Wireless Networks 12, 145–158, 2006

DOI: 10.1007/s11276-005-5262-2

User Independent Paging Scheme for Mobile IP

JIANG XIE
Department of Electrical and Computer Engineering, The University of North Carolina at Charlotte, Charlotte, NC 28773

Published online: 30 December 2005

Abstract. Multi-step paging has been widely proposed in personal communications services (PCS) systems to reduce the signaling overheads. Similar ideas can be applied to Mobile IP to provide IP paging services. However, current proposed multi-step paging schemes are user dependent under which the partition of paging areas and the selection of paging sequence are different for each user. The performance of a user dependent paging scheme for individual users may be affected by many factors. It is often difficult to achieve perfect performance for each user. In addition, when multiple users are paged at the same time, user dependent paging schemes may consume significant system resources. This paper introduces a user independent paging scheme where the paging criterion is not based on individual user information. The goal of user independent paging is to provide satisfactory overall performance of the whole system, when personalized optimal performance for each user is hard to obtain. The user independent paging scheme is proposed for IP mobility for its easy implementation and convenient combination with paging request aggregation. The paging criterion adopted is the mobility rate of each subnet determined by the aggregated movements of all mobile users. In order to implement the proposed scheme, a concept of "semi-idle state" is introduced and the detailed solution for obtaining mobility rate is presented. Analytical results show that when paging one user at a time, the performance of the proposed user independent paging scheme is comparable to that of the paging schemes based on perfect knowledge of user movement statistics. When paging multiple users simultaneously and when the knowledge on individual user behavior is not perfectly accurate, the proposed scheme has remarkable advantages in terms of reducing the overall paging cost.

Keywords: location tracking, multi-step paging, Mobile IP, user profile, paging cost

1. Introduction

Location tracking of mobile terminals (MTs) in current wireless personal communications services (PCS) systems includes two fundamental operations: location update and paging [4]. Location update is the reporting process of the current location area (LA) of an MT. Paging is used by the system to alert an MT of an incoming call by sending poll messages to the cells within the last reported LA. In the current paging strategy of GSM and IS-41 protocols, paging messages are broadcasted to each cell in the registered LA of an MT. The signaling cost of broadcast procedure is maximum, especially when the number of MTs increases. In order to improve the bandwidth utilization, multi-step paging or sequential paging schemes are proposed.

There is a tradeoff between the paging cost and the delay associated with locating an MT using multi-step paging schemes. It is stated in [1] that blocking users from the system due to bandwidth unavailability is much more undesirable from the user's and the operator's viewpoint than the delay of incoming data reaching the user. Therefore, when the system need not find MTs immediately, multi-step paging schemes are preferable. There are numerous link layer multi-step paging schemes proposed to reduce the paging cost [2,3,11,20,25]. A *shortest-distance-first* (SDF) paging scheme is proposed in [3] where cells close to the last registered location are paged first. This scheme is associated with a distance-based location update scheme. Under the *highest-probability-first* (HPF) scheme introduced in [20], an LA is divided into several partitions and each partition consists of a cluster of cells. The sequential paging is performed in decreasing order of cell location probabilities to minimize the mean number of cells being searched. In [25], three methods for dividing an LA are proposed, namely *reverse*, *semi-reverse*, and *uniform* paging. Given the location probabilities, cells are grouped in different ways to reduce the paging cost under delay bounds.

All the above mentioned paging schemes are user-dependent, i.e., the distance to the last registered location and location probabilities are user-variant. Therefore, the partition of paging areas and the selection of paging sequence are different for each user. If the system performs paging optimally for every MT, i.e., the average paging cost for each MT is minimum while satisfying its paging delay requirement, the overall performance of the entire system is also optimal. However, many factors may affect the performance of a paging scheme for individual users. For example, for paging schemes based on cell location probabilities, these schemes assume perfect knowledge on the user mobility statistics, which may not be readily available in practice. Moreover, the cell location probabilities are predicted and estimated values based on user movement history. They cannot reflect the up-to-date user mobility. If the user mobility has some unusual big changes to its normal average value, paging in the decreasing order of statistically average values of location probabilities cannot generate optimal performance for each user. Therefore, to reduce the dependency of the paging scheme on individual user information, but to provide satisfactory overall performance of the whole system is the basic consideration of this paper. Another disadvantage of user-dependent paging schemes is that the consumption of network resource and the signaling overhead may become very significant when a number of users are paged at the same moment, since every paging request is processed separately. This case may happen more often in Mobile IP.

Mobile IP [15,16] is being developed by Internet Engineering Task Force (IETF). It introduces three new functional entities: home agent (HA), foreign agent (FA), and mobile node (MN). When an MN moves out of its home network, it obtains a temporary address: care-of address (CoA). This address is used to identify the MN in the local network. When the MN moves from one foreign network to another, it registers its new location, i.e., its new CoA, to its HA. Packets for an MN are sent to its permanent address, i.e., its home address first. The HA intercepts all the IP packets destined to the MN and tunnels them to the serving FA of the MN. The FA decapsulates and forwards these packets to the MN.

A major problem of MNs is their limited battery capacity. In order to save the battery power consumption at MNs, IP paging is proposed as an extension for Mobile IP [7,13,18,19,21,26–28]. Under Mobile IP paging, an MN is allowed to enter a power saving idle mode when it is inactive for a period of time. During the idle mode, the system knows the location of the MN with coarse accuracy defined by a paging area which is composed of several subnets [7]. The MN may also deactivate some of its components for energy-saving purpose. An MN in idle mode does not need to register its location when moving within a paging area. It performs location update only when it changes paging areas. When packets are destined to an MN in idle mode, they are terminated at a paging initiator. The paging initiator buffers the packets and locates the MN by sending IP paging messages to all the subnets within the paging area. After knowing the subnet where the MN is residing, the paging initiator forwards the data packets to the serving FA of the subnet and further to the MN. Since the system and MNs synchronize on the time slots for paging, there are possibilities that multiple paging requests are needed to be sent out in one time slot. In this case, *paging request aggregation* [26] can be adopted to reduce the paging overheads, if the paging criterion is not user dependent. When an MN is in active transmission mode, it operates in the same manner as in Mobile IP and the system keeps the exact updated location information of the MN. The state transition diagram of MNs with paging support is shown in figure 1.

Current research activities on Mobile IP paging focus on the *paging architecture* design, i.e., which node initiates paging and how the messages exchange between nodes. They seldom consider the *paging algorithm* design, i.e., how an MN is searched or how the paging requests are sent by the paging initiator [19]. Broadcast procedure is assumed to be used in almost all the proposed paging architectures [7,13,18,19,21,26,27]. The ideas of multi-step link layer paging schemes can be applied to Mobile IP. However, link layer (layer 2) paging and IP layer (layer 3) paging are different. IP layer paging refers to locating the current IP attachment point of an MN within a layer 3 location area. A layer 3 location area is a set of IP subnets identified by IP addresses [28]. Link layer paging is the paging capability of an underlying radio system. It refers to sending poll messages through wireless links to the cells within the last reported link layer location area. Link layer paging is tightly coupled with the specific wireless technology [6]. Note that an IP paging scheme does not make any assumption on how the underlying link layer paging is implemented. When both IP layer paging and link layer paging are supported, a layer 3 location area should be mapped to layer 2 location areas. Moving out of a layer 2 location area does not necessarily imply moving out of a layer 3 location area, and vice versa. Thus, there is possibility that the corresponding subnets of two geographically close cells are not close together in the Internet. Therefore, when applying the ideas of link layer multi-step paging schemes to Mobile IP, differences between layer 2 and layer 3 paging should be paid attention and modifications are needed.

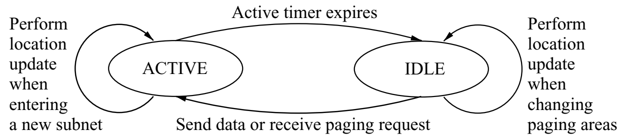

Figure 1. State transition diagram of Mobile IP paging.

In this paper, we introduce the concept of user independent paging where the paging criterion is not based on individual user information. The goal of user independent paging is to provide satisfactory overall performance of the whole system, although the paging performance for each user may not be optimal. User independent paging can be applied to both link layer paging and IP layer paging, as long as the selected paging criterion is user independent. In this paper, we choose the mobility rate of each subnet as the paging criterion for its easy implementation and propose a user independent paging scheme for IP mobility. We focus on how the IP paging messages are sent by the paging initiator to the FAs within a paging area over the wired links. We do not change the link layer paging support by which each FA sends out poll messages through wireless links to locate an MN. The proposed scheme can be employed by the current proposed IP paging architectures: home agent paging [19], foreign agent paging [26,27], domain paging [18,19], IDMP-based paging [13], hierarchical paging [7,21], etc. The proposed scheme is user independent in the sense that the partition of paging areas is determined by the aggregated movements of all mobile users, without the knowledge on the behavior of individual ones. Moreover, we also explain how to obtain the mobility rate in the proposed scheme.

This paper is organized as follows. In Section 2, the proposed paging algorithm is explained. In Section 3, the analysis of the paging cost for the proposed scheme and another scheme are given. In Section 4, analytical results under various scenarios are presented, followed by the conclusions in Section 5.

2. User independent paging scheme for mobile IP

In this section, we introduce the new user independent IP paging scheme. We also present a solution for implementing the proposed scheme in real systems.

2.1. Overview of the user independent paging scheme

The proposed user independent paging scheme is a multi-step paging scheme which limits the number of paging steps below a pre-designed value while reducing the average paging cost. Instead of broadcasting IP paging messages, the paging initiator pages an idle MN in smaller areas sequentially. Specifically, the registered FA first locates the MN in its last registered subnet. If the MN is in the last registered subnet, the paging procedure is terminated. The MN replies to the paging initiator so that the data packets can be forwarded. If the MN is not in the last registered location, it means the MN has moved since last location update. Then the paging initiator divides the remaining subnets into several partitions based on the up-to-date subnet mobility rates and sends out IP paging messages in the decreasing order of mobility rates in the following steps. In other words, the paging initiator first sends paging messages to the FAs of the subnets with the highest user mobility rates, i.e., the areas with more *new idle* MNs moved in within the latest time period. If there is no response within a timeout interval, the paging initiator sends out paging messages to the subnets with lower mobility rates. We will describe how to obtain the up-to-date user mobility rate of each subnet in the next section. The total number of partitions is determined by the maximum paging delay the user may tolerate. Therefore, the proposed paging scheme is a combination of *last-location-first* paging and *highest-mobility-first* paging. Note that the paging procedure is neither based on geographic distance information which is not suitable for Internet environment, nor based on the user-variant predicted location probabilities which assumes perfect knowledge on the user movement statistics. The subnet partitioning is not dependent on the *individual* behavior of each user. Instead, it considers the *overall* aggregated user mobility as the basis. Therefore, the proposed paging scheme is user independent.

The partitioning method of subnets other than the last registered subnet is flexible. Here, we employ a similar idea to that of the uniform paging proposed in [25], i.e., the number of subnets in each partition is of approximately the same.

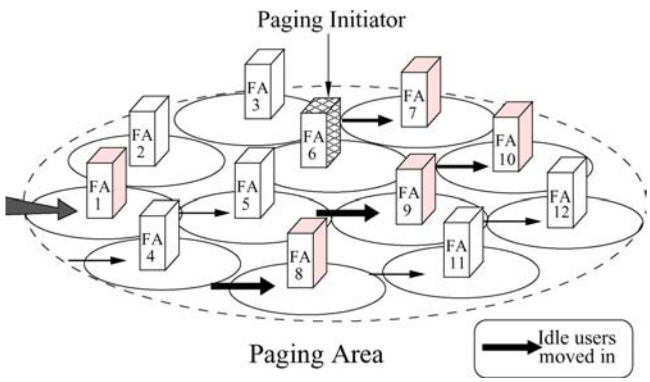

Figure 2. User independent paging scheme based on location and mobility rate.

For example, assume there are totally N subnets in a paging area. If the maximum number of paging steps is $\mathcal{L}$, then after first paging the last registered location, the remaining $N-1$ subnets are evenly divided into $\mathcal{L}-1$ groups based on user mobility rates. Similar to the calculation in [25], assume

$$n = \left\lfloor \frac{N-1}{\mathcal{L}-1} \right\rfloor \tag{1}$$

where $N-1 = n(\mathcal{L}-1)+k$ and k is an integer less than $\mathcal{L}-1$. Then, from the second to the $\mathcal{L}-1-k$ paging steps, n subnets are paged each time and $n+1$ subnets are paged during each of the following k paging steps. The n subnets with the n highest user mobility rates got the paging messages simultaneously.

The proposed paging scheme is illustrated in figure 2. In the figure, there are totally 12 FAs within a paging area, i.e., $N=12$. Assume foreign agent paging architecture [26,27] is used in this case. FA6 is the registered FA and is responsible for initiating paging requests. The width of the solid arrows in the figure is proportional to the number of new idle users moved into each subnet within the latest time period. Assume the total number of paging steps is set to be 3, i.e., $\mathcal{L}=3$. During the paging procedure, FA6 first checks whether the paged MN is in its subnet. If not, since $\lfloor \frac{N-1}{\mathcal{L}-1} \rfloor = 5$ and the mobility rates of subnets 1, 7, 8, 9, and 10 are the five highest ones, FA6 sends paging messages to FA1, FA7, FA8, FA9, and FA10 in the second step. Each of the above FA checks whether the MN is in its subnet. If the MN is found, then the paging procedure is terminated. If not, FA6 continues to send paging messages to the remaining FAs in the paging area.

Note that unlike in PCS systems, the number of paging steps is not necessarily proportional to the paging delay in Mobile IP. The transmission of paging messages in the IP core network is a multi-hop transmission where queuing delays may influence the transmission time of each paging message, depending on the traffic load of the network. Thus, the paging delay of each paging step varies within a certain range. However, the air interface in the wireless network is treated as a single hop. Therefore, the paging delay of each polling cycle in PCS systems is generally considered as a constant.

A comprehensive analysis on the calculation and estimation of end-to-end delay bound of Internet services is provided in [23]. Based on the paging delay requirement of each application and the general end-to-end delay bound for IP packet transmissions, the system may set an appropriate number of paging steps for each user. In this paper, we use the term "the maximum number of paging steps" for $\mathcal{L}$, instead of the conventional term "delay bound" as used in PCS systems.

2.2. Detailed solution for obtaining subnet mobility rate

Since MNs in idle mode do not perform location registrations while roaming within a paging area, FAs have no knowledge on how many idle MNs are visiting their subnets. Each FA keeps an updated visitor list of all the active MNs in its subnet as well as idle MNs who have performed idle mode location registrations through the FA when changing paging areas.

In order to implement the new paging scheme, we propose a solution for each FA to obtain the up-to-date user mobility rate of its subnet. We introduce a new operation mode for MNs named "*semi-idle*" mode. When an MN is in semi-idle mode, the system still does not know the accurate location of the MN. But unlike in idle mode, the MN in semi-idle mode provides minimum user information to the corresponding FA of the subnet it is visiting. Thus, based on this minimum user information, each FA has some knowledge on how many idle MNs are in its subnet. More importantly, MNs in semi-idle mode still save battery consumption compared to working in active mode. The state transition diagram of MNs for the proposed paging scheme is shown in figure 3 and the detailed procedure is explained below.

2.2.1. Operations at MNs

An MN is able to detect whether it has moved into a new subnet by periodically receiving unsolicited *Agent Advertisement* messages broadcasted from each FA [16]. If paging is supported, the MN and the visited subnet agree on communication time slots used for Agent Advertisement and paging,

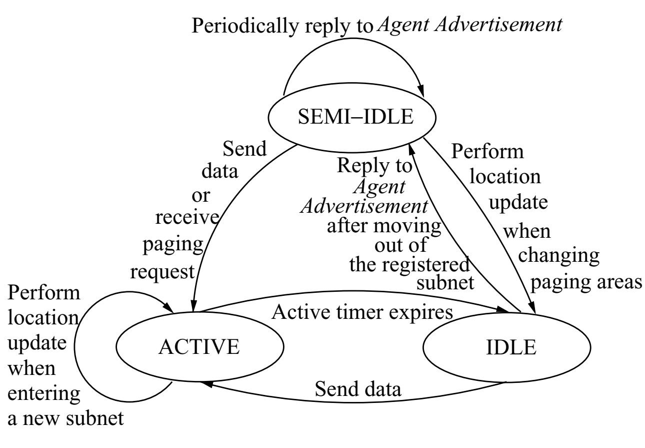

Figure 3. State transition diagram of the proposed paging scheme.

to restrict link interface power-on time in the MN [7]. Under this mechanism, an MN in idle mode powers on its receiver when an unsolicited Agent Advertisement or a paging request is expected and keeps its receiver powered off at other time slots. If an idle MN finds that it is in a subnet other than its registered subnet, the MN extends its power-on time slots a little bit and replies to the Agent Advertisement message by sending its home address and the registered CoA to the corresponding FA of its current subnet. The registered CoA is obtained from the registered FA when the MN changes paging areas and performs idle mode location registration. The content of this reply is the minimum basic information of the MN. Note that replying to the Agent Advertisement message is different from performing a location registration: the idle MN does not get a new CoA from the current FA and it does not send a location update message to the HA. Therefore, the signaling delay and the power consumption of replying to Agent Advertisement message are much less than those of performing a location registration. An MN in semi-idle mode changes to idle mode when it enters a new paging area and performs an idle location update to its HA. The corresponding FA of the registered subnet adds the MN to the visitor list and marks its mode as idle. The MN stays in the idle mode as long as it does not move out of the registered subnet. An MN in idle mode does not need to reply to Agent Advertisement message.

2.2.2. Operations at FAs

After receiving the reply message from an MN, the FA compares the CoA of the idle MN with its network prefix. If they are the same, the FA refreshes the idle state of the MN on its visitor list. If they are different, it implies that the MN is in idle mode but registered with another FA. The current FA adds the MN to the visitor list and marks its mode as semi-idle. The MN does not have to reply to every Agent Advertisement message. It may reply to the Agent Advertisement message periodically for every $\mathcal{M}$ advertisement slots to refresh its semi-idle state in the visitor list of the current FA. Same as active and idle states, the semi-idle state is also a soft state. If there is no further refreshment message, the state is expired. Therefore, when the MN leaves the current subnet, it does not need to send a cancellation message actively to remove its record on the visitor list. As a result, the total number of actual users in each subnet is the number of users in active mode as well as those in idle and semi-idle modes. Each FA keeps a counter. If within a time period $\mathcal{T}$, there is a *new* MN in semi-idle mode added to the visitor list, the counter is incremented by one. At the end of the time period, the counter is reset. So the counter value indicates the mobility rate of new idle MNs within the latest time period $\mathcal{T}$. The operations at FAs are illustrated in figure 4.

At the end of each time period $\mathcal{T}$, all FAs within a paging area exchange the user mobility information. They agree on the time slots of this exchange. When there is a paging request for an idle MN, the registered FA first checks its visitor list. If the paged MN has a record of idle state on the list, it means the

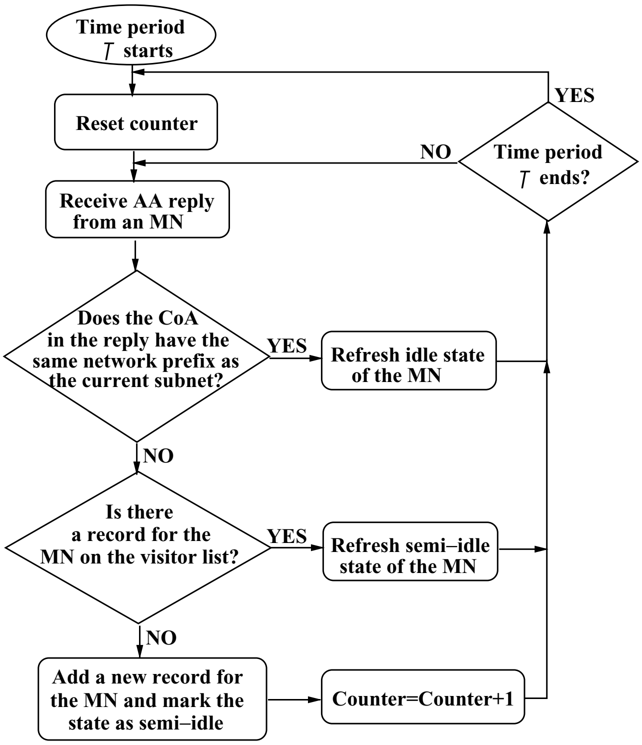

Figure 4. Flowchart of operations at FAs.

paged MN is in the subnet of the registered FA. The paging procedure is terminated. If the paged MN is not on the list, the paging initiator sends out IP paging messages to subnets in decreasing order of user mobility rates. When an FA receives an IP paging message, it checks the visitor list. If the MN is on the list with semi-idle state, the FA pages the MN over the air so that the MN may reply to the paging initiator and register its current location to the HA.

2.3. Advantages of the user independent paging scheme

The most significant feature of the proposed paging scheme is its user independent nature. This feature is reflected in the partition of subnets other than the last registered subnet of an MN. In contrast to the user dependent paging schemes that perform partitioning differently for each user according to the user-variant parameters, the proposed scheme uses one mutual criterion which is related to the aggregated behavior of all users. Although the aggregated mobility rate of each subnet cannot represent the behavior of an individual user precisely sometimes, we will demonstrate in Section 4 that the performance of the proposed scheme is comparable to that of user dependent paging schemes based on the assumption that perfect knowledge on user location probabilities are known. After that, we will show that the proposed scheme has remarkable advantages when paging multiple users simultaneously and when the assumption of perfect knowledge on user location probabilities is loose.

Moreover, the proposed paging scheme combines the advantages of last-location-first paging, highest-mobility-first paging, and uniform paging. In the case of networks with low mobility users, searching the last known location of the paged MN can save the paging cost significantly. In the case of networks with high mobility users, uniformly grouping the subnets based on the overall mobility rate of all users and paging each group in the decreasing order of mobility rates can also reduce the paging load and paging delay.

The advantages of the proposed user independent paging scheme are summarized as follows.

- The proposed scheme has the common advantage of multi-step paging schemes, that is, compared with broadcast paging procedure, the average number of paging messages sent out is reduced under the new scheme, since the system will find the user in the last registered location and high mobility rate areas with high probability.
- The location probability is determined by many factors, such as the user movement model and calling patterns [12]. The accuracy of the user movement model and the efficiency of the location probability prediction algorithm directly determine the capability of paging schemes. The mobility rate in the proposed scheme is the up-to-date value for each subnet. It represents the exact amount of movements within the latest time period. Therefore, compared with the paging schemes choosing location probabilities as paging criterion [2,11,20,25], the proposed paging scheme results in better system performance, especially when there is some unusual changes to the normal value of user movements.
- Unlike the schemes based on user-variant parameters, the proposed scheme is based on the mobility rate of each subnet for all the users. So paging request aggregation [26] can be adopted and the overall system performance can be further improved when paging multiple users at one moment.
- The proposed scheme is scalable. We will show in Section 4 that as the number of MNs in a paging area increases, the average paging cost caused by the user independent paging (UIP) scheme does not change much.

2.4. Tradeoffs of introducing "semi-idle" state

The introduction of the new operation mode, semi-idle mode, will cause extra signaling overheads due to the periodically replying to Agent Advertisement messages from MNs and message exchanges between FAs. These extra overheads will consume additional bandwidth and battery resources. The impact of the extra signaling overheads can be reduced by setting a relatively large value for the period of message exchanges. There is a tradeoff between the performance of the proposed scheme and the additional resource consumption. The more often the MNs and FAs exchange mobility information, the more accurate the mobility rate values are and the better performance the proposed scheme may achieve, but the more additional overheads. On the other hand, a small error of the mobility rate values does not necessarily affect the performance of the proposed scheme, since it is the ranking of the mobility rate of each subnet among all the mobility rates that determines the partition of a paging area, not the absolute values.

We will show in the following section that compared with a user dependent paging scheme where location probabilities are given in user profiles, the extra cost of introducing semi-idle mode is comparable to the extra cost of setting up user profiles. Therefore, the overheads caused by the introduction of semi-idle mode can be treated as the maintenance cost for the system to obtain accurate mobility rate information in order to employ the proposed user independent paging scheme.

3. Analytical model

In this section, we derive the expected paging cost of the proposed user independent paging (UIP) scheme. We choose a user dependent paging scheme which is purely based on the location probabilities of each MN for our performance comparison. Here, for IP paging schemes, location probabilities are the probabilities that an MN will visit each subnet. They are different from the cell location probabilities in link layer paging context. We assume the system has a user profile for each MN. In the user profile, the subnet location probabilities of an MN at different time of a day are provided which can be obtained either through empirical measurements or analysis of user movement models [17]. We call this scheme user profile paging (UPP) scheme.

3.1. Costs of obtaining mobility rates and setting up user profiles

In order to implement the proposed UIP scheme, the system provides extra resources to obtain mobility rates of each subnet. Similarly, in order to implement the UPP scheme, the system pays extra costs to set up a user profile for each mobile user and obtain location probability distributions. For both schemes, these extra costs can be summarized as: sampling and data transmission cost; data storage cost; and computation cost. More specifically, the costs of obtaining mobility rates of each subnet in the UIP scheme include:

- Radio resource consumption of periodically replying to Agent Advertisement messages from each MN;
- Processing load on each FA of updating the visitor list after receiving the replies to Agent Advertisement messages;
- Wireline bandwidth consumption of mobility rate information exchange between FAs.

The costs of obtaining location probabilities in the UPP scheme depend on how the user profile is defined and set up. User profiles can be provided and updated manually by mobile users or determined automatically by monitoring the movement history over a period of time [22]. Methods of obtaining cell location probability distributions in PCS systems are discussed in [25]. Similar methods can be applied to Mobile IP to set up subnet location probabilities. The costs of obtaining subnet location probabilities are:

- Radio resource consumption of periodically sending the location information to the system database from each MN, if the user profile is updated manually by the mobile user;
- Processing load of updating the system database. If the user profile is updated manually by the mobile user [5], after receiving the location information sent from each MN, the system updates the database; If the user profile is updated by the system, the system updates the database whenever the MN initiates communications or the MN receives packets from others;
- Processing load on the system database for MN velocity estimation, movement estimation, subnet residence time estimation, traffic condition estimation, etc., depending on how the user profile is defined. Each of the above computations may consume extra wireline and wireless bandwidth;
- Processing load of estimating and predicting location probabilities using mathematical models. An algorithm for location probability estimation in PCS systems is proposed in [24], where cell location probabilities depend on historic records, current position, velocity, and moving directions of mobile users.

From the above analysis, we may see that to predict location probabilities and to set up mobility profiles for each user require intensive computation. The extra costs of obtaining mobility rates for the UIP scheme is comparable or less than the extra costs of obtaining location probabilities for the UPP scheme, depending on how the user profile is defined. Hence, in this paper, we consider the costs of obtaining mobility rates and setting up user profiles as the maintenance cost for the system to employ the UIP and UPP schemes, and these costs are not counted in the paging cost comparison in the following.

3.2. Relationship between location probabilities and mobility rates

In order to compare the expected paging costs of the proposed UIP scheme and UPP scheme, we first derive the relationship between user location probabilities and mobility rates. Let the total number of users in a paging area be M and the total number of subnets in a paging area be N. We assume the movements of a mobile user are independent of those of other users. Assume during the next time period $\mathcal{T}$, the probability that user x will move out of its current subnet to subnet y is $q_{x\rightarrow y}$, where $x = 1, 2, \ldots, M$ and $y = 1, 2, \ldots, N$. Now, we find the probability distribution that there are k no users moves into subnet y during the next time period.

The probability that there is no user moves to subnet y is equal to the probability that all the users moved to other subnets except subnet y, i.e.,

$$P_y(K=0) = \prod_{x=1}^{M}(1 - q_{x\to y}) \tag{2}$$

where $\sum_{\substack{y=1\\ y\neq\upsilon}}^{N} q_{x\to y} = 1$, and υ represents the subnet user x is currently visiting. The probability that there is one user moves to subnet y during the next time period is:

$$\begin{aligned}
&P_y(K=1)\\
&\quad = q_{1\to y}\prod_{\substack{x=1\\x\neq 1}}^{M}(1-q_{x\to y}) + q_{2\to y}\prod_{\substack{x=1\\x\neq 2}}^{M}(1-q_{x\to y})\\
&\qquad + \cdots + q_{M\to y}\prod_{\substack{x=1\\x\neq M}}^{M}(1-q_{x\to y})\\
&\quad = \sum_{l=1}^{M} q_{l\to y}\cdot\prod_{\substack{x=1\\x\neq l}}^{M}(1-q_{x\to y})
\end{aligned} \tag{3}$$

Similarly, the probabilities that two users and k users move to subnet y during the next time period are shown in the following, respectively:

$$P_y(K=2) = \sum_{\substack{l_1,l_2=1\\ l_1\neq l_2}}^{M} q_{l_1\to y}q_{l_2\to y}\cdot\prod_{\substack{x=1\\ x\neq l_1,l_2}}^{M}(1-q_{x\to y}) \tag{4}$$

$$P_y(K=k) = \sum_{\substack{l_1,\ldots,l_k=1\\ l_1\neq\cdots\neq l_k}}^{M} q_{l_1\to y}\cdots q_{l_k\to y}\prod_{\substack{x=1\\ x\neq l_1\neq\cdots\neq l_k}}^{M}(1-q_{x\to y}) \tag{5}$$

where $k = 1, \ldots, M$.

Given the above probability distribution, we may get the expected number of users who move to subnet y during the next time period as:

$$E[P_y(K)] = \sum_{k=0}^{M} k\cdot P_y(K=k), \quad \text{where } y = 1,\ldots,N \tag{6}$$

$E[P_y(K)]$ can be treated as the mobility rate of subnet y in the proposed paging scheme, i.e., the number of new idle users who move into subnet y in a certain time period.

Note that we do not impose geographic proximity of subnets as the constraint on our mobility model as used in the analysis of PCS paging schemes [2,3,8] and other Mobile IP paging schemes [26].

3.3. Paging costs

Now, we derive the paging cost functions for the proposed UIP scheme and the UPP scheme. We define the following parameters for our analysis:

- V_{air} The wireless paging cost including broadcasting the polling messages over the air.
- V_{wire} The wireline paging cost including transmission and processing of IP paging messages.
- U_t The transmission cost of IP paging messages between the paging initiator and any other FA.
- U_p The processing cost of IP paging messages at each FA.
- $\mathcal{L}$ The maximum number of paging steps.
- n_i The number of paged subnets in the ith paging step.
- p_{out} The probability that the paged MN is not in the last registered subnet.
- p_i The probability that the paged MN is residing in the ith paging group.
- ω_i The paging cost spent when the paged MN is successfully located, given that the MN is residing in the ith paging group.

V_{wire} and V_{air} account for the wireline and wireless costs for bandwidth utilization and the computational requirements in order to process the paging messages. U_t may represent the delay cost for sending the paging message through a particular path. U_p may represent the computational cost for an FA to check its visitor list to find whether there is a record for an MN [9,10]. V_{wire} can be expressed as:

$$V_{\text{wire}} = U_t + U_p \tag{7}$$

3.3.1. UIP paging scheme

The average paging cost of the proposed UIP scheme between two location tracking requests for each MN is:

$$E[C(\mathcal{L})]_{(UIP)} = \begin{cases} NV_{\text{wire}} + V_{\text{air}} & \mathcal{L} = 1\\ (1-p_{\text{out}})V_{\text{wire}} & \\ + p_{\text{out}}\cdot\sum_{i=2}^{\mathcal{L}} p_{i_{(UIP)}}\omega_{i_{(UIP)}} & 2\leq\mathcal{L}\leq N. \end{cases} \tag{8}$$

$\omega_{i_{(UIP)}}$ can be calculated as:

$$\omega_{i_{(UIP)}} = \sum_{j=2}^{i} n_j V_{\text{wire}} + V_{\text{air}} \tag{9}$$

where n_j can be obtained from (1).

(5) and (6) give the relationship between location probabilities and mobility rates. Since we use mobility rate of all users in a subnet as the paging criterion in the UIP scheme, the probability that the paged MN is residing in the ith paging group, i.e., $p_{i_{(UIP)}}$ in (8), can be approximated as:

$$p_{i_{(UIP)}} = \frac{\sum_{y\in A_i} E[P_y(K)]}{\sum_{y=1}^{N} E[P_y(K)]} \tag{10}$$

where A_i is the set of subnets in the ith paging group. Note that $p_{i_{(UIP)}}$ is the same for all the users.

3.3.2. UPP paging scheme

The average paging cost of the UPP scheme between two location tracking requests for each MN is:

$$E[C(\mathcal{L})]_{(UPP)} = \sum_{i=1}^{\mathcal{L}} p_{i_{(UPP)}} \omega_{i_{(UPP)}} \tag{11}$$

where $\omega_{i_{(UPP)}}$ is:

$$\omega_{i_{(UPP)}} = \sum_{j=1}^{i} n_j (U_t + V_{\text{air}}) \tag{12}$$

Note that $p_{i_{(UPP)}}$ is user-variant. For different MNs, $p_{i_{(UPP)}}$ is different. Assume for user x, the probability that user x is in the ith paging group at the paging moment can be calculated as:

$$p^x_{i_{(UPP)}} = \sum_{y \in A_i} \pi^x_y \tag{13}$$

π^x_y is different from $q_{x\to y}$. π^x_y is the location probability that user x is in subnet y at the paging moment, while $q_{x\to y}$ is the transition probability that user x moves out of its current subnet to subnet y. They can be related as:

$$\pi^x_y = p_{\text{out}} \cdot q_{x\to y} \tag{14}$$

Note that for (10), when there is only one user inside the paging area, the value of $E\left[P_y(K)\right]$ is between [0, 1], and $\sum_{y=1}^{N} E\left[P_y(K)\right] = 1$. Therefore in this case, $p_{i_{(UIP)}}$ calculated based on mobility rate is exactly the same as $p_{i_{(UPP)}}$ in (13) for a specific user.

4. Performance evaluation

In this section, we demonstrate the performance comparison between the UPP scheme and the proposed UIP scheme. Based on (8) and (11), we compare the paging costs of these two schemes for various scenarios. We will first investigate the paging cost based on the assumption that accurate location probability information is provided in each user profile. Then we will consider the case when there is discrepancy between the actual location probabilities and the ones provided in user profiles.

For the analysis in this paper, we assume the costs for transmitting and processing paging messages are available. These costs account for the wireless and wireline bandwidth utilization and the computational requirements in order to process the paging messages [3]. The methods for determining the cost parameters are discussed in [9,10]. Table 1 lists the cost parameters used in our performance analysis. For performance comparison purpose, all the cost parameters are normalized to U_t such that $U_t = 1$. We consider two sets of cost parameters. The selected data sets allow us to study the effect of varying the ratio of V_{air} to U_p on the performance of the proposed paging scheme. Since generally the wireless resource is more scarce compared with wireline bandwidth, the transmission cost over the wireless link is several times higher than the wireline transmission cost. In our analysis, we set the paging cost of broadcasting the polling messages over the air, V_{air}, the same and twice higher than the processing cost at each FA in the two sets, respectively. We also assume there are totally 20 subnets in a paging area, i.e., $N = 20$, and the total number of users in a paging area is 100, i.e., $M = 100$. Note that experiments for different values of M are conducted, and for most of the results we show below, the average paging cost of the UIP scheme does not change much when $M \geq 20$.

Table 1.
Cost parameters.

Cost parameters	Set 1	Set 2
V_{wire}	3	3
U_t	1	1
U_p	2	2
V_{air}	2	4

4.1. Paging a single user

First, we compare the paging costs when the system pages one user at a time.

In (8), the paging cost is dependent on the user mobility parameter p_{out}. In order to make (8) and (11) comparable, we introduce a "*virtual subnet*" concept. We assume at the end of the last time period $\mathcal{T}$, all the users are in a virtual subnet which is located outside the whole paging area. During the current time period, all the users move out of the virtual subnet into subnets inside the paging area under consideration. Thus, $p_{\text{out}} = 1$ and $\pi^x_y = q_{x\to y}$ in this case. The advantage of the introduction of this virtual subnet concept is that the subnet dependent parameter p_{out} is removed from our analysis and the performance comparison is simply between paging based on user mobility rate and paging based on subnet location probability. However, under this assumption, we lose the chance that each MN stays in its last registered subnet. Therefore, the paging cost calculated under this virtual subnet assumption is the upper bound of the paging cost for the UIP scheme. (8) is then changed to:

$$E[C(\mathcal{L})]_{(UIP)} \leq \begin{cases} NV_{\text{wire}} + V_{\text{air}} & \mathcal{L} = 1 \\ \sum_{i=2}^{\mathcal{L}} p_{i_{(UIP)}} \omega_{i_{(UIP)}} & 2 \leq \mathcal{L} \leq N. \end{cases} \tag{15}$$

$\omega_{i_{(UIP)}}$ and $p_{i_{(UIP)}}$ are obtained from (9) and (10), respectively.

4.1.1. Uniform location probability distribution

We first study the relationship between the upper bound of the paging cost of the proposed UIP scheme and the paging cost of the UPP scheme, under uniform location probability distribution.

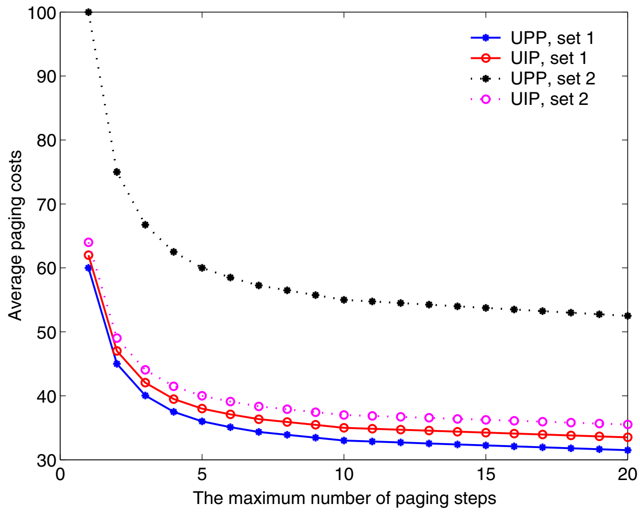

Figure 5. The average paging cost for uniform location probability distribution, when paging a single user.

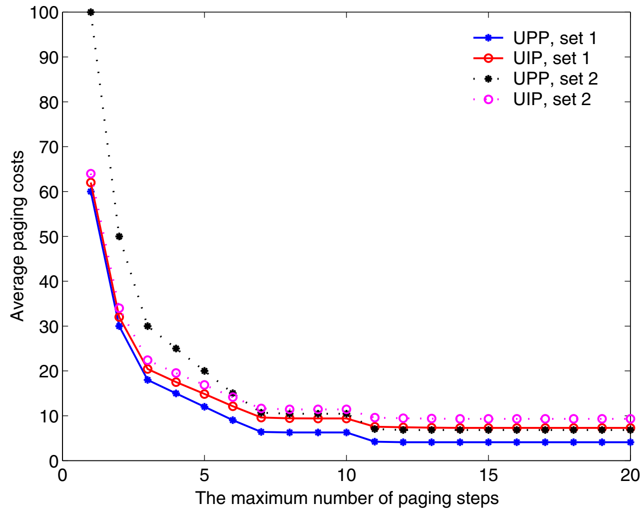

Figure 6. The average paging cost for shifted truncated Gaussian location probability distribution, when paging a single user.

Figure 5 plots the average paging cost as a function of the maximum number of paging steps, $\mathcal{L}$, when the subnet location probabilities of all the users are uniformly distributed. Since all the users are equally likely to be anywhere in the paging area, the total number of users in a paging area, M, does not influence the result.

In figure 5, the solid lines are for parameter set 1 when $V_{\text{air}} = U_p$, while the dashed lines are for parameter set 2 when $V_{\text{air}} = 2U_p$. It can be seen from the figure that the average paging cost decreases as the maximum number of paging steps increases. This result is consistent with the conclusions given in [25]. When all the users are uniformly located in each subnet, the probability of the UIP scheme calculated based on user mobility rate, $p_{i_{(UIP)}}$, is exactly the same as the probability of the UPP scheme calculated based on location probabilities provided in user profiles, $p_{i_{(UPP)}}$. It is observed in figure 5 that the upper bound of the paging cost of the proposed UIP scheme is slightly higher than that of the UPP scheme, when $V_{\text{air}} = U_p$. The maximum difference is only 5%. However, when V_{air} is larger than U_p, the UIP scheme may save paging cost significantly. Our results demonstrate that up to 34% cost can be saved by the proposed UIP scheme when $V_{\text{air}} = 2U_p$. This is because that under the UIP scheme, after receiving the paging request from the paging initiator, each FA does not need to send polling messages to all the MNs in its subnet through wireless links. Instead, it consumes processing cost U_p by checking its visitor list of semi-idle users. Therefore, the more precious the wireless resources are, the more cost can be saved by the proposed UIP scheme.

4.1.2. Truncated gaussian location probability distribution

Truncated Gaussian distribution is a typical location probability distribution for systems under isotropic random motion [14]. The discretized version of truncated Gaussian distribution with zero mean mentioned in [20] is expressed as:

$$\pi_y = \frac{1}{\text{erf}\left(\frac{N}{\sigma}\right)} \frac{2}{\sqrt{2\pi\sigma^2}} \int_{y-1}^{y} e^{-\frac{x^2}{2\sigma^2}} dx, \quad \text{where } y = 1, \ldots, N, \tag{16}$$

σ^2 is the variance and $\text{erf}(\cdot)$ is the error function defined as:

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \tag{17}$$

Note that the $p_{i_{(UIP)}}$ calculated based on mobility rate is an aggregated result of the motions of all MNs. Theoretically, the distribution of $p_{i_{(UIP)}}$ can be of any type depending on the mobility pattern of each user. The more chaotic and irregular the mobility patterns of all MNs are, the closer the aggregated $p_{i_{(UIP)}}$ approaches to uniform distribution.

Figure 6 shows the upper bound of the average paging cost of the UIP scheme and the average paging cost of the UPP scheme, when the user location probabilities are of truncated Gaussian distribution with mean zero and variance one. Since MNs are located in different subnets, we circularly shift the values in the location probability distribution of each MN by sizes ranging in [0,20]. Thus, the index of the mean of each shifted distribution indicates the most likely subnets an MN will be.

When the user location probabilities are of truncated Gaussian distribution, the average paging cost drops very quickly when $\mathcal{L}$ varies from 1 to 6. This result is also similar to the conclusion in [25]. It is noticed from figure 6 that the upper bound of the average paging cost of the UIP scheme is still slightly higher than that of the UPP scheme, when $V_{\text{air}} = U_p$. The maximum difference is 9%. When $V_{\text{air}} = 2U_p$, the UIP scheme results in lower paging cost when $\mathcal{L} \leq 6$. The cost saving is up to 33%. For $\mathcal{L} > 6$, the UIP scheme pays slightly higher cost compared with the UPP

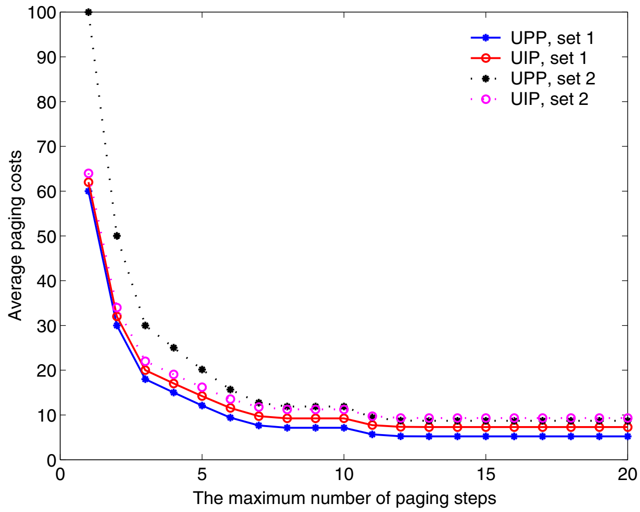

Figure 7. The average paging cost for variant truncated Gaussian location probability distribution, when paging a single user.

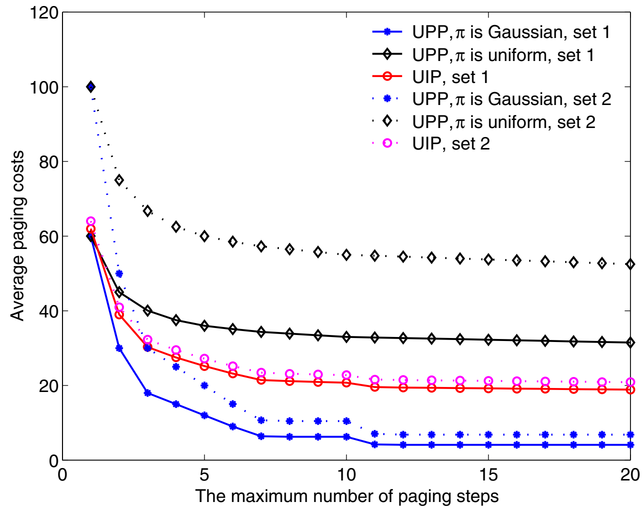

Figure 8. The average paging cost for user-variant location probability distribution, when paging a single user.

scheme. This is due to the discrepancy between the aggregated probability $p_{i(UIP)}$ and the individual probability $p_{i(UPP)}$.

Figure 7 gives the upper bound of the average paging cost of the UIP scheme and the average paging cost of the UPP scheme, when the user location probabilities are of truncated Gaussian distribution with different variances. Standard deviation σ is chosen between [1.0, 2.0] for different MNs. Standard deviation of the subnet probability distribution of the paged MN is assumed to be 1.5.

Figure 7 shows a similar result to that in figure 6, i.e., when $V_{\text{air}} = 2U_p$, the upper bound of the average paging cost of the UIP scheme is reduced by up to 34% when $\mathcal{L} \leq 10$. For $\mathcal{L} > 10$, the upper bound of the paging cost of the UIP scheme is slightly higher than the paging cost of the UPP scheme. We also perform experiments when σ of the subnet probability distribution of the paged MN changes from 1.0 to 2.0. Our results show that as σ of the paged MN increases, more paging cost can be reduced by the proposed UIP scheme compared with the UPP scheme. When σ of the paged MN is small, the likely locations of the MN is concentrated on a small portion of subnets with high probabilities. The average paging cost is small in this case. On the other hand, when σ is large, the likely locations of the paged MN will be stretched to more subnets, which leads to a higher average paging cost. The mobility rate employed in the UIP scheme is an aggregated result of mobility behaviors of all MNs. Thus, the performance of the UIP scheme based on the aggregated $p_{i(UIP)}$ should be in between of these two cases.

4.1.3. User-variant location probability distribution

The location probability distribution of each MN may not be the same. Next, we investigate the impact of user-variant location probability distribution. We assume there are two groups of users. The location probability of the first group users follows a truncated Gaussian distribution with mean zero and variance one. The location probability of the other group users follows a uniform distribution. Assume that each group has 50% of the total users. The paged MN is randomly chosen from all the users. Its location probability may follow either a truncated Gaussian distribution or a uniform distribution.

Figure 8 plots the average paging costs for user-variant location probability distribution. Two cases of the UPP scheme are considered. One is for the paged MN with a truncated Gaussian distribution. The other is for the paged MN with a uniform distribution. Our results show that the upper bound of the paging cost of the UIP scheme is larger than the paging cost of the UPP scheme when the subnet probability of the paged MN follows a truncated Gaussian distribution, but less than the case when the location probability of the paged MN is uniformly distributed. It is concluded in [20] that the uniform distribution achieves the worst performance of any distribution in the sense that it results in more paging cost. When the location probabilities of a specific user are of uniform distribution, the UPP scheme achieves the worst performance. It is equivalent to the case that the system does not have any information on the future locations of the user at all. This may possibly happen in real systems. However, for the UIP scheme, the worst case corresponds to the uniform distribution of mobility rates which is equivalent to the case that all the subnets have the same mobility rates. In other words, within the same time period, all the subnets have the same number of new idle users moved in. This is unlikely to happen.

4.1.4. Summary

Note that the performance results of the proposed UIP scheme are obtained under the worst case: the average paging costs shown are the upper bound, i.e., the information of the last registered location is not considered, and the cost of paging through wireless links is the same or only twice higher than the processing cost at each FA. The actual paging cost of the UIP scheme is lower than that in above results if the last registered location information is incorporated or the wireless resources are more precious.

From the above results, we may conclude that for the case of paging one user at a time, the performance of the proposed UIP scheme is comparable with that of the UPP scheme. When there is not much information on individual user behavior, the proposed UIP scheme performs better than the UPP scheme.

4.2. Paging multiple users

Since the system and MNs synchronize on the time slots for paging, there are possibilities that multiple paging requests are needed to be sent out in one time slot. When there are multiple users to be paged at one moment, the paging initiator may aggregate all paging requests into a single paging message. This optimization method is described in [26] and the paging message format for paging multiple MNs is also illustrated. Paging request aggregation helps to reduce the paging overhead as the number of paged MNs increases. However, this method is not suitable for the UPP scheme since each paged MN follows different location probability distributions. Different partitions of the paging area are used for each user.

We compare the paging costs of the UPP and UIP schemes for paging multiple MNs at one moment. We assume the paging initiator and each FA have the ability to aggregate multiple paging requests and send out one single paging message to other FAs and through wireless links, respectively.

Since it is hard to implement paging request aggregation for the UPP paging scheme, the system processes each paging request separately when there are more than one users to be paged at a time. The total average paging cost of the UPP paging scheme is:

$$E[C(\mathcal{L})]_{(UPP)} = \sum_{x=1}^{\Omega} \sum_{i=1}^{\mathcal{L}} p^{x}_{i_{(UPP)}} \omega_{i_{(UPP)}} \tag{18}$$

where Ω is the total number of MNs to be paged at one time. $\omega_{i_{(UPP)}}$ can be calculated according to (12). $p^{x}_{i_{(UPP)}}$ is user-variant and it is defined in (13). Here we assume the number of partitions for all the paged MNs are the same, i.e., the paged MNs have the same paging delay requirement.

We still incorporate the "*virtual subnet*" concept and compute the upper bound of the paging cost of the UIP scheme. When multiple MNs are found on the visitor lists of FAs during a paging step, those FAs poll the single or multiple users wirelessly in their subnets. So the worst case is that all the n_i FAs in the ith paging group send out polling messages through wireless links. The upper bound of the average paging cost of the UIP scheme is:

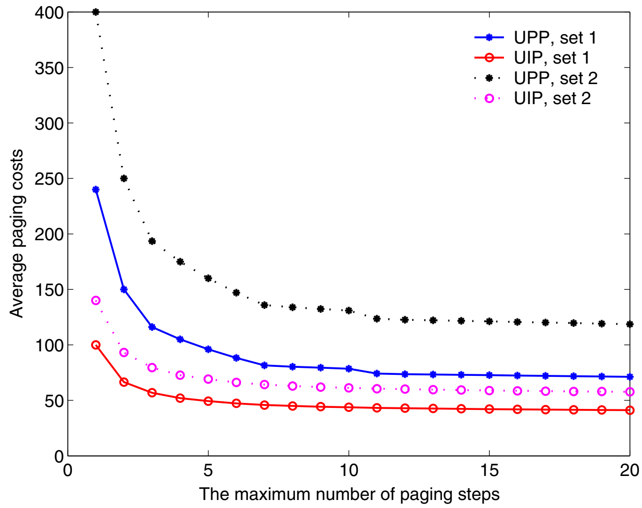

Figure 9. The average paging cost for user-variant location probability distribution, when paging multiple users, $\Omega = 4$.

$$E[C(\mathcal{L})]_{(UIP)} \le \begin{cases} N(V_{\text{wire}} + V_{\text{air}}) & \mathcal{L} = 1 \\ \sum_{i=2}^{\mathcal{L}} p_{i_{(UIP)}} \omega_{i_{(UIP)}} & 2 \le \mathcal{L} \le N. \end{cases} \tag{19}$$

$p_{i_{(UIP)}}$ is the same for all the users and it is defined in (10). Here $\omega_{i_{(UIP)}}$ is:

$$\omega_{i_{(UIP)}} = \sum_{j=2}^{i} n_j (V_{\text{wire}} + V_{\text{air}}) \tag{20}$$

Note that the upper bound of the average paging cost of the UIP scheme is independent of the number of the paged MNs at one time, Ω. Therefore, the UIP scheme is very efficient in saving the system resource when paging multiple MNs, since the upper bound of the average paging cost does not change as the number of paged users grows, if the last location information is ignored.

Figures 9 and 10 show the average paging cost for user-variant location probability distribution, when paging multiple MNs at a time. The upper bound of the paging cost of the UIP scheme does not change when the total number of paged MNs, Ω, changes from 4 to 8 in the two figures. From the figures we may see that the UIP scheme reduces the paging cost drastically as Ω increases. When $\Omega = 4$, the UIP scheme saves up to 50% and 58% cost compared to the UPP scheme for parameter set 1 and set 2, respectively. When $\Omega = 8$, the maximum cost reduction is 75% and 79% for set 1 and set 2, respectively.

The advantage of the UIP scheme is obvious in this case. The user independent nature of the UIP scheme determines that it is very convenient and cost-efficient to page multiple users using the UIP scheme and paging request aggregation.

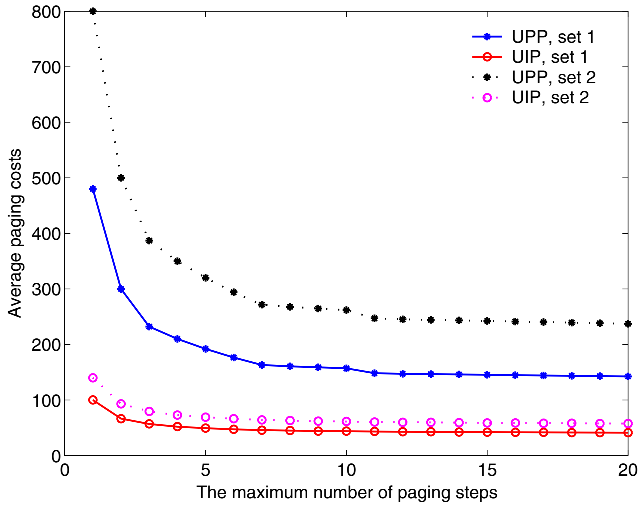

Figure 10. The average paging cost for user-variant location probability distribution, when paging multiple users, $\Omega = 8$.

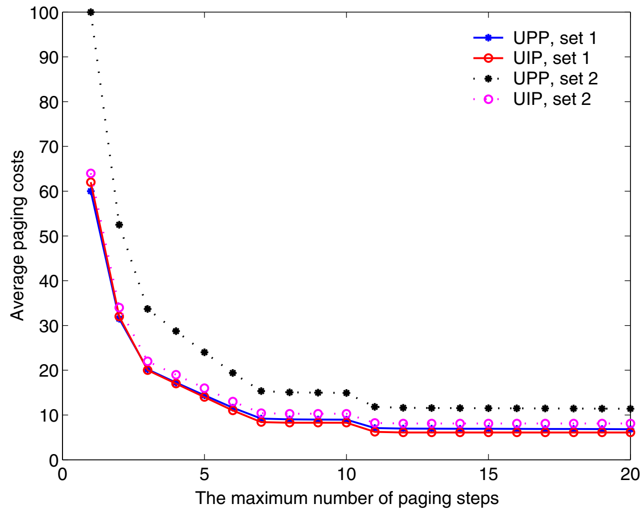

Figure 12. The average paging cost when imperfect location information is used, $\alpha = 90\%$.

Considering the complexity of performing subnet partition and polling paging request individually for each MN when using the UPP scheme, the UIP scheme is more preferable.

4.3. Confidence of location probabilities

For the above results, we assume perfect user location information is provided in the user profiles, i.e., accurate subnet probability distribution as the basis for the UPP scheme. Now, we study the impact of using erroneous location information.

Assume the confidence level of the prediction of the location probability is α. Confidence level implies the uncertainty of the predicted parameter. It provides a range of plausible values for the unknown parameter. In order to investigate the effect of confidence level on the paging schemes, we consider a simple model where the actual locations of each MN follow the truncated Gaussian distribution with mean zero and variance one. However, since the user profiles give imperfect location information with confidence α, there is $(1-\alpha)$ possibility that the UPP scheme uses erroneous location information for paging. When erroneous location information is used, it is equivalent that the system does not have any information of users at all. Thus, $(1-\alpha)$ percent of the total paging cost comes from the calculation based on uniform location distribution, i.e.,

$$E[C(\mathcal{L})]_{(UPP)} = \alpha E[C(\mathcal{L})]^{g}_{(UPP)} + (1-\alpha) E[C(\mathcal{L})]^{u}_{(UPP)} \tag{21}$$

where $E[C(\mathcal{L})]^{g}_{(UPP)}$ is the paging cost computed based on shifted truncated Gaussian distribution and $E[C(\mathcal{L})]^{u}_{(UPP)}$ is the paging cost computed based on uniform distribution. Since the paging cost of the UIP scheme is calculated based on the actual user mobility rate, the confidence level does not influence its result and the upper bound of the paging cost is expressed in (8).

Figures 11 and 12 plot the average paging cost of the two paging schemes, when $\alpha = 80\%$ and $\alpha = 90\%$, respectively. Comparing with figure 6, the results indicate that when imperfect location information is used, the paging cost of the UPP scheme increases. The increase percentage is 16% when $\alpha = 80\%$ and 10% when $\alpha = 90\%$. In both figures, the UIP scheme pays less cost compared with the UPP scheme. Therefore, the UIP scheme provides relatively good performance consistently.

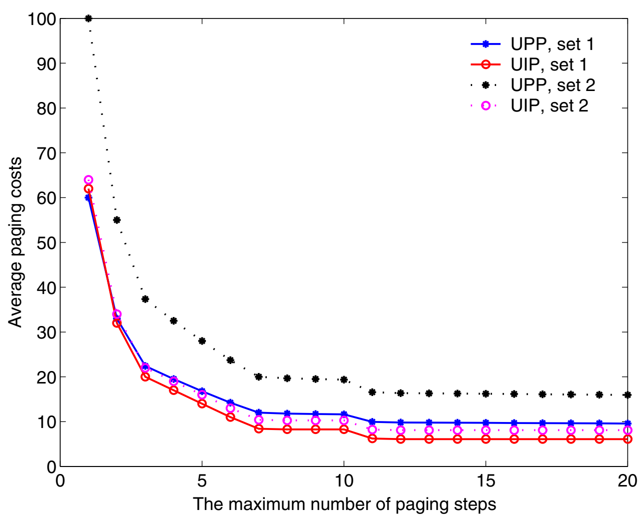

Figure 11. The average paging cost when imperfect location information is used, $\alpha = 80\%$.

5. Conclusion

In this paper, we introduced a user independent paging scheme based on last-known location and mobility rate information for Mobile IP. User independent paging can be applied to both link layer paging and IP layer paging, as long as the selected paging criterion is user independent. In this paper, we proposed an efficient IP paging scheme which can be employed by all the proposed paging architectures. In contrast to the user dependent paging schemes that choose the user-variant parameters as the paging criterion, the proposed scheme takes the aggregated behavior of all mobile users as the basis for paging. It combines the advantages of last-location-first paging, highest-mobility-first paging, and uniform paging. In order to obtain the mobility rate of each subnet, a new operation mode named "semi-idle" mode is introduced. Analytical results demonstrated that when paging a single user at a time, the performance of the proposed paging scheme is comparable to that of the paging scheme based on perfect knowledge of user movement statistics. However, when paging multiple users at one moment and when the assumption of perfect knowledge is loose, the proposed paging scheme saves signaling bandwidth significantly.

The proposed user independent paging scheme may be considered as an alternative approach. If the system can perform paging optimally for every user, user dependent paging scheme is a good solution to provide personalized services. However, when it is hard to achieve perfect performance for each user, or obtaining user mobility profiles causes great cost, user independent paging scheme may provide satisfactory overall performance for the whole system.

Acknowledgments

Jiang Xie was with the Broadband and Wireless Networking Laboratory, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta GA 30332 when this work was performed. This work was supported by National Science Foundation (NSF) under grant no. CCR-99-88532.

References

[1] A. Abutaleb and V.O.K. Li, Paging strategy optimization in personal communication systems, ACM-Baltzer Journal of Wireless Networks (WINET) 3 (August 1997) 195–204.

[2] A. Abutaleb and V.O.K. Li, Location update optimization in personal communication systems, ACM-Baltzer Journal of Wireless Networks (WINET) 3 (August 1997) 205–216.

[3] I.F. Akyildiz, J.S.M. Ho and Y.-B. Lin, Movement-based location update and selective paging for PCS networks, IEEE/ACM Transactions on Networking 4(4) (August 1996) 629–638.

[4] I.F. Akyildiz, J. McNair, J.S.M. Ho, H. Uzunalioglu and W. Wang, Mobility management in next generation wireless systems, Proceedings of the IEEE 87(8) (August 1999) 1347–1384.

[5] E. Cayirci and I.F. Akyildiz, User mobility pattern scheme for location update and paging in wireless systems, IEEE Trans. Mobile Computing 1(3) (July-September 2002) 236–247.

[6] F.M. Chiussi, D.A. Khotimsky and S. Krishnan, Mobility management in third-generation all-IP networks, IEEE Communications Magazine (September 2002), pp. 124–135.

[7] H. Haverinen and J. Malinen, Mobile IP regional paging (work in progress), Internet Draft, Internet Engineering Task Force, draft-haverinen-mobileip-reg-paging-00.txt, June 2000.

[8] J.S.M. Ho and I.F. Akyildiz, Mobile user location update and paging under delay constraints, ACM-Baltzer Journal of Wireless Networks (WINET) 1(4) (February 1995) 413–425.

[9] J.S.M. Ho and I.F. Akyildiz, Local anchor scheme for reducing signaling costs in personal communications networks, IEEE/ACM Transactions on Networking 4(5) (October 1996) 709–725.

[10] J.S.M. Ho and I.F. Akyildiz, Dynamic hierarchical database architecture for location management in PCS networks, IEEE/ACM Transactions on Networking 5(5) (October 1997) 646–660.

[11] H. Lee and J. Sun, Mobile location tracking by optimal paging zone partitioning, in: *Proc. IEEE International Conference on Universal Personal Communications (ICUPC'97)* 1 (1997) 168–172.

[12] T. Liu, P. Bahl and I. Chlamtac, Mobility modeling, location tracking, and trajectory prediction in wireless ATM networks, IEEE Journal on Selected Areas in Communications (JSAC) 16(6) (August 1998) 922–936.

[13] A. Misra et al., IDMP: An intra-domain mobility management protocol using mobility agents (work in progress), Internet Draft, Internet Engineering Task Force, draft-mobileip-misra-idmp-00.txt, July 2000.

[14] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, (McGraw-Hill, New York, 1965).

[15] C.E. Perkins, Mobile IP, IEEE Communications Magazine (May 1997) 84–99.

[16] C.E. Perkins, IP mobility support for IPv4, Request for Comments (RFC) 3220, January 2002.

[17] G.P. Pollini and C.-L. I, A profile-based location strategy and its performance, IEEE Journal on Selected Areas in Communications (JSAC) 15(8) (October 1997) 1415–1424.

[18] R. Ramjee, T. La Porta and L. Li, Paging support for IP mobility using HAWAII (work in progress), Internet Draft, Internet Engineering Task Force, draft-ietf-mobileip-paging-hawaii-01.txt, January 2001.

[19] R. Ramjee, L. Li, T. La Porta and S. Kasera, IP paging service for mobile hosts, ACM-Kluwer Journal of Wireless Networks (WINET) 8(5) (September 2002) 427–441.

[20] C. Rose and R. Yates, Minimizing the average cost of paging under delay constraints, ACM-Baltzer Journal of Wireless Networks (WINET) 1 (1995) 211–219.

[21] B. Sarikaya et al., Mobile IPv6 hierarchical paging (work in progress), Internet Draft, Internet Engineering Task Force, draft-sarikaya-seamoby-mipv6hp-00.txt, September 2001.

[22] S. Tabbane, Location management methods for third-generation mobile systems, IEEE Communications Magazine (August 1997) 72–84.

[23] K. van der Wal, M. Mandjes and H. Bastiaansen, Delay performance analysis of the new Internet services with guaranteed QoS, Proceedings of the IEEE 85(12) (December 1997) 1947–1957.

[24] W. Wang and I.F. Akyildiz, On the estimation of user mobility pattern for location tracking in wireless networks, Proc. IEEE GlOBECOM 2002 1 (2002) 610–614.

[25] W. Wang, I.F. Akyildiz, G.L. Stüber and B.-Y. Chung, Effective paging schemes with delay bounds as QoS constraints in wireless systems, ACM-Baltzer Journal of Wireless Networks (WINET) 7 (September 2001) 455–466.

[26] X. Zhang, J.G. Castellanos and A.T. Campbell, P-MIP: paging extensions for Mobile IP, ACM Mobile Networks and Applications (MONET) 7(2) (April 2002) 127–141.

[27] X. Zhang, J.G. Castellanos, A.T. Campbell, K. Sawada and M. Barry, P-MIP minimal paging extensions for Mobile IP (work in progress), Internet Draft, Internet Engineering Task Force, draft-zhang-pmip-00.txt, July 2000.

[28] T. Zhang, S.-W. Li, Y. Ohba and N. Nakajima, A flexible and scalable IP paging protocol, Proc. IEEE GLOBECOM 2002, 1 (2002) 630–635.

Jiang Xie received her B.E. degree from Tsinghua University, Beijing, China, in 1997, M.Phil. degree from Hong Kong University of Science and Technology in 1999, and M.S. and Ph.D. degrees from Georgia Institute of Technology in 2002 and 2004, respectively, all in electrical engineering. She is currently an assistant professor with the Department of Electrical and Computer Engineering at the University of North Carolina-Charlotte. Her current research interests include resource and mobility management of wireless networks, QoS provisioning, and next-generation Internet. She is a member of IEEE and ACM.
E-mail: jxie1@uncc.edu