Performance of Improved Probabilistic Location Update Scheme for Cellular Mobile Networks

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Abstract—This paper suggests an improved probabilistic location update (IPLU) scheme for advanced cellular mobile networks. The location management cost with IPLU is analyzed, and various performance characteristics of IPLU are investigated. It is shown that IPLU has the parameter $q$ that can be used as a control parameter to achieve the best performance when the unit location update cost ($U$) and the unit paging cost ($P$) are given. In addition, this paper provides some recommendable values of $q$ in two cases, $P > U$ and $P \leq U$. As a result, we demonstrate a merit of IPLU, that is, simple implementation with an acceptable performance level, especially, under the future cellular mobile network environments where a vast number of microcells/picocells exist and the relative user mobility is very high.

Index Terms—Cellular mobile communications, improved probabilistic location update (IPLU), location management, location update, paging, probabilistic decision-making.

I. INTRODUCTION

The next-generation mobile communications networks should provide not only voice and low-speed data services but also multimedia services requiring high data rate to the users of high density. To fulfill these requirements with scarce radio resource, the future networks will adopt a vast number of much smaller cells (microcells/picocells) [1]. In the cellular networks with many microcells/picocells, the moving users change their serving cells more frequently, and thus the relative user mobility becomes much higher than that in the current networks. As well known, one of the key issues in cellular mobile communications is how to deliver incoming calls appropriately to the called user roaming from place to place. In the future mobile communications, this issue (especially, the location tracking or management) will become more important because of high user mobility [2].

Two basic operations of location management in current digital cellular networks (e.g., based on IS-95 [3] and IS-41 [4]) are the paging and the location update. The signaling for finding out the target mobile terminal (MT) is called the paging, which is performed by the network. When an MT termination call is arrived, if all the base stations (BSs) in the network page the target MT, the MT can easily be found. However, since there are many BSs in a network, this strategy results in an excessive paging cost.

To reduce the cost, the concept of location area (LA), which consists of one or more cells, is used (see Fig. 1). The network first pages the LA where the target MT most likely exists. If the network cannot receive the response, it pages other LAs. In this strategy, to increase hit ratio in paging, each MT reports its location to the network when LA changes. The reporting procedure is called the location update. The MT plays a leading role in the location update process, although the network can support MTs (in some location update strategies). Note that a location update is also performed implicitly when a call is set up. Although we use the LA concept, a location update for each LA change is still unnecessary if there will be no MT termination call during residence in the LA. Thus, the main problem in location management is to minimize the total cost, which is the sum of paging and location update cost.

In traditional cellular networks, each MS performs a location update every LA change. That is, an unconditional location update (ULU) strategy has been used. With ULU strategy, the main problem is finding out optimal LA patterns (especially optimal LA size) [5], [6]. This strategy is static in the sense that the LA pattern and size are fixed. The static strategy is based on the assumption of uniform pattern in call arrival rate and in user mobility. However, these parameters are different according to user. Moreover, even for a user, these are time-varying parameters under real situations.

For more effective location management, the dynamic strategies have been studied. The first type of dynamic strategy is to assign explicitly the LA for each MT according to its call arrival rate and mobility level [7], [8].

The second type is the conditional location update (CLU) with fixed LA configuration. When an MT crosses an LA...
boundary, the condition by which it performs location update is varied according to its call arrival rate and mobility level (That is a decision-making problem on carrying out a location update when LA changes.) Therefore, the effective LA pattern is dynamically varied in the CLU method. In this sense, the above two types of strategies are based on a similar concept.

There have been several studies on CLU strategy, including time-based [9], movement-based [9], [10], and distance-based [9], [11]–[13] schemes. In [9], it was shown that the time-based strategy is simplest and the distance-based scheme has the best performance with highest complexity.

In mobile communications, however, the complexity of portable MT should be minimized as far as possible since, for popular use of portable MT, it should consume low power for a light battery, and its implementation cost should be low. This means that the computational overhead in MT should be minimized. In turn, this requires a location update scheme that can be implemented simply due to a leading role of an MT in the location update process. We have proposed a probabilistic location update (PLU) scheme in [14]. The main advantage of the PLU scheme is that it is able to be implemented simply with an acceptable performance level.

However, [14] has not presented diversely the performance characteristics of PLU. Moreover, it is necessary for the PLU scheme to be improved in adaptation speed under the situation that traffic patterns rapidly vary. We in this paper suggest a scheme that does not only improve PLU but also can be implemented simply as much as PLU. Also, we investigate various performance characteristics of the proposed scheme. In order to distinguish the proposed scheme from PLU in [14], we will call it the improved probabilistic location update (IPLU).

The remainder of this paper is organized as follows. The next section describes the IPLU scheme. Section III analyzes the performance of IPLU with Markov chain model, and Section IV presents some numerical results with discussion. Section V compares the performances of IPLU and PLU. Conclusions are offered in Section VI.

II. IMPROVED PROBABILISTIC LOCATION UPDATE

In a PLU scheme, when the LA of an MT is changed, the MT performs a location update with probability p. An MT can use a fixed value of p. A merit of this scheme is its very simple implementation. However, its performance depends heavily on the value of p, and the optimal p varies according to the call arrival rate and the mobility level (i.e., LA change rate). Note that the call arrival rate and the mobility level for an MT are time-varying parameters. Thus, the difficulty in the above scheme is to find out the optimal p for each MT in a given network [14].

To overcome this difficulty, we consider adaptive control of p where p of an MT is adapted to its call arrival rate and LA change rate. However, to estimate the call arrival rate and the LA change rate becomes another overhead to the MT. Therefore, the problem in adaptive control is how to implement it simply. We suggest an implementation based on the concept of exponential backoff scheme in [15].

Let us observe an MT at each LA change. \(c_k\) denotes the duration from \(k\)th LA change to \((k+1)\)st change, where \(k = 0\) represents the initial time. The MS counts the number of termination calls to it between two LA changes. Let \(l_k\) denote this number during \(c_k\), and let \(p_k\) be the value of \(p\) during \(c_k\). Then \(p_{k+1}\) is determined as

\[
p_{k+1} = \begin{cases} \min\{p_k/q_k, 1\}, & \text{if } l_k \geq 1 \\ \max\{q_k/p_k, p_{\min}\}, & \text{if } l_k = 0 \end{cases}
\]

where \(q\) is a parameter such that \(0 < q \leq 1\). Note that \(q = 1\) represents the case of fixed \(p\). Hereafter, we consider only the case \(q < 1\) and set \(p_{\min} = q^m\). When LA changes, the update of \(p\) precedes the decision on location update. Note also that the original PLU in [14] is a variant of (1). It has been given in [14] that \(p_{k+1} = \min\{p_k/q, 1\}\) if \(l_k \geq 1\).

III. PERFORMANCE ANALYSIS

A. Model

We analyze the performance of IPLU. Since the purpose of analysis in this paper is to demonstrate the efficiency of IPLU itself, we use a general methodology in [10] and [11] with the following simple discrete-time system model.

**LA Configuration:** We assume that an LA consists of seven hexagonal cells, as exemplified in Fig. 1.

**Mobility Model:** We use a random walk model. At discrete time \(t\), an MT moves to one of the neighboring LAs with probability \(r\) or stay at the current LA with probability \(1-r\). If the MT decides to move to another LA, it selects any one of the neighboring LAs as the destination with equal probability.

**Call Arrival Process:** The call arrivals for each MT are also geometrically distributed. At discrete time \(t\), a call is generated for an MT with probability \(c\). The call is an MT origination call with probability \(P_O\) or a termination call with probability \(P_T\), where \(P_O + P_T = 1\).

B. Paging Strategy

The paging strategy affects directly the location management cost. However, since the purpose of this section is to evaluate the performance of the location update scheme relatively rather than absolutely, we assume the following simple paging strategy.

The network pages the seven cells in the LA that is reported last (let us say, for example, LA A in Fig. 1). If the network fails to receive the response from the target MT, it pages all the cells in the first ring of surrounding LAs (LAs B1, B2, . . . , B6 in Fig. 1). If it fails again, it tries on the second ring of surrounding LAs (LAs C1, C2, . . . , C12 in Fig. 1) and so on. When an MT is on the \(j\)th ring, the “distance” between the actual LA of the MT and the last-reported LA is said to be equal to \(k\).

C. Markov Analysis

Let us observe an MT both at each LA change and at each call arrival. Then, a system state can be represented by \((i, j)\), where \(i\) is the distance between the current LA of the MT and the last-reported LA and \(j\) represents the location update probability \(p\) with the relationship \(p = q^j\) (\(0 \leq j \leq m\)).

A call arrival is accompanied with (implicit) location update. Therefore, if a call arrives, the system enters a state with \(i = 0\). That is, a call arrival causes a state transition to occur. On
the other hand, an MT updates the probability \( p \) at LA change. This means that the state transition occurs at LA change. Since the location update probability \( p \) is affected by the number of termination call arrivals between two LA changes [refer to \( l_k \) in (1)], the system should track the number of termination calls arrived since the last LA change. For this, we partition a state with \( i = 0 \) [say, \((0, j)\)] into several (sub)states so that each of the (sub)states reflects the number of termination calls arrived since the last LA change. We replace a state \((0, j)\) with \(0, j\) states, \((0, k)\) \((0 \leq k < j)\). A state \((k^*, j)\) \((0 \leq k < j - 1)\) represents the situation that \( k \) termination calls are arrived since the last LA change and the current location update probability is \( q^j \). Let us consider the case that the number of termination calls arrived since the last LA change is more than or equal to \( j \), when \( p = q^j \). In this case, if LA is changed, the location update probability becomes one even though the number of termination call arrivals is larger than \( j \) [see (1)]. Therefore, we represent the arrival of \( j \) or more termination calls with a state \((j^*, j)\). In addition, the state \((1^*, 0)\) represents the arrival of one or more termination calls since the last LA change when \( p = 1 \).

The system is modeled as an embedded Markov chain with the state space in Fig. 2. The state space is partitioned into two disjoint sets, \( S_1 \) and \( S_2 \), where

\[
S_1 = \{(i, j); 1 \leq i \leq j, 1 \leq j \leq m - 1\} \cup \{(i, s); 1 \leq i\}
\]

\[
S_2 = \{(k^*, j); 0 \leq k \leq j, 0 \leq j \leq m\} \cup \{(1^*, 0)\}.
\]

Note that the set \( S_1 \) contains the states with nonzero distance and all states in the set \( S_2 \) have zero distance.

As stated above, a state transition occurs either at a call arrival or at an LA change. Let us investigate the state transition probabilities. Let the random variables \( M \) and \( T \) denote the time intervals from an instant of state transition to the next LA change and to the next call arrival, respectively. Then the probability that the next state transition occurs due to an LA change, \( \theta = \Pr\{M < T\} \), is

\[
\theta = (1 - c)^r \sum_{k=0}^{\infty} (1 - c)^k (1 - r)^k
\]

\[
= \frac{(1 - c)^r}{1 - (1 - c)(1 - r)}. \tag{2}
\]

For the simplicity of the state transition model, we use the following approximation: when a call arrival and an LA change occur simultaneously, we ignore the LA change and consider only the call arrival. Then the probability of state transition by a call arrival is equal to \( 1 - \theta \).

Fig. 3 shows the state transition diagram. We only present the transition probabilities of outflows from the shadowed states to avoid overcrowding of the figures, but one can easily redraw the entire diagram from the information in Figs. 2 and 3. In the following, the state transition probabilities in Fig. 3 are explained in more detail.

Let us examine the transitions from a state \((i, j)\) in Fig. 3(a) \((1 \leq i \leq j, 1 \leq j < m)\). If an MT origination call arrives, an implicit location update occurs, and so the system state becomes \((0^*, j)\). The probability that the state changes from \((i, j)\) to \((0^*, j)\) due to an origination call arrival is \( (1 - \theta)P_{T_0} \). The arrival of an MT termination call also causes an implicit location update, and then the system enters a state \((1^*, j)\). The transition probability from \((i, j)\) to \((1^*, j)\) is \( (1 - \theta)P_{T_1} \). When the system state is in the set \( S_1 \), the occurrence of LA change before a call arrival means that there is no call arrival between two
LA changes. Therefore, when the system state is \((i, j)\), if LA is changed, the location update probability becomes \(q^{i+1}\). Then the MT performs an explicit location update with probability \(q^{i+1}\) or the MT moves to a neighboring LA (without a location update) with probability \(1-q^{i+1}\). If the MT updates its location, the system state becomes \((0^*, j+1)\). Since the probability of state transition by LA change is \(\theta\), the transition probability from \((i, j)\) to \((0^*, j+1)\) is \(\theta q^{i+1}\). If the MT does not perform the location update, the MT moves to a neighboring LA whose distance is \((i-1)\), \(i\), or \((i+1)\). Then, the movement probabilities to an LA with distance \((i-1)\), \(i\), \((i+1)\) are \((2i-1)/(6i)\), \(1/3\), and \((2i+1)/(6i)\), respectively [10]. Therefore, the transition probabilities from \((i, j)\) to \((i-1), j+1), (i, j+1), (i+1), j+1\) become, respectively, \([2i-1]/(6i)\theta(1-q^{i+1}), (1/3)\theta(1-q^{i+1})\), and \([2i+1]/(6i)\theta(1-q^{i+1})\). Note that when \(i = 1\), the state \((i-1, j+1)\) represents \((0^*, j+1)\).

On the other hand, since \(p \geq q^m\), there is no state with \(j > m\). Therefore, when the system is in the state \((i, m)\) \((i \geq 1)\), if LA is changed, it enters \((0^*, m)\), \((i-1, m)\), \((i, m)\), and \((i+1, m)\), respectively, in place of \((0^*, m+1)\), \((i-1, m+1)\), \((i, m+1)\), and \((i+1, m+1)\) [see Fig. 3(a) and (b)]. It is noted that there is no state such that \(i > j\) when \(j < m\), whereas there are infinite states such that \(i > j\), for \(j = m\). For example, when the system is in state \((m, m)\), if an LA change occurs without location update, it enters the state \((m+1, m)\) with probability \([(2m+1)/(6m)]\theta(1-q^{i+1})\).

Fig. 3(c) shows the state transitions from \((0^*, j)\) \((0 \leq j < m)\). At the arrival of an origination call, the system remains unchanged. If a termination call arrives, the system enters the state \((1^*, j)\). This is, the system enters the state \((0^*, j)\) with probability \((1-\theta)P_{O}\) or the state \((1^*, j)\) with probability \((1-\theta)P_{T}\). On the other hand, the occurrence of LA change in the state \((0^*, j)\) means that no termination call arrives between two LA changes. Therefore, if LA is changed, the MT performs the location update with probability \(q^{i+1}\) or moves (without a location update) to the LA whose distance is one with probability \((1-q^{i+1})\). That is, the system enters the state \((0^*, j+1)\) with probability \(\theta q^{i+1}\) or the state \((1, j+1)\) with probability \(\theta(1-q^{i+1})\). As in Fig. 3(b), when the state is \((0^*, m)\), if LA is changed, the system enters \((0^*, m+1)\), \((1, m)\) in place of \((0^*, m+1)\) and \((1, m+1)\) [Fig. 3(d)].

Let us examine the transitions from state \((k^*, j)\) \((1 \leq k < j, 2 \leq j \leq m)\). These are shown in Fig. 3(e). The system remains unchanged with probability \((1-\theta)P_{O}\) (at the arrival of an origination call) or enters the state \(((k+1)^*, j)\) with probability \((1-\theta)P_{T}\) (at the arrival of a termination call). If LA is changed, the location update probability becomes \(q^{i-k}\) and the MT reports its location with probability \(\theta q^{i-k}\) or moves to a neighboring LA with probability \(1-q^{i-k}\). Note that since \((k^*, j)\) has zero distance, the distance of the neighboring LA is one. That is, the system enters \((0^*, j-k)\) with probability \(\theta q^{i-k}\) or enters \((1, j-k)\) with probability \(\theta(1-q^{i-k})\). Fig. 3(f) shows the state transitions from \((j^*, j)\) \((1 \leq j \leq m)\). As stated above, the state \((j^*, j)\) represents the situation where \(j\) or more termination calls have arrived since the last LA change and the current location update probability is \(q^j\). If LA is changed, the location update probability becomes one according to (1) and so the MT updates its location. As a result, the state
becomes \((0^*, 0)\). On the other hand, even though a termination call is arrived, the system state remains unchanged as at the arrival of an origination call. Therefore, the system enters \((0^*, 0)\) with probability \(\theta\) or remains \((j^*, j)\) with probability \(1 - \theta\). The transitions from state \((1^*, 0)\) also follow the same explanation as those from \((j^*, j)\).

Let \(\pi_{i^*, j}\) and \(\pi_{i, j}^*\) denote the stationary probabilities of the states \((i^*, j)\) and \((i, j)\), respectively. From Figs. 2 and 3, we can obtain several flow-balance equations in steady state. The following probabilities can be derived from these equations:

\[
\pi_{1^*, 0} = \frac{(1 - \theta)P_O}{\theta} \pi_{0^*, 0},
\]

\[
\pi_{1^*, 1} = \frac{\theta + (1 - \theta)P_T}{1 + (1 - \theta)P_O + \theta} \pi_{0^*, 0},
\]

\[
\pi_{1^*, 2} = \frac{\theta^2 \{1 - (1 - \theta)P_O\}}{(1 - \theta)P_T \{1 - (1 - \theta)P_O + \theta\}^2} \pi_{0^*, 0},
\]

\[
\pi_{1^*, j} = \frac{(1 - \theta)P_O}{\theta} \pi_{0^*, 0} + \frac{\theta^2 \{1 - (1 - \theta)P_O\}}{(1 - \theta)P_T \{1 - (1 - \theta)P_O + \theta\}^2} \pi_{0^*, 0},
\]

\[
\pi_{1^*, m} = \frac{(1 - \theta)P_O}{\theta} \pi_{1^*, m-1},
\]

\[
\pi_{i^*, j} = \frac{(1 - \theta)P_O}{\theta} \pi_{0^*, 0} - \frac{(1 - \theta)P_O}{\theta} \pi_{0^*, 0} \sum_{i=1}^{j-1} \pi_{i^*, i},
\]

\[
\pi_{i^*, m} = \frac{(1 - \theta)P_O}{\theta} \pi_{i^*, m-1},
\]

\[
\pi_{i^*, j} = \frac{(1 - \theta)P_O}{\theta} \pi_{0^*, 0} \sum_{i=1}^{j-1} \pi_{i^*, i},
\]

\[
\pi_{i^*, m} = \frac{(1 - \theta)P_O}{\theta} \pi_{i^*, m-1},
\]

As seen in (3)–(9), the stationary probabilities \(\pi_{i^*, 0}\) and \(\pi_{i^*, j}\) \((1 \leq i \leq j, 1 \leq j \leq m)\) need \(\pi_{0^*, 0}\). Let us calculate \(\pi_{0^*, 0}\).

The global balance equation for the state \((0^*, 0)\) is as follows:

\[
\pi_{0^*, 0} = \frac{\theta}{1 + (1 - \theta)P_O} \left( \pi_{1^*, 0} + \sum_{j=1}^{m} \pi_{j^*, j} \right).
\]

Then, we can obtain \(\pi_{0^*, 0}\) from (3)–(9) and (10). If \(\pi_{0^*, 0}\) has been calculated, we also can obtain \(\pi_{1^*, 0}\) and \(\pi_{i^*, j}\) \((1 \leq i \leq j, 1 \leq j \leq m)\) by using (3)–(9).

Let us derive the global balance equations for the states \((0^*, j)\) \((1 \leq j \leq m)\) from Figs. 2 and 3:

\[
\pi_{0^*, 1} = \theta_1 \pi_{0^*, 0} + \frac{\theta P_O}{P_T} \pi_{1^*, 1} + \theta_1 \sum_{i=2}^{m} \pi_{(i-1)^*, i},
\]

\[
\pi_{0^*, 2} = \theta_1^2 \frac{(1 - \theta)P_O}{(1 - \theta)P_T} \pi_{1^*, 1} + \frac{P_O}{P_T} \{1 - (1 - \theta)P_O\} \pi_{1^*, 2} + \frac{\theta_1^2 (1 - \theta)P_O}{6(i - 1)} \pi_{1^*, 2} \sum_{i=3}^{m} \pi_{(i-2)^*, i},
\]

\[
\pi_{0^*, m} = \theta_1^m \frac{(1 - \theta)P_O}{(1 - \theta)P_T} \left( \pi_{m^*, m-1} + \pi_{1^*, m} \right) + \frac{P_O}{P_T} \{1 - (1 - \theta)P_O\} \pi_{1^*, m} + \frac{\theta_1^m (1 - \theta)P_O}{6(i - 1)} \pi_{1^*, m} \sum_{i=3}^{m} \pi_{(i-2)^*, i}.
\]

The global balance equations for the states in set \(S_1\) are

\[
\pi_{i^*, j} = I_{i=1} \theta(1 - q^i) \left( \pi_{0^*, 0} + \sum_{k=1}^{i} \pi_{(k-j)^*, k} \right)
\]

\[
+ I_{i \neq 1} \frac{2(i - 1) + 1}{6(i - 1)} \theta(1 - q^i) \pi_{i-1, i-1} + I_{i < j} \frac{1}{6} \theta(1 - q^i) \pi_{i+1, i-1} + I_{i = j} \frac{2(i - 1) - 1}{6(i - 1)} \theta(1 - q^i) \pi_{i, i-1} + \frac{\theta_1}{6(i - 1)} \theta(1 - q^i) \pi_{i+1, i-1} + \frac{\theta_1}{6(i - 1)} \theta(1 - q^i) \pi_{i+1, i-1} + \frac{\theta_1}{6(i - 1)} \theta(1 - q^i) \pi_{i, i-1}.
\]

\[
\pi_{i^*, m} = I_{i=1} \theta(1 - q^i) \left( \pi_{0^*, m-1} + \pi_{0^*, m} \right) + I_{i \neq 1} \frac{2(i - 1) + 1}{6(i - 1)} \theta(1 - q^i)
\]

\[
+ I_{i \leq m} \frac{1}{6(i - 1)} \theta(1 - q^i) \pi_{i, i-1} + \frac{\theta_1}{6(i - 1)} \theta(1 - q^i) \pi_{i+1, i-1} + \frac{\theta_1}{6(i - 1)} \theta(1 - q^i) \pi_{i+1, i-1} + \frac{\theta_1}{6(i - 1)} \theta(1 - q^i) \pi_{i, i-1}.
\]
is the sum of transition probabilities by an explicit location update from any state to the state $(0^*, j)$ $(0 \leq j \leq m)$

$$C'_u = \theta \pi^r_{1^*, 0} + \sum_{j=0}^{m-1} \theta^j \sum_{i=j+1}^{m} \pi_{i^r, j} + \sum_{j=0}^{m-1} \pi_{0^*, j} + \sum_{j=1}^{m-1} \sum_{i=1}^{j} \pi_{i^r, j} + \theta \pi^m_{1^*, m} + \sum_{i=1}^{\infty} \pi_{i^r, m}. \quad (18)$$

We can substitute $\frac{1}{\theta} = \frac{1}{\sum_{i=0}^{m} \pi_{i^r, m}}$ (from the global balance equation of the state $(1^*, m)$). Denoting the cost of one location update (i.e., the unit location update cost) by $U$, since average state sojourn time is equal to $\frac{1}{\sum_{i=0}^{m} \pi_{i^r, m}}$, the mean location update cost is obtained as

$$C_u = U \left\{ 1 - (1 - c)(1 - r) \right\} C'_u, \quad (19)$$

**Paging Cost:** Let $C'_p$ denote the mean number of LAs being paged per state transition. If a termination call arrives at any state $(i, j)$ in the set $S_1$, the system enters the state $(0^*, j)$ and then the number of LAs being paged is $(3^2 + 3i + 1)$ for hexagonal configurations of Fig. 1. Also, if a termination call arrives at any state $(0^*, j)$ in the set $S_2$, the number of LAs being paged is one because the state has zero distance. Therefore

$$C'_p = (1 - \theta)P_T \left\{ \pi_{1^*, 0} + \sum_{j=0}^{m} \sum_{i=0}^{j} \pi_{i^r, j} + \sum_{j=1}^{m-1} \sum_{i=1}^{m} (3^2 + 3i + 1) \pi_{i^r, j} + \sum_{i=1}^{\infty} (3^2 + 3i + 1) \pi_{i^r, m} \right\}. \quad (20)$$

Denoting the cost of one LA paging (i.e., the unit paging cost) by $P$, the mean paging cost $C_p$, is as follows:

$$C_p = P \left\{ 1 - (1 - c)(1 - r) \right\} C'_p. \quad (21)$$

**Total Cost:** Then, the total cost $C$ is

$$C = C_u + C_p. \quad (22)$$

IV. NUMERICAL EXAMPLE

We now discuss some numerical results obtained by (3)–(22).

**A. Extreme Strategies**

For the purpose of comparison, we also examine the results for two extreme strategies:

1) **Unconditional Location Update (ULU):** Each MT performs a location update every LA change. Under ULU, a location update explicitly occurs with rate $(1 - c)r$, and the mean location update cost is $c_P T P_U$. Therefore, the total cost under ULU equals $(1 - c)r$ $U + c_P T P_U$.

2) **No Location Update (NLU):** Each MT does not update its location for any LA change. Therefore, a location update cost is zero under NLU. To evaluate the paging cost (that is, the total cost) under NLU, we have used the Markov analysis in [10].

With ULU, the network always can find the target MT at the first paging trial. This results that the mean paging cost of ULU is lower than that of any other strategy (including IPLU and NLU). The main portion of the location management cost of ULU is incurred from an update cost. Therefore, if the unit location update cost of a given network is extremely lower than the unit paging cost (i.e., $P/U \gg 1$), ULU will have the lowest total cost. On the other hand, if $U/P \gg 1$, NLU will have the best performance.

The values of $P$ and $U$ in a particular network depend on the cell configuration and the access protocol for radio network, the feature and size of the LA and paging zone, and the architecture and signaling protocol of fixed network. Thus, it is hard to assume typical values of $P$ and $U$ in general. Nevertheless, the lessons from some operational experiences of digital cellular network (based on IS-95 [3] and IS-41 [4]) show that the values lay between two extreme cases mentioned above.

**B. Effect of the Ratio of Termination Calls, $P_T$**

Fig. 4 illustrates the effect of $P_T$ on the costs of three comparative schemes. The parameter values for the results in Fig. 4 are that $c = 0.05, r = 0.2, P = 1, U = 3, q = 0.9$, and $m = 20$; thus $p_{\min} = 0.00$. The costs of IPLU and NLU are increased as $P_T$ increases, whereas that of ULU is not greatly influenced by $P_T$. However, IPLU has the best performance for a value of $P_T$ between 0.2–0.8. Considering that the value of $P_T$ is around 0.2–0.4 in current cellular mobile networks and is expected to
become about 0.5 in future mobile networks, IPLU gives superior cost performance to NLU or ULU for an usual value of $P_T$.

C. Cost According to Mobility

Fig. 5 depicts the total costs of three strategies according to the mobility rate $r$. The parameter values for the results in Fig. 5 are that $c = 0.05$, $P = 1$, $U = 6$, $P_T = 0.5$, and $m = 20$. As expected, for a small value of $P/U$, NLU has the best performance and ULU the worst performance. We can also see in Fig. 5 that the performance of IPLU depends on a value of $q$ and is able to become better than that of NLU by setting $q$ to an appropriate value.

On the contrary, if a value of $P/U$ is large, the performance of ULU is the best and NLU the worst. Fig. 6 shows well this point. The parameter values used in Fig. 6 are the same as those in Fig. 5 except that $P = 3$ and $U = 1$. As seen in the figure, the performance of IPLU is better than that of NLU, and becomes as good as that of ULU as $q$ approaches to one.

From Figs. 5 and 6, we can see that the comparative merits of ULU, NLU, and IPLU depend heavily on $P/U$. However, the performance of IPLU for given $U$ and $P$ can be easily improved by adjusting the value of $q$.

D. $q$ as the Control Parameter

Now, we examine the effect of $q$ on the location management cost in more detail. Fig. 7 illustrates the cost according to $q$ for several values of $P_T$ and $r$ when $c = 0.05$, $P = 3$, $U = 1$, and $m = 20$. Fig. 8 has the same parameter values as Fig. 7 except that $P = 1$ and $U = 3$. As shown from Figs. 7 and 8, the cost is more largely influenced by $q$ in the system with high mobility than in the system with low mobility, that is, at $r = 0.2$ than at $r = 0.03$. We can also see from Fig. 7 that for a large value of $P/U$, the cost decreases with the increment of $q$ regardless of the other parameter values ($r$, $P_T$) and approaches a minimum as $q$ closes to one. On the other hand, when $P$ is smaller than $U$ (see Fig. 8), the value of $q$ providing the minimum cost varies according to the values of the parameters $r$ and $P_T$. If the values of the other parameters except $q$ are fixed, we can find the value of $q$ at which the cost becomes a minimum.

Fig. 9 depicts the value of $q$ with the minimum cost when $c = 0.05$, $P = 1$, $U = 3$, and $m = 20$. As shown from the
figure, the value of $q$ with the minimum cost is largely affected by $r$ and $P_T$. As the mobility increases, the value of $q$ providing the minimum cost converges to a certain value greater than 0.8 as long as $P_T$ is not very small (for $P_T > 0.1$). As stated before, $P_T$ is usually expected to be a value between 0.2–0.5. For this range of $P_T$, the convergence value is smaller than 0.95. On the other hand, when the mobility is low, the value of $q$ with the minimum cost is changed more sensitively to the variation of $P_T$ and $r$. However, as seen from Fig. 8, the difference between the minimum and the maximum cost is not large in the system with low mobility. This means that $q$ can be set to a value greater than 0.8 with negligible performance degradation.

In summary, we recommend that $q$ should be set to nearly one in the system with $P > U$ and a value between 0.8–0.95 in the system with $P \leq U$.

E. Cost According to $P/U$

Fig. 10 illustrates the costs of three comparative strategies according to $P$ for a given $U$, when the appropriate values of $q$ are used for IPLU. The parameter values are $c = 0.05$, $r = 0.2$, $U = 5$, $P_T = 0.5$, and $m = 20$. For a given pair of $(P, U)$, $q$ in IPLU has been set to the value which provides a minimum cost. In this case, we can see from the figure that IPLU has the best performance without regard to the values of $P$ and $U$.

V. PERFORMANCE COMPARISON BETWEEN IPLU AND PLU

In this paper, we have suggested the IPLU scheme that improves the performance of PLU proposed in [14]. To examine a performance improvement in IPLU, we illustrate in Fig. 11 the total costs of IPLU and PLU according to the mobility rate. The parameter values used to obtain the results of the figure are $c = 0.3$, $P = 5$, $U = 1$, $P_T = 0.5$, $q = 0.9$, and $m = 20$. As shown from the figure, the cost of IPLU is lower than that of PLU at medium mobility rate, whereas IPLU has a similar performance to PLU at low or high mobility rate. This results from the difference between the mean location update probabilities of two protocols, as seen in Fig. 12.
Let us compare the performances of IPLU and PLU under the real situation that traffic patterns change rapidly. To do this, we investigate the convergence speeds of two protocols to a new steady-state when traffic changes, by using computer simulation. The simulation parameter values are that \( P = 5 \), \( U = 1 \), \( P_T = 0.9 \), \( q = 0.9 \), and \( m = 20 \). The simulation scenario for traffic pattern is as follows: from \( t = 0 \) to \( t = 10000 \), a call arrival rate \( c \) is 0.3 and an LA change rate \( r \) is 0.5. At \( t = 10000 \), an LA change rate is changed to 0.1, whereas a call arrival rate remains unchanged.

Figs. 13 and 14, respectively, depict the location update probability and the cost according to the lapse of time. To demonstrate the performance difference between IPLU and PLU more clearly: 1) we used \( P_T = 0.9 \), although the value in a real system might be less than or equal to about 0.5 and 2) 400 simulation runs were performed and the average values were plotted.

As shown from Fig. 13, when \( c = 0.3 \) and \( r = 0.1 \), the location update probabilities of two protocols converge to nearly the same value but IPLU has faster convergence speed in \( p \) than PLU. This reason is that IPLU updates \( p \) using the number of termination calls between two LA changes, whereas PLU considers only whether a termination call has arrived or not. Since the location update probability of IPLU converges more rapidly to a new steady-state value than that of PLU, IPLU has the lower cost than PLU for a transient period of traffic change (see Fig. 14). We see from this example that IPLU copes better with the real situation that traffic patterns change continually.

VI. CONCLUSIONS

We have suggested IPLU and evaluated its performance. The results have shown that the performances of IPLU, ULU, and NLU (and, in general, any location update scheme) vary with the parameter values, especially with \( P \), \( U \), and \( P_T \). Thus, a good location update scheme should be adjustable according to a given \( P/U \) (that is, for a given specific network) and, for such a scheme, the engineering issue is to tune appropriately the parameter. With IPLU, parameter \( q \) can be used as a control parameter to achieve the best performance for a given \( P/U \). In this paper, we have examined which value of \( q \) minimizes the cost and suggested some recommendable values of \( q \) in two cases, \( P > U \) and \( P < U \).

Basically, with IPLU, an MT makes a decision on location update without support of the network. However, in an MT initialization phase (for example, at power-on, etc.), if the network is able to adjust a value of \( q \) using the estimated \( P/U \) and inform the MT of the value via control channel (e.g., the paging channel in IS-95 [3] networks), the MT can use this information without even calculation overhead. This method could lower the location management cost remarkably. In addition, it is noted that, for the performance evaluation in this paper, we use only a simple paging scheme. If IPLU operates with a more advanced paging scheme, further cost saving could be expected. Our results are summarized as follows.

1) The IPLU scheme can be implemented simply as in (1) and gives acceptably good performance.
2) IPLU copes well with change of traffic patterns by dynamically controlling the location update probability.
3) IPLU can be adopted in current networks since the implementation is limited to MT and requires no modification to existing networks.
4) If future networks can provide the information on \( q \) (or \( P/U \)), the merit of IPLU could be enlarged.

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REFERENCES


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