The Lookahead Strategy for Distance-Based Location Tracking in Wireless Cellular Networks

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***Abstract*—Based on a multi-scale, straight-oriented mobility model, this paper presents a lookahead strategy for distance-based location tracking so the rate of location update can be reduced without incurring extra terminal paging costs. For linear mobility graphs, the optimal registered cell is found by an iterative algorithm so the average cycle length is maximized. For planar mobility graphs, the authors employ the results from linear cases to determine the eligible registered cell. Performance gain is evaluated by using Monte Carlo simulation for mobiles with different degrees and scales of mobility. Analysis shows that the tracking cost for mobile users with large mobility scales in microcellular networks, costs which are usually underestimated by the traditional random walk model, can be effectively reduced.**

I. Introduction

As the number of mobile subscribers skyrockets, signaling traffic for mobility management places a heavy burden on wireless cellular networks [1] [2] [3]. Efficiently utilizing the limited bandwidth of air interface is thus one of the most important issues for wireless networks. To track mobile terminals in *idle mode*, some scarce radio resources are consumed without any profit. By way of air interface, each *mobile* should report its current location to the network occasionally (known as *location update*) so a determinate search procedure (called *terminal paging*) can be invoked by the network to inform the called mobile the instant a new call comes in. A *location area* or *registration area* is a cluster of cells. Once a mobile leaves the current location area, another location update (registration) shall be done by the mobile so only those cells in the registered location area have to be paged when a *mobile terminated call* to the mobile arrives.

The size of a cell depends on the traffic demands and the cost of network infrastructure, whereas the size of a location area is determined by the cost of location update and terminal paging. On the one hand, if a location area is divided into two partitions, the number of location updates is increased by one if a mobile goes through both partitions. On the other hand, the number of cells to be paged for the called mobile is reduced to that in one of the two partitions. Thus, location update and terminal paging are trade-offs. In general, networks with small location areas suffer from heavy location updates whereas networks with large location areas incurs a large number of terminal paging messages.

Conventional location tracking schemes [4] are said to be *static* because the shape and size of location areas are fixed partitions for all mobile users. A number of studies about *dynamic* schemes have been proposed recently to reduce the total cost of location update and terminal paging, such as the *multi-layered* scheme[5], *time-based* scheme[6] [7] [8] [9], *movement-based* scheme[6] [10] [11], *distance-based* scheme[6] [12] [13], *profile-based* scheme[14], and *probabilistic* scheme[15], etc.

In the *distance-based* scheme, every base station has to broadcast its identifier and coordinate so mobile terminals are able to know where they are visiting. When a mobile moves across a cell boundary and *camps on* another cell, the displacement from the new serving cell to the previous registered cell is calculated. A location update is taken if the distance is greater than a predefined threshold, known as *distance threshold*.

Distance-based location tracking has several advantages. One, it is flexible because the size of the location area (determined by distance threshold) can be adjusted dynamically in response to individual behavior. Two, it is load-balanced because updating traffic will not concentrate on those cells around the boundary of static location areas. Three, it has a relatively low location tracking cost [6]. And four, as we will see later, it has a simple implementation[1] and low computational cost on mobile terminals.

The spread of mobile communications reveals the scarcity of the radio spectrum. Cell size becomes smaller and smaller for the sake of *frequency reuse*. This trend makes the moving patterns more straight-oriented in a sense when we look at a smaller cell (*i.e.,* micro-cell). Suppose a mobile moves along the path $< ..., O, ..., P, ..., Q, ... >$ and performs a location update at cell O initially as shown in Figure 1. In traditional distance-based schemes, if the mobile has registered at O (exactly the cell where the mobile located at the time the mobile performs a location update), then the next location update will happen at cell P where the distance from O is greater than the radius of the location area, i.e., the predefined distance threshold. However, if the registered cell is at the "look-ahead" cell O' on the expected rectilinear path, the next location update will happen at Q but not at P. (The determination of the optimal look-ahead cell O' is to be described in Section 4.) Obviously the expected distance between the consecutive registered cells is extended, provided that the mobile keeps straight on. In such a case, the number of location updates decreased while terminal paging costs were about the same. On the one hand, if a one-step blanket paging scheme is used then the paging cost is not increased, because the size location area is not enlarged (i.e., still with the same distance threshold as its radius). On the other hand,

[1] Different from [6] [13], mobile users do not need information about the topology of the cellular network.

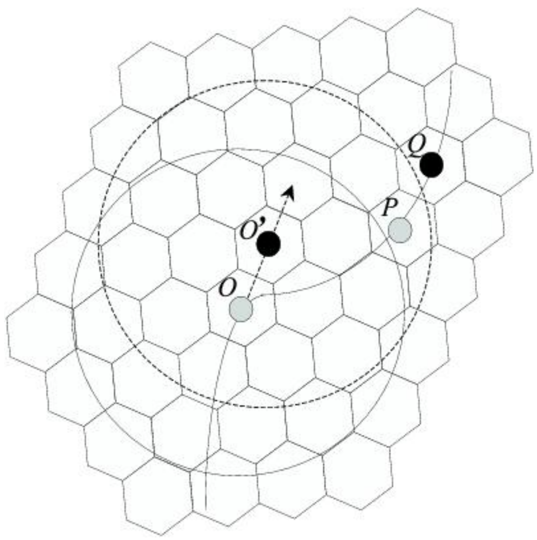


Fig. 1. Lookahead in distance-based location tracking.

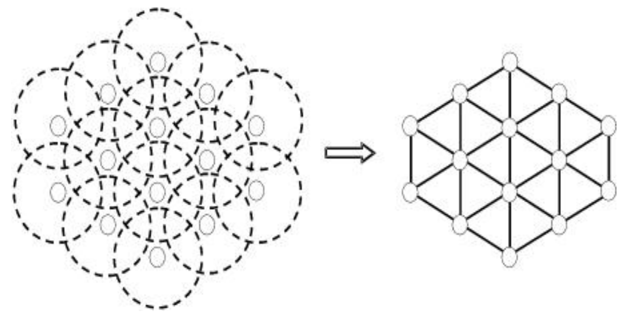


Fig. 2. Transformation from cellular network to mobility graph.

if a stepwise sequential paging process is employed then the paging costs is determined by the partition of the paging areas but not by the consequence of lookahead. More specifically, a win/loss of lookahead does not cause an decrease/increase on the paging cost. Reducing the number of location updates means fewer radio resources are consumed, signaling traffic on wired networks is reduced, the load of location registers (database) is relieved, and more battery power is saved on the mobile. Besides, it keeps the performance of the common access channel (such as the RACH in GSM-900/-1800 [16]) from degrading because an excess of location updates will lead to longer page response times and call setup delays [17].

Previous works determined the distance threshold mainly by the *degree* of mobility (the inverse of the so-called *call-to-mobility-ratio* [10]), whereas the *scale* of mobility was ignored. Under this observation, this paper considers the *distance-based location tracking* problem not only as to *when* to update but also *where* to update (*i.e.,* which cell is the best one to be registered as a central cell). The organization of this paper is as follows. In the next section, the idea of lookahead in distance-based location tracking is described formally. Section 3 presents a stochastic model named *normal walk* for a user's mobility with different scales. An algorithmic approach used for optimizing lookahead based on a one-dimensional normal walk model is demonstrated in Section 4. By applying the results from the linear case, a simple method is suggested in Section 5 to find a lookahead cell for planar mobility graphs. Section 6 gives the optimization of the distance threshold. By applying the optimal rectilinear lookahead, Section 7 gives a performance evaluation for the effectiveness of lookahead on a planar mobility graph. Conclusions are given in the last Section.

II. The Lookahead Strategy

Mobility models are usually embedded in the physical layout of cellular networks. In general, a cellular network can be transformed into a *mobility graph* $G = (V, E)$. Each vertex in set V stands for a base station; an edge (u, v) is in E if the signal coverage of base station u and v overlap. Figure 2 demonstrates the transformation from cellular network to mobility graph.

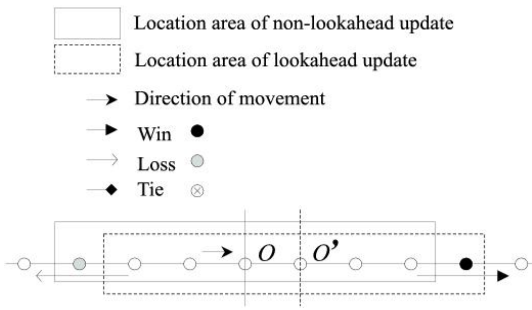
Consider the mobility graphs shown in Figure 3. Assume a mobile initially performs location update at the cell of coordinate O. An acknowledgement is sent back from the network side, telling the mobile that its *registered cell* is at O' (a "lookahead update" if O' gets ahead of O), and *distance threshold* is d. Each time the mobile moves to another cell, say P, the distance from the new serving cell P to O' is calculated by the mobile. A location update must be taken if the displacement, denoted as $\|P - O'\|$, is *greater than* d. Suppose the mobile moves along the trace $< ..., O, ..., P, ..., Q, ... >$ and the location update next to O happens at Q. We call this lookahead update a

- *win*: if there is any cell X (*e.g.,* the black circle) between O and Q such that $\|X - O\| > d$;
- *loss*: if $\|Q - O\| \leq d$ (*e.g.,* Q is the gray circle);
- *tie*: otherwise (*e.g.,* Q is the crossed circle);

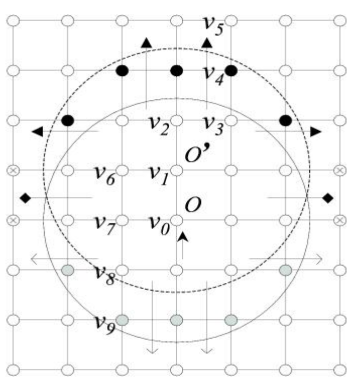
For example, consider a mobile moving along the trace $< O = v_0, v_1, v_2, v_3, v_4, v_5 = Q >$ shown in Figure 3(b). This lookahead update is a win since $\|v_4 - v_0\| > d$ (radius of the round location area). However, if the mobile moves along $< O = v_0, v_1, v_6, v_7, v_8, v_9 = Q >$, then the lookahead update is a loss since $\|v_9 - v_0\| < d$.

III. Mobility Modeling

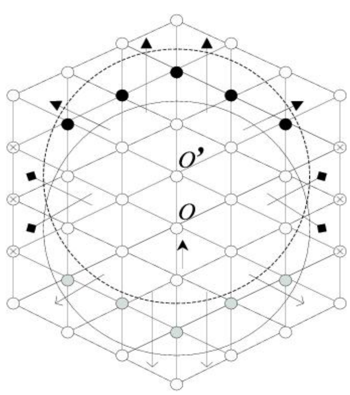
In order to find the optimal registered cell for the lookahead strategy, we should specify a mobility model to represent the mobile behavior. There is extensive literature dealing with the optimization of *location tracking* by means of the *random walk* model [5] [6] [10] [12] [18]. However, mobility models should be built around the concept of "shortest path" for real trips because a symmetric random-walked mobile will constantly change its direction after a few cell hops (*e.g.,* an average of *two* in the one-dimensional case). If we define a *path* as the consecutive cell crossing along the same direction and its *scale* as the average length measured in unit of cell hop, we can then say that the modeling of a user's mobility by the symmetric random walk can only represent *paths* with single *scale*. This phenomenon may result in, as we can see later, an underestimation of the traffic volumes of location updates if users with large mobility scales are tracked by the *distance-based* scheme. In addition, the definition of "independent"



(a) Lookahead on the linear layout



(b) Lookahead on the mesh layout



(c) Lookahead on the hexagonal layout

Fig. 3. Win, loss, and tie of a lookahead on three typical regular layouts in which the mobility models are usually embedded.

moving direction of consecutive cell hops in random walks does not perfectly match reality. For such reasons, the traditional random walk mobility model should be modified to meet the evolution. We propose an alternative model, named *normal walk*, which is more powerful to represent and characterize a PCS user's motion in microcellular networks, in which the consecutive moving directions are assumed to be highly *dependent*, and each moving direction depends on the previous one only. This multi-scale, straight-oriented mobility model referred to as *normal walk* is formulated as follows.

Assume the mobile moves in unit steps on a Euclidean plane. Let Y_{i-1} denote the moving direction of step $i-1$, and that of step i after counterclockwise rotation through an angle θ_i be Y_i, then

$$Y_i = R(\theta_i)Y_{i-1} \tag{1}$$

where

$$R(\theta) = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix}. \tag{2}$$

Consequently we have

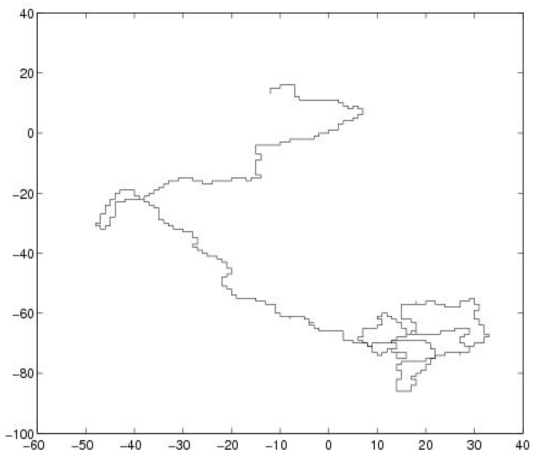
$$\begin{aligned} Y_n &= R(\theta_n)R(\theta_{n-1})...R(\theta_1)Y_0 & (3)\\ &= R(\sum_{i=1}^{n}\theta_i)Y_0. & (4)\end{aligned}$$

Let Z_n denote the coordinate of the mobile after the nth movement; initially we set $Z_0 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ and $Y_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$. Then,

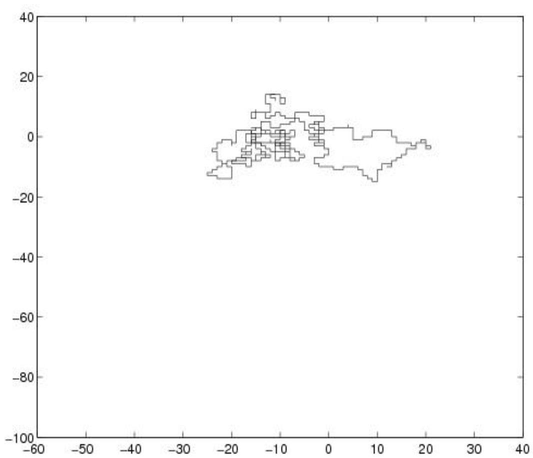
$$\begin{aligned} Z_n &= Z_{n-1} + Y_n & (5)\\ &= \sum_{i=1}^{n} R(\sum_{j=1}^{i}\theta_j)\begin{pmatrix} 1 \\ 0 \end{pmatrix} & (6)\\ &= \sum_{i=1}^{n}\begin{pmatrix} cos(\sum_{j=1}^{i}\theta_j) \\ sin(\sum_{j=1}^{i}\theta_j) \end{pmatrix}. & (7)\end{aligned}$$

The probability distribution of θ depends on individual behavior. A normal walk is said to be *restricted* if θ is approximated by *discrete* probability distribution and confined to some certain values. If we restrict θ to two reverse directions, *e.g.,* 0 and π, in order to embed in a *linear* mobility graph, then this model becomes *one dimensional*. For simplicity, the value of θ is usually confined to the *mesh* layout with four moving (/turning) directions, *i.e.,* θ = 0, $\pm\frac{\pi}{2}$, or π; or to the *hexagonal* layout with six directions, *i.e.,* θ = 0, $\pm\frac{\pi}{6}$, $\pm\frac{\pi}{3}$, or π [10]. Unfortunately, if we do restrict the normal walk to regular layouts like mesh or hexagon, the curve will be rigid and abrupt although it appears to be capable of having large-scale paths.

To smooth the curve, we liberate the motion from the inlet/outlet restriction of the mobility graph by making the distribution of θ continuous, *i.e., normal distribution* with zero mean, and then round Z_n to the nearest base station (*e.g.,* integer point for mesh layout). Figure 4 shows the normal walk with $\theta \sim N(\mu = 0, \sigma^2 = 0.25)$ and $N(\mu = 0, \sigma^2 = 1.0)$. It is important that the lower the variance of θ (the less the degree of the turning angle), the smoother the curve, the larger the *mobility scale*.



(a) $\sigma = 0.5$



(b) $\sigma = 1.0$

Fig. 4. The trajectory of normal walk with 500 cell hops.

Normal walk. Let $\theta_1, \theta_2, \ldots, \theta_n$ be independently and identically distributed random variables. The discrete-state stochastic process $\{Z_n, n \geq 0\}$, defined by

$$Z_n = \sum_{i=1}^{n} \begin{pmatrix} cos(\sum_{j=1}^{i} \theta_j) \\ sin(\sum_{j=1}^{i} \theta_j) \end{pmatrix}, \tag{8}$$

is called a planar *normal walk* process if θ is *normally* distributed with zero mean.

There are several reasons why we chose normal distribution with zero mean. First, the majority of trips have the same forward and backward routes. In these cases, the number of left turns equals that of right turns. This conforms to the symmetric feature of normal distribution. Second, most trips follow the shortest paths (*i.e.,* pseudo-linear routes from source to destination). Thus the probability density increases as the rotation angle approaches to zero. Third, the bell-shaped distribution serves as an excellent approximation to a large class of distributions which have great practical importance. Furthermore, this well-known distribution has a number of very desirable mathematical properties which make it possible to derive useful theoretical results.

Clearly, the normal walk can model random paths of larger scale while the random walk can not. The difference between these two models in *microcellular* network becomes especially more apparent than that in *macrocellular* networks. One may argue that the *asymmetric* random walk can also generate multi-scale paths. However, an asymmetric random walk will result in the mobile drifting toward a certain direction endlessly. In contrast, in normal walk this bias disappears once the moving direction is changed.

IV. Optimization of Rectilinear Lookahead

This section only focuses on the linear (one-dimensional) case which can be applied when a mobile moves back and forth on a railroad or super highway. Extension to planar graphs, by using the results of the linear case, is given in the next section.

Consider a mobility graph $G = (V, E)$ where $V = \{-m, -m+1, ..., -1, 0, 1, ..., m-1, m\}$ and $E = \{(i, i+1) | i = -m, -m+1, ..., m-1\}$. Vertex i represents a base station with coordinate i. A mobile moves back and forth on this regular linear layout. In a distance-based scheme with distance threshold d, if a mobile has registered in vertex k, then a location update occurs after the mobile moves from $k+d$ to $k+(d+1)$ or from $k-d$ to $k-(d+1)$. This paper defines a *trip* as a sequence of vertices $< v_0, v_1, ..., v_n >$ that represents a walk of the mobile in G. A *path* is defined as the consecutive cells crossing along a same direction (with length as its *scale*.) Thus, a trip is a concatenation of rectilinear paths. Furthermore, a sub-trip between two consecutive location updates is called a *cycle*. For example, a *trip* with the trace $< 0, 1, 2, 1, 0, -1, 0, 1, 2 >$ contains three *paths* $< 0, 1, 2 >$, $< 2, 1, 0, -1 >$, and $< -1, 0, 1, 2 >$, of *scales* 2, 3, and 3, respectively. If the mobile registered at 0 initially and has a distance threshold of $d = 1$, then there are three *cycles* in this trip, say, $< 0, 1, 2 >$, $< 2, 1, 0 >$, and $< 0, -1, 0, 1, 2 >$, of *cycle lengths* 2, 2, and 4, respectively.

Let random variable X_i represent the mobile going straight or turning back at the ith movement. That is,

$$X_i = \begin{cases} 1 & \text{if the mobile goes straight} \\ -1 & \text{if the mobile turns back.} \end{cases} \tag{9}$$

Let p be the probability that the mobile will go straight on each step with respect to the previous movement, *i.e.,* $P\{X_i = 1\} = p = 1 - P\{X_i = -1\}$. Let Y_i represent the moving direction at step i. That is,

$$Y_i = \begin{cases} 1 & \text{if the mobile moves from cell } k \text{ to } k+1 \\ -1 & \text{if the mobile moves from cell } k \text{ to } k-1. \end{cases} \tag{10}$$

Initially, assume $Y_0 = 1$. Then

$$Y_i = Y_{i-1} X_i \tag{11}$$

$$= \prod_{j=1}^{i} X_j. \tag{12}$$

Let random variable Z_0 be the cell coordinate in which the last location update occurred, and Z_n denote the mobile situated away from the origin[2] Z_0 up to the nth movement. Then,

$$\begin{aligned} Z_n &= Z_{n-1} + Y_n & (13) \\ &= Z_{n-1} + \prod_{j=1}^{n} X_j & (14) \\ &= \sum_{i=1}^{n} \prod_{j=1}^{i} X_j & (15) \end{aligned}$$

Specifically, a stochastic process $\{Z_n, n \geq 0\}$, where

$$Z_n = \sum_{i=1}^{n} \prod_{j=1}^{i} X_j \quad (16)$$

is said to be a *linear normal walk*[3] if X_1, X_2, ..., and X_n are independently and identically distributed with $P\{X_i = 1\} = p = 1 - P\{X_i = -1\}$.[4] The value of Z_n, conditioned on the values of Z_{n-2} and Z_{n-1}, is independent of Z_i for $i < n-2$. It is easy to see that the bivariate chain,

$$\widehat{Z_n} \stackrel{\text{def}}{=} (Z_n, Z_{n-1}) \quad (17)$$

is a *Markov chain*.

Let S_i^+ represent the state that a mobile is at cell i and its moving direction is from cell i to cell $i+1$ (*i.e.,* $Z = i$ and $Y = +1$), and S_i^- represents the state that a mobile is at cell i and its moving direction is from cell i to cell $i-1$ (*i.e.,* $Z = i$ and $Y = -1$). Figure 5(a) shows a state diagram for the location tracking with distance threshold d, which can be formulated as a normal walk with absorbing barriers at $-d-1$ and $d+1$ for each cycle. That is, the initial state is S_0^+ or S_0^- if no lookahead, and the final state is S_{d+1}^+ or S_{-d-1}^-.

The state diagram shown in Figure 5(a) can be reduced to another one in Figure 5(b) where state S_i denotes that the mobile's location is i-hop away from the next update point (absorbing state S_0). This is because, in Figure 5(a), state transitions from S_i^+ to S_{i+1}^+ or S_{i-1}^- (going straight or turning back on the one hand) are symmetrically equivalent to the transitions from S_{-i}^- to S_{-i-1}^- or S_{-i+1}^+ (going straight or turning back on the other hand). Thus these two transitions can be merged into the transition from S_{d+1+i} to S_{d+i} or S_{d-i}, for $i = -d, -d-1, \ldots, -1, 0, 1, \ldots, d$.

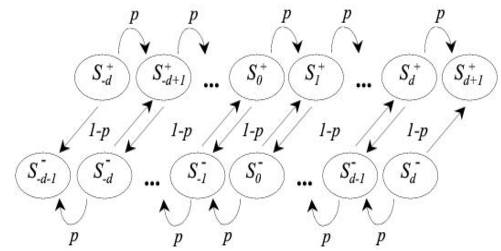
We have formulated the distance-based tracking problem with a normal walk process. Below, we will determine the best lookahead cell where the mobile should be registered so the number of location updates is minimized.

Let M_i be the expected number of movements to S_0 starting from S_i. A cycle starts at state $S_{d+1+\Delta}$ where Δ is the lookahead value. So, the average length of a cycle is $M_{d+1+\Delta}$ (the expected number of cell hops between two update points; we call it the *cycle length*). Let λ_m denote the cell crossing rate, then the location update rate $\lambda_{lu} = \lambda_m / M_{d+1+\Delta}$. Our first goal is to find the optimal lookahead value Δ^* so the rate of location updates is minimized with respect to a given d and p. Because the rate of location updates is inversely proportional to the cycle length, thus the optimal lookahead Δ^* is the one making $M_{d+1+\Delta}$ maximal where Δ is not greater than d. Note that Δ cannot be negative because $M_{d+1+\Delta}$ is greater than $M_{d-\Delta}$.

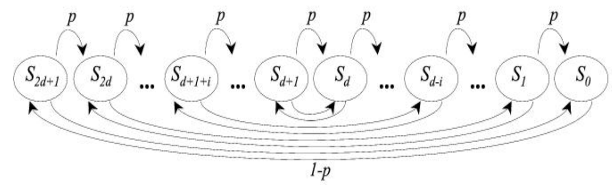
[2]For the sake of simplicity, we take $Z_0 = 0$ as a relative cell coordinate for each cycle.

[3]Because $R(\sum_{j=1}^{i} \theta_j) = \prod_{j=1}^{i} R(\theta_j)$, the linear case can be derived by replacing $R(\theta_j)$ with X_j.

[4]Obviously, the path scale is *geometrically* distributed with parameter $1-p$. Its mean mean value is $1/(1-p)$.



(a) Normal walk with absorbing barriers (original)



(b) Normal walk with absorbing barriers (reduced)

Fig. 5. State diagrams of distance-based location tracking based on normal walk.

The balance equations are

$$M_i = \begin{cases} 0 & , \quad i = 0 \\ 1 + pM_{i-1} + (1-p)M_{2d+1-i} & , \quad 1 \leq i \leq 2d+1. \end{cases} \quad (18)$$

Summing over all i yields $M_{2d+1} = 2d+1$. This gives $M_{2d} = 2d/p$. Then all M_i's can be obtained by solving iteratively (no closed-form expression was found). A brief pseudocode for the optimal lookahead is shown in the following procedure.

```
Procedure LOOKAHEAD(d, p)
    M_0 = 0
    M_2d = 2d/p
    M_2d+1 = 2d + 1
    for i = 1 to d − 1 do
        M_i = 1 + p M_i−1 + (1 − p) M_2d+1−i
        M_2d−i = (M_2d+1−i − (1 − p) M_i − 1)/p
    M_k ← max{M_j | d + 1 ≤ j ≤ 2d + 1}
    Δ* ← k − d − 1
    return(Δ*)
```

For an example of distance threshold $d = 3$ and $p = 0.75$ (mobility scale of average length 4), applying **Procedure** LOOKAHEAD, we can find $M_4 = 8.0$, $M_5 = 8.3$, $M_6 = 8.0$, and $M_7 = 7.0$. So, the optimal lookahead $\Delta^* = 1$.

Figure 6 shows the average cycle length with respect to

p for various d's. It is trivial that, for a certain p, cycle length increases (the number of location updates falls) as d grows. Similarly, for a fixed distance threshold d, cycle length decreases (the number of location updates rises) as p grows. It is now recognized that a mobile user with small mobility *scale* may make fewer location updates in spite of its high mobility *degree* (mobile users are constantly on the move). This is why tracking cost is usually underestimated if a small-scale model such as symmetric random walk is used in microcellular networks.

Figure 6 shows that for a fixed d, the larger the p, the more difference the cycle lengths between tracking *with* and *without* lookahead. This confirms what we expected: by using the lookahead strategy in distance-based location tracking, the straighter the path, the more the number of location updates that can be saved.

Intuitively, if we are sure that the mobile user will keep straight on, then the distance between the consecutive registered cells can be lengthened when we take a larger lookahead (thus the number of location updates can be reduced). So, we define

$$\alpha = \frac{\Delta^*}{d} \tag{19}$$

as the *aggressiveness* of a lookahead to demonstrate an obvious corollary: the straighter the path, the more aggressively should lookahead. This property is shown in Figure 7. In this study we also found that the lookahead strategy takes effect ($\Delta^* > 0$, *i.e.,* $M_{d+1+\Delta^*} > M_{d+1}$) if only p is more than $\frac{2}{3}$, no matter how large the value of d is. Furthermore, it is surprising to see that the aggressiveness of lookahead has a nice property of synchronized stairing up, with the limitation of distance threshold. That is, the break points for Δ^*=1, 2, 3, ..., d happened at p=$\frac{2}{3}$, $\frac{4}{5}$, $\frac{6}{7}$, ..., $\frac{2d}{2d+1}$. Therefore, the **Procedure** LOOKAHEAD(d, p) can be simplified as

$$\Delta^* = \min\{n, d\} \tag{20}$$

if

$$\frac{2n}{2n+1} \leq p < \frac{2(n+1)}{2(n+1)+1} \tag{21}$$

for integer $n \geq 0$. For the example of $d = 3$ and $p = 0.75$ again, we find $n = 1$ and then $\Delta^* = 1$.

V. Lookahead in Planar Mobility Graph

Those results in the above section suggest that the one-dimensional *scale index* p which determines the optimal lookahead Δ^* can be an indicator of *trackability* (*i.e.,* the predictability of mobility trace) for mobile users moving in linear mobility graphs. As an extension to planar mobility graphs, we have to determine both the magnitude and direction of lookahead $\vec{\Delta}$ by the two-dimensional scale index σ (standard deviation of θ).

The proposed lookahead strategy on a planar graph is illustrated in Figure 8. Suppose a mobile initially performed a location update at O_{i-1}, with lookahead $\vec{\Delta_{i-1}}$. Thus, O'_{i-1} becomes its registered cell. Once the mobile moves to O_i where $||O'_{i-1} - O_i|| > d$, the mobile should take a new location update with lookahead $\vec{\Delta_i}$ along the direction of two consecutive location updates, $\overrightarrow{O_{i-1}O_i}$.

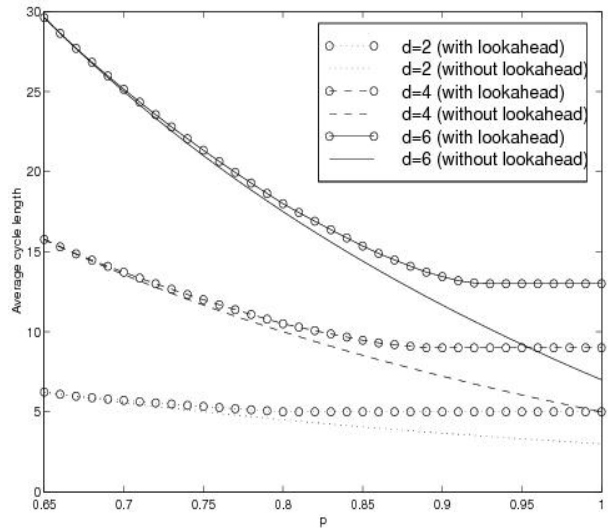


Fig. 6. The average path length a mobile traveled between two consecutive location updates (the linear case).

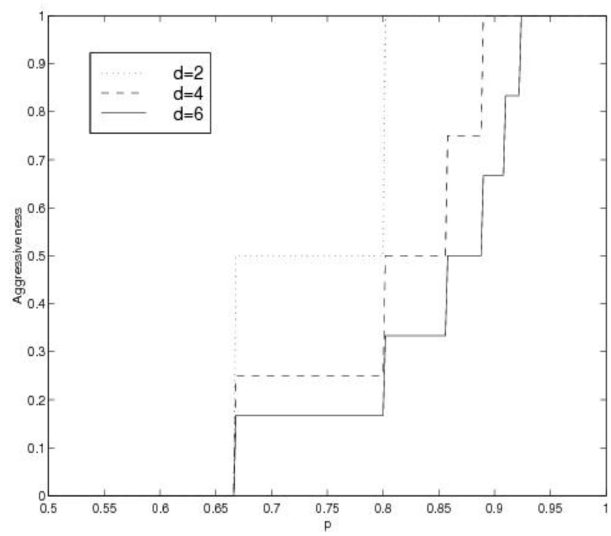


Fig. 7. Aggressiveness of lookahead.

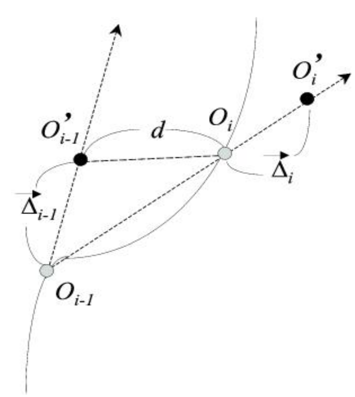


Fig. 8. Lookahead in a planar mobility graph.

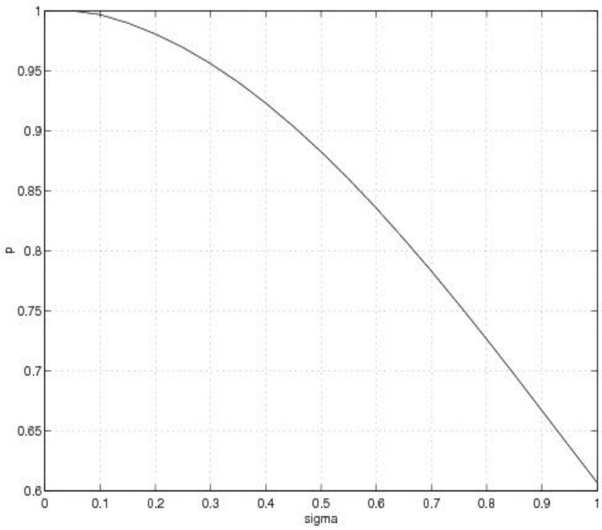


Fig. 9. Transformation of scale index.

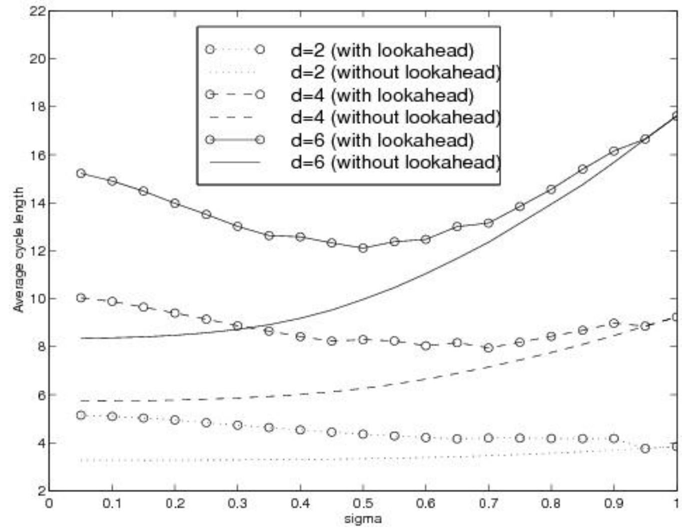


Fig. 10. The average path length a mobile traveled between two consecutive location update (the mesh case).

Next, we employ the result of optimal lookahead in the one-dimensional case to calculate the magnitude of $\vec{\Delta}_i$. By integrating all the vector components of rotation that are parallel to the direction of $\theta = 0$, the two-dimensional scale index σ can be transformed to the one-dimensional scale index

$$p \simeq \int_{-\infty}^{\infty} f(\theta) cos\theta d\theta \quad (22)$$

where the normal density function with parameters $\mu = 0$ and σ^2 are

$$f(\theta) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{\theta}{\sigma})^2}, \quad -\infty < \theta \leq \infty. \quad (23)$$

The result is shown in Figure 9. For now, in a planar graph, given distance threshold d and scale index σ, we can also determine the magnitude of lookahead vector $\vec{\Delta}_i$. That is, for given parameter σ, we transform it to p by Equation (22) first. Then for given distance threshold d and parameter p, we apply Equations (20) and (21) to determine the magnitude of lookahead vector $\vec{\Delta}_i$.

However, the magnitude of optimal lookahead $\vec{\Delta}_i^{\,*}$ cannot be determined until the optimal distance threshold d^* is obtained. In the following section, the determination of optimal distance threshold d^* for the minimal total tracking cost is presented. The setting of distance thresholds should be based on the statistics of each user's personal history. In other words, it should be dynamically adaptive to the mobility and call patterns on a per user basis.

VI. Optimization of Distance Threshold

The total cost of location tracking on a certain mobile can be defined as the sum of location update cost plus terminal paging cost. The location update cost can be written as $C_{lu} = U\lambda_{lu}$, where U denotes the cost per location update and λ_{lu} is the location update rate. The terminal paging cost is $C_{tp} = V\lambda_{tp}$, where V denotes the cost per terminal paging request for a mobile terminated call in one cell and λ_{tp} is the terminal paging rate. Therefore, the total tracking cost can be defined as the sum of a decreasing function and an increasing function of d:

$$C \stackrel{\text{def}}{=} C_{lu} + C_{tp} \quad (24)$$
$$= U\lambda_{lu} + V\lambda_{tp} \quad (25)$$
$$= \frac{U\lambda_m}{E[M(d,\sigma)]} + V\lambda_c N(d) \quad (26)$$

where $E[M(d,\sigma)]$ is the expected cycle length with respect to distance threshold d and scale index σ, λ_c is the call arrival rate, and $N(d)$ is the *cardinality* of location area with distance threshold d (the number of cells wherein). Here we assume that each location area has equal cell density, *i.e.,* $N(d_1) = N(d_2)$ if $d_1 = d_2$. For example, in a regular mesh layout, for $d = 0, 1, 2, 3, 4, 5, 6$, $N(d) = 1, 5, 13, 29, 49, 81, 113$. Furthermore, we assume that location update is only performed by the mobile terminal due to its mobility, and the duration of incoming(/outgoing) calls to(/from) the mobile terminal is negligible compared to the *cell dwell time* $(1/\lambda_m)$.

The expected cycle length with (resp., without) lookahead $M_{d+1+\Delta}$ (resp., M_{d+1}) with respect to d and p in linear mobility graph can be easily calculated in **Procedure** LOOKAHEAD. However, the expected cycle length $E[M(d,\sigma)]$ for the planar mobility graph does not appear readily available. By using the *Monte Carlo* (simulation) method, the values of $E[M(d,\sigma)]$ in a mesh layout are summarized in Figure 10. For example, for $d = 4$ and $\sigma = 0.4$, the average cycle length is 8.42 for location updates with lookahead strategy but only 6.01 for location updates without it. So, the location update rate is reduced by 29 percentage in this case.

Clearly, the optimal distance threshold d^* can be found easily by using a linear exhaustive search. That is, for $d = 0, 1, ..., d_{max}$, we compute the total cost C_d individually. The optimal distance threshold d^* is the one making total tracking cost minimal, C^*. A simplified pseudo-code for finding d^* is shown in the following procedure.

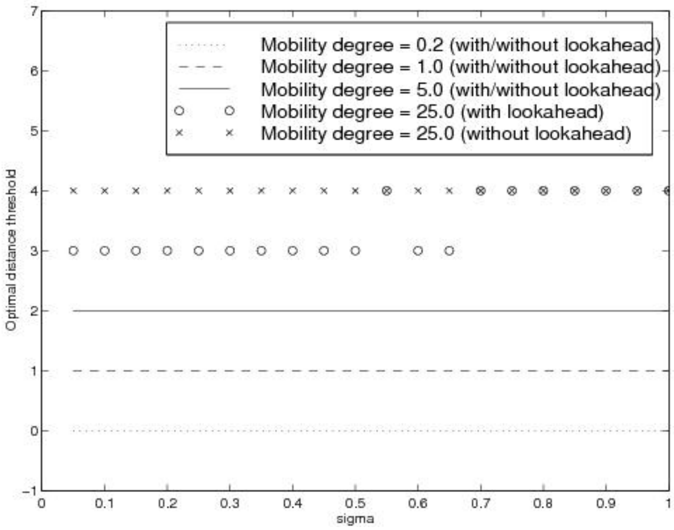


Fig. 11. Optimal distance threshold for various mobility degrees and scales (U=20, V=1).

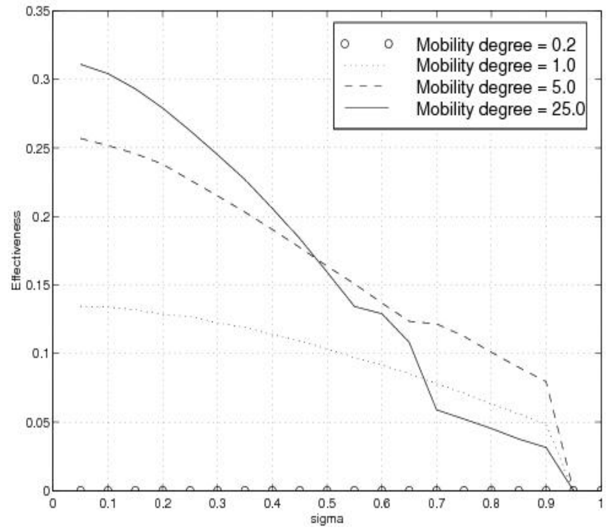


Fig. 12. Effectiveness of lookahead.

Procedure THRESHOLD($\lambda_c, \lambda_m, \sigma$)
  $C^* \leftarrow \infty$
  for $d = 0$ **to** d_{max} **do**
    if $d = 0$ **then**
      $C \leftarrow U\lambda_m + V\lambda_c$
    else if $d = d_{max}$ **then**
      $C \leftarrow V\lambda_c N(d_{max})$
    else
      $C \leftarrow \frac{U\lambda_m}{E[M(d,\sigma)]} + V\lambda_c N(d)$
    if $C < C^*$ **then**
      $C^* \leftarrow C$
      $d^* \leftarrow d$
  return(d^*)

Here the network's size is limited by diameter d_{max}; for the sake of simplicity, we assume that the layout is wrapped up so that the boundary effect can be ignored [19]. Intuitively, if a mobile is relatively static, then the distance threshold should be shrunk in order to lower the excess terminal paging cost. In contrast, if a mobile takes relatively few incoming calls, then the distance threshold should be expanded to reduce the frequency of updates. If the optimal d is tailored to 0 for a certain mobility degree then it means "always update." That is, the mobile will update its location at every cell crossing ($M = N = 1$). So, the tracking cost is $U\lambda_m + V\lambda_c$, which is irrelevant to mobility scale. On the other hand, if $d^* = d_{max}$, then the mobile will "never update" no matter how long it traveled within the system. In such a case, the total cost is $V\lambda_c N(d_{max})$.

Figure 11 shows the optimal distance threshold with respect to scale index σ for various mobility *degrees* ($\frac{\lambda_m}{\lambda_c}$). In general, the greater the mobility degree, the larger the optimal distance threshold. Although the optimal distance threshold is mainly determined by mobility degree, it is still remarkable that, for the same mobility degree and scale, the optimal distance thresholds for distance-based schemes *with* and *without* lookahead strategies may be different.

VII. Effectiveness of Lookahead

This section examines the effectiveness of lookahead for mobile users with various mobility patterns on a planar graph. Due to the important relationship between location update and terminal paging, it is inadequate to consider performance gain on location update only, because the total tracking cost to be saved by using the lookahead strategy is limited by the fraction of location update cost. In this section, we also take the terminal paging cost into account in spite of no reduction on it.

Let the minimized total tracking cost with (resp., without) lookahead be C_L^* (resp., C^*). We can define the *effectiveness* of lookahead as the *cost saving ratio*

$$\beta = \frac{C^* - C_L^*}{C^*}. \quad (27)$$

Figure 12 shows the effectiveness of lookahead for a planar mobility graph with mesh layout. For instance, if the mobility degree is $\lambda_m/\lambda_c = 5.0$ and mobility scale index is $\sigma = 0.4$, we obtained a total savings of 19 percentage. Apparently the more straight-oriented the mobile user (with a smaller σ) is, the more the lookahead strategy saves.

Finally, the optimality of the proposed lookahead strategy for a planar mobility graph is investigated even though the total tracking cost is reduced significantly. By the brute force method, for a given distance threshold d and scale index σ, we can apply the Monte Carlo method to estimate the average cycle length $E[M(d,\sigma)]$ for $\vec{\Delta}$ with magnitude $|\vec{\Delta}| = 0, 1, ..., d$, respectively. Then, the "best" lookahead magnitude $\vec{\Delta}$ can be found by choosing the one with maximal $E[M(d,\sigma)]$. Surprisingly, the original method[5] proposed in Section 5 [6] is

[5]Theoretically the optimal lookahead direction based on the planar normal walk should be the same as that of the last cell crossing. However, we choose the long-term moving direction to reduce the performance sensitivity with respect to the distortion of topology embedding and the accuracy of mobility modeling (on which the percentages of location update of type "win", "loss" and "tie" depend).

[6]Note that the formulation in Equations (20) and (21) are for the linear mobility graph.

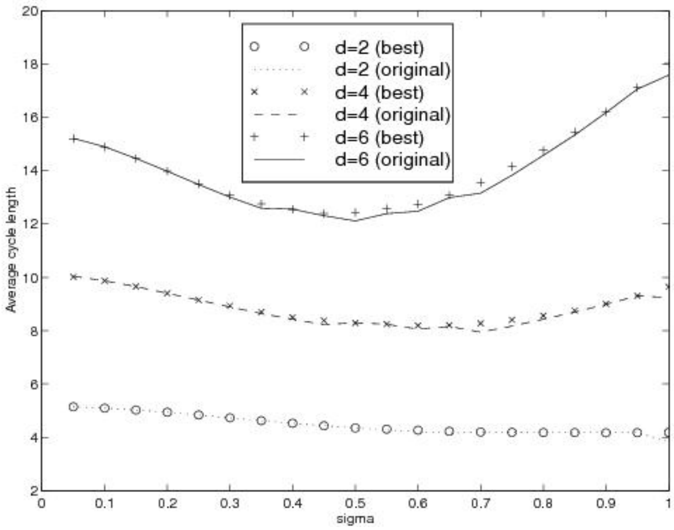
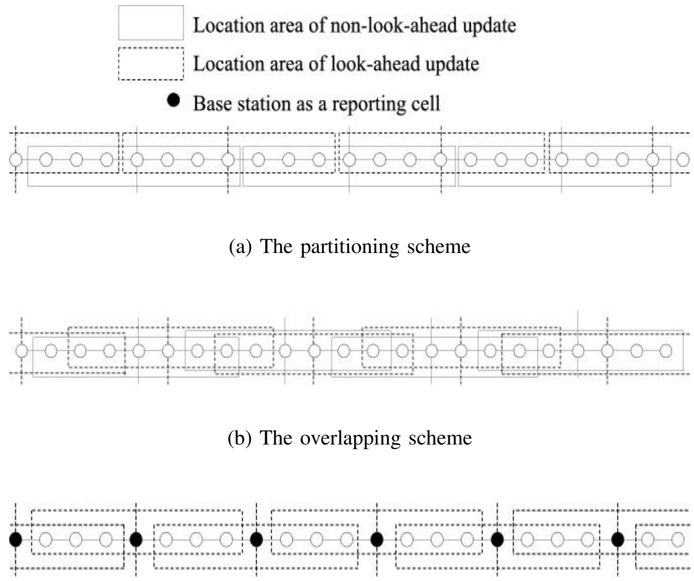


Fig. 13. The optimality of the proposed lookahead in a planar mobility graph.



(a) The partitioning scheme

(b) The overlapping scheme

(c) The reporting cell scheme

Fig. 14. Equivalence of distance-based location tracking with lookahead strategy.

very close to the best value found by simulation (see Figure 13).

VIII. Concluding Remarks

This paper modeled user's mobility as a Markov chain and introduced the lookahead strategy for distance-based location tracking. By applying the algorithmic approach developed in this paper, for a certain mobile, given its mobility degree and scale index, the appropriate distance threshold and lookahead value can be derived such that the total location tracking cost is reduced significantly.

It is remarkable that, for a linear network layout, distance-based location update combined with the lookahead strategy is a general form of *static topology-based* tracking schemes (*i.e.*, the partitioning scheme [4], the overlapping scheme[20] [21], and the reporting cell scheme [22] [23] [24]). First, a *partitioning scheme* with mutually exclusive location areas of the same cardinality $2n+1$ is equivalent to the distance-based scheme with fixed distance threshold n and lookahead n (see Figure 14(a)). Secondly, an *overlapping scheme* with location areas of cardinality $2n+1$ and hysteresis h $(0 \leq h \leq n)$ is equivalent to the distance scheme with fixed distance threshold n and lookahead $n-h$ (see Figure 14(b)). Finally, a *reporting cell scheme* in which every other n cell is a reporting cell is equivalent to the distance-based scheme with distance threshold n and zero lookahead (see Figure 14(c)).

A mobile terminal in idle mode (without dedicated traffic channel is allocated) is by no means idle. In addition to continuously keeping synchronized with the serving cell, monitoring downlink signal strength and quality around, receiving various system information from beacon channels and periodically listening to terminal paging messages; every mobile should also update its location at both the right *time* and right *place*.

Several reasons may cause mobiles to perform location update even if they do not change location:

- *Periodic updating*: Mobile updates its location periodically in order to enhance the reliability of the location register.
- *Power on/off*: Mobile terminal notifies network that it is switched on/off so the system can decide whether the terminal paging request should be issued whenever a new mobile terminated call is made (so-called IMSI attach/detach [16]).
- *Cell reselection*: Mobile reselects a new cell to camp on which belongs to another location area in case the state of downlink signaling channel is not good enough.
- *Network reselection*: Mobile user makes a registration to another service provider manually.

One may argue that, first, over a long time interval a mobile may reside at the same cell: it is of no use to lookahead for the mobile if it keeps static at some specific position such as home or office. Secondly, it is useless to lookahead when the mobile terminal is switched off. Thirdly, lookahead direction cannot be determined when the tracking process is reset (power on or network reselection). Nevertheless, an aggressive lookahead does no harm because the location information is not lost and no extra terminal paging cost is incurred. Thus we can conclude it is never necessary to prevent location updates from lookahead, even if the above conditions cannot be distinguished in the update message.

The future works include the validation of normal walk, the estimation of location probability for muti-step paging, and other methods that optimize the look-ahead direction in planar graphs. We believe the proposed strategy can be realized since the mobility degree and scale are likely to be available in each user's profile [14] [25] and road map. In short, battery power and radio resources are more expensive than computing power on fixed networks. By exchanging computation overhead such as profiling and prediction on a network, the cost of mobility management for personal communication services can be reduced.

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