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Effective Paging Schemes with Delay Bounds as QoS Constraints in Wireless Systems *

WENYE WANG, IAN F. AKYILDIZ and GORDON L. STÜBER
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

BOO-YOUNG CHUNG
Korea Telecom Access Network Laboratory, 17 Woomyun-Dong, Seocho-Gu, Seoul 137792, Korea

Abstract. In this paper new paging schemes are presented for locating mobile users in wireless networks. Paging costs and delay bounds are considered since paging costs are associated with bandwidth utilization and delay bounds influence call setup time. In general, location tracking schemes require intensive computation to search for a mobile terminal in current PCS networks. To reduce the paging costs, three new paging schemes, reverse, semi-reverse and uniform, are introduced to provide a simple way of partitioning the service areas and decrease the paging costs based on each mobile terminal's location probability distribution. Numerical results demonstrate that our approaches significantly reduce the paging costs for various probability distributions such as uniform, truncated discrete Gaussian, and irregular distributions.

Keywords: wireless networks, delay bounds, paging costs, QoS, paging areas

1. Introduction

In current personal communication service (PCS) systems, location update and paging are two fundamental operations for locating a mobile terminal (MT). As the demand for wireless services grows rapidly, the signaling traffic caused by location update and paging increases accordingly, which consumes limited available radio resources. Location update is concerned with the reporting of the current locations of the MTs. In a paging process, the system searches for the MT by sending poll messages to the cells close to the last reported location of the MT at the arrival of an incoming call. Delays and costs are two key factors in the paging issue. Of the two factors, *paging delay* is very important as the quality of service (QoS) requirement for multimedia services. Paging cost, which is measured in terms of cells to be polled before the called MT is found, is related to the efficiency of bandwidth utilization and should be minimized under delay bound [3,5].

In this paper we focus on the paging problem, that is, to reduce the paging costs under delay bound. According to the current GSM and IS-41 protocols being used in paging process, paging is accomplished through a broadcast or one-step procedure [10,14,19]. Each service area is divided into many location areas (LAs) or registration areas (RAs) in IS-41 system; and each LA consists of a number of cells. An MT registers to the wireless system whenever it enters a new LA so that the system is always aware of the current location of an MT. When an incoming call arrives, the paging process is triggered; thus, the mobile switching center (MSC) broadcasts the paging request to all cells in an LA to find the called MT. Under this broadcast paging scheme, the paging delay is minimal since there is only *one polling cycle* required to find the called MT and all cells within the LA receive the paging request simultaneously. A *polling cycle* is the round trip time from when a paging message is sent until the response is received. However, the cost of this paging scheme is high and the utilization of bandwidth is low since all cells in the LA are searched, which consumes a large amount of radio resources.

To improve the efficiency of bandwidth utilization, many paging schemes [6,12,14,18] have been proposed to reduce the paging cost based on location probability which can be computed using different methods. The location probability is determined by many factors such as mobility model, calling pattern, and so on. Many tracking schemes are designed to predict the cell location probability and estimate the next location of MT's movement accurately [1,7,12]. Therefore, it is reasonable to develop paging schemes based on given location probability and to compare the paging schemes over similar parameters [15]. A selective paging scheme is proposed to map the cells within an LA into a probability line [1]. In this scheme, the LAs are divided into several sub-areas (called partitions) and each sub-area consists of a cluster of cells. These sub-areas are searched in decreasing order of probabilities. In [16], the paging areas are estimated through the semi-real time mobility pattern of each MT, and the location probability is assumed to be a uniform distribution. An alternative paging zone partition is presented in [10] in which the LAs are partitioned into optimal paging zones based on an MT's mobility pattern and location probability. According to this scheme, individual MT's mobility pattern is recorded for partitioning LAs. Then the LA is further di-

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vided into multiple paging zones by a genetic algorithm to obtain the optimal paging cost.

Furthermore, multi-step paging schemes are suggested to satisfy the delay bound while reducing the paging costs [1,2,9,15]. In each step, a subset of LA called paging area (PA) is searched in one polling cycle. The paging delay could then be represented by the number of required polling cycles; in other words, the number of PAs need to be searched before the called MT is found. On the condition of delay bound, the minimization of paging costs necessitates the problem of how to partition an LA into PAs. However, it has been proved that the partition of PAs subject to delay constraint is an NP-complete problem and involves complex and time-consuming computation when an LA is very large [1,15]. In [4], it is assumed that the MTs are able to initiate location update messages only in specific cells called *reporting cells*. The paging delay is guaranteed by limiting the neighboring cells around the reporting cells. The minimization of paging costs depends on the optimal design of reporting cells based on the geometric characteristics of the overall system. A highest-probability-first (HPF) scheme is introduced in which the sequential polling is performed in decreasing order of probabilities to minimize the mean number of cells being searched [15]. The delay constraint is considered as a weighted function in determining the minimum paging cost. This paper illustrates that the paging cost can be minimized by appropriate grouping of cells in paging areas. Nevertheless, to find the optimal delay weighted factor, an analogous or correspondent continuous probability density function for a discrete probability distribution must be found. This is not a trivial problem because it is very difficult to find a continuous probability density function for irregular discrete location probability distribution.

In this paper, we present three feasible methods for dividing an LA into paging areas. They are easy to implement and are applicable to both regular and irregular location probability distributions. The rest of this paper is organized as follows: In section 2, we describe the problem formulation in which the paging delay bound is taken into account. In section 3, three paging schemes are presented. The details of partition procedure, paging costs, and average delays are also described in this section. We demonstrate numerical results over various location probability distributions in section 4 and conclude the paper in section 5.

2. System model

We assume that each LA consists of the same number N of cells in the system. The worst-case paging delay is considered as delay bound, $\mathcal{D}$, in terms of polling cycle. When $\mathcal{D}$ is equal to 1, the system should find the called MT in one polling cycle, requiring all cells within the LA to be polled simultaneously. The paging cost, C, which is the number of cells polled to find the called MT, is equal to N. In this case, the average paging delay is at its least, which is one polling cycle, and the average paging cost is at its highest, $C = N$.

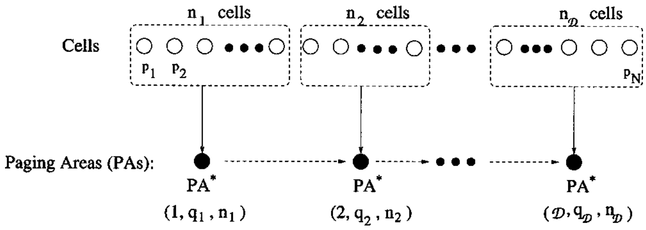

Figure 1. Partition a location area (LA) into paging areas (PA) under delay bound, $\mathcal{D}$.

On the other hand, when $\mathcal{D}$ is equal to N, the system will poll one cell in each polling cycle and search all cells one by one. Thus, the worst-case occurs when the called MT is found in the last polling cycle, which means the paging delay would be at its maximum and equal to be N polling cycles [17]. However, the average paging cost may be minimized if the cells are searched in decreasing order of location probabilities [15].

We consider the partition of PAs given that $1 \leqslant \mathcal{D} \leqslant N$, which requires grouping cells within an LA into the smaller PAs under delay bound $\mathcal{D}$. Suppose, at a given time, the initial state $\mathbf{P}$ is defined as $\mathbf{P} = [p_1, p_2, \ldots, p_j \ldots, p_N]$, where p_j is the location probability of jth cell to be searched in decreasing order of probability. Thus the time effect is reflected in the location probability distribution. We use triplets $\mathrm{PA}^*_{\mathcal{P}}(i, q_i, n_i)$ to denote the PAs under the paging scheme $\mathcal{P}$ in which i is the sequence number of the PA; q_i is the location probability that the called MT can be found within the ith PA and n_i is the number of cells contained in this PA. In figure 1, an LA is divided into $\mathcal{D}$ PAs because the delay bound is assumed to be $\mathcal{D}$. Thus, the worst case delay is guaranteed to be $\mathcal{D}$ polling cycles. The system searches the PAs one after another until the called MT is found.

Accordingly, the *location probability* q_i of the ith PA is

$$q_i = \sum_{j \in \mathrm{PA}^*(i)} p_j. \tag{1}$$

If the called MT is found in the ith PA, the *average paging cost* under delay bound $\mathcal{D}$, $E[C(\mathcal{D})]$, is computed as follows:

$$E\big[C(\mathcal{D})\big] = \sum_{i=1}^{\mathcal{D}} q_i \sum_{k=1}^{i} n_k, \tag{2}$$

and the average delay, $E[D(\mathcal{D})]$, is

$$E\big[D(\mathcal{D})\big] = \sum_{i=1}^{\mathcal{D}} i q_i. \tag{3}$$

The location probability distributions of the MTs, can be obtained in many ways [1,10–13]. Basically, there are three methods being used to find the probabilities.

- *Geographical computation.* First, each cell in the service area of a wireless system is represented by a unique two-dimensional coordinate [1,11]. Then the position of an MT can be mapped to the cell in which it is residing and the movement of the MT is measured by the number of cells it traversed. Based on the MT's velocity and its position, the future position of this MT can be estimated in terms of location probabilities in the surrounding coordinates.

- *Empirical data.* Each MT's mobility pattern can be collected during its movement [13]. For example, the user profiles can be determined by a three dimensional observation such as the time in a day, day in a week, and the geographical location [10]. The simplest method is as follows. Let the total number of records of an MT in a specific time be n. Of these records, the numbers of visiting each cell are $x_1, x_2, \dots, x_n$. Then the location probability of an MT in each cell can be induced accordingly, e.g., the probability of the MT in the first cell is x_1/n and so on.
- *Mathematical models.* As in many literature, the location probability can be obtained by using mathematical models. The most common used models are random-walk, fluid-flow, and semi-Markov models [11,12]. Random-walk model is well suited for pedestrian movement while fluid-flow and semi-Markov models can be used for describing the vehicular users. Moreover, the combination of these models may be used for analyzing some users with regular behaviors [8].

3. Paging schemes for reducing the paging costs

In this section, we present three paging schemes: *reverse, semi-reverse and uniform* paging to reduce the average paging costs for different location probability distributions.

3.1. Reverse paging

This scheme is designed for a situation where the called MT is most probable to be found in a few cells. We consider the first $(\mathcal{D}-1)$ highest probability cells as the first $(\mathcal{D}-1)$ PAs to be searched. Each of these $(\mathcal{D}-1)$ PAs consists of only one cell. We then lump the remaining $(N-\mathcal{D}+1)$ lower probability cells to be the last PA, i.e., the $\mathcal{D}$th PA. The new formed PAs become $\mathrm{PA}_r^*(1, p_1, 1), \mathrm{PA}_r^*(2, p_2, 1), \dots, \mathrm{PA}_r^*(\mathcal{D}-1, p_{\mathcal{D}-1}, 1), \mathrm{PA}_r^*(\mathcal{D}, q_{\mathcal{D}}, N-\mathcal{D}+1)$, where r denotes the *reverse* paging scheme. The *average paging cost*, $E[C_r(\mathcal{D})]$, is computed from

$$E\big[C_r(\mathcal{D})\big] = \sum_{j=1}^{\mathcal{D}-1} jp_j + N\sum_{j=\mathcal{D}}^{N} p_j, \tag{4}$$

and the *average delay*, $E[D_r(\mathcal{D})]$, is obtained from:

$$E\big[D_r(\mathcal{D})\big] = \sum_{j=1}^{\mathcal{D}-1} jp_j + \mathcal{D}\sum_{j=\mathcal{D}}^{N} p_j. \tag{5}$$

3.2. Semi-reverse paging

Since the average paging cost can be minimized by searching cells in decreasing order of location probability if a delay bound $\mathcal{D}$ is not applied [15], intuitively, we examine that the paging cost can be reduced by searching the PAs in decreasing order of probability. Under *semi-reverse paging* scheme, a set of PAs is created in a non-increasing order of location probabilities.

We first combine the two cells with the lowest location probabilities into one PA, then reorder all PAs in non-increasing order of location probabilities. We keep combining the two lowest probabilities PAs and reordering them until the total number of PAs is equal to $\mathcal{D}$. If two PAs have the same probability, the PA with fewer cells has higher priority, i.e., its sequence number is smaller. As a result, the *average paging cost*, $E[C_s(\mathcal{D}))]$, is:

$$E\big[C_s(\mathcal{D})\big] = \sum_{i=1}^{\mathcal{D}} s_i q_i = q_1 n_1 + q_2(n_1+n_2) + \cdots + q_{\mathcal{D}} N, \tag{6}$$

where q_i is the summation of the location probabilities of cells in $\mathrm{PA}^*(i, q_i, n_i)$ as in (1), and s_i is the cumulated number of cells for finding the called MT and is calculated from $s_i = \sum_{k=1}^{i} n_k$. The *average delay*, $E[D_s(\mathcal{D})]$, is computed from:

$$E\big[D_s(\mathcal{D})\big] = \sum_{i=1}^{\mathcal{D}} i q_i. \tag{7}$$

Semi-reverse paging scheme guarantees that the location probability of each PA is in a non-increasing order. However, the cell with lower probability may be searched before the cell with higher probability because the initial sequence of the cells is reordered during the semi-reverse paging procedure. Consequently, the paging costs may not be minimized. To minimize the paging costs, we introduce the following *uniform paging* scheme in which the reordering problem is avoided.

3.3. Uniform paging

Under this scheme the LA is partitioned into a series of PAs in such a way that all PAs consist of approximately the same number of cells. With the same denotations as for the previous two schemes, the *uniform paging* procedure is as follows:

- Calculate the number of cells in each PA as
$$n_0 = \left\lfloor \frac{N}{\mathcal{D}} \right\rfloor, \tag{8}$$
where $N = n_0\mathcal{D} + k$.
- Determine a series of PAs as $\mathrm{PA}_u^*(1, q_1, n_1), \mathrm{PA}_u^*(2, q_2, n_2), \dots, \mathrm{PA}_u^*(\mathcal{D}, q_{\mathcal{D}}, n_{\mathcal{D}})$. Note that there are n_0 cells in each of the first $(D-k)$ PAs and there are n_0+1 cells in each of the remaining k PAs. This means $n_1 = n_2 = \cdots = n_{\mathcal{D}-k} = n_0$, and $n_{\mathcal{D}-k+1} = \cdots = n_{\mathcal{D}} = n_0 + 1$. For example, the first PA consists of n_0 cells and the last PA, i.e., $\mathcal{D}$th PA, consists of n_0+1 cells.

- The network polls one PA after another sequentially until the called MT is found.

According to this procedure, for $1 \leqslant i \leqslant \mathcal{D} - k$, $\mathrm{PA}_u^*(i, q_i, n_i)$ consists of n_0 cells ranging from the $[(i-1)n_0 + 1]$th cell to the $[n_0 i]$th cell as in the initial paging sequence. If $\mathcal{D} - k + 1 \leqslant i \leqslant \mathcal{D}$, the ith PA is composed of $n_0 + 1$ cells ranging from the $[i(n_0+1) - n_0 - (\mathcal{D}-k)]$th cell to the $[i(n_0+1) - (\mathcal{D}-k)]$th cell. Therefore, the location probability of $\mathrm{PA}_u^*(i, q_i, n_i)$, q_i, is obtained by

$$q_i = \begin{cases} \displaystyle\sum_{j=(i-1)n_0+1}^{n_0 i} p_j, & 1 \leqslant i \leqslant \mathcal{D} - k, \\ \displaystyle\sum_{j=i(n_0+1)-n_0-(\mathcal{D}-k)}^{j=i(n_0+1)-(\mathcal{D}-k)} p_j, & \mathcal{D} - k + 1 \leqslant i \leqslant \mathcal{D}. \end{cases} \tag{9}$$

Finally, the *average paging cost*, $E[C_u(\mathcal{D})]$, is calculated from

$$E\big[C_u(\mathcal{D})\big] = \sum_{i=1}^{\mathcal{D}-k} i q_i n_0 + \sum_{i=\mathcal{D}-k+1}^{\mathcal{D}} \big[i(n_0+1) - (\mathcal{D}-k)\big] q_i, \tag{10}$$

Table 1
The initial location probabilities.

Page area	Sequence number j	Location probability p_j	Number of cells
PA_1	1	0.3	1
PA_2	2	0.2	1
PA_3	3	0.15	1
PA_4	4	0.10	1
PA_5	5	0.05	1
PA_6	6	0.05	1
PA_7	7	0.05	1
PA_8	8	0.05	1
PA_9	9	0.03	1
PA_{10}	10	0.03	1

and the *average delay*, $E[D_u(\mathcal{D})]$, can be obtained by substituting (9) into (7).

3.4. Example

Supposing that there are $N = 10$ cells in an LA, and the probability that an MT resides in each cell is given in table 1. The delay bound $\mathcal{D}$ is 4 polling cycles. In figure 2(a), the initial cell sequence is shown in decreasing order of probabilities.

If we do not apply delay constraint, each cell is equivalent to a PA. The system searches one cell in one polling cycle. The worst case paging delay is the maximum number of polling cycles for finding the called MT, corresponding to 10 polling cycles because there are 10 cells within the LA for this example. The *average paging cost*, $C_{\min}$, and the *average delay*, $D_{\max}$, are calculated as [15]:

$$C_{\min} = \sum_{j=1}^{10} j p_j = 3.34 \quad \text{and} \quad D_{\max} = \sum_{j=1}^{10} j p_j = 3.34. \tag{11}$$

This is the theoretical result of *minimum average paging cost* and *maximum average delay.* For the broadcast scheme [10, 14,19], the *average paging cost*, $C_{\max}$, is maximum and the *average delay*, $D_{\min}$, is minimum:

$$C_{\max} = 10 \quad \text{and} \quad D_{\min} = 1. \tag{12}$$

As described in section 3.1, the procedure of *reverse paging* is shown in figure 2(b). We let the first $(\mathcal{D} - 1) = 3$ highest probability cells to be the first three PAs, which are $\mathrm{PA}_r^*(i, 0.3, 1)$, $\mathrm{PA}_r^*(2, 0.2, 1)$ and $\mathrm{PA}_r^*(3, 0.15, 1)$. Then, we merge the remaining $(N - \mathcal{D} + 1) = 7$ cells to be the 4th PA

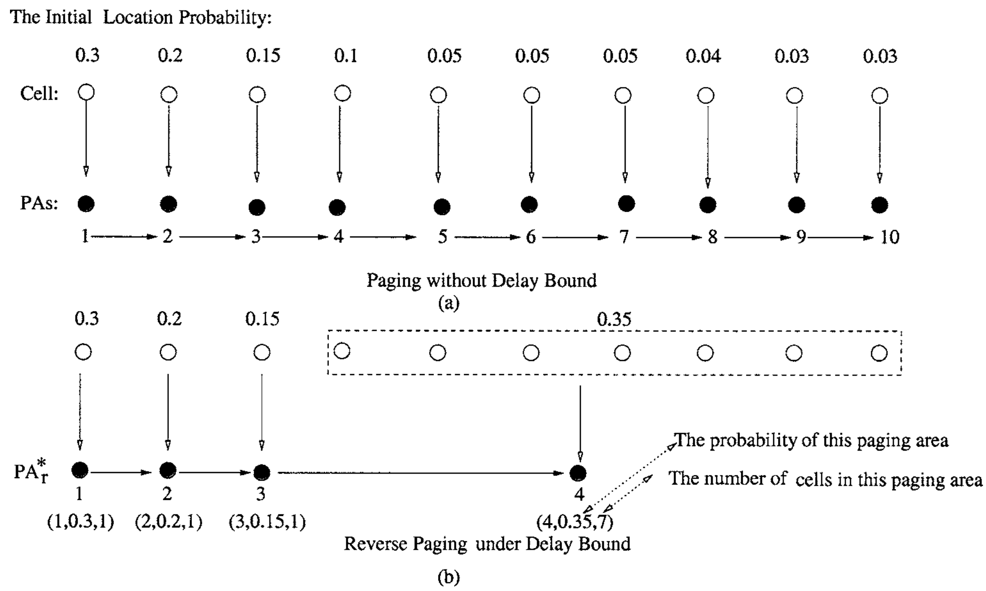

Figure 2. The average paging cost under delay bound $\mathcal{D}$ using reverse paging.

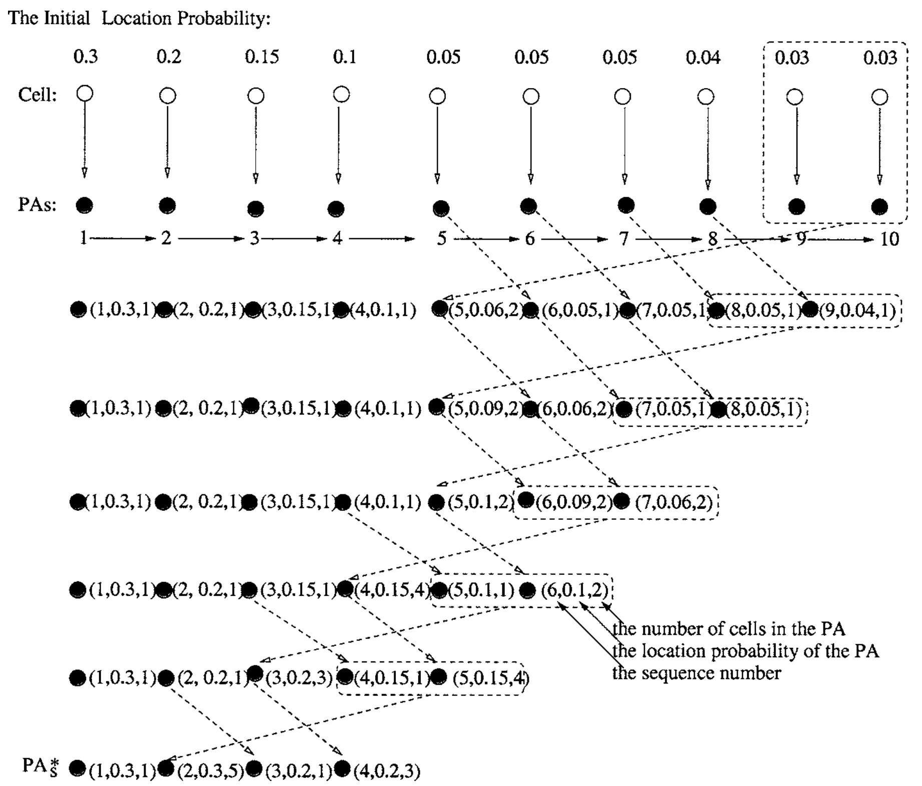

Figure 3. The average paging cost under delay bound $\mathcal{D}$ using semi-reverse paging.

which is $\mathrm{PA}_r^*(4, 0.35, 7)$. The *average paging cost* and the *average delay* are calculated using (4) and (5), respectively:

$$E\left[C_r(\mathcal{D})\right] = \sum_{j=1}^{3} j p_j + 10 \sum_{j=4}^{10} p_j = 4.65 \tag{13}$$

and

$$E\left[D_r(\mathcal{D})\right] = \sum_{j=1}^{3} j p_j + 4 \sum_{j=4}^{10} p_j = 2.55. \tag{14}$$

As shown in figure 3, under *semi-reverse paging*, the two lowest probability cells are combined as a new PA with location probability of $(0.03 + 0.03 = 0.06)$. Then we reorder the PAs in a decreasing order of probability. On the third row in figure 3, the new PA is moved to the front of all PAs with probability less than 0.06. We keep repeating this procedure until $\mathcal{D}$ PAs are acquired. After all, the PAs are created as $\mathrm{PA}_s^*(1, 0.3, 1)$, $\mathrm{PA}_s^*(2, 0.3, 5)$, $\mathrm{PA}_s^*(3, 0.2, 1)$ and $\mathrm{PA}_s^*(4, 0.2, 3)$.

The *average paging cost* and *average delay* are then calculated using (6) and (7):

$$E\left[C_s(\mathcal{D})\right] = \sum_{i=1}^{4} s_i q_i = 5.5,$$
$$E\left[D_s(\mathcal{D})\right] = \sum_{i=1}^{4} i q_i = 2.3. \tag{15}$$

It is obvious that the PAs are organized in a non-increasing order of the probability under *semi-reverse paging* scheme. However, the *average paging cost* is larger than the cost we obtained from *reverse paging* scheme. This is induced by searching the PAs with more cells prior to searching the PAs with less cells, i.e., some cells with lower probability are searched before the cells with higher probability. For example, $\mathrm{PA}_s^*(2, 0.3, 5)$ is searched before $\mathrm{PA}_s^*(3, 0.2, 1)$ and the 9th and 10th cells are searched before the second cell in the initial sequence. This problem can be eliminated in the *uniform paging* scheme.

The procedure of *uniform paging scheme* is shown in figure 4. First, we calculate $n_0 = \lfloor 10/4 \rfloor = 2$ and $k = (N - n_0\mathcal{D}) = 2$. Then each of the first $(\mathcal{D} - k) = 2$ PAs consists of $n_0 = 2$ cells and each of the remaining $k = 2$ PAs consists of $(n_0 + 1) = 3$ cells. Accordingly, the PAs are $\mathrm{PA}_u^*(1, 0.5, 2)$, $\mathrm{PA}_u^*(2, 0.25, 2)$, $\mathrm{PA}_u^*(3, 0.15, 3)$ and $\mathrm{PA}_u^*(4, 0.1, 3)$. With (7), (9) and (10), the *average paging cost*, $E[C_u(\mathcal{D})]$, and *average delay*, $E[D_u(\mathcal{D})]$, are calculated by:

$$E\left[C_u(\mathcal{D})\right] = 2\sum_{j=1}^{2} p_j + 4\sum_{j=3}^{4} p_j + 7\sum_{j=5}^{7} p_j + 10\sum_{j=8}^{10} p_j = 4.05, \tag{16}$$

$$E\left[D_u(\mathcal{D})\right] = \sum_{j=1}^{2} p_j + 2\sum_{j=3}^{4} p_j + 3\sum_{j=5}^{7} p_j + 4\sum_{j=8}^{10} p_j = 1.85. \tag{17}$$

In this example, the proposed three schemes significantly reduce the paging cost compared to the broadcast scheme. The average paging costs are little higher than $C_{\min}$ in (11)

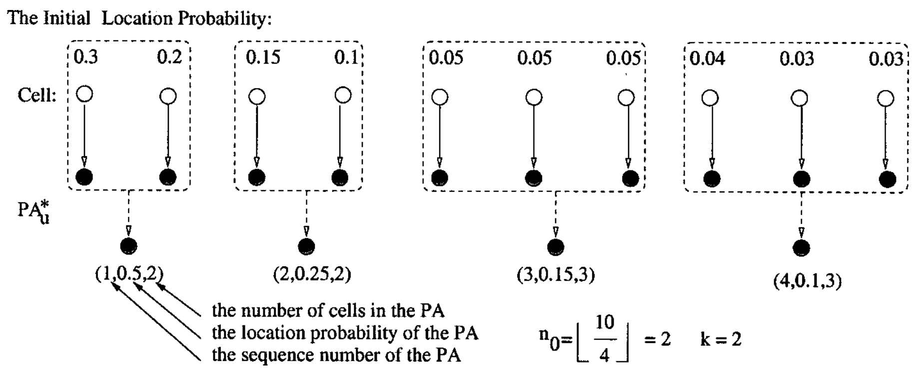

Figure 4. The average paging cost under delay bound $\mathcal{D}$ using uniform paging.

because each PA consists of multiple cells that are searched in one polling cycle. However, the average delays are much lower than $D_{\max}$ in (11) and the upper delay bound requirement is guaranteed, which is critical for satisfying QoS requirements for the multimedia services in wireless systems. Thus, the proposed paging methods provide a good tradeoff between paging costs and delays.

3.5. Paging failure probability

In this section, we investigate the call loss probability, which is a general problem of multi-step paging schemes. Since only a subset of the LA is searched in one polling cycle, if the MT is moving during the paging process, the MT may be missed. For example, when the first PA is polled while the MT is in the second PA, thus the MT does not response. Then the system proceeds to poll the second PA. At this moment, the MT moves from the second PA to the first PA. As a result, the system fails to locate the MT, this is *called paging failure*.

The paging failure depends heavily upon the MT's mobility pattern. We consider this problem based on the mobility model as in [20]. In this context, the MTs are allowed to move between PAs during the paging process. For simplicity, we consider a simple model where the MT moves back and forth along a one-dimensional state diagram in one polling cycle, with transition probability m_{ij}.

$$m_{ij} = \text{prob[MT is at the } j\text{th cell} \mid \text{at the } i\text{th cell]} = \begin{cases} \alpha & 0 < |j-i| \leqslant K, \\ 1-2K\alpha & i = j, \\ 0 & \text{else,} \end{cases} \tag{18}$$

where i is the sequence number of a cell in the LA in a decreasing order of location probabilities.

The simplest case is $K = 1$, in which the MT is allowed to move one step forwards or backwards. Specifically, for the first paging area, the MT is allowed to move from the least probable cell to the most probable cell in the second PA. For the last polling cycle, the paging fails only when the MT moves from the last PA to the $(\mathcal{D}-1)$th PA. If the MT is in the PAs other the first and the last PA, the paging failure occurs when the MT leaves the PA from the most probable cell or the least probable cell. By using the same denotation as in the previous section, the paging failure probability for $K = 1$, $P_1(i)$, in the ith polling cycle can be computed from

$$P_1(i) = \begin{cases} p_{n_1}\alpha \text{ with prob. } q_1 \\ \quad \text{for } i = 1, \\ (p_{k_i+1} + p_{k_n+n_i})\alpha \text{ with prob. } Q_1(i) \\ \quad \text{for } 1 < i < \mathcal{D}, \\ p_{N-n_{\mathcal{D}}}\alpha \text{ with prob. } Q_1(i) \\ \quad \text{for } i = \mathcal{D}, \end{cases} \tag{19}$$

where $k_i = \sum_{x=1}^{i} n_x$ and $Q_1(i)$ is defined as:

$$Q_1(i) = \begin{cases} q_1, & i = 1, \\ q_i + \sum_{m=2}^{i} Q_1(m-1)P_1(m-1), & \text{otherwise.} \end{cases} \tag{20}$$

Therefore, the average paging failure for $K = 1$, P_1^{f} is obtained by

$$P_1^{\mathrm{f}} = p_{n_1}\alpha q_1 + \sum_{i=1}^{\mathcal{D}} Q_1(i)P_1(i). \tag{21}$$

When K is equal to 2, the MTs are allowed to move two steps in a polling cycle. In each step, it moves from one cell to another. The corresponding state diagram is shown in figure 5. Each state (k, i) represents that the MT is residing in the kth cell of the ith PA. According to the MT's current position, there are three possibilities of the paging failure.

- If the MT is in the ith PA ($i > 1$), then the probability that it moves to the $(i-1)$th PA, $P(\mathrm{h}) = \alpha(1+\alpha)$.
- If the MT is in the ith PA ($\mathcal{D} > i > 1$), then the probability that it moves to the $(i+1)$th PA, $P(\mathrm{l}) = \alpha(1+\alpha)$.
- Otherwise, the probability that an MT moves to another PA, $P(\mathrm{o}) = \alpha^2$.

Accordingly, the paging failure probability of the first polling cycle, $P_2(1)$ is computed from

$$P_2(1) = \begin{cases} p_1\alpha(1+\alpha), & n_1 = 1, \\ p_1\alpha + p_2\alpha(1+\alpha), & n_1 = 2, \\ p_{n_1-1}P(\mathrm{o}) + p_{n_1}P(\mathrm{l}), & n_1 \geqslant 3. \end{cases} \tag{22}$$

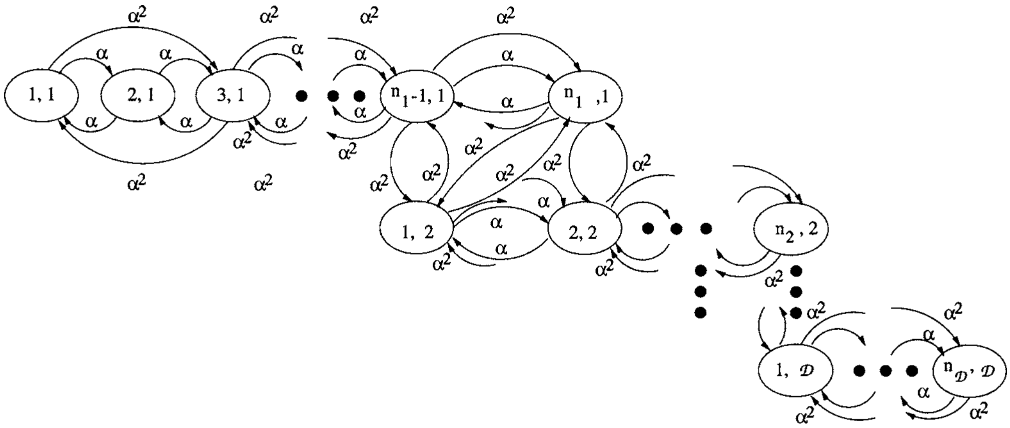

Figure 5. The analytical model of paging failure.

For other polling cycles where $1 < i < \mathcal{D}$, the paging failure probability $P_2(i)$ is computed from

$$P_2(i) = \begin{cases} 2p_{k_i}\alpha(1+\alpha), & n_i = 1, \\ p_{k_i-1}P(\mathrm{h}) + p_{k_i}P(\mathrm{l}), & n_i = 2, \\ p_{k_{i-1}+1}P(\mathrm{h}) + p_{k_{i-1}+2}P(\mathrm{o})N \\ \quad +p_{k_i}P(\mathrm{h}), & n_i = 3, \\ p_{k_{i-1}+1}P(\mathrm{h}) + p_{k_{i-1}+2}P(\mathrm{o})N \\ \quad +p_{k_{i-1}}P(\mathrm{o}) + p_{k_i}P(\mathrm{h}), & n_i \geqslant 4. \end{cases} \tag{23}$$

The paging failure probability of the last polling cycle, i.e., $i = \mathcal{D}$th, $P_2(\mathcal{D})$ is computed from

$$P_2(\mathcal{D}) = \begin{cases} p_N\alpha(1+\alpha), & n_\mathcal{D} = 1, \\ p_N\alpha + p_{N-1}\alpha(1+\alpha), & n_\mathcal{D} = 2, \\ p_{N-n_\mathcal{D}+2}P(\mathrm{o}) \\ \quad +p_{N-n_\mathcal{D}+1}P(\mathrm{h}), & n_\mathcal{D} \geqslant 3. \end{cases} \tag{24}$$

Similarly, $Q_2(i)$ is

$$Q_2(i) = \begin{cases} q_1, & i = 1, \\ q_i + \sum_{m=2}^{i} Q_2(m-1)P_2(m-1), & \text{otherwise.} \end{cases} \tag{25}$$

The *average paging failure probability* for $K = 2$, P_2^{f}, is then obtained by

$$P_2^{\mathrm{f}} = \sum_{i=1}^{\mathcal{D}} Q_2(i)P_2(i). \tag{26}$$

4. Performance evaluation

The numerical results for uniform distribution, truncated discrete Gaussian distribution, and irregular distribution are provided in this section. We compare the average paging costs and paging delays of proposed schemes with three other paging schemes: broadcast paging, selective paging and highest probability first (HPF) paging introduced in section 1.

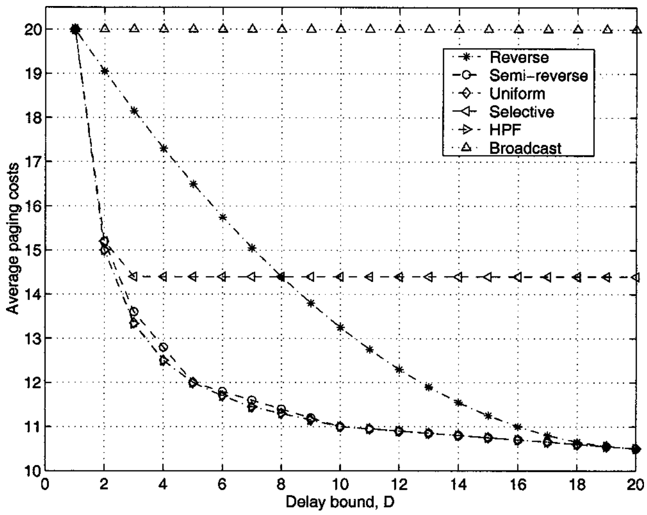

Figure 6. The average paging costs for uniform distribution.

4.1. Paging cost and delay for uniform probability distribution

First we study the relationship between the average paging cost, C, and the delay bound, $\mathcal{D}$, under different paging schemes. For the selective paging scheme, we choose one of its simulated cases in which an LA is divided into three partitions with location probability 0.6, 0.2 and 0.2 [1]. Figure 6 shows the average paging cost $C(\mathcal{D})$ as a function of $\mathcal{D}$ for an LA with twenty cells ($N = 20$).

It can be seen in figure 6 that the paging costs decrease with the increasing paging delay bounds for all paging schemes except broadcast scheme. The average paging costs of using *semi-reverse, uniform*, and HPF paging schemes fall much faster than that of the *reverse paging* scheme. Specifically, when the paging delay bound is 5, the paging costs of *semi-reverse, uniform,* and HPF paging achieve small asymptotic values. The broadcast scheme always produces the highest paging cost even though the delay bound changes. The paging costs caused by selective scheme remain the same after $\mathcal{D} = 3$ since there are three partitions and each partition is searched in one cycle, so the maximum delay is three polling cycles. On the other hand,

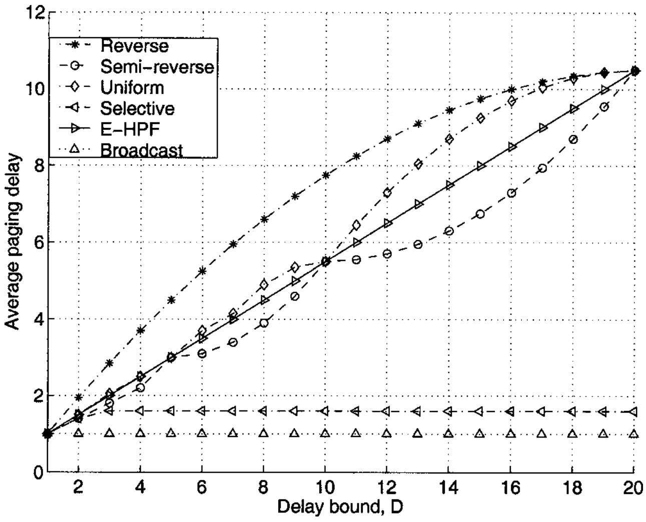

Figure 7. The average paging delays for uniform distribution.

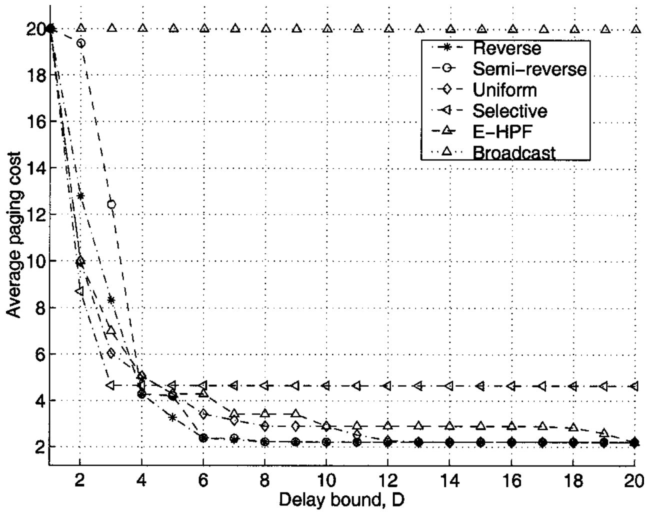

Figure 8. The average paging costs for truncated discrete Gaussian distribution.

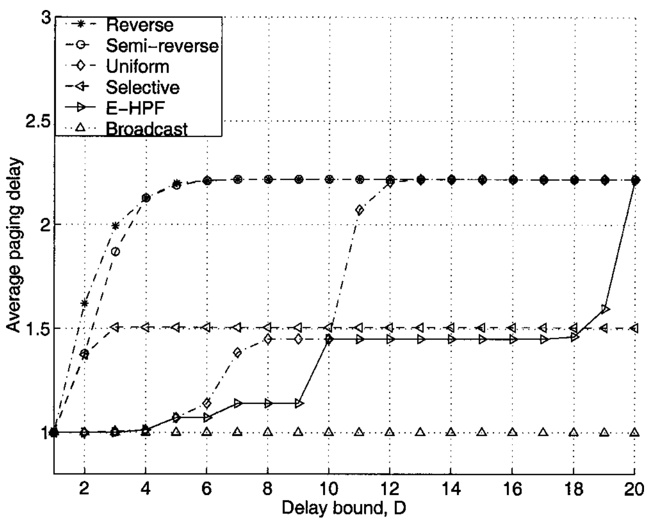

Figure 9. The average paging delays for truncated discrete Gaussian distribution.

the semi-reverse and uniform paging schemes cause the minimum paging costs which are the same as the theoretical result from HPF scheme.

The average paging delays are also investigated and the results are shown in figure 7. We consider that the paging cost has higher priority than the average paging delay when the delay bound is satisfied. It is observed that the average delays increase as the delay bound increases. The average delays of *semi-reverse paging* increase more slowly than that of other schemes. Considering that the three paging schemes, semi-reverse, uniform, and HPF, result in almost the same paging costs, we conclude that the *semi-reverse paging* is the most suitable scheme among them for the location probability of uniform distribution.

4.2. Average paging cost and delay for truncated Gaussian distribution

In this section, the average paging costs and delays versus delay bounds are investigated for truncated Gaussian distribution. When the mobile users are moving on the highway, they are likely to keep going or exit at some points. Thus, the truncated Gaussian distribution is more appropriate for describing this type of movement. It is necessary to mention that in the original paper of the HPF scheme, a non-increasing probability density function $g(x)$ must be found to be comparable to the non-increasing discrete distribution [15]. However, finding the optimal solution to function $g(x)$ is not fully researched and is not provided in the paper. In order to obtain the numerical results and make complete comparison, we design the paging procedure for the original HPF scheme, which is called the enhanced-HPF (E-HPF) scheme. The average paging costs and delays of different paging schemes are revealed in figures 8 and 9 for truncated discrete Gaussian distribution with mean zero and variance one.

When an MT's location probability p_j is a truncated discrete Gaussian distribution, the average paging cost, C, decreases very quickly as $\mathcal{D}$ changes from 1 to 4, then it converges to the minimum value. The selective scheme results in lower signaling costs compared to uniform scheme when $\mathcal{D} = 2$. However, at the expense of increased paging costs by 12%, uniform scheme gains by a 44% reduction in average delays compared to selective scheme. We can also see that the uniform paging scheme provides lower paging costs when $\mathcal{D} \leqslant 4$, but reverse and semi-reverse schemes result in lower paging costs for $\mathcal{D} > 4$. The important result is that the paging costs can be reduced significantly. Thus, it is reasonable to attain substantial reduction in the paging costs with a little increase in paging delay.

The average paging delays are illustrated in figure 9. As the delay bound increases, the average paging delay also increases and maintains the same value after delay bound $\mathcal{D} = 6$ for reverse and semi-reverse scheme, but it reaches steady value after $\mathcal{D} = 12$ and $\mathcal{D} = 10$ for uniform and E–HPF schemes, respectively. Another observation is the

Table 2
The irregular location probability distributions.

Cell sequence	1	2	3	4	5	6	7	8	9	10
Case A	0.36	0.31	0.05	0.05	0.045	0.045	0.04	0.04	0.03	0.03
Case B	0.16	0.16	0.16	0.16	0.06	0.06	0.06	0.06	0.06	0.06
Case C	0.28	0.26	0.08	0.08	0.05	0.05	0.05	0.05	0.05	0.05

Delay Bound	Paging Scheme \ Paging Areas	PA* (i, q_i , n_i)	Average Paging Cost	Average Paging Delay
$\mathcal{D} = 3$	Reverse	(1, 0.36, 1); (2, 0.31, 1); (3, 0.33, 8)	**4.28**	1.97
	Semi–reverse	(1, 0.36, 1); (2, 0.33, 8); (3, 0.31, 1)	6.43	1.95
	Uniform	(1, 0.72, 3); (2, 0.14, 3); (3, 0.14, 4)	4.40	1.42
	Selective	(1, 0.55, 5); (2, 0.31, 1); (3, 0.14, 4)	6.01	1.59
	E–HPF	(1, 0.77, 4); (2, 0.13, 3); (3, 0.10, 3)	4.99	*1.33*
$\mathcal{D} = 4$	Reverse	(1, 0.36, 1); (2. 0.31, 1); (3, 0.05, 1); (4, 0.28, 7)	3.93	2.25
	Semi–reverse	(1, 0.36, 1); (2, 0.31, 1); (3, 0.19, 4); (4, 0.14, 4)	**3.52**	2.11
	Uniform	(1, 0.67, 2); (2, 0.10, 2); (3, 0.13, 3); (4, 0.10, 3)	3.65	1.66
	Selective	(1, 0.55, 5); (2, 0.31, 1); (3, 0.14, 4)	6.01	1.59
	E–HPF	(1, 0.72, 3); (2, 0.14, 3); (3, 0.08, 2); (4,0.06, 2)	4.28	*1.48*
$\mathcal{D} = 5$	Reverse	(1, 0.36, 1); (2, 0.31, 1); (3, 0.05, 1); (4, 0.05, 1); (5, 0.23, 6)	3.63	2.48
	Semi–reverse	(1, 0.36, 1); (2, 0.31, 1); (3, 0.14, 4); (4, 0.10, 2); (5, 0.09, 2)	**3.52**	2.25
	Uniform	(1, 0.67, 2); (2, 0.10, 2); (3, 0.09, 2); (4, 0.08, 2); (5, 0.06, 2)	**3.52**	1.76
	Selective	(1, 0.55, 5); (2, 0.31, 1); (3, 0.14, 4)	6.01	*1.59*
	E–HPF	(1, 0.67, 2); (2, 0.10, 2); (3, 0.09, 2); (4, 0.08, 2); (5, 0.06, 2)	**3.52**	1.76
Broadcast		(1, 1, 10)	10	1.0

Figure 10. The average paging costs and delays for case A.

"stairstep" curve which is induced by using uniform and E-HPF paging schemes. In the presence of uniform paging, the floor number of n_0 is calculated during the procedure of grouping cells. For example, $n_0 = \lfloor N/\mathcal{D} \rfloor$ is equal to 2 for $N = 20$ and $\mathcal{D} = 7$ to 10 in (8). As a result, the average paging delays are very close for $\mathcal{D} = 7$ to 10. The paging delay is changed when $\mathcal{D} = 11$ corresponding to $n_0 = 1$. This is shown as a jump in figure 9, and the average paging delay remains the same after $\mathcal{D} = 12$. The similar effect is also applicable to the E-HPF scheme. The results from both paging costs and delays demonstrate that the most suitable paging scheme for the truncated discrete Gaussian distribution is the selective scheme for $\mathcal{D} \leqslant 3$ and uniform scheme for $\mathcal{D} > 3$.

4.3. Paging costs and delays for irregular probability distribution

We look into the average paging costs and paging delays for irregular location probability distributions in this section when the location probability distribution may not be represented by a particular function. Three irregular distribution cases created randomly are considered in table 2.

The *average paging costs* and *average delays* of case A are shown in figure 10. The details of each PA, such as the paging sequence, the location probability, and the number of cells under $\mathcal{D} = 3, 4, 5$, are also illustrated. The minimum average paging costs are indicated in bold and the minimum average delays are indicated in italic in figure 10. It can be seen that the reverse paging and semi-reverse paging result in the minimum paging costs when $\mathcal{D}$ is equal to 3 and 4, respectively. The uniform paging produces both small average paging costs and delays. When $\mathcal{D} = 5$, the semi-reverse, uniform, and E-HPF cause the same value of average paging cost, even though the partitions are different. The uniform and E-HPF paging causes lower average delays than that of the semi-reverse paging.

According to the *average paging costs* and *average delays* of case B in figure 11, the selective and E-HPF paging scheme produces the minimum average paging cost and delay for $\mathcal{D} = 3$. The uniform paging scheme produces the minimum paging cost for both $\mathcal{D} = 4$ and $\mathcal{D} = 5$; meanwhile, selective results in minimum average delays. We show the *average paging costs* and *average delays* for case C in figure 12. The uniform and selective paging produce minimum paging costs when the delay bound $\mathcal{D}$ is equal to 3. The uniform method causes the minimum paging costs for $\mathcal{D} = 4$ and 5. We also notice that the average paging costs using semi-reverse scheme are very close to the minimum values when $\mathcal{D}$ is 4 and 5.

The paging failure probabilities are investigated for $\alpha = 0.1\%$, $N = 10$ and $K = 1$. The comparison of uniform,

Delay Bound	Paging Scheme \ Paging Areas	PA* (i, q_i, n_i)	Average Paging Cost	Average Paging Delay
$\mathcal{D}=3$	Reverse	(1, 0.16, 1); (2, 0.16, 1); (3, 0.68, 8)	7.28	2.52
	Semi-reverse	(1, 0.40, 5); (2, 0.32, 2); (3, 0.28, 3)	7.04	1.88
	Uniform	(1, 0.48, 3); (2, 0.28, 3); (3, 0.24, 4)	5.80	1.76
	Selective	(1, 0.64, 4); (2, 0.18, 3); (3, 0.18, 3)	5.70	*1.54*
	E-HPF	(1, 0.64, 4); (2, 0.18, 3); (3, 0.18, 3)	**5.62**	*1.54*
$\mathcal{D}=4$	Reverse	(1, 0.16, 1); (2, 0.16, 1); (3, 0.16, 1); (4, 0.52, 6)	6.16	3.04
	Semi-reverse	(1, 0.32, 2); (2, 0.28, 3); (3, 0.24, 4); (4, 0.16, 1)	7.40	2.88
	Uniform	(1, 0.32, 2); (2, 0.32, 2); (3, 0.18, 3); (4, 0.18, 3)	**4.98**	2.22
	Selective	(1, 0.64, 4); (2, 0.18, 3); (3, 0.18, 3)	5.70	*1.54*
	E-HPF	(1, 0.48, 3); (2, 0.28, 3); (3, 0.12, 2); (4, 0.12, 2)	5.28	1.88
$\mathcal{D}=5$	Reverse	(1, 0.16, 1); (2, 0.16, 1); (3, 0.16, 1); (4, 0.16, 1); (5, 0.36, 6)	5.20	3.40
	Semi-reverse	(1, 0.28, 3); (2, 0.24, 4); (3, 0.16, 1); (4, 0.16, 1); (5, 0.16, 1)	6.84	2.68
	Uniform	(1, 0.32, 2); (2, 0.32, 2); (3, 0.12, 2); (4, 0.12, 2); (5, 0.12, 2)	**4.80**	2.40
	Selective	(1, 0.64, 4); (2, 0.18, 3); (3, 0.18, 3)	5.70	*1.54*
	E-HPF	(1, 0.32, 2); (2, 0.32, 2); (3, 0.12, 2); (4, 0.12, 2); (5, 0.12, 2)	**4.80**	2.40
Broadcast		(1, 1, 10)	10.0	1.0

Figure 11. The average paging costs and delays for case B.

Delay Bound	Paging Scheme \ Paging Areas	PA * (i, q_i, n_i)	Average Paging Cost	Average Paging Delay
$\mathcal{D}=3$	Reverse	(1, 0.28, 1); (2, 0.26, 1); (3,0. 46, 8)	5.40	2.18
	Semi-reverse	(1, 0.46, 5); (2, 0.28, 1); (3, 0.26, 4)	6.58	1.80
	Uniform	(1, 0.62, 3); (2, 0.18, 3); (3, 0.20, 4)	**4.94**	1.58
	Selective	(1, 0.62, 3); (2, 0.18, 3); (3, 0.20, 4)	**4.94**	1.58
	E-HPF	(1, 0.70, 4); (2, 0.15, 3); (3, 0.15, 3)	5.35	*1.45*
$\mathcal{D}=4$	Reverse	(1, 0.28, 1); (2, 0.26, 1); (3, 0.08, 1); (4, 0.38, 7)	4.84	2.56
	Semi-reverse	(1, 0.28, 1); (2, 0.26, 1); (3, 0.26, 4); (4, 0.20, 4)	4.36	2.38
	Uniform	(1, 0.54, 2); (2, 0.16, 2); (3, 0.15, 3); (4, 0.15, 3)	**4.27**	1.91
	Selective	(1, 0.62, 3); (2, 0.18, 3); (3, 0.20, 4)	4.94	*1.58*
	E-HPF	(1, 0.62, 3); (2, 0.18, 3); (3, 0.10, 2); (3, 0.10, 2)	4.74	1.68
$\mathcal{D}=5$	Reverse	(1, 0.28, 1); (2, 0.26, 1); (3, 0.08, 1); (4, 0.08, 1); (5, 0.30, 6)	4.36	2.86
	Semi-reverse	(1, 0.28, 1); (2, 0.26, 1); (3, 0.20, 4); (4, 0.16, 2); (5, 0.10, 2)	4.28	2.54
	Uniform	(1, 0.54, 2); (2, 0.16, 2); (3, 0.10, 2); (4, 0.10, 2); (5, 0.10, 2)	**4.12**	2.06
	Selective	(1, 0.62, 3); (2, 0.18, 3); (3, 0.20, 4)	4.94	*1.58*
	E-HPF	(1, 0.54, 2); (2, 0.16, 2); (3, 0.10, 2); (4, 0.10, 2); (5, 0.10, 2)	**4.12**	2.06
Broadcast		(1, 1, 10)	10.0	1.0

Figure 12. The average paging costs and delays for case C.

truncated Gaussian distribution and three examples for irregular distributions are shown in figures 13(a)–(e). We plot the paging failure probabilities in each cluster from left to right as: reverse, semi-reverse, uniform, selective, E-HPF, and broadcast schemes. As paging response is received in one polling cycle for broadcast scheme so that the probability of paging failure is zero. In most of the cases, the probabilities of paging failure increase as delay bounds increase. Occasionally, the reverse paging produce high failure probabilities such as $D = 2$. For uniform distribution, all other paging schemes produce almost the same paging failure probabilities. For the truncated Gaussian distribution, the semi-reverse, uniform, and E-HPF are all good for $D = 2$. The semi-reverse paging yields a high value for $D = 5$ because there are five cells with lowest probabilities in the last PA which results high paging failure probabilities. For the irregular probability distributions, selective paging results better performance compared to other schemes. We expect to see this observation since the corresponding paging costs are higher. If α is very small, the probabilities of

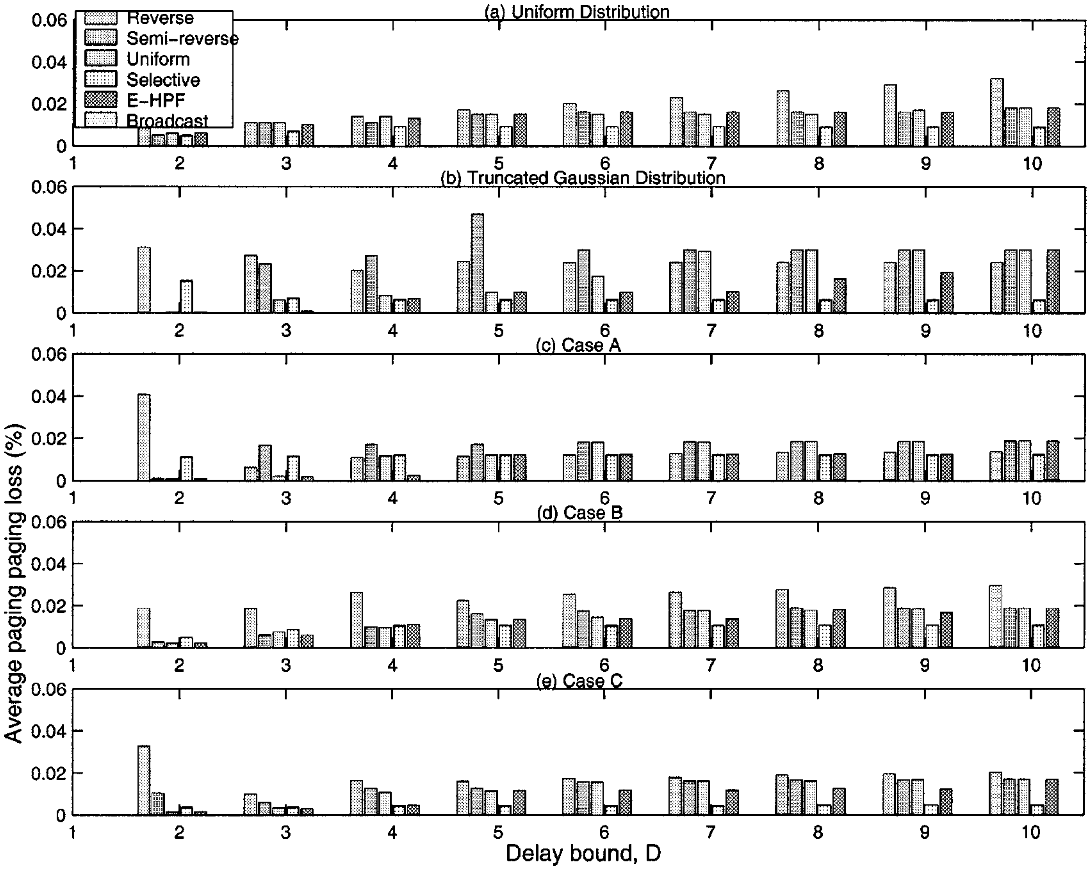

Figure 13. The paging failure probabilities.

paging failure can be ignored. In summary, there is tradeoff between paging costs, paging delays, and paging failures. Each system can decide which performance is more critical to its subscribers based on the system architecture and users' mobility pattern.

With the above observations, we find that the semi-reverse and uniform paging schemes are more likely to reduce the *average paging costs* when the location probability is irregular. The selective paging scheme also causes good results in some cases but it needs to group the cells into PAs using complex computation; furthermore, it depends on the size and shape of the LA, which makes it not flexible. Our proposed schemes are very simple to implement and definitely reduce the paging costs significantly over various probability distributions.

5. Conclusions

In this paper, we introduced three paging schemes which are applicable to different location probability distributions in wireless systems. All schemes are easy to implement and they greatly reduce the paging costs under delay bounds. Semi-reverse paging is the most suitable scheme for the uniform distribution considering both the *average paging costs* and *average delays* performance. Uniform paging scheme produces the minimum paging cost as well. For the truncated discrete Gaussian distribution, reverse and uniform paging schemes are applicable; especially, the reverse paging scheme converges to the minimal value faster than the other schemes. When the location probability is irregular, which is not considered in many paging schemes, our proposed schemes such as semi-reverse and uniform paging are still very helpful to reduce the average paging costs. In conclusion, these new paging schemes provide scalable paging methods for the wireless systems.

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Wenye Wang (Student Member, IEEE, ACM) received the B.S. and M.S. degrees from Beijing University of Posts and Telecommunications, Beijing, China, in 1986 and 1991, respectively. She also received the M.S.E.E. from Georgia Institute of Technology in 1999. She is currently pursuing the Ph.D. degree at the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta. She is a Research Assistant in the Broadband and Wireless Networking Laboratory in Georgia Institute of Technology. Her research interests include wireless multimedia networks, mobility management, mobile computing and IP mobility management.

Ian F. Akyildiz (Fellow, IEEE, ACM) received the B.S., M.S., and Ph.D. degrees in computer engineering from the University of Erlangen-Nuernberg, Germany, in 1978, 1981 and 1984, respectively. Currently, he is a Distinguished Chair Professor with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, and Director of the Broadband and Wireless Networking Laboratory. His current research interests are in wireless networks, satellite networks, and the Internet. Dr. Akyildiz is the Editor-in-Chief of the Computer Networks (Elsevier Publishing Company) and an Editor for IEEE/ACM Transactions on Networking, ACM–Springer Journal for Multimedia Systems, ACM–Kluwer Journal of Wireless Networks, and Journal of Cluster Computing. He is a past Editor for IEEE Transactions on Computers (1992–1996). He was the Program Chair of the "9th IEEE Computer Communications" workshop held in Florida in October 1994. He also served as the Program Chair for ACM/IEEE MOBICOM'96 (Mobile Computing and Networking) conference, as well as for the IEEE INFOCOM'98. He will be the General Chair for ACM/IEEE MOBICOM 2002 conference and the Technical Program Chair of IEEE ICC'2003. He is an ACM FELLOW (1996). He received the "Don Federico Santa Maria Medal" for his services to the Universidad of Federico Santa Maria in Chile. He served as a National Lecturer for ACM from 1989 until 1998 and received the ACM Outstanding Distinguished Lecturer Award for 1994. He received the 1997 IEEE Leonard G. Abraham Prize award for his paper entitled "Multimedia Group Synchronization Protocols for Integrated Services Architecture", published in the IEEE Journal on Selected Areas in Communications in January 1996.

Gordon L. Stüber (Fellow, IEEE) received the B.A.Sc. and Ph.D. degrees in electrical engineering from the University of Waterloo, Ontario, Canada, in 1982 and 1986, respectively. Since 1986, he has been with the School of Electrical and Computer Engineering, Georgia Institute of Technology, where he is currently a Professor.

He spent the summers of 1993 and 1996 with Nortel Networks in Richardson, TX and Ottawa, Canada, respectively. Dr. Stüber is also Vice President for Research with WiLAN Wireless Data Communications (WWDC), Inc. Dr. Stüber's research interests are in wireless communications and communication signal processing. He was co-recipient of the *Jack Neubauer Memorial Award* for the best paper of the year published by the IEEE Vehicular Technology Society on the subject of Vehicular Technology Systems. He is an author of the textbook *Principles of Mobile Communication* (Kluwer Academic, 1996; 2nd ed. 2000). Dr. Stüber served as Technical Program Chair for the 1996 IEEE Vehicular Technology Conference (VTC'96), Technical Program Chair for the 1998 IEEE International Conference on Communications (ICC'98), and Chair of the Fifth IEEE Workshop on Multimedia, Multiaccess and Teletraffic for Wireless Communications (MMT'2000). He is a past Editor for Spread Spectrum with the IEEE Transactions on Communications (1993–1998). He is currently a member of the IEEE Communications Society Awards Committee, a member of the IEEE Vehicular Technology Society Board of Governors (2001–2003), and a Chair of the Fifth YRP International Symposium on Wireless Personal Multimedia Communications (WPMC'2002). He is an IEEE Fellow.

Boo-Young Chung received the B.S. degree in avionics from Hankook Aviation University, and the M.S. degree in electronics from Kunkook University, Seoul, Korea in 1985 and 1987, respectively. In 1998, he received the Ph.D. degree in electronics from Hankook Aviation University. Since 1988, he has been with Korea Telecom. He is currently with Access Network Laboratory, where his main interests are in the physical layer and MAC layer of third-generation wireless system. His research interests include wireless communications, mobile communication systems.