Performance Analysis of Blanket Paging, Sequential Probability Paging, and Pipeline Probability Paging for Wireless Systems

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***Abstract*—Most paging schemes are considered on a per-user basis, i.e., when an incoming call arrives to a mobile terminal (MT), a paging request (PR) is put in a queue in mobile switching center, and PRs are served in a first-in first-out manner. In this paper, we propose a simplified pipeline probability paging (PPP) scheme, which handles PRs in a pipeline manner with a paging delay constraint under the condition of known knowledge on location probabilities of individual MTs. We then provide a performance evaluation and comparison for blanket paging scheme, sequential probability paging, and PPP in wireless networks. Both analytical models and extensive simulations are adopted to study these schemes.**

***Index Terms*—Concurrent, paging, parallel, performance evaluation, pipeline, wireless systems.**

I. Introduction

EXISTING personal communication service (PCS) networks adopt the Blanket-Paging (BP) scheme, in which, when an incoming call arrives at a location area (LA), all cells in the LA are paged. Such a scheme wastes significant bandwidth. Therefore, many sequential probability paging (SPP) schemes were proposed to reduce the paging cost [1]–[6], in which, when an incoming call arrives to a mobile terminal (MT), the associated LA is divided into several paging areas (PAs), which are paged one by one until the MT is found, with known knowledge of location probabilities of MTs. However, in all these schemes, the paging process is considered on a per-user basis to explore the best paging strategy for a particular user to reduce paging delay or other system cost. In addition, paging requests (PRs) for different MTs are served on a first-in first-out (FIFO) manner. Therefore, they introduce extra and unnecessary delay due to the fact that, during each paging cycle, unpaged cells may be idle and unused in terms of paging. In reality, many MTs can be paged simultaneously [8]. For most of the proposed SPP schemes in the literature, paging multiple users in parallel may not be possible due to conflicts, such as different PAs or different paging sequences for different users. In other words, due to the per-user basis in the sense that each PR is handled independently, PAs for one PR may conflict with PAs for another PR. Ensemble-paging algorithms [7]–[11] have been proposed to improve system performance. In [7], a group-paging scheme (or batch paging), which is adapted from a single MT paging method, provides the grouping of k most likely cells to be paged for each PR in each paging cycle, assuming known knowledge on location probabilities of individual MTs. In [8], the ensemble paging is conducted on a per-cell basis, in which the distance between a cell and the last known cell where an MT stays is used as a priority to put a PR into the priority PR queue of the cell. In [11], concurrent paging for a group of k PRs is considered on a per-cell basis, in which the location probability of an MT is used as a priority to put a PR into the priority PR queue of the cell, and the concurrent paging is also a group-paging scheme. However, in the group-paging schemes [7], [11], the paging process is considered on a per-group basis in exploring the best paging strategy per group but ignores other PRs that are not in the current group but are in the queue. We proposed a simple parallel shuffled paging (PSP) scheme in [9] and a pipeline-paging (PP) scheme in [10] under a paging delay constraint. In the PP scheme, multiple PRs are paged in a pipeline manner in different PAs. In the PSP, all PAs are shuffled to avoid paging a PA twice for a PR. However, both the PSP and PP schemes do not utilize the known knowledge of location probabilities of MTs. In [12], we proposed a pipeline probability paging (PPP) scheme that handles PRs in a pipeline manner with a paging delay constraint under the condition of known knowledge on location probabilities of individual MTs. However, in [12], we did not provide a comprehensive evaluation due to limited space, and the scheme in [12] is pretty complex. In this paper, we propose a simplified PPP scheme, and we provide a comprehensive performance evaluation for the PPP scheme. We study and compare the SPP, BP, and PPP schemes in terms of discovery rate, paging cost, paging delay, total delay, maximum discovery rate, and domain, which are defined in a later section.

One advantage of a group-paging scheme in [7] and [11] is that it is easy to derive analytical models. However, since the group-paging scheme is a per group basis scheme, it ignores other PRs that are not in the current group but are in the queue. The proposed pipeline-paging scheme is better than the group-paging approach in terms of the concept of pipeline.

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TABLE I
COMPARISON OF GROUP-PAGING AND PIPELINE-PAGING SCHEMES

Cycle	1	2	3
Paging Requests	P_1, P_2	P_3, P_4	
Group Paging [7]	P_1, P_2	P_1, P_2	P_2
Pipeline Paging	P_1, P_2	P_1, P_2, P_3, P_4	P_2, P_4

The group-paging approach considers paging multiple PRs each time as a group. In other words, it considers one group at a time but does not consider other PRs waiting in the queue, and therefore, we call it batch paging, which cannot achieve pipelining. In the proposed pipeline paging, as long as there is an empty PA, the PR will be served. On the other hand, a PA in the group-paging scheme must wait until the previous group finishes before the next group is served. The contributions of this paper also include providing a different scheme other than the group paging [7], [11], as well as providing a very good performance analysis, which provides some deep understanding of the schemes.

Table I shows the comparison of the group-paging [7], [11] and pipeline-paging schemes. Assume that there are four cells, and each PA has one cell, i.e., $D = 4$. PRs P_1 and P_2 arrive in cycle 1 and are served by both the group-paging and pipeline-paging schemes; At cycle 2, when PRs P_3 and P_4 arrive, for the group-paging scheme, P_3 and P_4 must wait in the queue, whereas for the pipeline-paging scheme, P_3 and P_4 can be served. Assume that P_1 and P_2 cannot be all found in the cycle 2. At cycle 3, the group-paging scheme still cannot serve P_3 and P_4 since it is a batch paging. On the other hand, for the pipeline paging, P_3 and P_4 do not need to wait and can be served in both cycles 2 and 3.

This paper is organized as follows: Section I introduces these paging schemes, including the proposed simplified PPP scheme. Section II provides a mathematical analysis. Performance evaluation is provided in Section III. Finally, we conclude and discuss the results in Section IV.

II. PAGING SCHEMES

In current PCS networks, a service area is partitioned into LAs. Within each LA, there are a number of cells. In each cell, there are a base station (BS) and many MTs. All the BSs within one LA are connected to a mobile switching center (MSC). All the MSCs are finally connected to public switching telephone networks. Location management includes two basic operations: location update and paging. Location update is a procedure used to determine the current location of an MT in terms of the area such as an LA or a PA. Paging is a search process conducted in a PA to locate the MT in terms of a cell. A PA may include one or more cells and is normally a subset of an LA.

A. Blanket Paging (BP)

Existing systems use the BP scheme, in which, when an incoming call arrives, all cells in an LA are paged. In other words, the PA is the same as the LA. Such a scheme wastes significant bandwidth. Advantages of this scheme are easy to use and reasonably fast.

B. Sequential Probability Paging (SPP)

Many sequential paging (SP) schemes were proposed to reduce the paging cost. In an SP scheme, when an incoming call arrives to an MT, the associated LA is divided into several PAs, which are paged one by one until the MT is found. An SPP scheme is similar to an SP scheme, except for the way of dividing the LA into PAs using known knowledge on location probabilities of individual MTs.

C. Pipeline Probability Paging (PPP)

In [12], we proposed a nonblocking PPP scheme with known knowledge on location probabilities of individual MTs. In this section, we briefly introduce the PPP scheme, and then, in the next section, we propose a simplified PPP scheme. Blocking is defined as the case that during one paging cycle, a PR being served still has unpaged PAs, and the corresponding MT has not been found yet, but all the unpaged PAs were occupied by other PRs. Let D denote the paging delay bound. To remove some of the blocking cases, an LA is divided into D PAs with relatively the same size independent of individual MTs.

A PSP scheme [9] is a special example of the PP scheme [10]. The PP scheme does not assume known knowledge on location probabilities of individual MTs. An LA is divided into fixed PAs for all MTs, and multiple MTs can be paged in parallel. For the rest of this paper, we assume that there are L paging channels in each cell, where $L \leq 1$.

All the PRs are queued and served in the MSC under the FIFO discipline. Similar to the SPP scheme, for each served PR, PAs are paged one by one (each PA per paging cycle) until the MT is found or all PAs are paged. In contrast to the SPP scheme, in the PP scheme, up to $D \times L$ PRs can be served in parallel during one paging cycle. For the case $L = 1$, up to D PRs can be paged in different PAs in parallel. In the next paging cycle, those PRs whose corresponding MTs were found or all PAs that had been paged will be removed, new PRs in the queue will be added, and up to $D \times L$ PRs (including both old ones and new ones) can be served in parallel. The algorithm is homogenous in the sense that no matter how many PRs are being served, the algorithm is the same.

When a PR arrives, it is put into the waiting queue and will be served in FIFO manner. Assume that there are N cells in an LA. Let $p(i, j)$ denote the location probability that the corresponding MT-i of the PR-i is in the cell j, where $1 \leq i \leq n$ and $1 \leq j \leq N$, where n is the number of MTs in the cell. Let $\Pr(i, k)$ denote the location probability that the MT-i is in the PA-k, where $1 \leq k \leq D$. We have

$$\Pr(i, k) = \sum_{j \in \mathrm{PA}_k} p(i, j). \tag{1}$$

Based on $\Pr(i, k)$, the MT-i can choose its PA for each paging cycle. For the rest of this paper, we do not distinguish a PR and its corresponding MT, and we will use them interchangeably for convenience of the presentation. We assume that $L = 1$. Algorithms and analysis can be easily applied to the case of $L > 1$.

Define a serving list as an ordered list of PRs being served. The order of the list is based on the arrival time of PRs:

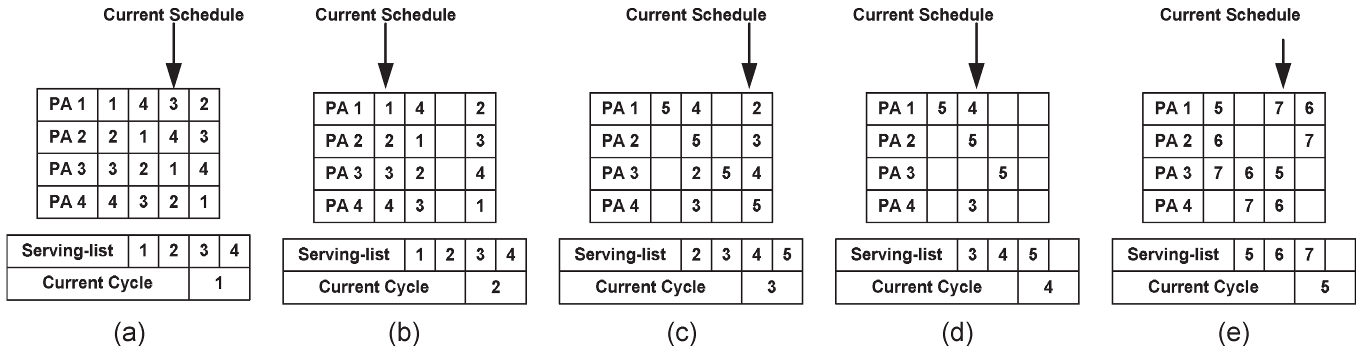

Fig. 1. Simplified PPP scheme. (a) PSM at the cycle 1. (b) Based on (a), one cycle is advanced. (c) Based on (b), one cycle is advanced, PR-1 is found and removed, and PR-5 is added and placed at PR-1's position. (d) Based on (c), one cycle is advanced, PR-2 is found and removed, and there is no new PR. (e) Based on (d), one cycle is advanced, PR-3 and PR-4 are found and removed, and PR-6 and PR-7 are added.

An earlier PR is nearer to the front. A PR being served will not be removed from the serving list until the corresponding MT is found or all the PAs have been paged [12]. The first one in the serving list is important and is called Head.

At the beginning of a paging cycle t, denote the PRs in the serving list from front to end with $n(t,1), n(t,2), n(t,3), \ldots, n(t, m(t))$, where $m(t)$ is the number of PRs in the serving list, and $0 \leq m(t) \leq D$. A PA schedule $S(t,j)$ is defined as a scheduled PR at the paging cycle t and the PA-j. All the PA schedules at the paging cycle t form a cycle schedule, i.e., $\{S(t,j); 1 \leq j \leq D\}$. A moving pipeline schedule table (MPST) at the paging cycle t includes D consecutive cycle schedules. An MPST can move/advance with paging cycles. An MPST can be denoted as $\{S(c,j); 1 \leq j \leq D, t \leq c \leq t + D - 1\}$ and a current paging cycle t, where j stands for PA-j, and c stands for the paging cycle c. Therefore, an MPST is a $D \times D$ matrix.

To avoid blocking, our solution is to use only $n(t,1)$'s probability information but not $n(t,i)$'s, where $m(t) \geq i > 1$. The idea is that $n(t,1)$ selects its PA list by probabilities, i.e., PAs with higher probabilities will be scheduled earlier, and then, other PRs in the serving list will follow the PP approach. Although only $n(t,1)$ uses location probabilities, we showed in [12] that, on average, there are more than one among $m(t)$ using location probabilities if $m(t) > 1$. In the case where $m(t) = 1$, all PRs use location probabilities. The difficulty is to decide how to schedule after a PR is removed. If $n(t,1)$ is removed at the paging cycle t', the new $n(t',1)$ may have some PAs paged and some PAs unpaged. Paged PAs' probabilities are set to be zero, and $n(t',1)$ may be needed to reschedule unpaged PAs according to its probabilities. In order to avoid blocking, others $n(t',i)$ $(m(t') \geq i > 1)$ should do corresponding changes. The $n(t',1)$'s new schedule can be achieved by many pair exchanges. To avoid blocking, whenever $n(t',1)$ does a pair exchange, others $n(t',i)$ $(m(t') \geq i > 1)$ should perform a corresponding pair exchange. These are achieved by column exchanges. We can easily prove that after such pair exchanges, there is no blocking [12].

To avoid blocking, we define a concept called marked pipe (MP) [12]. An MP is a series of marked PA schedules with the following attributes: 1) There is one PA schedule per paging cycle, and 2) there are no two the same PA schedules within D consecutive cycles. There are a total of D MPs, i.e., MP-1, MP$-2, \ldots,$ and MP$-D$. The MPs are closely related to the MPST: 1) When the MPST advances a cycle, the MPs also advance a cycle, and 2) when the MPST exchanges two columns, the MPs perform corresponding columns' exchange [12].

D. Simplified PPP

We propose a simplified scheme as follows. In the previous discussion about the scheme in [12], each cycle schedule is associated with one cycle, and there are a total of D cycle schedules used each time. In other words, there are $D - 1$ additional cycle schedules that are settled beforehand, unless there are PRs added or removed from the serving list. In these cases, the prescheduled $D - 1$ cycle schedules are subjected to change. In the following approach, future paging will not be scheduled. The approach is illustrated in Fig. 1 in which five cycles are shown. Define a potential schedule matrix (PSM) as $E(i,j)$, where $1 \leq i \leq D$, and $1 \leq j \leq D$. An example of PSM is shown in Fig. 1(a), in which each column of the PSM is a potential schedule. Define a current schedule pointer (CSP) as a pointer to a column of the PSM. The initial PSM is just a PSP schedule shown in Fig. 1(a). Assume that $\Pr(1,3) \geq \Pr(1,1) \geq \Pr(1,2) \geq \Pr(1,4)$ holds. Fig. 1(a) shows that the Head is PR-1, and based on location probabilities of PR-1, PA3 should be paged first so that the CSP is pointed to column 3. When paging is performed, the schedule at the CSP is performed. Based on that in Fig. 1(a), Fig. 1(b) shows the result of advancing one paging cycle, finding no users and setting the CSP to the first column based on PR-1's location probabilities. The paged PA's location probabilities are set to zeros. Based on Fig. 1(b), Fig. 1(c) shows the result of the following operations: 1) One paging cycle is advanced; 2) PR-1 is found and removed; 3) PR-5 is added in PR-1's positions; and 4) based on the new Head (PR-2)'s location probabilities, PA-1 should be paged first for the Head so that the CSP is set to column 4. A new PR can be added if a PR is removed from the serving list and the PSM and if there is an available PR in the waiting queue. Based on Fig. 1(c), Fig. 1(d) shows the result of the following operations: 1) One paging cycle is advanced; 2) PR-2 is found and removed; and 3) based on the new Head (PR-3)'s location probabilities, PA-4 should be paged first for the Head so that the CSP is set to column 2. Based on Fig. 1(d), Fig. 1(e) shows the result of the following operations: 1) One paging cycle is advanced; 2) PR-3 and PR-4 are found and removed; 3) PR-6 and PR-7 are added in PR-2 and PR-3's positions, respectively; and 4) based on the new Head (PR-5)'s location probabilities, PA-3 should be paged first for the Head so that the CSP is set to column 3. A detailed algorithm is omitted due to limited space.

III. Analytical Models

The performance metrics are defined as follows: Discovery rate (DR) is defined as the departure rate of PRs on average; cost (C) is defined as the number of cells paged per PR on average; paging delay ($\overline{D}$) (also called the service time) is defined as the time period between a PR's time of being served and the PR's departure time on average, where the PR's departure time is defined as the time when either the corresponding MT is found or all the PAs have been paged for this PR; and total delay (T) is defined as the time period between a PR's arrival time and the PR's departure time on average. Discovery rate is also treated as throughput of the paging system, and total delay includes both queuing delay and paging delay. Maximum discovery rate (MD_R) is defined as the maximum discovery rate when the traffic load is very large; domain (Domain) of a paging scheme is defined as the traffic load range that allows the total delay of the scheme to have a finite value when the system reaches a stable state.

We adopt the total delay as one of the performance metrics instead of the paging delay since the total delay is a more accurate metric for delay. We assume that PAs have relatively the same size in our evaluations, all corresponding MTs are inside the LA, and their mobile phones are ON. We further assume that each PR is for a different user. In other words, the busy-paging and busy-line effects are not considered. The busy paging is defined as a PR being served while another PR for the same user is also being served. The busy line is defined as a PR being served while its user has an ongoing call. We assume that PR arrival rate follows a Poisson distribution with rate λ, and the paging cycle defined in the previous section follows an exponential distribution with rate m ($\lambda < \mu$). It is clear that the service time is independent of the PR arrival process and the paging service time (per paging cycle). The exponential distribution is adopted in [3]–[5] and [10] to model the paging service time. We further assume that the queue length is infinite.

For an M/G/1 queuing system (arrival rate λ, mean service time $1/\mu$, and variance σ), the total delay is given as (2) [13]. Without losing generality, assume that the current PR of the SPP scheme or the Head of the PPP scheme is PR-1. Let $\Pr(1,i)$ ($i \le i \le D$) denote the PR-1's location probability in PA-i. Without losing generality, we can also assume that $\Pr(1,i) \ge \Pr(1,j)$ (if $i < j$). Under the above assumption, we define an important performance metric m as (3), shown below:

$$T_{\mathrm{M/G/1}}\left(\frac{1}{\mu}, \sigma^2\right) = \frac{1}{\mu} + \frac{\frac{\lambda}{\mu}(1+\sigma^2\mu^2)}{2(\mu-\lambda)} \tag{2}$$

$$m = \sum_{i=1}^{D} i \Pr(1,i) \tag{3}$$

$$\sum_{i=1}^{D} \Pr(1,i) = 1. \tag{4}$$

In later sections, we show that the metric m characterizes some useful features of the location distribution. We refer to m as the location probability factor. The metric m has some features, and we can easily prove the following Lemma.

Lemma 1: If we assume that $\Pr(1,i) \ge \Pr(1,j) \ge 0$ (if $i < j$) and $\sum_{i=1}^{D} \Pr(1,i) = 1$, the following equations hold:

$$\Pr(1,D) \le \frac{1}{D} \tag{5}$$

$$\sum_{i=1}^{k} \Pr(1,i) \ge \frac{k}{D} (k = 1, \ldots, D) \tag{6}$$

$$1 \le m = \sum_{i=1}^{D} i \Pr(1,i) \le \frac{D+1}{2}. \tag{7}$$

Proof: Since $\Pr(1,1) \ge \Pr(1,2) \ge \cdots \ge \Pr(1,D)$ and $\sum_{i=1}^{D} \Pr(1,i) = 1$, we have (5). Otherwise, assume that $\Pr(1,D) > (1/D)$, and then, we have $\sum_{i=1}^{D} \Pr(1,i) \ge \sum_{i=1}^{D} \Pr(1,D) > \sum_{i=1}^{D} (1/D) = 1$, which is a contradiction! Therefore, we have (5).

$$\begin{aligned}
&\sum_{i=1}^{k} \Pr(1,i) \\
&\quad = \frac{k\left[\sum_{i=1}^{k} \Pr(1,i)\right] + \sum_{i=1}^{k} (D-k)\Pr(1,i)}{D} \\
&\quad \ge \frac{k\left[\sum_{i=1}^{k} \Pr(1,i)\right] + \sum_{i=1}^{k} \sum_{j=k+1}^{D} \Pr(1,j)}{D} \\
&\quad = \frac{k\left[\sum_{i=1}^{k} \Pr(1,i) + \sum_{j=k+1}^{D} \Pr(1,j)\right]}{D} \\
&\quad = \frac{k\left[\sum_{i=1}^{D} \Pr(1,i)\right]}{D} = \frac{k}{D}
\end{aligned}$$

$$\begin{aligned}
&\sum_{i=1}^{D} i \Pr(1,i) - \frac{D+1}{2} \\
&\quad = \sum_{i=1}^{D} i \left[\Pr(1,i) - \frac{1}{D}\right] \\
&\quad = \left[\Pr(1,1) - \frac{1}{D}\right] + \sum_{i=2}^{D} i \left[\Pr(1,i) - \frac{1}{D}\right] \\
&\quad \le 2\left[\Pr(1,1) - \frac{1}{D}\right] + \sum_{i=2}^{D} i \left[\Pr(1,i) - \frac{1}{D}\right] \text{ by (6)} \\
&\quad = 2\left[\sum_{i=1}^{2} \Pr(1,i) - \frac{2}{D}\right] + \sum_{i=3}^{D} i \left[\Pr(1,i) - \frac{1}{D}\right] \\
&\quad \le 3\left[\sum_{i=1}^{2} \Pr(1,i) - \frac{2}{D}\right] + \sum_{i=3}^{D} i \left[\Pr(1,i) - \frac{1}{D}\right] \text{ by (6)} \\
&\quad \ldots
\end{aligned}$$

$$= (D-1)\left[\sum_{i=1}^{D-1}\Pr(1,i)-\frac{D-1}{D}\right]+D\left[\Pr(1,D)-\frac{1}{D}\right]$$

$$\leq D\left[\sum_{i=1}^{D}\Pr(1,i)-\frac{D}{D}\right] \text{ by } (6)=0.$$

■

From Lemma 1, the minimum value of m is 1, and the maximum value of m is $(D+1)/2$. The SPP and PPP schemes will have better performance if m has a smaller value and is changing from 1.0 to $(D+1)/2$. When $m=1$, we have $\{\Pr(1,1),\ldots,\Pr(1,D)\}=\{1,0,\ldots,0\}$, in which case, we know for sure that the MT is in a particular PA, and the MT can be found in one paging cycle. On the other hand, when $m=(D+1)/2$, we have $\{\Pr(1,1),\ldots,\Pr(1,D)\}=\{1/D,\ldots,1/D\}$, in which case, we have the worst performance, and this is equivalent to the case in which the location probabilities are not available. Therefore, we will adopt m as one of the parameters in evaluating the paging schemes.

A. BP Scheme

Let $I(e)$ denote the indication function that returns 1 if e is true; otherwise, it returns 0. The paging system for the BP scheme can be modeled with an M/M/1 queue, and we have

$$\overline{D}^{\mathrm{BP}} = 1/\mu \tag{8}$$

$$T^{\mathrm{BP}} = [1/(\mu-\lambda)]\, I(\lambda<\mu)+\infty\times I(\lambda\geq\mu) \tag{9}$$

$$D_R^{\mathrm{BP}} = \lambda I(\lambda<\mu)+\mu I(\lambda\geq\mu) \tag{10}$$

$$C^{\mathrm{BP}} = N \tag{11}$$

$$\mathrm{Domain}^{\mathrm{BP}} = \{\lambda|\lambda/\mu<1\} \tag{12}$$

$$\mathrm{MD}_R^{\mathrm{BP}} = \mu. \tag{13}$$

B. SPP Scheme

We assume that PAs in the SPP scheme are fixed in this analysis. For the SPP scheme, the location probability information is useful, and m equals to the number of paging cycles needed per MT, on average. In other words, under the assumption of $\Pr(1,i)\geq\Pr(1,j)$ if $(i<j)$, a PR needs to go through one waiting queue and m paging stages. We can model the SPP scheme with an M/Em/1 queuing model. The m-stage Erlangian server Em has the mean m/μ and the variance $\sigma^2 = m/\mu^2$. Plugging the mean and the variance into (2), we have

$$T^{\mathrm{SPP}} = \begin{cases} \frac{m}{\mu}+\frac{\lambda m(m+1)}{2\mu(\mu-\lambda m)}, & \lambda m<\mu \\ \infty, & \lambda m\geq\mu \end{cases} \tag{14}$$

$$\overline{D}^{\mathrm{SPP}} = \frac{m}{\mu} \tag{15}$$

$$D_R^{\mathrm{SPP}} = \begin{cases} \lambda, & \lambda m<\mu \\ \frac{\mu}{m}, & \lambda m\geq\mu \end{cases} \tag{16}$$

$$C^{\mathrm{SPP}} = \sum_{i=1}^{D}\Pr(1,i)\sum_{j=1}^{i}\frac{N}{D} = \frac{N}{D}\sum_{i=1}^{D} i\Pr(1,i) = \frac{N}{D}m \tag{17}$$

$$\mathrm{Domain}^{\mathrm{SPP}} = \{\lambda|\lambda/\mu<1/m\} \tag{18}$$

$$\mathrm{MD}_R^{\mathrm{SPP}} = \frac{\mu}{m}. \tag{19}$$

We claim that, in the case when the location distribution is uniform, it is the same as the case when location distribution is unavailable. In other words, the SP is a special case of the SPP scheme when the location distribution is a uniform distribution or the location distribution is unavailable. We have the following Lemma.

Lemma 2: The SPP scheme under a nonuniform location probability distribution is better than that under a uniform location probability distribution in terms of the total delay, the paging delay, the discovery rate, and the cost per PR. In other words, the SPP scheme is better than the SP scheme. Furthermore, the worst performance of the SPP scheme is achieved when under a uniform location probability distribution, i.e., that of the SP scheme.

Proof: Based on the study in [10], we have $\overline{D}^{\mathrm{SP}} = m_1/\mu, C^{\mathrm{SP}} = (N/D)m_1, T^{\mathrm{SP}} = [(m_1/\mu)+(\lambda m_1(m_1+1)/2\mu(\mu-\lambda m_1))]I(\lambda m_1<\mu)+\infty I(\lambda m_1\geq\mu)$, and $D_R^{\mathrm{SP}} = \lambda I(\lambda m<\mu)+(\mu/m)I(\lambda m\geq\mu)$, where a PR needs to go through one queue and m_1 paging stages. From Lemma 1, we have $m\leq m_1$, $\overline{D}^{\mathrm{SPP}}=(m/\mu)\leq(m_1/\mu)=\overline{D}^{\mathrm{SP}}$, $C^{\mathrm{SPP}} = (N/D)m\leq(N/D)m_1=(N/D)((D+1)/2)=C^{\mathrm{SP}}$, and $(\partial T^{\mathrm{SPP}}/\partial m)=(\partial T_{\mathrm{M/G/1}}((m/\mu),(m/\mu^2))/\partial m)=(1/\mu)+(\lambda/2\mu)((2m+1)(\mu-\lambda m)+\lambda(m^2+m)/(\mu-\lambda m))/((\mu-\lambda m)^2)>0$. Therefore, $T_{\mathrm{M/G/1}}((m/\mu),(m/\mu^2))$ is a strictly increasing function of m. Furthermore, we have $m\leq m_1$. Therefore, we have $T^{\mathrm{SPP}}\leq T^{\mathrm{SP}}$ and $D_R^{\mathrm{SPP}}\geq D_R^{\mathrm{SP}}$.

Since the SP scheme is a special case of the SPP scheme when the location distribution is the uniform distribution or location probability information is unavailable, the worst performance is achievable through the SP scheme. ■

From (3)–(19), we can easily have the following Lemma.

Lemma 3: The SPP scheme's maximum discovery rate, cost, and paging delay have the following range:

$$\frac{2\mu}{D+1}\leq\mathrm{MD}_R^{\mathrm{SPP}}\leq\mu \tag{20}$$

$$\frac{N}{D}\leq C^{\mathrm{SPP}}\leq\frac{N}{D}\frac{D+1}{2} \tag{21}$$

$$\frac{1}{\mu}\leq\overline{D}^{\mathrm{SPP}}\leq\frac{D+1}{2\mu}. \tag{22}$$

C. PPP Scheme

In the previous two sections, we provided analytical models for the BP and SPP schemes, respectively. It is very difficult

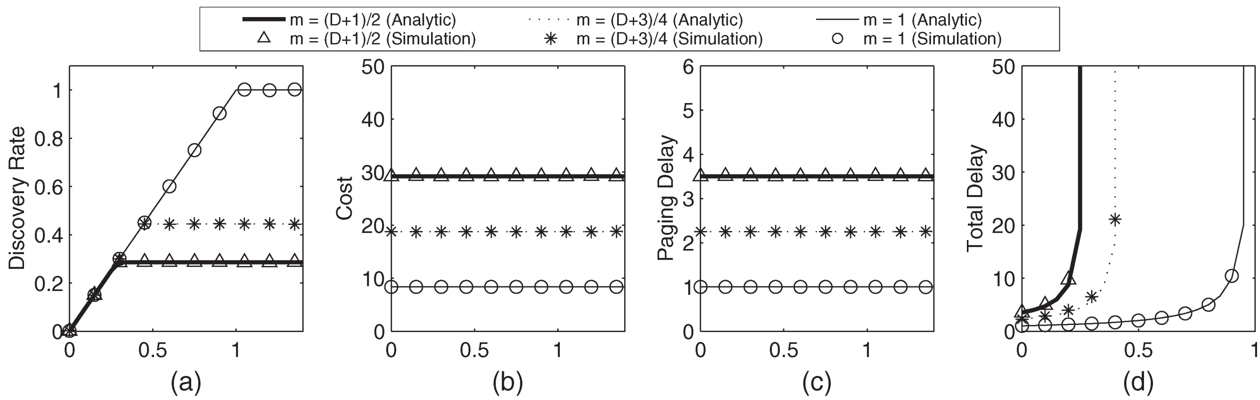

Fig. 2. Metrics over the PR load. (a) Discovery rate versus ρ. (b) Cost versus ρ. (c) Paging delay versus ρ. (d) Total delay versus ρ.

to provide an accurate analytical model for the PPP scheme, i.e., results match simulation results exactly, mostly due to the complexity of the algorithm. Instead of presenting a very rough approximation of the PPP analytical model, we provide simulation studies in the next section since we believe that simulation results are more accurate for the PPP scheme.

IV. Performance Evaluation

In this section, we evaluate the page schemes, the BP scheme, the SPP scheme, and the PPP scheme, with simulations. For the BP and SPP schemes, the simulation results are also compared with the analytical results. In the simulations, we utilize the discrete event simulation approach to implement schemes in C++, and there are two different types of events: call arrival event and PR departure event. The simulation programs generate the call arrival events, and interarrival time follows an exponential distribution with rate λ. The paging cycle length forms an exponential distribution with rate μ.

According to the definitions of the four metrics defined earlier, they are measured as follows: $D_R = N_{\text{total}}(t)/t$, $\overline{D} = L_{\text{total}}(t)/N_{\text{total}}(t)$, and $C = C_{\text{total}}(t)/N_{\text{total}}(t)$, where $N_{\text{total}}(t)$ is the total number of PRs that have departed at the simulation time t, $L_{\text{total}}(t)$ is the total cycle length at the simulation time t, $T_{\text{total}}(t)$ is the total delay, including both the queuing delay and the paging delay at simulation time t, and $C_{\text{total}}(t)$ is the total number of PAs that have been paged at the simulation time t. Let ρ denote the λ/μ, which is the PR load.

In this section, $N = 50$, $\mu = 1$, $D = 6$, $\rho = \{0.1, 0.2, \ldots, 1.0\}$, and $m = \{1, 2, \ldots, (D+1)/2\}$, unless otherwise stated. Note that the range of m is $[1, (D+1)/2]$, where $m = 1$ stands for the case that the user can be found in one paging procedure, and $m = (D+1)/2$ stands for the case that the location probabilities are not available. Sometimes, we adopt a middle point $m = [1 + (D+1)/2]/2 = (D+3)/4$ to evaluate the schemes.

In Sections IV-A and B, we study the SPP and PPP schemes, respectively, using the discovery rate, the cost, the paging delay, and the total delay over the PR load (ρ), the paging delay constraint (D), and the location probability factor m. Finally, we compare the BP, SPP, and PPP schemes in Section IV-C in terms of the discovery rate, the cost, the paging delay, and the total delay over the PR load (ρ), in terms of the maximum discovery rate over the paging delay constraint (D) and the domain over the PR load (ρ).

A. SPP Scheme

In this section, we study the performance of the SPP scheme. Fig. 2 shows the discovery rate, the cost, the paging delay, and the total delay over the PR load (ρ) for the SPP scheme for both simulation results and analytical results. As illustrated in the figures, the simulation results match exactly the analytical counterparts.

In Fig. 2(a), we observe that when ρ increases and is small, the discovery rate increases. However, as ρ reaches some value, the discovery rate becomes flat. This flat value is the maximum discovery rate or capacity of the system. With a smaller location probability factor m value, the system achieves a larger capacity (the maximum discovery rate). For one extreme case, when $m = 1$, the maximum discovery rate is one. Based on (20), the maximum discovery rate has the following range: $2/11 \leq \text{MD}_R^{\text{SPP}} \leq 1$, which is also observed in Fig. 2(a).

In Fig. 2(b), we observe that the cost is independent of ρ, and with a smaller location probability factor m value, the cost is smaller. Based on (21), the cost has the following range: $(50/6) \leq C^{\text{SPP}} \leq (50/6)((6+1)/2)$, which is also observed in Fig. 2(b).

In Fig. 2(c), we observe that the paging delay is independent of ρ, and with a smaller location probability factor m value, the paging delay is smaller. Based on (22), the cost has the following range: $1 \leq \overline{D}^{\text{SPP}} \leq ((6+1)/2) = 3.5$, which is also observed in Fig. 2(c).

In Fig. 2(d), we observe that the total delay increases exponentially as ρ increases, and with a smaller location probability factor m value, the total delay is smaller.

Fig. 3 shows the discovery rate, the cost, the paging delay, and the total delay over the paging delay constraint (D) for the SPP scheme, where $\rho = 0.6$.

In Fig. 3(a), we observe that when $m = 1$, the discovery rate is flat with D. A smaller m value has a larger discovery rate. When $m > 1$ and as D increases, the discovery rate decreases.

In Fig. 3(b), we observe that a smaller m value has a smaller cost. As D increases, the cost decreases.

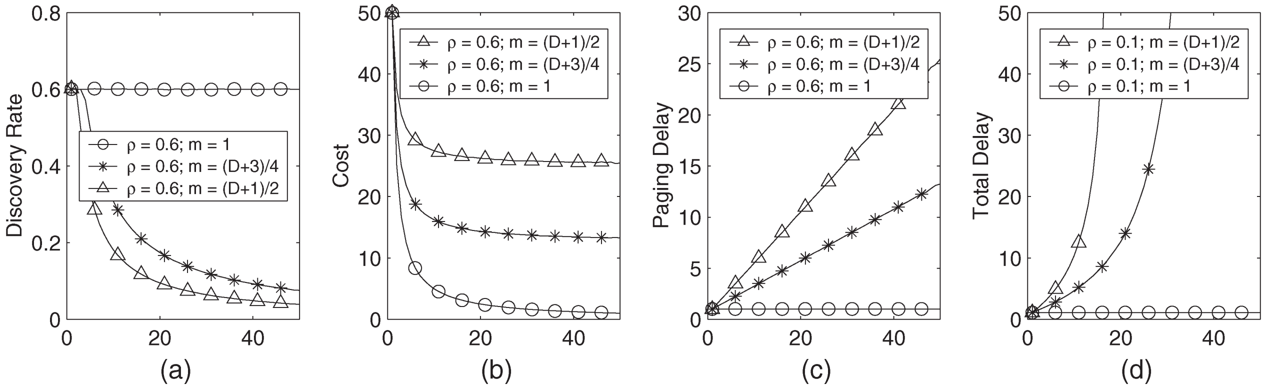

Fig. 3. Metrics over D. (a) Discovery rate versus D. (b) Cost versus D. (c) Paging delay versus D. (d) Total delay versus D.

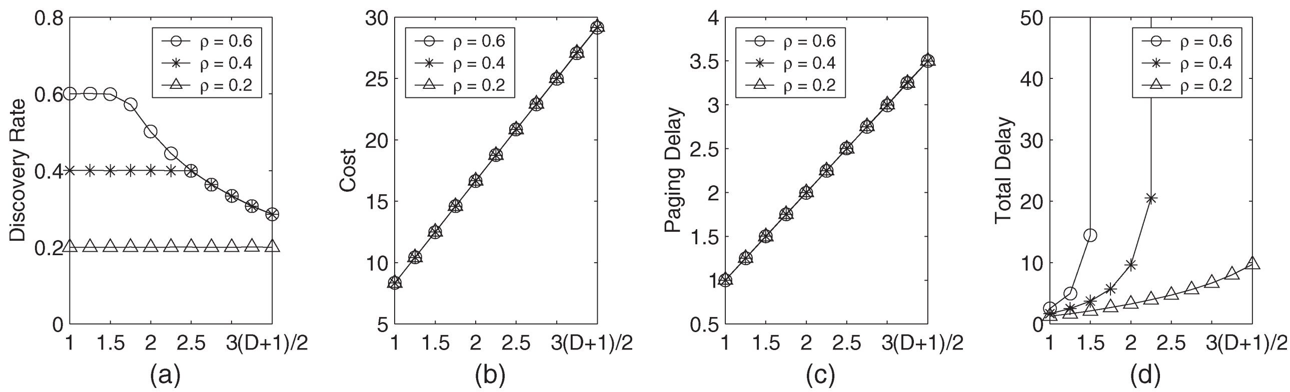

Fig. 4. Metrics over m. (a) Discovery rate versus m. (b) Cost versus m. (c) Paging delay versus m. (d) Total delay versus m.

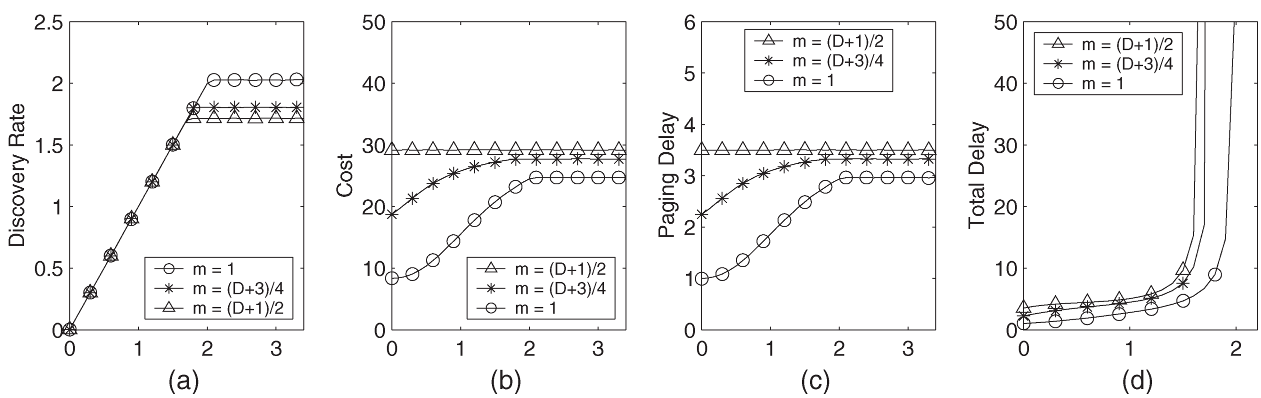

Fig. 5. Metrics over the PR load. (a) Discovery rate versus ρ. (b) Cost versus ρ. (c) Paging delay versus ρ. (d) Total delay versus ρ.

In Fig. 3(c), we observe that when $m = 1$, the paging delay is flat with D. A smaller m value has a smaller paging delay. When $m > 1$ and as D increases, the paging delay increases.

In Fig. 3(d), we observe that when $\rho = 0.1$ and as D increases, the total delay increases exponentially, except when $m = 1.0$; the total delay is flat with D since in this situation, all the PRs find empty PAs all the time so that the queuing delay is zero.

Fig. 4 shows the discovery rate, the cost, the paging delay, and the total delay over the location probability factor (m) for the SPP scheme.

In Fig. 4(a), we observe that with a larger PR load (ρ), the discovery rate is larger. As m increases, the discovery rate is flat at the beginning since under such a PR load, the system is saturated, even when m increases. However, when m is large enough to reach a point so that the paging process slows down due to a large m value, the discovery rate degrades and, therefore, decreases as m increases.

In Fig. 4(b), we observe that the cost increases as m increases, and the PR load has no influence on the cost. In Fig. 4(c), we observe that the page delay increases as m increases, and the PR load has no influence on the paging delay. In Fig. 4(d), we observe that the total delay increases exponentially as m increases, and with a lager PR load, the total delay becomes much larger.

B. PPP Scheme

In this section, we study the performance of the PPP scheme. Fig. 5 shows the discovery rate, the cost, the paging delay, and

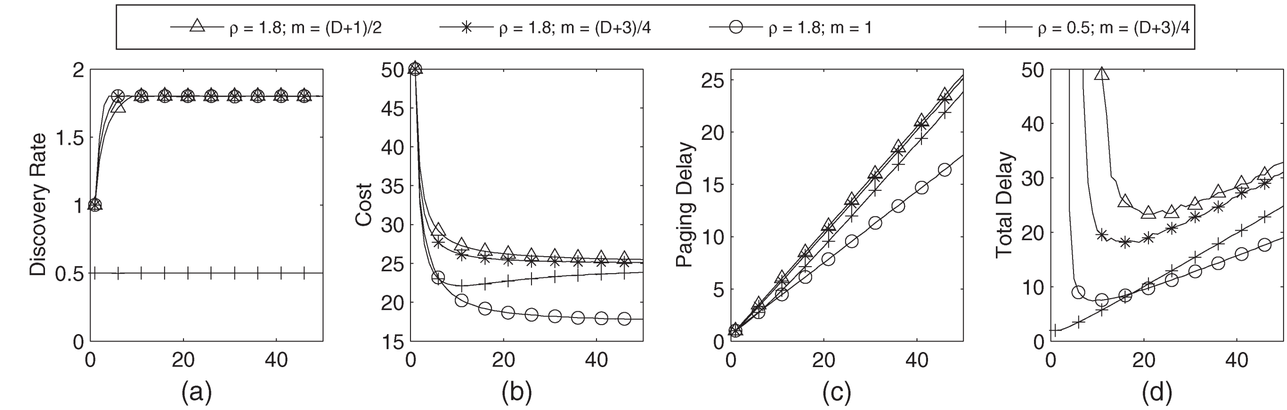

Fig. 6. Metrics over D. (a) Discovery rate versus D. (b) Cost versus D. (c) Paging delay versus D. (d) Total delay versus D.

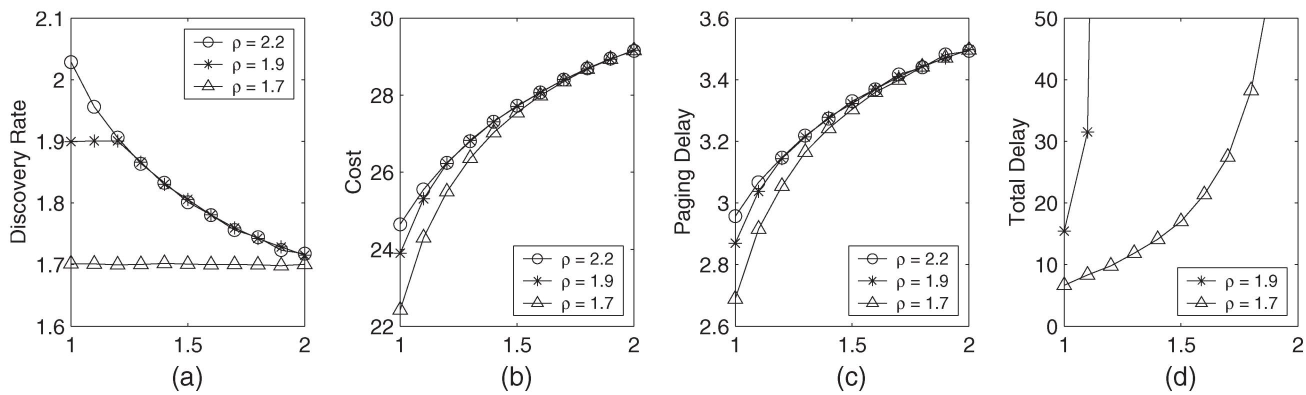

Fig. 7. Metrics over m. (a) Discovery rate versus m. (b) Cost versus m. (c) Paging delay versus m. (d) Total delay versus m.

the total delay over the PR load (ρ) for the PPP scheme with the simulation results.

In Fig. 5(a), we observe that when ρ increases and is small, the discovery rate increases. However, as ρ reaches some value, the discovery rate becomes flat. This flat value is the maximum discovery rate or capacity of the system. With a smaller location probability factor m value, the system achieves a larger capacity (the maximum discovery rate). The results are similar to those for the SPP scheme in Fig. 2(a).

In Fig. 5(b) and (c), we observe that when $m = (D+1)/2$, i.e., the location probabilities are not available, the cost and the paging delay are independent of ρ. With a smaller location probability factor m value, the cost and the paging delay are smaller. However, when $m < (D+1)/2$, the cost and the paging delay increase a little as ρ increases since a larger ρ means that more PRs cannot potentially use location probabilities.

In Fig. 5(d), we observe that the total delay increases exponentially as ρ increases, and with a smaller location probability factor m value, the total delay is smaller.

Fig. 6 shows the discovery rate, the cost, the paging delay, and the total delay over the paging delay constraint (D) for the PPP scheme, where $\rho = 1.8$, except that in Fig. 6(d), another value of ρ is adopted.

In Fig. 6(a), we observe that as D increases, the discovery rate first increases since a larger D value increases the parallel degree so that more PR traffic can be handled, and then, the discovery rate becomes flat since all PR traffic is handled.

In Fig. 6(b), we observe that a smaller m value has a smaller cost. As D increases, the cost decreases. In Fig. 6(c), we observe that a smaller m value has a smaller paging delay. As D increases, the paging cost increases.

In Fig. 6(d), we observe that with a smaller m value, the total delay is smaller. When $\rho = 1.8$ and D is small, the system cannot handle the current PR load so that the total delay is infinite. As D increases, the parallel degree becomes larger, and the system capacity increases, so that the system can handle the PR load, and the total delay decreases. As D increases further, the total delay increases since a larger D value means a little larger number of paging cycles. Therefore, there is an optimal D value noticed in the figure. When $\rho = 0.5$, the total delay increases as D increases since the PR load is very small.

Fig. 7 shows the discovery rate, the cost, the paging delay, and the total delay over the location probability factor (m) for the PPP scheme.

In Fig. 7(a), we observe that, with a larger PR load (ρ), the discovery rate is larger. As m increases, the discovery rate is flat at the beginning since under such a PR load, the system is saturated, even when m increases. However, when m is large enough to reach a point so that the paging process slows down due to a large m value, the discovery rate degrades and, therefore, decreases as m increases. These results are similar to those of the SPP scheme in Fig. 4(a).

In Fig. 7(b) and (c), we observe that the cost and the paging delay increase as m increases, which is different from that in

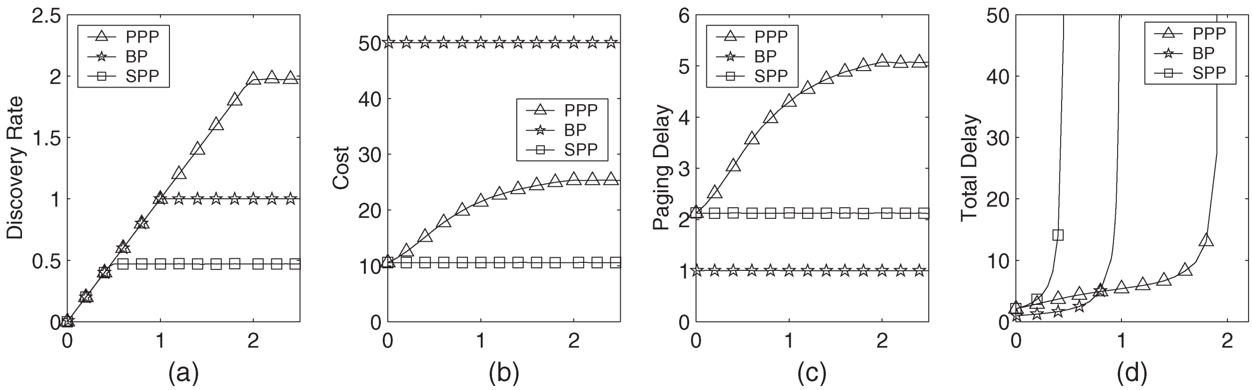

Fig. 8. Metrics over the PR load. (a) Discovery rate versus ρ. (b) Cost versus ρ. (c) Paging delay versus ρ. (d) Total delay versus ρ.

Fig. 5(b) and (c). The PR load does have influence on both the cost and the paging delay, i.e., a larger PR load has a slightly larger cost or paging delay, since a larger PR load means that PRs with a larger percentage cannot use location probabilities.

In Fig. 7(d), we observe that the total delay increases exponentially as m increases, and with a lager PR load, the total delay becomes much longer.

C. Comparisons

In this section, we compare the BP, SPP, and PPP schemes. Fig. 8 shows the comparison of the BP, SPP, and PPP schemes in terms of the discovery rate, the cost, the paging delay, and the total delay over the PR load (ρ) with simulation results, where $D = 10$ and $m = (D + 7)/8$.

In Fig. 8(a), we observe that the PPP scheme has a better discovery rate than the BP scheme, which has a better discovery rate than the SPP scheme.

In Fig. 8(b), we observe that both the PPP and SPP schemes have much lower costs than the BP scheme, and the PPP scheme has a slightly higher cost than the SPP scheme.

In Fig. 8(c), we observe that both the PPP and SPP schemes have larger paging delays than the BP scheme. The PPP scheme has a slightly larger paging delay than the SPP scheme. However, as we stated before, the paging delay is not very important, but the total delay is more important.

In Fig. 8(d), we observe that the PPP scheme always has a better total delay than the SPP scheme. The BP scheme has a better total delay than the PPP scheme when the PR load is small. However, when the PR load is large, the PPP outperforms the BP scheme.

Fig. 9(a) shows the comparison of the BP, SPP, and PPP schemes in terms of the maximum discovery rate over D, where $m = (D + 3)/4$. As illustrated in the figure, the PPP scheme has the best maximum discovery rate, and the SPP scheme has the worst maximum discovery rate among the three schemes.

Fig. 9(b) shows the comparison of the BP, SPP, and PPP schemes in terms of the domain, where $m = (D + 3)/4$. The domain of the SPP scheme is the area A; the domain of the BP scheme is the area $A + B$; and the domain of the PPP scheme is the area $A + B + C$. In other words, the PPP scheme can accommodate the largest PR load, and the SPP scheme can accommodate the least PR load.

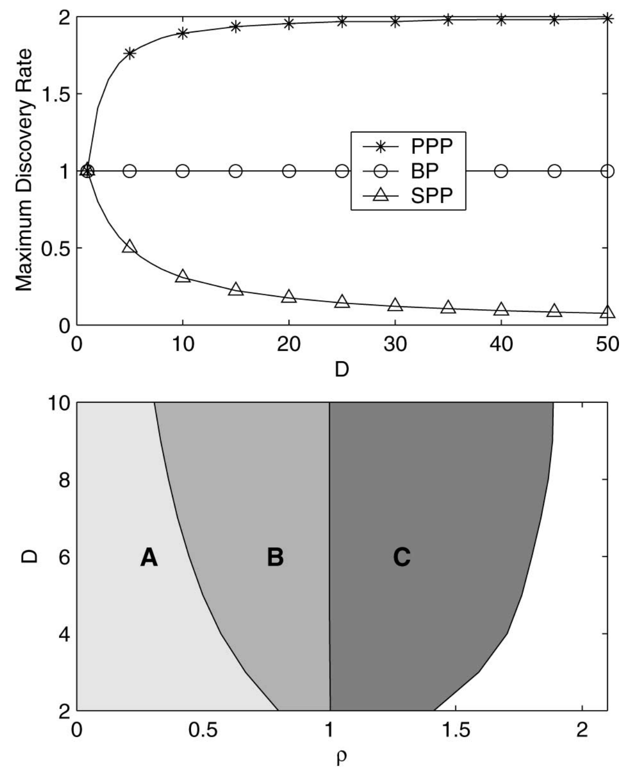

Fig. 9. (a) Maximum discovery rate versus D. (b) Domain versus ρ.

D. Summary of Major Observations

Some observations and results are summarized as follows: Simulation results match exactly the analytical results for the SPP scheme. For both the SPP and PPP schemes, with a smaller location probability factor m value, the system achieves a larger capacity (the maximum discovery rate) but a smaller cost, a smaller paging delay, and a smaller total delay.

For both the SPP and PPP schemes, when the PR load (ρ) increases and is small, the discovery rate increases. However, as ρ reaches some value, the discovery rate becomes flat. The total delay increases exponentially as ρ increases. For the SPP scheme, both the cost and the paging delay are independent of ρ.

For the PPP scheme, when $m = (D + 1)/2$, i.e., the location probabilities are not available, the cost and the paging delay are independent of ρ. However, when $m < (D + 1)/2$, the cost and the paging delay increase a little as ρ increases, since a larger ρ means that more PRs cannot potentially use location probabilities.

For the SPP scheme, when $\rho = 0.1$ and as D increases, the total delay increases exponentially, except when $m = 1.0$, the total delay is flat with D.

For the PPP scheme, as D increases, the discovery rate first increases and then becomes flat. As D increases, the cost decreases, but the paging cost increases. When D is small, the system cannot handle the current PR load so that the total delay is infinite. As D increases, the parallel degree becomes larger, and the system capacity increases so that the system can handle the PR load, and the total delay decreases. As D further increases, the total delay increases since a larger D value means a slight increase in paging cycles. Therefore, there is an optimal D value noticed in these results.

The PPP scheme is the best among three schemes in terms of the discovery rate, the maximum discovery rate, and the domain. The SPP scheme is the worst among the three schemes in terms of the discovery rate, the maximum discovery rate, and the domain. The PPP scheme can accommodate the largest PR load, and the SPP scheme can accommodate the least PR load.

Both the PPP and SPP schemes have much lower costs than the BP scheme, and the PPP scheme has a slightly higher cost than the SPP scheme.

The PPP scheme always has a better total delay than the SPP scheme. The BP scheme has a better total delay than the PPP scheme when the PR load is small. However, when the PR load is large, the PPP outperforms the BP scheme in terms of the total delay.

V. CONCLUSION

In this paper, we proposed a simplified PPP scheme and provided a performance evaluation and comparison for the BP, SPP, and PPP schemes via both analytical models and simulations. The major contribution of this paper is to provide a very good performance evaluation for these three schemes.

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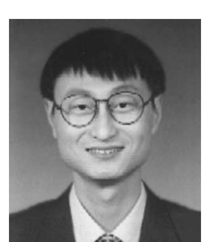

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