Reducing the Paging Costs under Delay Bounds for PCS Networks

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Abstract— **In this paper new paging schemes are presented for locating mobile users in wireless networks. Paging costs and delay bounds are considered since the paging cost is 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 cost, three new paging schemes – reverse, semi-reverse and uniform – are introduced to provide a simple way of partitioning the service areas and accordingly minimizing the paging cost based on each mobile terminal's location probability distribution. Numerical results demonstrate that our approaches significantly reduce the paging cost for various location probability distributions such as uniform, truncated discrete Gaussian, and irregular distributions.**

Keywords: **PCS Networks, Mobility Management, Paging.**

I. INTRODUCTION

In current personal communication service (PCS) networks, location update and paging are two fundamental operations to locate a mobile terminal (MT). Location update, which is concerned with the reporting of the current locations of the MTs, occurs when an MT moves from one location area to another area, allowing the network to authenticate users and revise the user location profiles. In a paging process, the network searches for an MT by sending poll messages to the cells close to the last reported location of the MT.

In this paper we focus on the paging problem, that is, to reduce the paging cost under delay bounds. According to the current GSM and IS-41 protocols used to perform paging procedure, paging is accomplished through a one-step or broadcast procedure [2], [3] in which the mobile switching center (MSC) broadcasts the paging request to all cells in the MT's last registered location area (LA). 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 in the LA receive the paging request simultaneously. A polling cycle is the time elapsed between sending a paging message and receiving the response. The cost of this paging process is very high and the utilization of bandwidth is inefficient since all cells in the LA are searched, which consumes a large amount of radio resources.

To improve the efficiency of bandwidth utilization, many schemes have been proposed to reduce the paging cost based on location probabilities which can be computed using different methods [5], [7]. In particular, multi-step paging schemes under the delay bounds are suggested in order to reduce the paging cost while maintaining the delay bound requirements [1], [2], [9]. In each step, a subset of LA called paging area (PA) is searched in one polling cycle. And 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], [9]. In [4], it is suggested that the MTs initiate location update messages only in the specific cells called *reporting cells*. The paging delay is guaranteed by limiting the neighboring cells around the reporting cells. The highest-probability-first (HPF) scheme, in which the delay constraint is considered as a weighted factor in determining the minimum paging cost, is introduced in [9]. It is demonstrated that the paging cost can be minimized by appropriately grouping cells in paging areas. However, to find the optimal delay weighted factor, an analogous or corresponding 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 in the presence of irregular discrete location probability distributions.

In this paper, we present three feasible methods for dividing a location area into paging areas, which are applicable to different location probability distributions. The rest of this paper is organized as follows. In Section II, we describe the problem formulation in which the paging delay bound is taken into account. In Section III, three paging schemes are presented. The details of partition procedure, paging costs, and average paging delays are also described in this section. We demonstrate the numerical results over various location probability distribution in Section IV and conclude the paper in Section V.

II. ANALYTICAL MODEL

The current PCS networks partition their coverage areas into a number of location areas (LAs) also known as registration areas (RAs) [10]. Each LA consists of a group of cells, and each MT sends location update request to the network when it enters a new LA. Therefore, the network is always aware of the location information of an MT in the level of LA. We assume that each LA consists of the same number of cells in the network, which is denoted as N. The worst case delay is considered as paging delay bound, $\mathcal{D}$, in terms of polling cycle. When $\mathcal{D}$ is equal to 1,

This work is supported by NSF under grant NCR-97-04393 and by Korea Telecom – Wireless Communications Research Laboratory (WCRL).

the network 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 searched before the MT is found, is equal to N. In this case, the average paging delay is minimum which is only one polling cycle and the average paging cost is maximum ($C = N$). On the other hand, when $\mathcal{D}$ is equal to N, the network polls one cell in each polling cycle and searches all cells one by one. The worst case occurs when the called MT is found in the last polling cycle, thus causing maximum paging delay, i.e., N polling cycles. Meanwhile, the average paging cost may be minimized if the cells are searched in decreasing order of location probability which can be computed in many ways. For example, each mobile terminal can be equipped with a counter to record the number of boundary crossings for each cell. After a long period, the frequency of visiting a specific cell can be computed based on the aggregated historic records, thus obtaining the experimental results. Also, the location probabilities of an MT can be estimated by combining the user mobility model, a user's velocity and its previous position [5], [7], [8].

We consider the partition of paging areas given that $1 \le \mathcal{D} \le N$, which requires grouping cells within an LA into PAs under paging delay bound $\mathcal{D}$. The initial state is defined as $\mathbf{P} = [p_1, p_2, \cdots, p_j, \cdots, p_N]$, where p_j is the location probability of j^{th} cell to be searched in decreasing order of probability at a specific time instant. We use triplets $PA^*_{\mathcal{P}}(i, q_i, n_i)$ to denote the PAs under paging scheme $\mathcal{P}$, where i is the sequence number of the PA; q_i is the location probability that the called MT can be found within the i^{th} PA and n_i is the number of cells contained in this PA as shown in Fig. 1. The network first searches the n_1 cells in $PA^*(1, q_1, n_1)$, if the called MT is not found, the network searches the n_2 cells in the second PA. This procedure continues searching PAs one after another until the called MT is found.

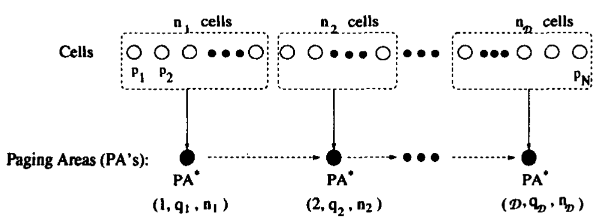

Fig. 1. Partition a Location Area (LA) into Paging Areas (PA) under Delay Bound, $\mathcal{D}$.

Accordingly, the location probability of an MT being found in the i^{th} PA, q_i, is:

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

If the called MT is found in the i^{th} PA, the average paging cost under delay bound $\mathcal{D}$, $C(\mathcal{D})$, is computed as follows:

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

and the average paging delay, $D(\mathcal{D})$ is:

$$D(\mathcal{D}) = \sum_{i=1}^{\mathcal{D}} i \cdot q_i. \tag{3}$$

Therefore, the problem is formulated as how to find the optimal n_i for each PA and appropriately group cells into PAs in order to minimize the paging costs.

III. New 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.

A. 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 $PA^*_r(1, p_1, 1)$, $PA^*_r(2, p_2, 1)$, $\cdots$, $PA^*_r(\mathcal{D} - 1, p_{\mathcal{D}-1}, 1)$, $PA^*_r(\mathcal{D}, q_{\mathcal{D}}, N - \mathcal{D} + 1)$, where r denotes the *reverse* paging scheme. The *average paging cost*, $C_r(\mathcal{D})$, is computed from

$$C_r(\mathcal{D}) = \sum_{j=1}^{\mathcal{D}-1} j \cdot p_j + N \cdot \sum_{j=\mathcal{D}}^{N} p_j, \tag{4}$$

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

$$D_r(\mathcal{D}) = \sum_{j=1}^{\mathcal{D}-1} j \cdot p_j + \mathcal{D} \cdot \sum_{j=\mathcal{D}}^{N} p_j. \tag{5}$$

B. 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 [9], 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*, $C_s(\mathcal{D})$, is :

$$\begin{aligned} C_s(\mathcal{D}) &= \sum_{i=1}^{\mathcal{D}} s_i \cdot q_i \\ &= q_1 n_1 + q_2(n_1 + n_2) + \cdots + q_{\mathcal{D}} N, \end{aligned} \tag{6}$$

where q_i is the summation of the location probabilities of cells in $PA^*(i, q_i, n_i)$ as in Eq. (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*, $D_s(\mathcal{D})$, is computed from:

$$D_s(\mathcal{D}) = \sum_{i=1}^{\mathcal{D}} i \cdot q_i. \tag{7}$$

This scheme guarantees that the location probability of each PA is in 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.

C. *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 $PA_u^*(1, q_1, n_1)$, $PA_u^*(2, q_2, n_2)$, $\cdots$, $PA_u^*(\mathcal{D}, q_{\mathcal{D}}, n_{\mathcal{D}})$. Note that there are n_0 cells in each of the first $(\mathcal{D} - k)$ 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 $1 \leq i \leq \mathcal{D} - k$, $PA_u^*(i, q_i, n_i)$ consists of n_0 cells ranging from the $[(i-1)n_0 + 1]^{th}$ cell to the $[n_0 \cdot i]^{th}$ cell as in the initial paging sequence. If $\mathcal{D} - k + 1 \leq i \leq \mathcal{D}$, the i^{th} 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 $PA_u^*(i, q_i, n_i)$, q_i, is obtained by:

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

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

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

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

IV. Numerical Results

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 I.

A. *Paging Costs and Delays 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]. Fig. 2 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 Fig. 2 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, the semi-reverse and uniform paging schemes cause the minimum paging costs which are the same as the theoretical result from HPF scheme.

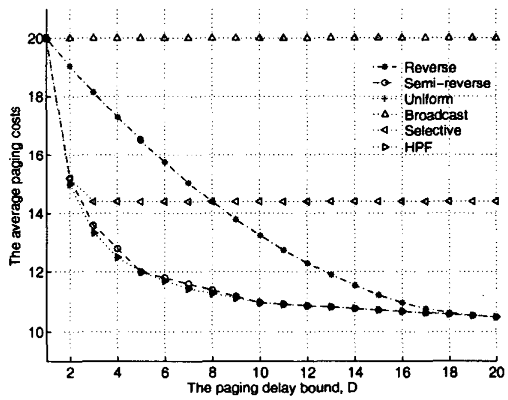

Fig. 2. The Average Paging Costs for Uniform Distribution.

The average paging delays are also investigated and the results are shown in Fig. 3. 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.

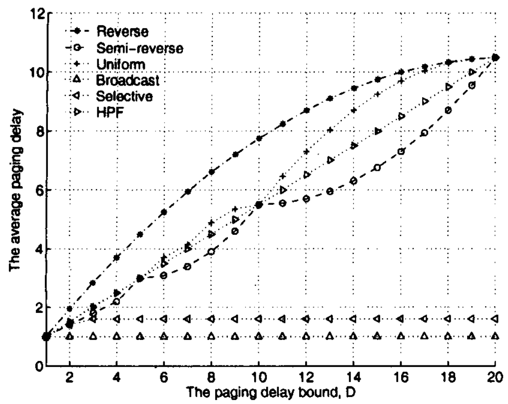

Fig. 3. The Average Paging Delays for Uniform Distribution.

B. *Paging Costs and Delays for Truncated Gaussian Distribution*

We demonstrate the average paging costs and delays of reverse, semi-reverse, uniform, selective paging and broadcast schemes for truncated discrete Gaussian distribution with mean zero and variance one. The HPF scheme is not considered because a non-increasing probability density function $g(x)$ must be found, which is comparable to the non-increasing discrete distribution. However, finding the optimal solution to the function $g(x)$ is not fully researched and is not provided in this paper.

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 when compared to selective scheme. We can also see that the uniform paging scheme provides lower paging costs when $\mathcal{D} \leq 4$, 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 Fig. 5. 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 $\mathcal{D} = 12$ for uniform scheme. Another observation is the "stair-step" curve which is induced by using uniform paging scheme. Under this scheme, the floor number of n_0 is calculated during the procedure of uniform paging. For example, $n_0 = \lfloor N/\mathcal{D} \rfloor$ is equal to 2 for $N = 20$ and $\mathcal{D} = 7$ to 10 in Eq. (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 Fig. 5, and the average

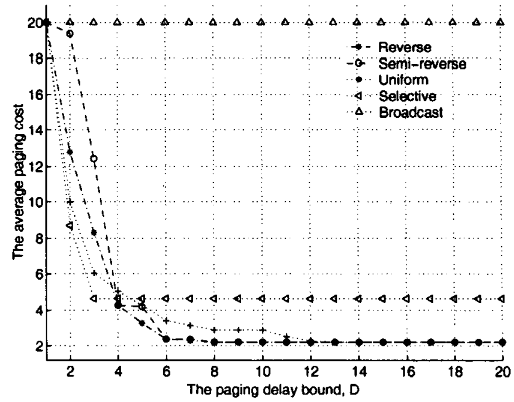

Fig. 4. The Average Paging Costs for Truncated Discrete Gaussian Distribution.

paging delay remains the same after $\mathcal{D} = 12$. The results from both paging costs and delays demonstrate that the most suitable paging scheme for the truncated discrete Gaussian distribution is the uniform paging.

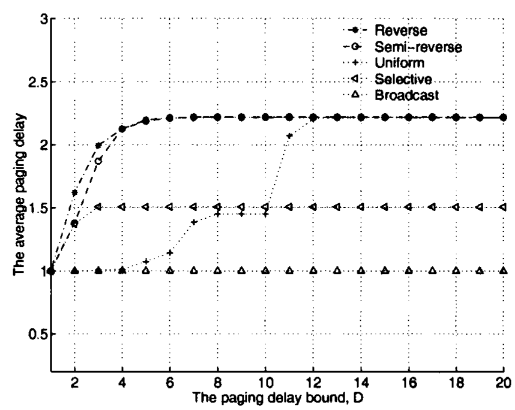

Fig. 5. The Average Paging Delays for Truncated Discrete Gaussian Distribution.

C. *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. Two irregular distribution cases created randomly are considered in Table 1.

The average paging costs and paging delays for delay bound $\mathcal{D} = 3, 4, 5$, and the details of each PA, such as the paging sequence, the location probabilities, and the number of cells are shown in Fig. 6. The minimum average paging costs are indicated in bold and the minimum average paging delays of case A and B are indicated in italics in Fig. 6 and Fig 7, respectively. For case A, 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 $\mathcal{D} = 5$,

TABLE I
THE INITIAL LOCATION PROBABILITIES.

Page Area	Sequence Number j	Location Probability p_j		Number of Cells
		Case A	Case B	
PA_1	1	0.36	0.28	1
PA_2	2	0.31	0.26	1
PA_3	3	0.05	0.08	1
PA_4	4	0.05	0.08	1
PA_5	5	0.045	0.05	1
PA_6	6	0.045	0.05	1
PA_7	7	0.04	0.05	1
PA_8	8	0.04	0.05	1
PA_9	9	0.03	0.05	1
PA_{10}	10	0.03	0.05	1

the semi-reverse and uniform schemes cause the same values of the average paging cost, even though the partitions are different. The uniform paging causes less paging delays than the semi-reverse paging does. For case B, the uniform and selec-

Delay Bound \ Paging Scheme \ PAs		PA (i, q_i, n_i)	Average Paging Cost	Average 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
$\mathcal{D} = 4$	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*
$\mathcal{D} = 5$	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*
Broadcast		(1, 1, 10)	10	1.0

Fig. 6. The Average Paging Costs and Paging Delays of Case A.

tive scheme produce minimum paging costs and delays when the delay bound $\mathcal{D}$ is equal to 3. The uniform paging results in the minimum paging costs for both $\mathcal{D} = 4$ and 5. We also notice that the average paging costs obtained by semi-reverse scheme are very close to the values resulted from uniform scheme when $\mathcal{D}$ is 4 and 5. With some other experiments, we conclude that semi-reverse and uniform paging schemes are suitable for irregular location probability distributions.

V. CONCLUSIONS

In this paper, we introduced three paging schemes for the PCS networks which are applicable to different location probability distributions. All of them are very simple to implement and are able to reduce the paging costs significantly under paging delay bound. Our simulation results demonstrate that the semi-reverse paging is the most suitable scheme for the uniform distribution when both the average paging costs and delay performance are taken into account. For the truncated discrete Gaussian distribution, reverse and uniform paging schemes are applicable; especially, reverse paging scheme results in minimum paging costs after a certain value of delay bound. When the location probability is irregular, which is not considered in many paging schemes before, our proposed schemes such as semi-reverse and uniform paging are still applicable to reduce the paging costs. In conclusion, these new schemes provide a scalable paging method for various cases in actual PCS networks.

Delay Bound \ Paging Scheme \ PAs		PA (i, q_i, n_i)	Average PagingCost	Average 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, 8); (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*
$\mathcal{D} = 4$	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*
$\mathcal{D} = 5$	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*
Broadcast		(1, 1, 10)	10	1.0

Fig. 7. The Average Paging Costs and Paging Delays of Case B.

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