User-Independent Paging Scheme based on Mobility Rate for Mobile IP

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Abstract— **Multi-step paging has been widely proposed to reduce 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. This paper introduces a user-independent paging scheme for Mobile IP 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 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 scheme is comparable to that of the user-dependent paging schemes. When paging multiple users simultaneously, the proposed scheme has remarkable advantages.**

I. INTRODUCTION

In the current paging strategy of GSM and IS-41 protocols, paging messages are broadcasted to each cell in the registered location area of a mobile terminal (MT). The signaling cost of broadcast procedure is maximum. 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]-[5]. All these paging schemes are user-dependent, i.e., 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, that is, 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. Therefore, to reduce the dependency of a paging scheme on individual user information, but to provide satisfactory overall performance of the whole system is the basic consideration of this paper.

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Mobile IP [6] is a solution for mobility on the global Internet. However, the basic Mobile IP does not support paging. The main benefit of providing paging services is to save the battery power consumption at MTs. Thus, IP paging is proposed as an extension for Mobile IP [7]-[10]. Under Mobile IP paging, a mobile node (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]. An MN in idle mode 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 foreign agent (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 sent out in one time slot. In this case, *paging request aggregation* [9] can be adopted to reduce the paging overheads. 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 Fig. 1.

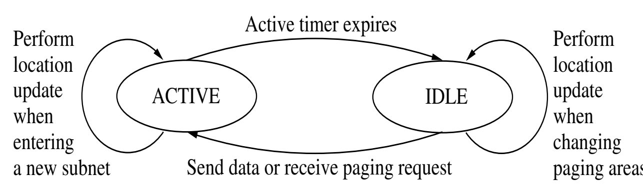

Fig. 1. State transition diagram of Mobile IP paging.

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 [8]. Broadcast procedure is assumed to be used in almost all the proposed paging architectures [7]-[9]. 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 [10]. Link layer paging 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. 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.

In this paper, we introduce the concept of user-independent paging which can be applied to both link layer and IP layer, as long as the selected paging criterion is user-independent. We choose the mobility rate of each subnet as the paging criterion 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 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. This paper is organized as follows. In Section II, the proposed paging algorithm is explained. In Section III, the analysis of the paging cost is given. In Section IV, analytical results are presented, followed by the conclusions in Section V.

II. User-Independent Paging Scheme

A. 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. If not, 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. The total number of partitions is determined by the maximum paging delay the user may tolerate. Note that 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 propose the number of subnets in each partition is of approximately the same. 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 [4], assume

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

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.

B. Detailed Solution for Obtaining Subnet Mobility Rate

In order to obtain the up-to-date user mobility rate of each subnet, we introduce a new operation mode for MNs named "*semi-idle*" mode. The state transition diagram of MNs for the proposed paging scheme is shown in Fig. 2 and the detailed procedure is explained below.

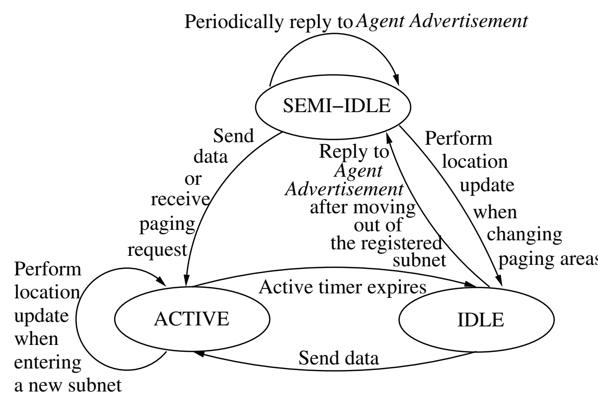

Fig. 2. State transition diagram of the proposed paging scheme.

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 [6]. If paging is supported, the MN and the visited subnet agree on communication time slots used for Agent Advertisement and paging [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 care-of-address (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. 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 home agent (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 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.

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 may reply to the Agent Advertisement message periodically for every $\mathcal{M}$ advertisement slots to refresh its semi-idle state. Same as active and idle states, the semi-idle state is a soft state. If there is no further refreshment message, the state is expired. 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 $\mathcal{T}$.

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 is not on the list, the paging initiator sends out IP paging messages to subnets in decreasing order of user mobility rates.

C. Tradeoffs of Introducing "Semi-Idle" State

The introduction of the semi-idle mode will cause extra signaling overheads due to periodically replying to Agent Advertisement messages from MNs and message exchanges between FAs. These extra overheads will consume additional bandwidth and battery resources. 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.

III. 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. The subnet location probabilities at different time of a day are usually provided in the user profile of each MN, which can be obtained either through empirical measurements or analysis of user movement models [11]. We call this scheme user profile paging (UPP) scheme.

A. Location Probabilities vs. 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 during the next time period $\mathcal{T}$, the probability that user x will move out of its current subnet to subnet y is $q_{x\to y}$, where $x = 1, 2, \ldots, M$ and $y = 1, 2, \ldots, N$. The probability that there is no user moved 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 $\sum_{\substack{y=1\\ y\neq v}}^{N} q_{x\to y} = 1$, and v represents the subnet user x is currently visiting. The probability that there are k users moved to subnet y during the next time period is:

$$P_y(K=k) = \sum_{\substack{l_1,\ldots,l_k=1\\ l_1\neq\cdots\neq l_k}}^{M} q_{l_1\to y}\cdots q_{l_k\to y} \prod_{\substack{x=1\\ x\neq l_1\neq\cdots\neq l_k}}^{M} (1 - q_{x\to y}) \tag{3}$$

where $k = 1, \cdots, M$. Given the above probability distribution, the expected number of users moved to subnet y is:

$$E\left[P_y(K)\right] = \sum_{k=0}^{M} k\cdot P_y(K=k), \quad \text{where} \quad y = 1, \cdots, N \tag{4}$$

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

B. Paging Cost

We define the following parameters for our analysis:

- V_{air} The wireless paging cost including broadcasting 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 paging messages between the paging initiator and any other FA.
- U_p The processing cost of paging messages at each FA.
- $\mathcal{L}$ The maximum number of paging steps.
- p_{out} The probability that the paged MN is not in the last registered subnet.
- n_i The number of paged subnets in the ith paging step.
- 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.

where $V_{wire} = U_t + U_p$.

1) UIP Scheme: The average paging cost of the proposed UIP scheme for each MN is:

$$E[C(\mathcal{L})]_{(UIP)} = \begin{cases} NV_{wire} + V_{air} & \mathcal{L} = 1 \\ (1-p_{out})V_{wire} \\ +p_{out}\cdot\sum_{i=2}^{\mathcal{L}} p_{i_{(UIP)}}\omega_{i_{(UIP)}} & 2 \leq \mathcal{L} \leq N. \end{cases} \tag{5}$$

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

$$\omega_{i_{(UIP)}} = \sum_{j=2}^{i} n_j V_{wire} + V_{air} \tag{6}$$

where n_j can be obtained from (1).

(3) and (4) 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, $p_{i_{(UIP)}}$ in (5) can be approximated as:

$$p_{i_{(UIP)}} = \frac{\sum_{y \in A_i} E\left[P_y(K)\right]}{\sum_{y=1}^{N} E\left[P_y(K)\right]} \tag{7}$$

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.

2) UPP Scheme: The average paging cost of the UPP scheme for each MN is:

$$E[C(\mathcal{L})]_{(UPP)} = \sum_{i=1}^{\mathcal{L}} p_{i_{(UPP)}} \omega_{i_{(UPP)}} \tag{8}$$

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

$$\omega_{i_{(UPP)}} = \sum_{j=1}^{i} n_j (U_t + V_{air}) \tag{9}$$

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

$$p^x_{i_{(UPP)}} = \sum_{y \in A_i} \pi^x_y \tag{10}$$

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: $\pi^x_y = p_{out} \cdot q_{x \to y}$.

IV. Performance Evaluation

Table I lists the cost parameters used in our performance analysis. We consider two sets of cost parameters. 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. We 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., $M = 100$.

TABLE I

Cost Parameters

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

A. Paging A Single User

In (5), the paging cost is dependent on the user mobility parameter p_{out}. In order to make (5) and (8) 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, $p_{out} = 1$ and $\pi^x_y = q_{x \to y}$ in this case. The advantage of the introduction of virtual subnet 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, 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 UIP scheme. (5) is then changed to:

$$E[C(\mathcal{L})]_{(UIP)} \le \begin{cases} NV_{wire} + V_{air} & \mathcal{L} = 1 \\ \sum_{i=2}^{\mathcal{L}} p_{i_{(UIP)}} \omega_{i_{(UIP)}} & 2 \le \mathcal{L} \le N. \end{cases} \tag{11}$$

$\omega_{i_{(UIP)}}$ and $p_{i_{(UIP)}}$ are obtained from (6) and (7), respectively.

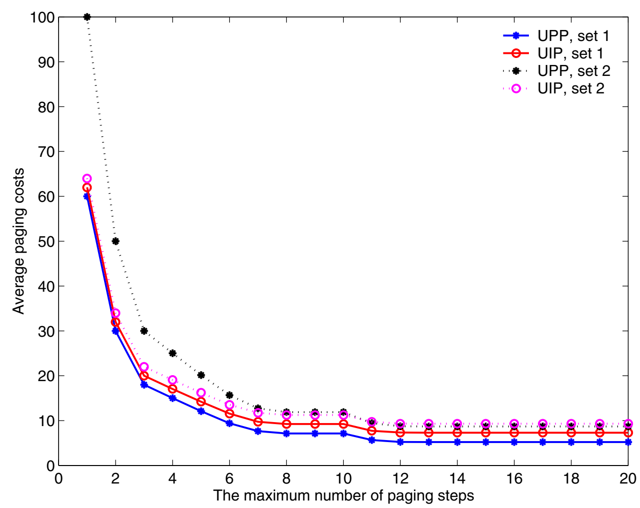

Fig. 3. The average paging cost for truncated Gaussian location probability distribution, when paging a single user.

Fig. 3 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 [12]. It shows that when $V_{air} = 2U_p$, the upper bound of the average paging cost of the UIP scheme is reduced by up to 34% when $\mathcal{L} \le 10$. 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.

B. Paging Multiple Users

Since the system and MNs synchronize on the time slots for paging, there are possibilities that multiple paging requests are sent out in one time slot. Paging request aggregation may help to reduce paging overheads as the number of paged MNs increases. However, this method is not suitable for UPP scheme since 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. The total average paging cost of the UPP paging scheme is:

$$E[C(\mathcal{L})]_{(UPP)} = \sum_{x=1}^{\Omega} \sum_{i=1}^{\mathcal{L}} p^{x}_{i_{(UPP)}} \omega_{i_{(UPP)}} \qquad (12)$$

where Ω is the total number of MNs to be paged at one time. $\omega_{i_{(UPP)}}$ can be calculated according to (9). $p^{x}_{i_{(UPP)}}$ is user-variant and it is defined in (10). 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. The upper bound of the average paging cost of the UIP scheme is:

$$E[C(\mathcal{L})]_{(UIP)} \leq \begin{cases} N(V_{wire} + V_{air}) & \mathcal{L} = 1 \\ \sum_{i=2}^{\mathcal{L}} p_{i_{(UIP)}} \omega_{i_{(UIP)}} & 2 \leq \mathcal{L} \leq N. \end{cases} \qquad (13)$$

$p_{i_{(UIP)}}$ is the same for all the users and it is defined in (7). Here $\omega_{i_{(UIP)}} = \sum_{j=2}^{i} n_j (V_{wire} + V_{air})$. 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.

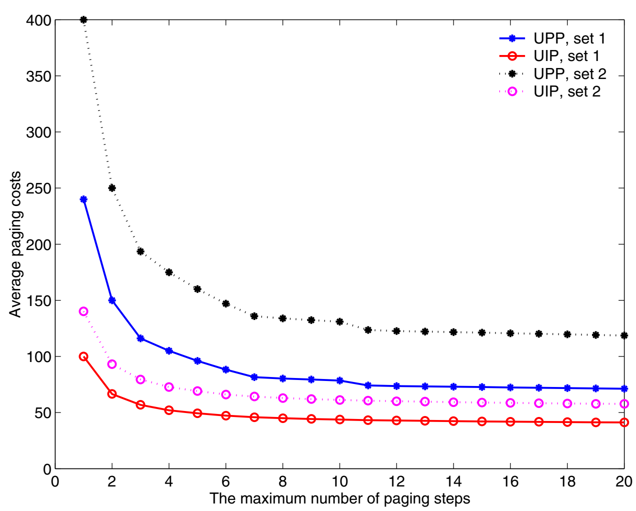

Fig. 4. The average paging cost for user-variant location probability distribution, when paging multiple users, $\Omega = 4$.

Fig. 4 shows the average paging cost for user-variant location probability distribution, when paging multiple MNs at a time. 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 MNs are randomly chosen from all the users. From our experiments, we find that 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. 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 UIP scheme and paging request aggregation.

V. Conclusion

In this paper, we proposed an efficient IP paging scheme. In contrast to 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. 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 movement statistics of each individual user. However, when paging multiple users at one moment, the proposed paging scheme saves signaling bandwidth significantly.

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