A Novel Distributed Dynamic Location Management Scheme for Minimizing Signaling Costs in Mobile IP

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Abstract—Mobile IP is a simple and scalable global mobility solution. However, it may cause excessive signaling traffic and long signaling delay. Mobile IP regional registration is proposed to reduce the number of location updates to the home network and to reduce the signaling delay. This paper introduces a novel distributed and dynamic regional location management for Mobile IP where the signaling burden is evenly distributed and the regional network boundary is dynamically adjusted according to the up-to-date mobility and traffic load for each terminal. In our distributed system, each user has its own optimized system configuration which results in the minimal signaling traffic. In order to determine the signaling cost function, a new discrete analytical model is developed which captures the mobility and packet arrival pattern of a mobile terminal. This model does not impose any restrictions on the shape and the geographic location of subnets in the Internet. Given the average total location update and packet delivery cost, an iterative algorithm is then used to determine the optimal regional network size. Analytical results show that our distributed dynamic scheme outperforms the IETF Mobile IP regional registration scheme for various scenarios in terms of reducing the overall signaling cost.

Index Terms—Mobile IP, regional registration, location management.

✦

1 INTRODUCTION

The growth of the Internet and the success of mobile wireless networks lead to an increasing demand for mobile wireless access to Internet applications. Mobile IP is a mobility-enabling protocol for the global Internet. Standards for Mobile IP have been developed by the Internet Engineering Task Force (IETF) and outlined in Request for Comments (RFC) 3220 [1] [2].

Mobile IP enables terminals to maintain all ongoing communications while moving from one subnet to another. It is a simple and scalable global mobility solution. However, it is not a satisfactory solution for highly mobile users [3]. When a mobile node (MN) moves among subnets, its location and routes must be updated. Mobile IP requires that an MN sends a location update to its home agent (HA) whenever it moves from one subnet to another one. This location registration is required even though the MN does not communicate with others while moving. The signaling cost associated with location updates may become very significant as the number of MNs increases [4]. Moreover, if the distance between the visited network and the home network of the MN is large, the signaling delay for the location registration is long.

Mobile IP regional registration aims to reduce the number of signaling messages to the home network, and also to reduce the signaling delay when an MN moves from one subnet to another. The detailed protocol specification can be found in [5] and the general model of operation is illustrated in Fig. 1. Regional registration is a solution for performing registrations locally in a regional network. When an MN first arrives at a regional network, it performs a home registration with its HA. During the home registration, the HA registers the care-of address of the MN, which is actually a publicly routable address of another mobility agent called gateway foreign agent (GFA). When an MN changes foreign agent (FA) within the same regional network, it performs a regional registration to the GFA to update its FA care-of address. When it moves from one regional network to another one, it performs a home registration with its HA. During the communication, when packets are sent to the MN by a correspondent node (CN), they are addressed to the HA of the MN first. The HA intercepts these packets and encapsulates them inside packets that are addressed to the care-of address of the MN. These packets are tunneled through the network until they reach the registered GFA of the MN. The GFA checks its visitor list and forwards the packets to the corresponding FA in the visiting subnet of the MN. The FA further relays the packets to the MN.

However, because of the centralized system architecture, i.e., a centralized GFA manages all the traffic within a regional network, Mobile IP regional registration is more sensitive to the failure of GFAs. The failure of a GFA will prevent packets routed to all the users in the regional network [6]. Another issue that draws our attention is how many FAs should be beneath a GFA within a regional network. The number of FAs under a GFA is very critical for the system performance. A small number of FAs will lead to excessive location updates to the home network and, consequently, cannot provide the full benefit of regional registration. A large number of FAs will also degrade the

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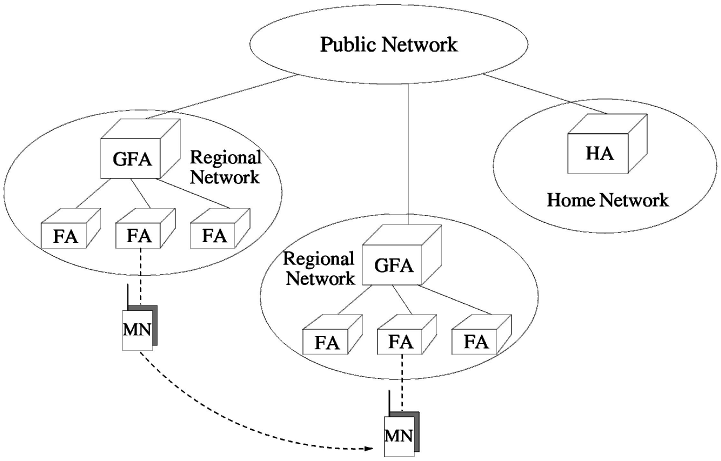

Fig. 1. The IETF mobile IP regional registration.

overall performance since it will generate a high traffic load on GFAs, which results in a high cost of packet delivery [4].

To improve the system performance, we propose a distributed GFA management scheme where each FA can function either as an FA or a GFA. Whether an agent should act as an FA or a GFA depends on the user mobility. Thus, the traffic load in a regional network is evenly distributed to each FA. Through this approach, the system robustness is enhanced. We also propose a dynamic scheme which is able to adjust the number of FAs under a GFA for each MN according to the user-variant and time-variant user parameters. In this dynamic system, there is no fixed regional network boundary for each MN. An MN decides when to perform a home location update according to its changing mobility and packet arrival pattern.

In order to minimize the signaling traffic, it is desirable to find the optimal number of FAs beneath a GFA in a regional network. This optimal number is user-variant and time-variant. A method for calculating the optimal location area (LA) size in personal communication service (PCS) systems to reach the minimal costs for location update and terminal paging is introduced in [7]. However, there are some differences between the analysis of location management schemes for Mobile IP and those in PCS. First, the cellular network is geographic-oriented. Most researchers adopted structured cell configurations for evaluations [8]. For example, mesh or hexagonal cell configurations are often used in two-dimensional models [9], [10]. But, the Internet is more spatial-oriented. We cannot use any geometric shape to accurately abstract a subnet, which increases the difficulty for analysis. Second, in PCS, the geographic distance between two cells is used for analysis [11]. However, the distance between two end points in the Internet has nothing to do with the geographic location of these two points. Their distance is usually counted by the number of hops packets travel. This type of distance is called "*virtual*" distance. Third, when an incoming call arrives, the cellular network locates the terminal by simultaneously paging all cells within an LA. Whereas in Mobile IP, HAs or GFAs know the corresponding FA of each MN. But, because of the triangular routing, packet delivery introduces extra processing and transmission costs. So, there is packet delivery cost instead of paging cost for Mobile IP.

In this paper, we also introduce a new mathematical model to calculate the optimal number of FAs under a GFA such that the total signaling traffic for location update and packet delivery consumes the minimal network resource. This model does not impose any restrictions on the shape and the geography of system topology. It is a general model which is applicable for all types of subnets. The distance unit in our model is the number of hops packets travel. Based on this model, we obtain the average location update and packet delivery costs. We use an iterative method to determine the optimal number of FAs under a GFA that will result in the minimal average signaling cost. We then incorporate this optimal value to our distributed and dynamic scheme to further enhance the system performance.

This paper is organized as follows: In Section 2, the distributed dynamic regional location management scheme is explained and the protocol for operating the scheme is given. Then, in Section 3, the mobility model is described and a method for deriving the total location update and packet delivery cost is introduced. After that, in Section 4, an algorithm for obtaining the optimal number of FAs beneath a GFA is provided. In Section 5, analytical results are presented, followed by the conclusions in Section 6.

2 DISTRIBUTED AND DYNAMIC REGIONAL LOCATION MANAGEMENT

In this section, we introduce our distributed dynamic regional location management scheme. We also present the operational protocols of our distributed dynamic scheme. In the following discussion, we assume that the regional registration protocol supports one level of foreign agent hierarchy beneath the GFA.

2.1 Overview of the Distributed Dynamic Scheme

We propose a new distributed system architecture where each FA can function either as an FA or a GFA. Whether an agent should act as an FA or a GFA depends on the user mobility. When an MN enters a regional network, the first FA of the subnet the MN visits will function as the GFA of

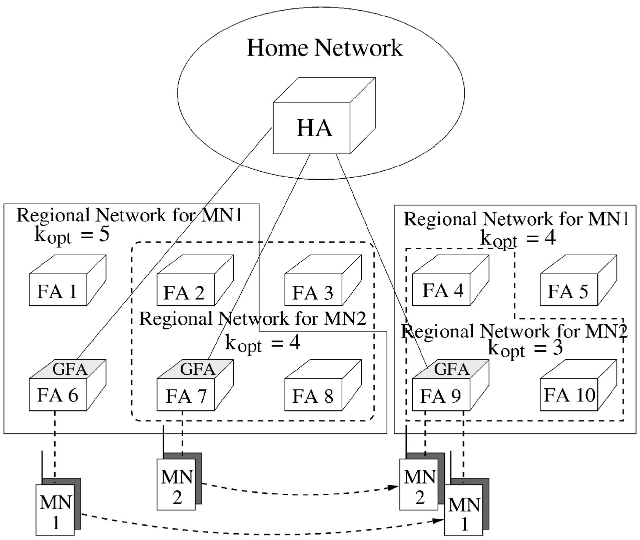

Fig. 2. The distributed dynamic mobile IP regional registration.

this regional network. If an agent acts as a GFA, it needs to maintain a visitor list and keeps entries in the list updated according to the regional registration requests sent from other FAs within the regional network. The GFA also relays all the home registration requests to the HA. Other agents in the regional network act as the general foreign agents for the MN. Of course, there should be some authentication setup between mobility agents to guarantee the security of message delivery.

We also propose a dynamic location management mechanism. In this scheme, the number of FAs under a GFA is not fixed but optimized for each MN to minimize the total signaling traffic. The optimal number is obtained based on the incoming packet arrival rate and mobility characteristics of each user. Since the mobility and the packet arrival rate of each user are different and they may also not be constant from time to time, the optimal number of FAs is different for each user and it is adjustable from time to time. Thus, the dynamic system is able to perform optimally for all users.

The system architecture of our new scheme is shown in Fig. 2 where FA6 functions as the GFA for MN1 at first. The optimal regional network size is equal to 5. After visiting five *different* subnets, i.e., subnets served by FA1, FA2, FA6, FA7, and FA8, MN1 moves to FA9 and FA9 becomes the GFA in the new regional network for MN1. Then, MN1 updates the new optimal regional network size based on its up-to-date mobility and traffic load values. Similar for MN2, FA7 functions as the GFA in the regional network at first. The optimal regional network size for MN2 is 4. After visiting subnets served by FA2, FA3, FA7, and FA8, MN2 moves FA9 and FA9 becomes the GFA in the new regional network for MN2 also. MN2 adjusts its regional network size and this optimal size will be dynamically changed each time MN2 moves into a new regional network.

Therefore, in our distributed and dynamic system, each user has different network configuration with others: Different mobility agents act as the GFA for each user and different size of a regional network in terms of the number of FAs. The advantages of this distributed dynamic system are:

1. The traffic load for all the users in a regional network is distributed to each mobility agent.
2. The system robustness is enhanced since the failure of a GFA will only effect the packets routing to MNs managed by the failing GFA.
3. Each MN has its own optimized system configuration from time to time.

2.2 Operations of the Distributed Dynamic Scheme

Now, we describe how MNs operate in real implementations. In particular, we explain how MNs determine the dynamically adjusted boundaries of regional networks.

Each MN keeps a buffer for storing IP addresses of mobility agents. An MN records the address of the GFA into its buffer when it enters a new regional network and then performs a home registration through the new GFA. After the home registration, the optimal number of FAs for a regional network is computed based on the up-to-date parameters of the MN. The algorithm for deriving the optimal value k_{opt} will be described in the next section. This optimal value k_{opt} is set for the buffer length threshold of the MN. If the MN detects that it enters a new subnet, it does a regional registration by sending a regional registration request to the recorded IP address of the GFA, i.e., the first FA it met in the regional network. The MN then compares the IP address of the FA in the new subnet with the addresses recorded in its buffer. If the address of the current FA has not been recorded in the buffer, then the MN records it and, otherwise, ignores it. If the total number of addresses in the buffer as well as the address of the current FA exceeds the threshold, it means the MN is in a new regional network. The MN deletes all the addresses in its buffer, saves the new one, and requests a home registration. Thus, there is no strict regional network boundary for each MN. An MN may move back and forth between two subnets and it may also visit a subnet more than once. The zigzag effect will not lead to excessive home location registrations since the MN will know that it has moved out of a regional network only after it has visited k_{opt} *different* subnets.

The protocol descriptions of the distributed dynamic regional location registration for MNs are shown in Fig. 3.

2.3 Comparison

Note that "*distributed* system architecture" and "*dynamic* regional network" are independent. "*Distributed*" means that GFAs of different users are distributed among FAs, and "*dynamic*" means changing regional network size k_{opt} from time to time. Consequently, there are four possible combinations as follows:

- *Centralized* system architecture and *fixed* regional network,
- *Centralized* system architecture and *dynamic* regional network,
- *Distributed* system architecture and *fixed* regional network, and
- *Distributed* system architecture and *dynamic* regional network.

```
if (MN enters a new subnet)
  compare the address of the new FA to the addresses in buffer;
  if (the new address $\neq$ any address in buffer)
    if (# of addresses in buffer + the new address > $k_{opt}$)
      delete all the addresses in buffer;
      record the new FA address in buffer;
      mark the new FA address as the new GFA address;
      perform a regional registration to the new GFA;
      perform a home registration through the new GFA;
      compute the new $k_{opt}$;
    else
      record the new FA address in buffer;
      perform a regional registration to the GFA;
    end
  else
    perform a regional registration to the GFA;
  end
end
```

Fig. 3. Protocols of the distributed dynamic scheme for MNs.

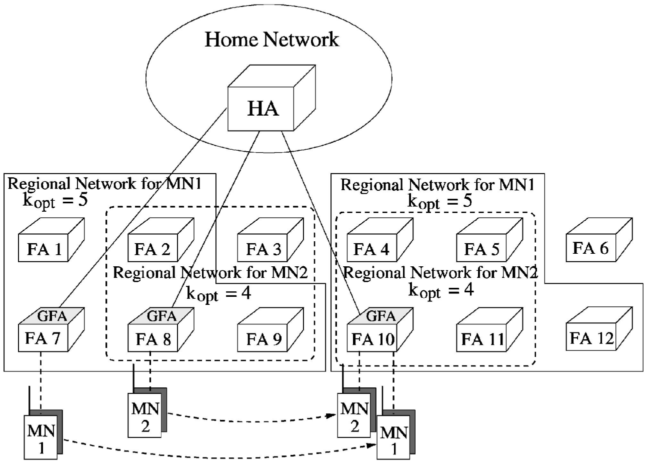

Fig. 4. The distributed fixed mobile IP regional registration.

Centralized fixed scheme is the IETF Mobile IP regional registration, which is shown in Fig. 1; centralized dynamic scheme is difficult for implementation, since each FA is required to know the entire network configuration in order to be aware of when to send registration requests to which GFA; distributed fixed scheme is shown in Fig. 4; and distributed dynamic scheme is our proposed scheme, which is shown in Fig. 2. Note that, for distributed fixed scheme, the regional network size k_{opt} may be either the same for all users or user-variant. Fig. 4 presents the user-variant fixed regional network size for MN1 and MN2. We will compare our distributed dynamic scheme to the centralized fixed scheme, i.e., the IETF Mobile IP regional registration, and the distributed fixed scheme in the following sections.

3 SIGNALING COST FUNCTION

In this section, we derive the cost function of location update and packet delivery to find out the optimal size of a regional network. The total signaling cost in location update and packet delivery is considered as the performance metric. We do not take the periodic binding updates that an MN sends to mobility agents to refresh their cache into account.

3.1 Location Update Cost

Similar to [12], we define the following parameters for location update in the rest of this paper:

1. C_{hg}. The transmission cost of location update between the HA and the GFA.
2. C_{gf}. The transmission cost of location update between the GFA and the FA.
3. C_{fm}. The transmission cost over the wireless link between the FA and the MN.
4. a_h. The processing cost of location update at the HA.
5. a_g. The processing cost of location update at the GFA.
6. a_f. The processing cost of location update at the FA.

Fig. 5 and Fig. 6 illustrate the signaling message flows for location registration with the home network and regional registration with the GFA, respectively. According to these message flows, the home registration cost and the regional registration cost for each location update can be calculated as follows [13]:

$$C_{Uh} = 2a_f + 2a_g + a_h + 2C_{hg} + 2C_{gf} + 2C_{fm}, \tag{1}$$

$$C_{Ur} = 2a_f + a_g + 2C_{gf} + 2C_{fm}. \tag{2}$$

Let l_{hg} be the average distance between the HA and the GFA in terms of the number of hops packets travel, and l_{gf} be the average distance between the GFA and the FA. We assume the transmission cost is proportional to the distance between the source and the destination mobility agents and the proportionality constant is δ_U. Thus, C_{hg} and C_{gf} can be expressed as $C_{hg} = l_{hg}\delta_U$ and $C_{gf} = l_{gf}\delta_U$. Since usually the transmission cost of the wireless link is generally higher than that of the wired link, we assume that the transmission cost over the wireless link is ρ times higher than the unit distance wireline transmission cost. The transmission cost between the FA and the MN can be written as $C_{fm} = \rho\delta_U$. Then, the home registration and regional registration costs can be expressed as:

$$C_{Uh} = 2a_f + 2a_g + a_h + 2(l_{hg} + l_{gf} + \rho)\delta_U, \tag{3}$$

$$C_{Ur} = 2a_f + a_g + 2(l_{gf} + \rho)\delta_U. \tag{4}$$

Note that, for distributed GFA architecture, the first FA of the subnet the MN visits acts as a GFA. When the MN resides in the subnet of the GFA, the regional registration cost is different from the one when the MN is in the subnet not serviced by the GFA. Define this special regional registration as $\widetilde{C}_{Ur}$. Then,

$$\widetilde{C}_{Ur} = a_g + 2C_{fm} = a_g + 2\rho\delta_U. \tag{5}$$

Assume an MN may move randomly between N subnets and there are k subnets within a regional network. The MN may visit a subnet more than once and it may also move back and forth between two subnets. We first consider the location update for centralized fixed scheme.

We call the action an MN moving out of a subnet "*a movement*." Define a random variable M so that an MN moves out of a regional network at movement M. We

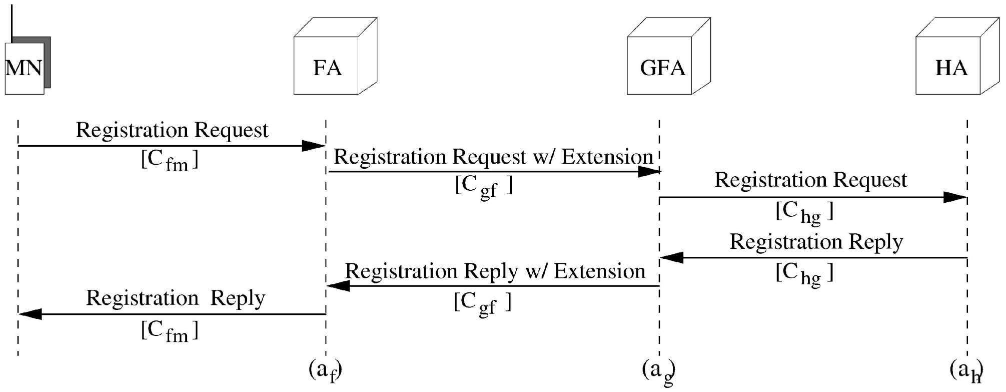

Fig. 5. Process of home location registration.

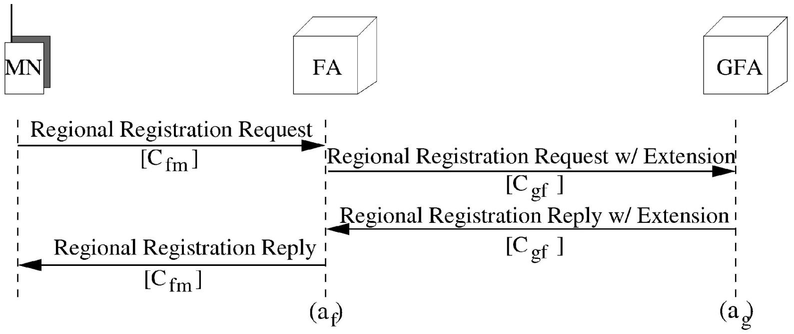

Fig. 6. Process of regional location registration.

model the movements of an MN as a discrete system. At movement 1, the MN may reside in either subnet $1,\ 2, \cdots$ or N. At movement 2, the MN may move to any of the other $N-1$ subnets. We assume the MN will move out to the other $N-1$ subnets with equal probability $\frac{1}{N-1}$.

For the centralized fixed scheme, the probability of moving out of a regional network, i.e., the probability of performing a home registration at movement m is:

$$P^m_{h\_cf} = \frac{N-k}{N-1}\cdot\left(\frac{k-1}{N-1}\right)^{m-2}, \quad \text{where } 2 \le m < \infty, \tag{6}$$

where m is an arbitrary integer larger than 1. It can be shown that the expectation of M is:

$$E[M]_{cf} = \sum_{m=2}^{\infty} mP^m_{h\_cf} = 1 + \frac{N-1}{N-k}. \tag{7}$$

Assume within a regional network, the average time an MN stays in each subnet before making a movement is T_f. Therefore, the average location update cost for centralized fixed scheme is:

$$C_{LU\_cf} = \frac{E[M]_{cf}C_{Ur} + C_{Uh}}{E[M]_{cf}T_f}. \tag{8}$$

For distributed GFA system architecture, the MN will move out of a regional network only after it has visited k *different* subnets. Previous researchers used either Markovian model [14] or random walk model [10] [15] for performance analysis. However, the movement of MNs for distributed scheme is not a Markov process because the decision of whether an MN can move out of a regional network depends on its mobility history, i.e., whether an MN is in another regional network depends on whether it has visited *different* k subnets. This increases the difficulty of analysis.

We define the paths by which the MN has visited different k subnets *"qualified"* paths. If an MN moves out of a regional network at movement m, where m is an arbitrary integer larger than k, the path by which the MN has gone through from movement 1 to movement $m-1$ must consist of k *and only* k different subnets. Fig. 7 shows an example of our discrete system in which $N=5$ and $k=3$. In the figure, each node represents a subnet. As shown in Fig. 7, at movement 3, the MN has visited subnet 1, 3, and 4. Therefore, subnet 2 and 5 belong to another regional network for this MN after this moment. If the MN moves out of its regional network to subnet 2 at movement 6, the

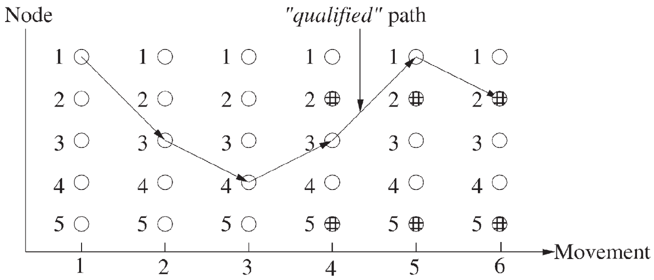

Fig. 7. Discrete system mobility model of an MN.

subnets it visited at movement 4 and 5 are among subnet 1, 3, and 4.

Therefore, the expectation of the moment at which an MN moves out of a regional network for distributed scheme is equal to the expectation of the moment at which an MN has visited *different* k subnets plus the expectation of the time period that an MN moves within specific k subnets. The latter one is exactly the $E[M]_{cf}$ for centralized fixed scheme. Define the expectation of the number of movements it takes an MN moving from its first subnet to its second *new* subnet as $E[M]_{1\to 2}$, i.e., an MN has visited two different subnets. Then,

$$E[M]_{1\to 2} = 1. \tag{9}$$

Similarly, when an MN has visited two different subnets, define the expectation of the number of movements it takes an MN moving to its third *new* subnet as $E[M]_{2\to 3}$. Then,

$$E[M]_{2\to 3} = \sum_{n=1}^{\infty} n \cdot \left(\frac{1}{N-1}\right)^{n-1} \frac{N-2}{N-1} = \frac{N-1}{N-2} \tag{10}$$

and the expectation of the number of movements it takes an MN moving from its $(k-1)$th subnet to its kth subnet is:

$$E[M]_{k-1\to k} = \sum_{n=1}^{\infty} n \cdot \left(\frac{k-2}{N-1}\right)^{n-1} \frac{N-k+1}{N-1} = \frac{N-1}{N-k+1}. \tag{11}$$

Then, the expectation of the moment at which an MN moves out of a regional network for distributed fixed scheme and distributed dynamic scheme is:

$$\begin{aligned} E[M]_{df} = E[M]_{dd} &= E[M]_{1\to 2} + E[M]_{2\to 3} + \cdots + E[M]_{k-1\to k} \\ &\quad + E[M]_{cf} \\ &= 1 + \frac{N-1}{N-2} + \cdots + \frac{N-1}{N-k+1} + \frac{N-1}{N-k} \\ &\quad + 1 \\ &= 1 + (N-1)\sum_{i=1}^{k} \frac{1}{N-i}. \end{aligned} \tag{12}$$

Note that the expectation of the moment at which an MN moves out of a regional network for distributed system is always larger than that for centralized system. As a result, the number of home registrations per unit time is reduced. The upper bound of the total location update costs per unit time for distributed fixed scheme and distributed dynamic scheme are:

$$C_{LU\_df} \le \frac{\widetilde{C}_{Ur} + (E[M]_{df} - 1)C_{Ur} + C_{Uh}}{E[M]_{df} T_f}, \tag{13}$$

$$C_{LU\_dd} \le \frac{\widetilde{C}_{Ur} + (E[M]_{dd} - 1)C_{Ur} + C_{Uh}}{E[M]_{dd} T_f}. \tag{14}$$

Based on (4), (5), (6), (7), (8), (9), (10), (11), (12), (13), and (14), we may get the average location update cost. Note that our method does not impose any restrictions on the shape and the geographic location of subnets. It is a general model which is applicable to arbitrary subnets.

3.2 Packet Delivery Cost

Under Mobile IP regional registration, every IP packet destined for an MN is first intercepted by the HA and is then tunneled to the registered GFA and further forwarded to the current serving FA of the MN. Because of this triangular routing, there are extra costs for packet delivery. The packet delivery cost includes the transmission and processing cost to route a tunneled packet from the HA to the serving FA of an MN. Assume

1. T_{hg}. The transmission cost of packet delivery between the HA and the GFA.
2. T_{gf}. The transmission cost of packet delivery between the GFA and the FA.
3. v_h. The processing cost of packet delivery at the HA.
4. v_g. The processing cost of packet delivery at the GFA.

The cost for packet delivery procedure can be expressed as:

$$C_{PD} = v_h + v_g + T_{hg} + T_{gf}. \tag{15}$$

Similar to the assumption for location update case, we assume the transmission cost of delivering data packets is proportional to the distance between the sending and the receiving mobility agents with the proportionality constant δ_D. Then, $T_{hg} = l_{hg}\delta_D$ and $T_{gf} = l_{gf}\delta_D$.

The processing cost at GFAs includes decapsulation of the tunneled IP packets from the HA, checking its visitor list to see whether it has an entry for the destination MN, reencapsulation of the IP packets, and management of routing packets to the FAs. The load on a GFA for processing and routing packets to each FA depends on k, the number of FAs under a GFA. If k is large, the complexity of the visitor list lookup and IP routing lookup in the GFA is high, and the system performance is degraded. In addition, since the total bandwidth of the network is limited, if the traffic to a GFA is heavy, the transmission delay and the number of retransmissions cannot be bounded. These factors will result in a high processing cost at the GFAs. Assume on average there are ω MNs in a subnet. For centralized system architecture, a GFA serves for all the MNs moving within a regional network, and the total number of MNs in a regional network is ωk on average. Therefore, the complexity of the GFA visitor list lookup is proportional to ωk. On the other hand, for distributed system architecture, different MNs choose different FAs as their GFAs. A GFA only serves the MNs which first enter the subnet managed by this GFA in a regional network. The packet processing load of a GFA in the distributed system is much lower than that in the centralized system because the traffic is allocated evenly among all the FAs in a regional network. Therefore, the complexity of the GFA visitor list lookup for distributed system is proportional only to ω. Since IP routing table lookup is based on the *longest prefix matching* and most implementations use the traditional *Patricia trie* [16], the complexity of IP address lookup is proportional to the logarithm of the length of the routing table k [17]. We define the packet processing cost functions at the GFA for centralized system and distributed system as:

$$v_{g\_cf} = \zeta k \cdot \lambda_a(\alpha\omega k + \beta log(k)), \tag{16}$$

$$v_{g\_df} = v_{g\_dd} = \zeta k \cdot \lambda_a(\alpha\omega + \beta log(k)), \tag{17}$$

where λ_a is the packet arrival rate for each MN, α and β are weighting factors of visitor list and routing table lookups, and ζ is a constant which captures the bandwidth allocation cost at the GFA. The larger the ζ is, the more negative effects an MN experiences from not enough network bandwidth available.

The processing cost function at the HA can be defined as: $v_h = \eta\lambda_a$, where η is a packet delivery processing cost constant at the HA. Then, the total packet delivery costs per unit time for the three schemes are:

$$C_{PD\_cf} = \eta\lambda_a + \zeta k \cdot \lambda_a(\alpha\omega k + \beta log(k)) + (l_{hg} + l_{gf})\delta_D, \tag{18}$$

$$\begin{aligned} C_{PD\_df} = C_{PD\_dd} = \eta\lambda_a + \zeta k \cdot \lambda_a(\alpha\omega + \beta log(k)) \\ + (l_{hg} + l_{gf})\delta_D. \end{aligned} \tag{19}$$

3.3 Total Signaling Cost

Based on the above analysis, we get the overall signaling cost function as:

$$C_{TOT\_(\cdot)}(k, \lambda_a, T_f) = C_{LU\_(\cdot)} + C_{PD\_(\cdot)}, \tag{20}$$

where $C_{TOT\_(\cdot)}$, $C_{LU\_(\cdot)}$, and $C_{PD\_(\cdot)}$ represent the total signaling cost, location update cost, and packet delivery cost for the three different schemes, i.e., centralized fixed scheme, distributed fixed scheme, and the proposed distributed dynamic scheme.

4 OPTIMAL REGIONAL NETWORK SIZE

The optimal number of FAs beneath a GFA, k_{opt}, is defined as the value of k that minimizes the cost function derived in Section 3. Because k can only be an integer, the cost function is not a continuous function of k. Therefore, it is not appropriate to take derivative with respect to k of the cost function to get the minimum. We use an iterative algorithm. Note that an iterative algorithm may result in a local minimum. Solutions to solving the local minimum problem were discussed in [11]. Similar to the algorithm proposed in [7], we define the cost difference function between the system with number k and the system with number $k-1$ ($k \geq 2$), i.e.,

$$\Delta_{cf}(k, \widetilde{\lambda}_a, \widetilde{T}_f) = C_{TOT\_cf}(k, \widetilde{\lambda}_a, \widetilde{T}_f) - C_{TOT\_cf}(k-1, \widetilde{\lambda}_a, \widetilde{T}_f), \tag{21}$$

$$\Delta_{df}(k, \bar{\lambda}_a, \bar{T}_f) = C_{TOT\_df}(k, \bar{\lambda}_a, \bar{T}_f) - C_{TOT\_df}(k-1, \bar{\lambda}_a, \bar{T}_f), \tag{22}$$

$$\Delta_{dd}(k, \lambda_a, T_f) = C_{TOT\_dd}(k, \lambda_a, T_f) - C_{TOT\_dd}(k-1, \lambda_a, T_f), \tag{23}$$

where $\widetilde{\lambda}_a$ and $\widetilde{T}_f$ are the average packet arrival rate and average subnet residence time for all MNs; $\bar{\lambda}_a$ and $\bar{T}_f$ are the average packet arrival rate and average subnet residence time for each MN. Given $\Delta_{(\cdot)}$, the algorithm to find the optimal value of k is defined as follows:

$$k_{opt\_cf}(\widetilde{\lambda}_a, \widetilde{T}_f) = \begin{cases} 1, & \text{if } \Delta_{cf}(2, \widetilde{\lambda}_a, \widetilde{T}_f) > 0 \\ \max\{k : \Delta_{cf}(k, \widetilde{\lambda}_a, \widetilde{T}_f) \leq 0\}, & \text{otherwise.} \end{cases} \tag{24}$$

$$k_{opt\_df}(\bar{\lambda}_a, \bar{T}_f) = \begin{cases} 1, & \text{if } \Delta_{df}(2, \bar{\lambda}_a, \bar{T}_f) > 0 \\ \max\{k : \Delta_{df}(k, \bar{\lambda}_a, \bar{T}_f) \leq 0\}, & \text{otherwise.} \end{cases} \tag{25}$$

$$k_{opt\_dd}(\lambda_a, T_f) = \begin{cases} 1, & \text{if } \Delta_{dd}(2, \lambda_a, T_f) > 0 \\ \max\{k : \Delta_{dd}(k, \lambda_a, T_f) \leq 0\}, & \text{otherwise.} \end{cases} \tag{26}$$

Note that the optimal value of the centralized fixed scheme is the same for all the MNs and is fixed all the time; the optimal value of the distributed fixed scheme is fixed all the time, but each user may have different optimal value; and the optimal value of the proposed distributed dynamic scheme is adapted to each MN and it depends on the up-to-date packet arrival rate and user mobility.

The algorithm for estimating packet arrival rate can be found in [7]. Each MN may use a timer to count the time it spent in each subnet and the average value within a regional network, T_f, is calculated before computing the k_{opt}. T_f can also be estimated if the probability density function (pdf) of the MN residence time in each subnet within a regional network is known. For example, if the pdf of the MN residence time $f_r(t)$ is of Gamma distribution which has Laplace transform $F_r(s) = \left(\frac{\mu\gamma}{s+\mu\gamma}\right)^{\gamma}$ with mean value $\frac{1}{\mu}$, variance V, and $\gamma = \frac{1}{V\mu^2}$. Then, $T_f = \frac{1}{\mu}$. Our algorithm also needs to know the number of hops between the HA and the GFA, l_{hg}, and the number of hops between the GFA and the FA, l_{gf}. If each MN has dedicated paths for transmitting signaling messages from FAs to GFAs and HAs, the number of hops between mobility agents (HA, GFA, and FA), l_{hg} and l_{gf}, are fixed numbers. If not, signaling packets may take different paths each time according to the traffic load and routing algorithms at each mobility agent. Thus, l_{hg} and l_{gf} vary within a certain range. An MN may use the *time-to-live* (TTL) field in IP packet headers to get the number of hops packets travel [18]. Then, the average value may be used for optimal number computation.

5 ANALYTICAL RESULTS

In this section, we demonstrate the performance improvement of the distributed dynamic scheme to the centralized fixed scheme, i.e., the IETF Mobile IP regional registration [5]. Since the distributed dynamic scheme and the centralized fixed scheme are not comparable, first we show the cost saving of the distributed fixed scheme to the centralized fixed scheme. Next, we demonstrate the advantages of the proposed distributed dynamic scheme over the distributed fixed scheme.

TABLE 1
Performance Analysis Parameters

Pkt Process Cost			Distance Cost Unit		Wireless Multiple	# of MNs/subnet	Weight		Pkt Process Const.	
a_h	a_g	a_f	δ_U	δ_D	ρ	ω	α	β	ζ	η
25.0	15.0	10.0	0.1	0.05	10	15	0.3	0.7	0.01	10.0

For the analysis in this paper, we assume the cost for transmitting signaling messages and the cost for packet processing at mobility agents are available. As discussed in [19], the cost parameters can be expressed in terms of the delay required to process the signaling messages. For example, a_h, a_g, and a_f may represent the delay required by the HA, GFA, and FA to process a location update requested by the signaling message, respectively; δ_U and δ_D may represent the delay for sending the signaling message through the particular path. Other measurements for the cost parameters are possible. For example, the network administration can assign relative costs to the mobility agents based on the current available bandwidth, computation resources in the system, and the expenses required to operate the particular mobility agent. In real implementations, the parameters in our model are designed values. They can be determined based on empirical measurements or some heuristic strategy. For different system architectures, the parameters are different. A table lookup process can be adopted in a particular network implementation, as mentioned in [20]. Given a particular time of a day, the table located at each FA provides a set of parameters for MNs to determine the optimal regional network size. The parameter table should be updated periodically to reflect the status of the network.

Table 1 lists some of the parameters used in our performance analysis. Since the total number of subnets that MNs may access through wireless channels is limited, we assume $N = 30$. For our numerical evaluation, we assume that l_{hg} and l_{gf} are fixed numbers. Since the TTL field in IP header is usually initialized by the sender to 32 or 64 [18], i.e., the upper limit on the number of hops through which a packet can pass is 32 or 64, we assume that $l_{hg} = 25$ and $l_{gf} = 10$.

5.1 Centralized Fixed Scheme versus Distributed Fixed Scheme

First, we compare the performance of the centralized fixed scheme and the distributed fixed scheme. Similar to the analysis in PCS, we define the call-to-mobility ratio (CMR) as the ratio of the packet arrival rate to the mobility rate, i.e., $CMR = \lambda_a T_f$. Since the cost functions of the two schemes derived in Section 3 are different, we focus on comparing the total signaling cost of the centralized fixed scheme $C_{TOT\_cf}(k_{opt\_cf}(\widetilde{\lambda}_a, \widetilde{T}_f), \lambda_a, T_f)$ with that of the distributed fixed scheme $C_{TOT\_df}(k_{opt\_df}(\bar{\lambda}_a, \bar{T}_f), \lambda_a, T_f)$ when the average values of residence time in each subnet and packet arrival rate of all the MNs are the same, i.e., $\widetilde{T}_f = \bar{T}_f$ and $\widetilde{\lambda}_a = \bar{\lambda}_a$.

Fig. 8 plots the optimal k as a function of CMR for the centralized fixed scheme and the distributed fixed scheme. Note that, for the two systems, the optimal regional network size k_{opt} is a designed value. It is computed before the communications based on the average values of user parameters. As shown in the figure, the optimal regional network size decreases as CMR increases for both centralized and distributed systems. When the CMR is low, the mobility rate is high compared to the packet arrival rate and the cost for location update dominates. Systems with larger regional networks may reduce the number of home registrations and provide the benefit of regional registration. When the CMR is high, the packet delivery cost dominates and the saving in packet delivery becomes significant. The saving can be attributed to the smaller regional network size. Note that the optimal regional network size of the distributed system is always larger than or equal to that of the centralized system. This means that for the same CMR, the distributed system has larger regional network size and, consequently, performs less home registrations compared with the centralized system.

Fig. 9 shows the total signaling cost as a function of CMR for the two schemes. The dashed line in the figure is the signaling cost of centralized fixed scheme when the regional network size is k_{opt_cf}. The dotted line is the signaling cost of the distributed fixed scheme with k_{opt_cf} as the regional network size. Note that k_{opt_cf} is the optimal value for the centralized fixed scheme, in the sense that the minimal cost can be reached. But, k_{opt_cf} is not the optimal value for the

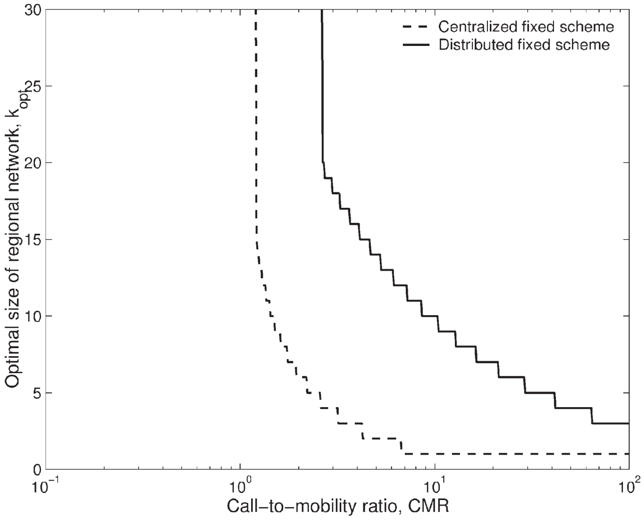

Fig. 8. Optimal regional network size for centralized and distributed systems.

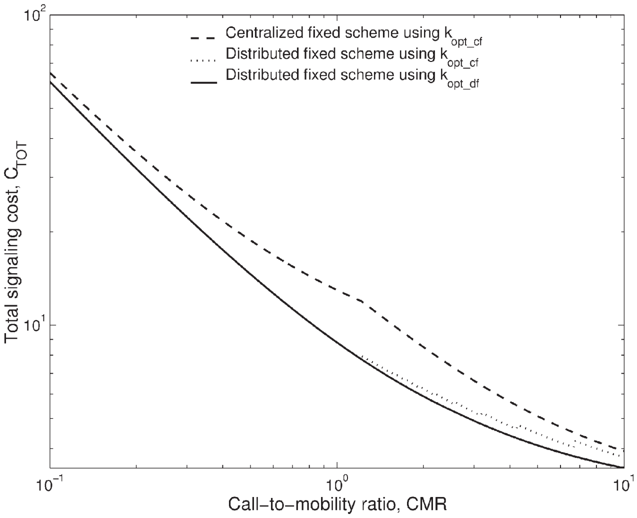

Fig. 9. Comparison of total signaling cost for fixed schemes.

distributed scheme. The solid line in the figure is the signaling cost of the distributed fixed scheme under k_{opt_df}. This line represents the minimal cost of the distributed fixed scheme. Fig. 9 indicates that, even under nonoptimal regional network size, the distributed scheme always performs better than the centralized IETF Mobile IP regional registration scheme. And, the distributed scheme with optimal regional network size can further improve the performance. Up to 36 percent of the signaling cost can be saved when using distributed system architecture.

5.2 Distributed Fixed Scheme versus Distributed Dynamic Scheme

Next, we compare the total signaling cost of the distributed fixed scheme $C_{TOT\_df}(k_{opt\_df}(\bar{\lambda}_a, \bar{T}_f), \lambda_a, T_f)$ with that of the proposed distributed dynamic scheme $C_{TOT\_dd}(k_{opt\_dd}(\lambda_a, T_f), \lambda_a, T_f)$ under various scenarios. Note that $k_{opt\_df}(\bar{\lambda}_a, \bar{T}_f)$ is precomputed before communications. Once it is set, it will not change. But, $k_{opt\_dd}(\lambda_a, T_f)$ is dynamically adapted to the user parameters during the communications. Since the cost functions of the two schemes are the same, the advantages of the dynamic scheme over the fixed scheme are reflected when the user parameters are different and changing from time to time. Therefore, we investigate the impacts of user-variant and time-variant user parameters.

5.2.1 The Impact of User-Variant Residence Time

We first investigate the impact of user-variant mobility. Let packet arrival rate λ_a be a fixed number, i.e., $\lambda_a = \bar{\lambda}_a = \text{constant}$. Similar to [7], we assume there are two groups of MNs. One group represents *"active"* users with an average residence time in each subnet of $\bar{T}_{f_1} = 1.0$. The other group is for *"passive"* users with average residence time in each subnet $\bar{T}_{f_2} = 100$. The residence time of group 1 users follows an exponential distribution, i.e.,

$$f_1(T_f) = \frac{1}{\bar{T}_{f_1}} e^{-T_f/\bar{T}_{f_1}}, \quad T_f \geq 0 \tag{27}$$

and the residence time of group 2 users follows a Gaussian distribution:

$$f_2(T_f) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\left(T_f - \bar{T}_{f_2}\right)^2/2\sigma^2}, \quad T_f \geq 0, \tag{28}$$

where $\sigma = 10$. Assume that each group has 50 percent of total users. The residence time T_f of a randomly selected user has pdf as:

$$f(T_f) = 0.5\big(f_1(T_f) + f_2(T_f)\big) \tag{29}$$

and the overall average residence time is:

$$\bar{T}_f = 0.5\bar{T}_{f_1} + 0.5\bar{T}_{f_2}. \tag{30}$$

Therefore, the total signaling cost of the distributed fixed scheme is:

$$\begin{aligned} C_{df} =& 0.5 \int_0^\infty f_1(T_f) C_{TOT\_df}(k_{opt\_df}(\bar{\lambda}_a, \bar{T}_{f_1}), \lambda_a, T_f) dT_f \\ &+ 0.5 \int_0^\infty f_2(T_f) C_{TOT\_df}(k_{opt\_df}(\bar{\lambda}_a, \bar{T}_{f_2}), \lambda_a, T_f) dT_f, \end{aligned} \tag{31}$$

where k_{opt} of group 1 users is computed based on their average residence time $\bar{T}_{f_1}$ and k_{opt} of group 2 users is computed based on $\bar{T}_{f_2}$. Note that, for distributed fixed scheme, the optimal regional network size may be user-variant or the same for all the users. Fig. 4 gives an example of user-variant k_{opt} and (31) indicates that group 1 and group 2 users adopt different fixed optimal regional network size. The total signaling cost of the distributed fixed scheme using fixed k_{opt} for all the users is:

$$\widetilde{C}_{df} = \int_0^\infty f(T_f) C_{TOT\_df}(k_{opt\_df}(\bar{\lambda}_a, \bar{T}_f), \lambda_a, T_f) dT_f \tag{32}$$

and the total signaling cost of the distributed dynamic scheme is:

$$C_{dd} = \int_0^\infty f(T_f) C_{TOT\_dd}(k_{opt\_dd}(\lambda_a, T_f), \lambda_a, T_f) dT_f. \tag{33}$$

Fig. 10 shows the total signaling cost of the distributed dynamic scheme and the distributed fixed scheme under user-variant residence time T_f. The dashed line in the figure is the signaling cost of the distributed fixed scheme using fixed k_{opt_df}, which is actually the case shown in Fig. 9 with a solid line. It is observed in Fig. 10 that the signaling cost of the distributed dynamic scheme is less than that of both the distributed fixed scheme using fixed optimal regional network size and using user-variant optimal size. Our results demonstrate that C_{TOT} is reduced by up to 33 percent using the dynamic scheme instead of the fixed scheme with fixed k_{opt}. Although the performance improvement of the distributed dynamic scheme is not large compared to the distributed fixed scheme under user-variant k_{opt}, in the following time-variant residence time situation, the dynamic scheme will demonstrate its advantage.

5.2.2 The Impact of Time-Variant Residence Time

Packet arrival rate λ_a is still a constant. The residence time of all MNs, T_f, is of exponential distribution:

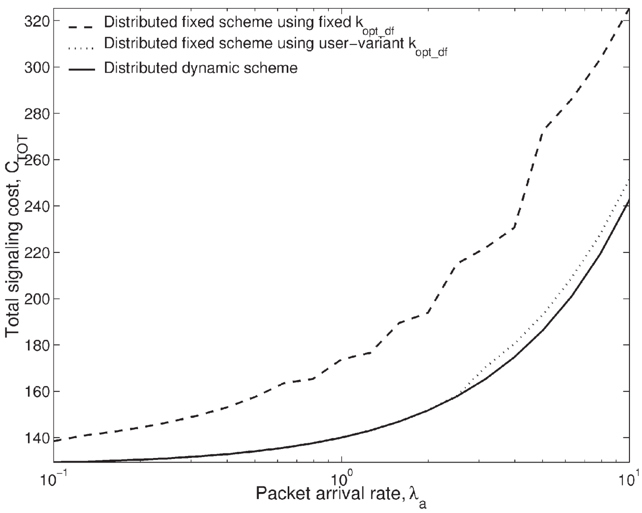

Fig. 10. Comparison of total signaling cost under user-variant residence time.

$$f(T_f) = \frac{1}{\bar{T}_f} e^{-T_f/\bar{T}_f}, \tag{34}$$

where $\bar{T}_f$ is the mean residence time and $\bar{T}_f$ is time-variant. The overall signaling cost of distributed fixed scheme is:

$$C_{df}(\bar{T}_f) = \int_0^\infty f(T_f) C_{TOT\_df}(k_{opt\_df}, \lambda_a, T_f) dT_f. \tag{35}$$

Note that, although $\bar{T}_f$ is varying during the communications, the optimal value for the fixed scheme k_{opt_df} is precomputed as a designed value and is fixed all the time during the communications. The signaling cost of the distributed dynamic scheme is given by (33) using the new pdf function $f(T_f)$ in (34).

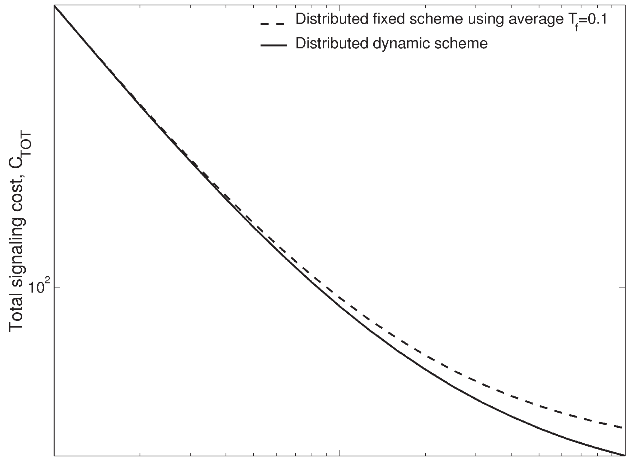

Fig. 11. Comparison of total signaling cost under time-variant residence time.

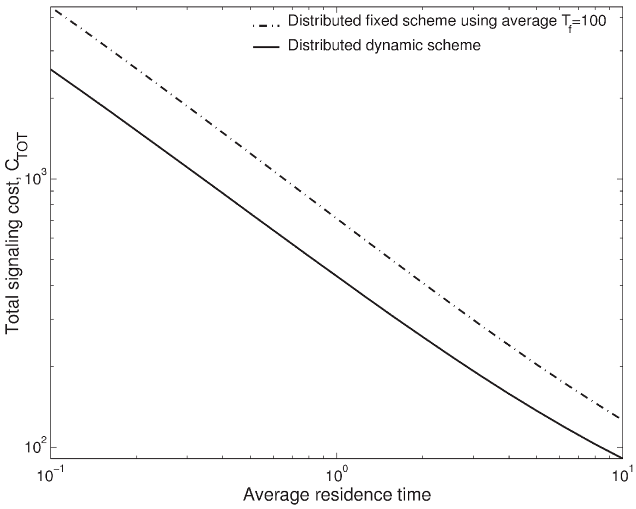

Fig. 12. Comparison of total signaling cost under time-variant residence time.

Fig. 11 and Fig. 12 show the total signaling cost as a function of the average residence time $\bar{T}_f$ when $\bar{\lambda}_a = 3.0$. Two cases of the distributed fixed scheme are shown: One is with the optimal regional network size k_{opt_df} precomputed using $\bar{T}_f = 0.1$ as the average residence time over all users, and the other is with the optimal size k_{opt_df} precomputed using $\bar{T}_f = 100$. Note that the distributed fixed system always pays higher cost than the distributed dynamic system. Our results show that up to 15 percent cost can be saved by the distributed dynamic scheme compared to the distributed fixed scheme using $\bar{T}_f = 0.1$ for the optimal regional network size computation, and up to 44 percent cost can be saved compared to the distributed fixed scheme using $\bar{T}_f = 100$ for the computation. We can see from the figures that the distributed fixed system using $\bar{T}_f = 0.1$ for optimal size computation may perform well when the user residence time is small, but when the residence time is large, the fixed scheme consumes more network resource. Similarly, the cost gap between the dynamic system and the fixed system using $\bar{T}_f = 100$ for computation is smaller when $\bar{T}_f$ is large, but the fixed system pays much more extra bandwidth when $\bar{T}_f$ is small. Therefore, it is a difficult task to design an optimal regional network size beforehand for the distributed fixed scheme. If the user mobility has some unusually large changes to its normal average value, the system with a predesigned fixed regional network size will consume much more bandwidth and the network may be congested.

5.2.3 The Impact of User-Variant Packet Arrival Rate

Now, we investigate the impact of user-variant packet arrival rate. Let user residence time T_f be a constant, i.e., $T_f = \bar{T}_f = \text{constant}$. Similar to the discussion in Section 5.2.1, we assume there are two groups of MNs. One represents normal users with average packet arrival rate $\bar{\lambda}_{a_1} = 0.1$. The other group is for special users with average packet arrival rate $\bar{\lambda}_{a_2} = 10.0$. The packet arrival rates of group 1 normal users follow an exponential distribution, i.e.,

$$f_1(\lambda_a) = \frac{1}{\bar{\lambda}_{a_1}} e^{-\lambda_a/\bar{\lambda}_{a_1}}, \quad \lambda_a \geq 0 \tag{36}$$

and the packet arrival rates of group 2 special users follow a Gaussian distribution:

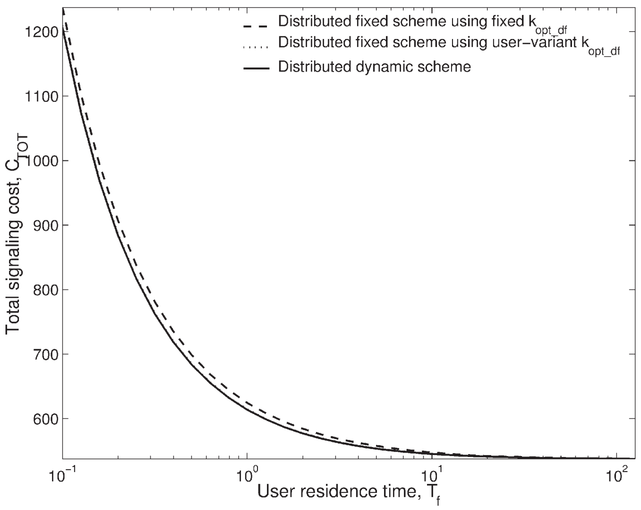

Fig. 13. Comparison of total signaling cost under user-variant packet arrival rate.

$$f_2(\lambda_a) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\left(\lambda_a - \bar{\lambda}_{a_2}\right)^2/2\sigma^2}, \quad \lambda_a \geq 0, \tag{37}$$

where $\sigma = 4.0$. Assume that each group contributes 50 percent of total users. For an arbitrary MN, the packet arrival rate has pdf as:

$$f(\lambda_a) = 0.5(f_1(\lambda_a) + f_2(\lambda_a)) \tag{38}$$

and the overall average packet arrival rate is:

$$\bar{\lambda}_a = 0.5\bar{\lambda}_{a_1} + 0.5\bar{\lambda}_{a_2}. \tag{39}$$

Therefore, the total signaling costs of the distributed fixed scheme using fixed k_{opt} for all the MNs and using different k_{opt} for group 1 and group 2 users are:

$$\widetilde{C}_{df} = \int_0^\infty f(\lambda_a) C_{TOT\_df}(k_{opt\_df}(\bar{\lambda}_a, \bar{T}_f), \lambda_a, T_f) d\lambda_a, \tag{40}$$

$$\begin{aligned} C_{df} = 0.5 &\int_0^\infty f_1(\lambda_a) C_{TOT\_df}(k_{opt\_df}(\bar{\lambda}_{a_1}, \bar{T}_f), \lambda_a, T_f) d\lambda_a \\ + 0.5 &\int_0^\infty f_2(\lambda_a) C_{TOT\_df}(k_{opt\_df}(\bar{\lambda}_{a_2}, \bar{T}_f), \lambda_a, T_f) d\lambda_a \end{aligned} \tag{41}$$

and the total signaling cost of the distributed dynamic scheme is:

$$C_{dd} = \int_0^\infty f(\lambda_a) C_{TOT\_dd}(k_{opt\_dd}(\lambda_a, T_f), \lambda_a, T_f) d\lambda_a. \tag{42}$$

Fig. 13 shows the total signaling cost of the distributed dynamic scheme and the distributed fixed scheme under user-variant packet arrival rate λ_a. The signaling cost of the distributed dynamic scheme is almost the same as that of both the distributed fixed scheme using fixed optimal regional network size and using user-variant optimal size. Only 3 percent cost can be reduced using the distributed dynamic scheme. It indicates that the optimal regional network size is relatively insensitive to the packet arrival rate. Although different users have widely ranged traffic load, their optimized regional network sizes do not vary much.

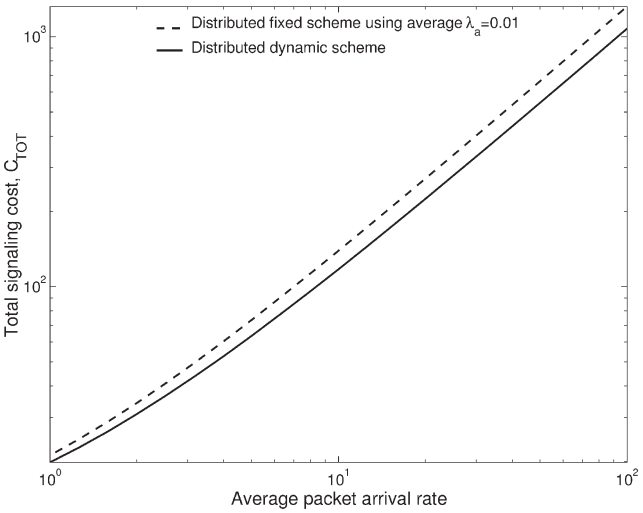

Fig. 14. Comparison of total signaling cost under time-variant packet arrival rate.

5.2.4 The Impact of Time-Variant Packet Arrival Rate

Finally, we study the impact of time-variant packet arrival rate. The user residence time T_f is still fixed. The packet arrival rates of all MNs are exponentially distributed:

$$f(\lambda_a) = \frac{1}{\bar{\lambda}_a} e^{-\lambda_a/\bar{\lambda}_a}, \tag{43}$$

where $\bar{\lambda}_a$ is the mean arrival rate and $\bar{\lambda}_a$ is time-variant. The overall signaling cost of the distributed fixed scheme is given by:

$$C_{df}(\bar{\lambda}_a) = \int_0^\infty f(\lambda_a) C_{TOT\_df}(k_{opt\_df}, \lambda_a, T_f) d\lambda_a, \tag{44}$$

where k_{opt_df} is precomputed and is fixed all the time. The signaling cost of the distributed dynamic scheme is given by (42) using $f(\lambda_a)$ in (43).

Fig. 14 and Fig. 15 plot the total signaling cost as a function of time-variant average packet arrival rate $\bar{\lambda}_a$, when $\bar{T}_f = 10$. The dashed line in Fig. 14 is based on k_{opt} calculated using $\bar{\lambda}_a = 0.01$. The dash-dot line in Fig. 15 is based on k_{opt} calculated using $\bar{\lambda}_a = 100$. The solid line in both figures is for the proposed distributed dynamic scheme where k_{opt} varies according to the up-to-date parameters. The figures show that the fixed system always pays higher cost than the dynamic system. The cost gap is larger when $\bar{\lambda}_a < 0.1$ in Fig. 15 and when $\bar{\lambda}_a > 10$ in Fig. 14. The dynamic system saves up to 19 percent and 36 percent cost compared to the fixed system using $\bar{\lambda}_a = 0.01$ and $\bar{\lambda}_a = 100$ for optimal value computation, respectively. This result is similar to that in Section 5.2.2. It indicates that the distributed dynamic scheme is more cost-efficient when the user parameters are time-variant.

6 CONCLUSION

In this paper, we introduced a distributed and dynamic regional location management mechanism for Mobile IP. We proposed a distributed GFA system architecture where each FA can function either as an FA or a GFA. This

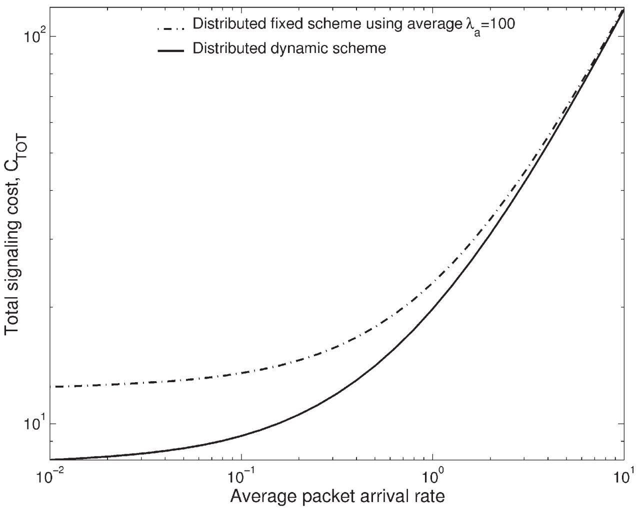

Fig. 15. Comparison of total signaling cost under time-variant packet arrival rate.

distributed system may allocate signaling burden more evenly. A dynamic scheme is adopted by the distributed system to dynamically optimize the regional network size of each MN according to its current traffic load and mobility. We also presented the operation protocols of the distributed dynamic scheme for MNs. The proposed distributed and dynamic scheme is able to perform optimally for all users from time to time and the system robustness is enhanced. Since the movement of MNs does not follow a Markov process, we introduced a novel discrete analytical model for cost analysis and an iterative algorithm to find out the optimal number of FAs in a regional network which consumes the minimal network resource. Our model does not have constraints on the shape and the geographic location of Internet subnets. Analytical results demonstrated that the signaling bandwidth is significantly reduced through our proposed distributed system architecture compared with the IETF Mobile IP regional registration scheme. It is also demonstrated that our dynamic scheme has great advantages under time-variant user parameters when it is not obvious to predetermine the optimal regional network size.

The proposed distributed dynamic location management scheme requires that all FAs are capable of functioning as both an FA and a GFA. It increases the requirement of the processing capability on each mobility agent. There is additional processing load on the mobile terminals, such as the estimation of the average packet arrival rate and subnet residence time.

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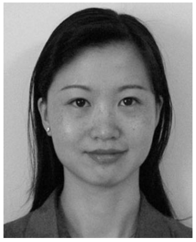

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