registration intervals because the fixed intervals yield a lower network cost. This result is derived under the assumption that switch-off actions and session arrival process follow Poisson distribution. As a further study, the analysis will be performed to the case when the switch-off actions and session arrival process do not follow Poisson distribution.

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