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A speed-adaptive strategy for location management cost reduction in cellular networks

Zhijun Wang · Jingyuan Zhang

Abstract A speed adaptive location management scheme will greatly reduce the cost of tracking mobile stations, because mobile stations can travel at a wide range of speeds. Recently, an elegant distance- and time-based scheme has been proposed. The scheme uses a look-up table which describes the relationship between the distance and the time: the distance decreases while the time increases. In the scheme, the paging area for a mobile station will be automatically reduced if the mobile station does not update its location over a certain time period. Therefore, the scheme performs well when a mobile station travels at a low speed. However, it does not perform well when the incoming call arrival rate is high or when the speed of a mobile station is high. To overcome those drawbacks, a novel speed-adaptive scheme is proposed in this paper. The proposed scheme uses an enhanced look-up table that consists of two parts: the distance in the first part increases while the time increases; in the second part, the distance decreases with the increasing time. By introducing the first part, the proposed scheme reduces the paging cost for a call arriving shortly after a location update, and adapts to the speed range of a mobile station. To reduce the paging cost further, a paging angle is introduced for high-speed mobile stations. Numerical simulations using various activity-based models and random walk models show that the proposed scheme performs well for mobile stations traveling at both high and low speeds.

Keywords Cellular networks · Location management · Location update · Paging · Performance comparison

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1. Introduction

Location management is one of the key issues in cellular networks. The goal of location management is to track the location of an active mobile station that is not in a call. A mobile station becomes active after it has performed a power-on registration with the network. Location management does not deal with a mobile station with a call in progress because the exact location of the mobile station must be known to the network during a call. Location management consists of two basic operations: location update and paging. A location update is performed by a mobile station. Through this operation, the mobile station sends its current location and other related information to the cellular system. The paging operation is performed by the cellular system when an incoming call for a mobile station arrives. In this operation, the cellular network pages the mobile station in all possible cells to find out the cell in which the mobile station is currently located, so the incoming call can be routed to the corresponding base station. Both location update and paging operations consume resources such as the wireless network bandwidth. In a cellular network, how to minimize the costs of these two operations is always an important and challenging problem.

There are two basic kinds of location management schemes: static and dynamic [4,5]. In a static scheme, there is a predetermined set of cells at which a location update must be generated by a mobile station, regardless of its mobility. The *location areas* scheme used in the current network is an example of the static scheme. In a dynamic scheme, a location update can be generated by a mobile station in any cell depending on its mobility. Examples of dynamic schemes include time-based [4,16], movement-based [1,4,9],and distance-based [4,8,11]. It has been shown that the distance-based schemes are more efficient than the movement-based and time-based ones [4]. In [10], the authors show how to implement a dynamic scheme on top of the current cellular network infrastructure. Other location management schemes include profile-based [17], topology-based [3], and entropy-based [5]. For detailed information about location management, please refer to recent surveys in [14, 21].

Since mobile stations can travel at a wide range of speeds, a speed adaptive scheme will greatly reduce the location management cost. Recently the author in [12] has proposed a distance- and time-based location management scheme, referred to as the ZN scheme hereafter, which uses a pre-defined look-up table for location updates. The table describes the relationship between the distance and the time: the distance decreases while the time increases. When a time in the table has elapsed, if a mobile station has traveled more than the corresponding distance, it performs a location update. In this way, the paging area for a mobile station will be automatically reduced if the mobile station does not update its location over a certain time period. Therefore, this scheme performs well when a mobile station travels at a low speed.

However, the ZN scheme does not perform well when the incoming call arrival rate is high or the speed of a mobile station becomes relatively high. To overcome these drawbacks, we propose a speed-adaptive scheme. The scheme uses an enhanced look-up table that consists of two parts: the distance in the first part increases while the time increases; in the second part, the distance decreases with the increasing time. The first part is introduced to deal with the high incoming call arrival rate and to adapt to the speed of a mobile station. To reduce the paging cost for a high-speed mobile station, a paging polar angle is introduced to associate with a speed range. This is because a high-speed mobile station does not makes frequent or big direction changes. We will show that the proposed scheme performs well for mobile stations traveling at a high speed as well as for those traveling at a low speed.

The rest of the paper is organized as follows. Section 2 introduces our speed-adaptive location management scheme, including the location update and paging rules of the scheme, a detailed explanation of the scheme, and the implementability of the scheme with real networks. Section 3 presents the results from numerical simulations in honeycomb networks, and shows the validity of the results in real networks. Section 4 summarizes the results and proposes future work.

2. Speed-adaptive location management scheme

In this section we will present our speed-adaptive location management scheme. We will first present the scheme in ideal honeycomb networks [15,18]. We then describe the implementability of the scheme with real networks.

2.1. The scheme in honeycomb networks

The scheme proposed in this paper is based on the ZN scheme [12]. The basic idea of the ZN scheme is that a mobile station makes use of a look-up table to perform location updates. The table describes the relationship between the distance and the time: the distance decreases while the time increases. The distance is measured in terms of cells. This is mainly because a cell is the smallest unit to be paged. The distance between two cells is defined as the minimal number of cells that needs to be crossed to reach one cell from the other.

Table 1 shows the general form of the look-up table with k columns, in which $D_1 > D_2 > \cdots > D_k$ and $T_1 < T_2 < \cdots < T_k$.

In the ZN scheme, when time T_i has elapsed since the last update, a mobile station performs a location update if the distance it has traveled exceeds D_i. This means that, if a mobile station has not performed any location update when time T_i has elapsed, the mobile station is within distance D_i from the last update location. Therefore, the cellular system only needs to page all the cells within distance D_i from the last update location when an incoming call arrives for the mobile station.

Table 2 shows an example of the look-up table in the ZN scheme. For ease of explanation, we use miles instead of cells for the distance. According to the ZN scheme, if 50 min has elapsed and the mobile station has not performed any location update, the system only needs to page a circular area with a radius of 10 miles from the last reported position when an incoming call arrives. Furthermore, if the mobile station does not perform any location update within the next 10 min, the system only needs to page an area with a 5-mile radius.

If a mobile station travels at a low speed, it will be unlikely for the mobile station to perform any location update. Yet, the cellular system can pinpoint its location by paging a very small area when a call arrives. However, the ZN scheme has some drawbacks. First, when a call arrives shortly after the location update, the cellular system needs to page a very large area according to the scheme. Secondly, when a mobile station travels at a high speed, it needs to perform location updates very frequently or the system needs to page a very large area for an incoming call. Our

Table 1 The look-up table in the ZN scheme

D_1	D_2	...	D_i	...	D_{k-1}	D_k
T_1	T_2	...	T_i	...	T_{k-1}	T_k

Table 2 An example of the look-up table in the ZN scheme

D (miles)	30	25	20	15	10	5
T (hours)	1/6	1/3	1/2	2/3	5/6	1

scheme is proposed to overcome these drawbacks. In our scheme, we will use an enhanced table that consists of two parts: the distance in the first part increases while the time increases; in the second part, the distance decreases with the increasing time.

Next we will show how to construct our look-up table of distance d_i and time t_i based on the look-up table in the ZN scheme. As in the ZN scheme, the distance d_i is measured in terms of cells. First, we compute the critical time T_c that is used to split the table into two parts: the first part deals with the situation when time $t < T_c$, while the second part deals with $t \geq T_c$. To compute the critical time, we need to introduce the concept of the speed mode. We assume that the speed of a mobile station falls into one of the speed ranges, in general, as below:

$$(0, v_1), (v_1, v_2), \ldots, (v_{k-1}, v_k), \ldots, (v_{m-1}, v_m).$$

Here v_{k-1} and v_k are the minimal and maximal speeds in cells per hour of a speed range, and they correspond to the actual minimal and maximal speeds permitted within a certain area. For example, the speed of a mobile station usually falls between 0 and 70 miles per hour, and we can divide the range into three speed ranges: (0, 15), (15, 45), and (45, 70), which correspond to travel in a crowded area (or walking), local travel, and highway travel, respectively. The unit used for distance in our scheme is in terms of cells. Those speed ranges can be represented in cells per hour based on the cell size. For convenience, we define $R_k = (v_{k-1}, v_k)$, and if a mobile station travels at a speed within (v_{k-1}, v_k), we say that it travels at speed mode k. Parameter m is the number of speed modes, v_m is the maximum possible speed, and v_k denotes the maximum speed under speed mode k. The critical time T_c is obtained by finding the intersection of the line $d = v_k * t$ and the curve defined by the look-up table in the ZN scheme as shown in Fig. 1. The parameter D_i is a non-increasing function of time, but it is not necessarily linear with time, as shown in the figure.

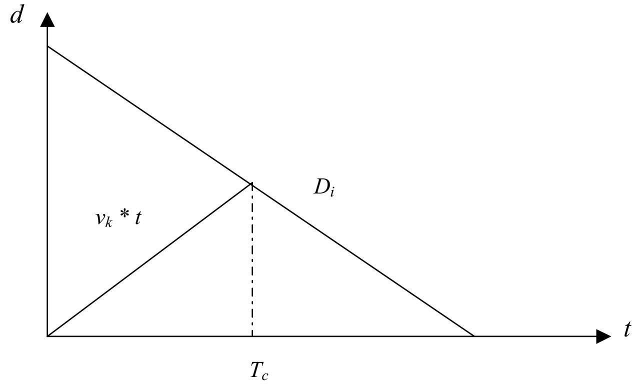


Fig. 1 Construction of the enhanced look-up table

In our look-up table, $t_i = T_i$ and d_i can be calculated from the following formula:

$$d_i = \begin{cases} v_k * t_i, & \text{if} \quad t_i < T_c. \\ D_i, & \text{if} \quad t_i \geq T_c. \end{cases}$$

Both the cellular system and the mobile station know the D_i vs. T_i table. The d_i vs. t_i table is obtained based on the speed mode, the D_i vs. T_i table, and the method described above. The d_i vs. t_i table is updated on both sides when a mobile station changes its speed mode and reports the speed mode change to the cellular system. The enhanced look-up (i.e. d_i vs. t_i) table consists of two parts divided by T_c. The first part deals with the situation when time $t < T_c$ while the second part deals with $t \geq T_c$. In the first part, the distance increases while the time increases; the distance in the second part decreases with an increase in time, just as in the ZN scheme.

2.1.1. *Location update scheme for mobile stations*

By using the enhanced look-up table, a mobile station performs a location update if either of the following conditions is true:

Condition I.

Part one: if $t < t_i < T_c$, the mobile station has moved a distance $d = d_i$ since the last update.

Part two: if $t \geq t_i \geq T_c$, the mobile station has moved a distance $d = d_i$ since the last update.

Condition II.

The mobile station is going beyond the polar angle permitted by its current speed mode. (The concept of a paging polar angle will be introduced in the paging scheme section.)

In our speed-adaptive scheme, a mobile station needs to perform a location update whenever it jumps into a new speed mode. This is included implicitly in Part one of Condition I. We can see that when $t < T_c$, the first part of the look-up table is used. So if $t_{i-1} \leq t < t_i$ and the mobile station has traveled a distance $d = d_i$, it actually exceeds the maximum speed permitted by the current speed mode based on the definition of d_i. In this case, a location update becomes necessary based on the scheme. The first part of Condition I is also able to deal with high incoming call rates. When the incoming call rate is high, a call can arrive shortly after the last location update. In this case, our scheme pages a much smaller area than the ZN scheme does.

Part two of Condition I corresponds to $t \geq T_c$. It states that, if the distance a mobile station has traveled exceeds d_i when time t_i has elapsed since last update, it needs to perform a location update. The second part is inherited from the ZN scheme. It deals with a mobile station traveling at a relatively low speed.

To reduce the paging cost for a high-speed mobile station, we will introduce the concept of paging polar angles later. To be consistent with the paging policy, a mobile station needs to update its location when it moves beyond the polar angle permitted by its current speed mode, as specified in Condition II.

2.1.2. Paging scheme for the cellular system

Our paging scheme uses two parameters to limit the paging area: paging radius and paging polar angle. There exist two cases in terms of time t for the paging radius parameter. If $t < t_i < T_c$ and a mobile station has not updated its location, the cellular system can use d_i as the paging radius because the mobile station must be within a distance d_i from its last update location. This is obvious because the maximal speed limit is built into the first part of the look-up table. We can see that the cellular system only needs to page a small radius when time t is small. If $t \geq t_i \geq T_c$ and a mobile station has not updated its location, it must be within d_i from its last update location, so d_i is the paging radius in this case. The idea for this part is similar to the ZN scheme; it performs well when the mobile station travels at a relatively low speed.

When an incoming call arrives, the cellular system only needs to perform paging within the paging radius as defined above. This operation could be very expensive, especially when the mobile station travels at a very high speed. From real-life mobility cases, we can see that the faster a mobile station is moving, the less likely it would make big or sudden direction changes. The concept of paging polar angles is introduced to reduce the paging cost for a high-speed mobile station. So when an incoming call arrives, for most of the time, the cellular system only needs to page a fraction of the paging circle instead of the whole circle. In our scheme, the paging polar angle is defined as a function of the speed mode:

$$\Phi_k = f(R_k) \quad \text{for} \quad k = 1, 2, \ldots, m.$$

Figure 2 illustrates the idea of the paging polar angle in our paging scheme. The x-y-z coordinate system is used for easy computation of the distance between cells in a honeycomb network [20]. As we can see from the figure, the paging area is the shaded area that is defined as the intersection of the paging polar angle and the paging circle.

For three speed ranges $\{R_1, R_2, R_3\}$ mentioned in the previous example, the corresponding paging polar angles can be set to 360°, 120°, and 60°, respectively. According to our location update and paging scheme, if the mobile station is traveling at R_3 (i.e. the highway speed mode), the cellular system only needs to page an angle of 60° when an incoming call arrives. Of course, the mobile station needs to update its location if it goes beyond the permitted 60°. To be precise, the mobile station needs to update its location if it moves into a cell whose base station is outside the permitted angle. Correspondingly, the system needs to page all the cells whose base stations are in the permitted angle.

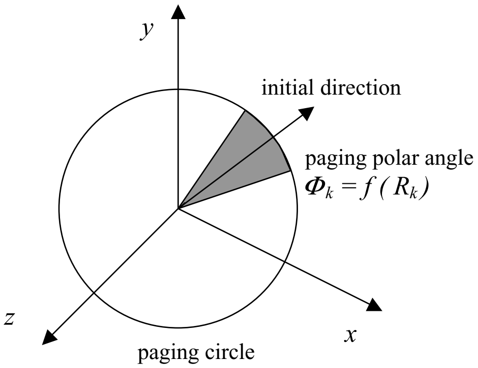


Fig. 2 Paging circle and paging polar angle

In the scheme, position, distance, and direction are defined in terms of cells. Each base station broadcasts its position, and a mobile station determines its position by listening to broadcasting from base stations. In [13,20], the authors proposed to use the base station position in the x-y-z coordinate system as the cell ID. With this cell ID assignment scheme, the distance and the direction in terms of cells can be computed easily.

Next let us analyze the possible mobility cases for a mobile station. First, if the mobile station travels at the low-speed range all the time, it uses the second part of the look-up table. In this case, our scheme acts similarly to the ZN scheme, except that there is an issue of the paging polar angle in our scheme. Usually, it does not make any difference, because the paging polar angle is 360° if the speed is relatively low. If the speed is not very low, and the paging polar angle is less than 360°, the mobile station needs to perform an update each time it goes out of this angle. In return, the paging effort is reduced because the cellular system does not need to perform paging over a 360° range. In the low-speed range, this is infrequent.

Secondly, if a mobile station stays in some high-speed mode all the time, location updates will not be more frequent than the ZN scheme because the enhanced look-up table is especially constructed for that speed mode. Although a mobile station needs to perform an update when it goes out the polar angle permitted by the current speed mode, this does not happen frequently in real-life mobility cases because the faster a mobile station moves, the less likely it will make big direction changes. The paging effort is much reduced in this case because the paging polar angle is small for a high-speed range.

If the mobile station switches from a higher speed mode to a lower speed mode, it does not perform a location update for a long time based on our look-up table. Finally, the mobile station will use the second part of the look-up table and the situation is just like the first case. The paging radius will be small because the second part of the table is used. On the other hand, if the mobile station switches from a lower speed mode to a higher speed mode, it will perform a location update and send its new speed mode to the cellular system. In this case, both the cellular system and the mobile station will compute a new look-up table to suit the current high-speed mode. Because the speed mode, represented by a few bits, is the only additional information a mobile station needs to send, it will not incur much network traffic.

2.2. Implementability of the scheme with real networks

Although a honeycomb network has a lot of virtues, real networks do not exactly follow the honeycomb pattern. In a real network, the base stations are not necessarily uniformly distributed, and the cells have different sizes and shapes. In addition, a current network such as the GSM system uses the location area location management scheme in which the whole service area is divided into location areas. Each location area consists of contiguous cells that are controlled by the same mobile switching center (MSC for short) [6].

In our scheme, each base station needs to broadcast its ID which indicates its position in the network. If the base stations are not uniformly distributed, we first compute a virtual uniform network such that each virtual cell contains at most one base station, as described in [7]. Note the position, not the coverage, of a base station is contained in a virtual cell. Figure 3 illustrates an example of a uniform virtual network constructed for seven non-uniformly distributed base stations. The ID of a base station will then be assigned based on the virtual cell in which the based station is located. The ID assigned to a base station approximates the physical location of the base station in terms of virtual cells. The computation of the virtual uniform network and the cell ID assignment can be done off-line in the network planning stage. Although there is a cost to upload the new IDs, we ignore it because it is a one-time cost.

The uniform virtual network described above is just for approximating the physical location of the base stations. The coverage of the base stations stays unchanged. In our scheme, a mobile station works similarly to one in the current system. It remembers the ID of the cell it is currently in and monitors the strength of control signals that are broadcast from neighboring base stations as well as the current base station. When the signal strength of a neighboring base station exceeds that of the current base station by a certain amount, it indicates that the mobile station moves into the neighboring cell. Correspondingly, the mobile station obtains the neighboring cell ID from the control signal and records it as the current cell ID. Based on the new ID, the mobile station computes the new distance as well as the direction relative to the last updated cell. The distance is represented in terms of virtual cells because the both IDs are in virtual cells. The speed can be computed from the distance because a mobile station also keeps the elapsed time. Finally, the mobile station can determine if a location update is needed based on the look-up table and the criteria described in Section 2.1. However, the look-up tables here are defined in virtual cells. When a location update is preformed, the network (either the visitor MSC or the home MSC [15]) can compute a new look-up table as the mobile station does.

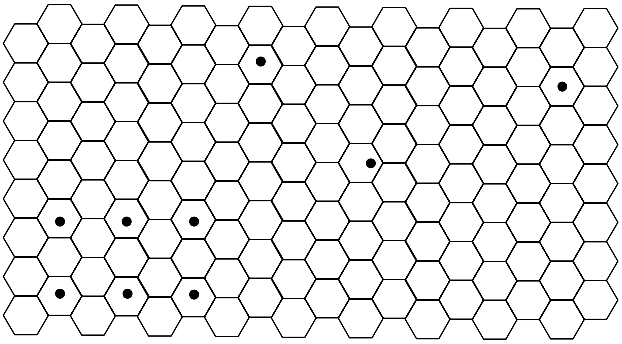


Fig. 3 A uniform virtual network for non-uniformly distributed base stations

Due to the dynamic nature of the scheme, the network needs to know how to page all the cells within a certain distance from the last reported cell based on cell IDs (referred to as the paging area hereafter). For our scheme to work with the current location area based system, the network (either the home MSC or the visitor MSC) needs to compute which location areas intersect with the paging area, and each MSC shall have the capability of paging a subset of cells in its location area. The idea is similar if the paging area is a sector.

It is worthy to mention that the scheme assumes that a mobile station reaches a base station whenever it enters the actual area covered by the base station and that the paging is always done in terms of actual cells. Although there is a difference between the distance computed in this scheme and the physical distance, the difference will not cause any paging error. This is because there is a correlation between the paging and location update strategies, and both the network and mobile stations follow the same strategies. A paging attempt would fail if the mobile station was not within the current paging area. However, the location update rule stipulates that, when the mobile station moves out of the current paging area, it needs to update its location and to have its new paging area calculated. Although the paging area (either a circle or a sector) is regular in our description, the actual paging area in a real network is the area covered by the base stations that are located within the circle or the sector. Correspondingly, if a mobile station moves into a cell whose base station is outside of the circle or the sector, the mobile station will initiate a location update.

Finally, the same look-up table needs to be stored in the mobile station and in the network. The basic table (the table used by the ZN scheme) can be decided at signup for service and stored at HLR (Home Location Register). If it is desired, the basic table can be updated during off-peak time periods. When a mobile station is roaming, the basic table will be sent to VLR (Visitor Location Register) of the visitor MSC. Whenever a mobile station performs a location update, it also reports the current speed mode in a few bits. Once the speed mode is known at both the network and the mobile station, the same enhanced look-up table can be derived from the basic table using the same algorithm.

Since the current network infrastructure and mobile stations are all programmable, our proposed scheme is implementable in the current network. In addition, the information required by our scheme is very small in terms of storage and wireline bandwidth. For example, 1 Kb should be more than enough to represent a look-up table. Consequently, no additional hardware is required for the implementation.

3. Simulations

In this section, we evaluate the performance of our speed-adaptive location management scheme. We first address main simulation-related issues, and then present the simulation results in the ideal honeycomb network under both the activity-based model and the random walk model. Finally we analyze the validity of the simulation results in real networks. Since it has been claimed in [12] that the ZN scheme performs better than timer-based, geographic-based, and distance-based schemes, we only compare the proposed scheme with the ZN scheme.

3.1. Simulation-related issues

How to construct look-up tables is the first issue to be addressed in the simulation. Our look-up tables are based on the look-up tables in the ZN scheme. There are two constraints on the look-up table in the ZN scheme: the distance variable has to be kept non-increasing and the corresponding time variable has to be kept non-decreasing. Since the ZN scheme does not specify how the look-up table is actually constructed, we will try different methods to construct it. To construct the look-up table in the ZN scheme, we can keep the distance variable linear while trying the time variable in different ways, or vice versa. Specifically, we will use various linear factors and random factors for the time variable. By using a linear factor (or a random factor), we mean that the time variable increases by a constant (or a random number) between two consecutive distances. Different table sizes are also used. The distance in the look up table is in terms of cells. In our simulation, the cell diameter is fixed at 2 miles, and three speed modes in miles per hour are assumed: (0, 15), (15, 45) and (45, 70), with the paging polar angles being 360°, 120°, and 60°, respectively. The speed modes are converted to be represented in cells per hour based on the cell diameter, which is statically accurate. The distance traveled by a mobile station in terms of cells is obtained from the actual travel path. Based on the look-up table constructed for the ZN scheme, the look-up table for our scheme can be constructed using the formula from Section 2.1.

The call arrivals rates (or call inter-arrival times) and mobility models are two important factors for evaluating location management schemes. It is assumed by many researchers that the call arrival process is a Poisson process. The discrete case is used in our simulations. Both the proposed scheme and the ZN scheme have been tested under various activity-based models and random walk models.

The location management cost includes wireline and wireless bandwidth utilization. Most researchers only focus on the bandwidth usage on the wireless part. This is because the bandwidth of the wireline network is always expandable whereas the radio frequency spectrum assigned for cellular communications is not. In other words, it is easier for a company to expand its wireline network. Yet it is much more difficult to ask authorities (FCC in the Unite States for example) to set aside more frequency spectrum for cellular communications. Therefore, making efficient use of the assigned wireless bandwidth is an ultimate goal for many researchers. In this paper, we will consider only the wireless bandwidth usage in accord with other researchers.

Both location update and paging consume wireless bandwidth. Each time a mobile station performs a location update, the total location update cost will be incremented by one; and each time the system performs a paging operation, the total paging cost will be increased by the number of cells it has paged because each base station needs to consume certain wireless bandwidth for paging. To compute the total location management cost, some researchers assume one location update operation costs the same amount of wireless bandwidth as performing a paging operation in a single cell whereas the others use different weights. To make it more general, in this paper, the total location update cost and total paging cost are separately considered, but they are stacked together in black and white in our presentation. Without considering the colors, the height indicates the total location management cost when the weights are the same.

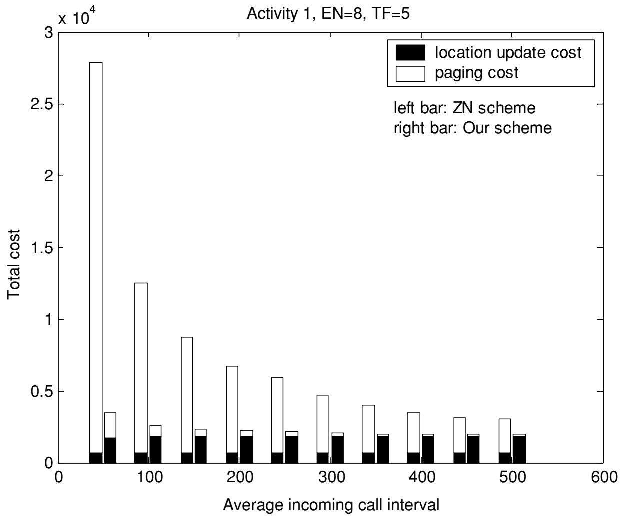


Fig. 4 Simulation result for Activity 1 with EN = 8 and TF = 5

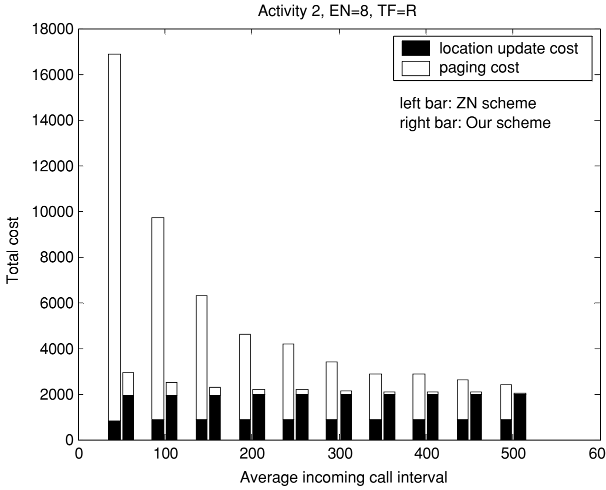


Fig. 5 Simulation result for Activity 2 with EN = 8 and TF = R

3.2. Activity-based model

In an activity-based model, some cells are designated as activity cells, in which a mobile user may perform certain activities [17]. The non-activity cells are referred to as route cells. At a certain speed, a mobile station usually travels from one activity cell to another and stays in an activity cell for a certain period of time. Different activity patterns are constructed and used to test the two schemes. We will show three cases in the following subsections: high-speeds, low-speeds and mixed-speeds. These cases (or activities) simulate three different kinds of real-life situations for mobile users.

3.2.1. Activity 1: High traveling speeds and infrequent direction changes

The first case is to model a mobile user making a long distance travel from one city to another. In this case, the mobile user is traveling at a high speed, mostly on the highway. Specifically, we assume that the mobile user travels at an average speed of 1 mile per minute, which is the fastest among the three cases. We also assume the mobile user only makes 10 direction changes along the whole path, because a mobile user traveling at a high speed makes infrequent direction changes. Each simulation has been run for 10,000 min that is about one week. Look-up tables are constructed systematically based on the methods explained in Section 2.1. Figure 4 shows the result from simulations with an 8-element look-up table.

In Fig. 4 and all of the following figures, "EN" is used to specify the number of elements in the look-up table, while "TF" stands for the time factor that tells how the time parameter values in the look-up table are specified. For example, "EN = 8" means that the look-up table has 8 elements. "TF = 5" indicates that the linear time factor is used and the time value increases by 5 min for each column in the table. The average incoming call interval varies from 50 to 500 min.

This case is similar to the fluid flow model. It is well known that under the fluid flow model, the direction of a mobile station is uniformly distributed in the range of $(0, 2\pi)$ [19]. This model is usually used to describe vehicles that travel with relatively high speed and with infrequent speed and direction changes. Apparently, the speed-adaptive scheme can address this case quite well. According to our scheme, a mobile station does not need to perform location updates frequently, because it is not likely that the mobile station goes out of the current speed mode. Also, it is not likely that it goes beyond the polar angle permitted by the current speed mode. For paging operations, a higher speed corresponds to a smaller paging polar angle, which reduces the paging cost. This is especially true when the call arrival rate is high as shown in the figure.

3.2.2. Activity 2: Low traveling speed and frequent direction changes

In this case, a mobile user travels at an average speed of 1 mile every 6 min. The mobile user can reach an activity cell after 1 or 2 route cells. The mobile user stays in every activity cell for 30 to 45 min to perform certain activities. Then it changes its direction and speed and goes to another activity cell. This case is to model low speed mobile users. Again, each simulation has been run for 10,000 min. Figure 5 shows the simulation result with the 8-element look-up table. "TF = R" stands for the use of a random time factor. In this case, the time value increases by a random number for each column.

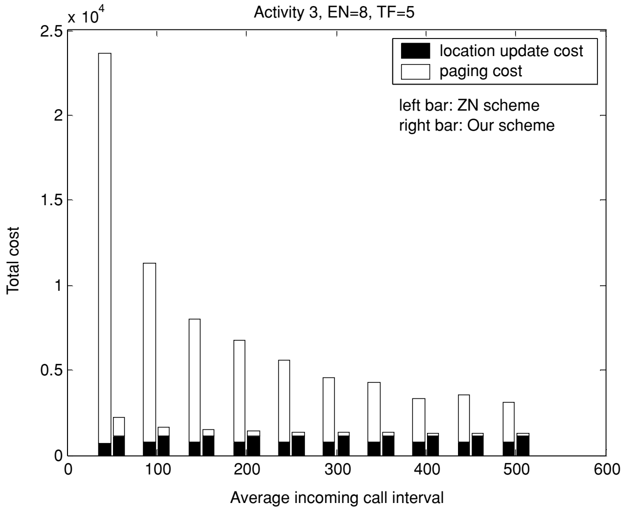


Fig. 6 Simulation result for Activity 3 with EN = 8 and TF = 5

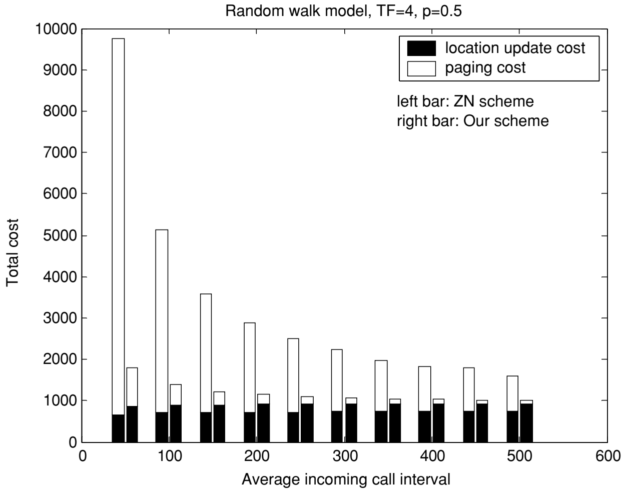


Fig. 7 Random walk model simulation with TF = 4 and $p = 0.5$

As Fig. 5 indicates, the location update cost incurred in our scheme is higher than that in the ZN scheme. This is mainly because, in our scheme, an update is required when a mobile station moves out of the associated polar angle. However, more frequent updates leads to a much lower paging cost as indicated in the figure. Overall, the cost of our scheme is lower than that of ZN scheme, especially when the call rate is high. When the call rate is high, a call can arrive shortly after the location update. In this situation, the paging radius of our scheme is much smaller than that of the ZN scheme. The figure also indicates that the cost of our scheme is about the same with all the incoming call rates.

3.2.3. Activity 3: Mixed traveling speeds

In this case, a mobile user may switch from high-speed traveling to low-speed traveling, and vice versa. A random speed magnitude and direction change happens right after the mobile user leaves an activity cell. The mobile user stays in every activity cell for 30 to 45 min to perform certain activities as in Activity 2. A mobile user travels at an average speed of 1 mile every 3 min, but unlike Activity 2, there are 1 to 10 route cells between 2 activity cells and the speed can go from high to low, or vice versa. Figure 6 shows the simulation result with an 8-element look-up table.

Figure 6 shows a similar behavior to Figs. 4 and 5, although their absolute costs are different. Our scheme performs much better than the ZN scheme does when the call arrival rate is high. The reason was stated in the previous section. When the call arrival rate is low, both schemes perform about the same. This is because, when the time intervals between incoming calls are long, the second part of the look-up table will be used. It is worthwhile to mention that, unlike the ZN scheme, the cost incurred in our scheme is not heavily dependent on the incoming call rate. This is achieved by introducing an additional part into the look-up table.

Figures 4–6 show that the cost of our scheme is not heavily affected by the speed or the incoming call arrival rate. In contrast, the cost of the ZN scheme increases as the speed increases and as the incoming call arrival rate increases.

3.3. Random walk model

In the random walk mobility model, time is assumed to be slotted and a mobile station decides where to move at each time slot [2,4]. We assume the probability that the mobile station stays in the current cell is p. This probability is referred to as the stationary rate. For the two-dimensional case, the probability that the mobile station will move to any of the six neighboring cells is $(1-p)/6$. To construct the look-up table, various time factors and table sizes were used. For each look up table, we tested five stationary rates: $p = 0.01$, 0.1, 0.5, 0.9, and 0.99, respectively. Those five parameter values represent five typical kinds of user mobility in the random walk model.

Figure 7 shows the simulation result with time factor 4 and stationary rate 0.5 under various incoming call rates. Just as in the activity-based model, the ZN scheme has a much higher paging cost than our scheme when the incoming call rate is high; whereas both schemes perform about the same when the incoming call rate is low.]

The stationary rate p indicates the user mobility. If p is small, the mobile station is more likely to move out of the current cell, so it is similar to traveling at a relatively high speed. In a case like this, the speed-adaptive scheme is efficient. However, when p becomes higher, it is more likely the mobile station stays in the current cell, and therefore, the speed is slow. In a situation like this, both the ZN scheme and our scheme perform well.

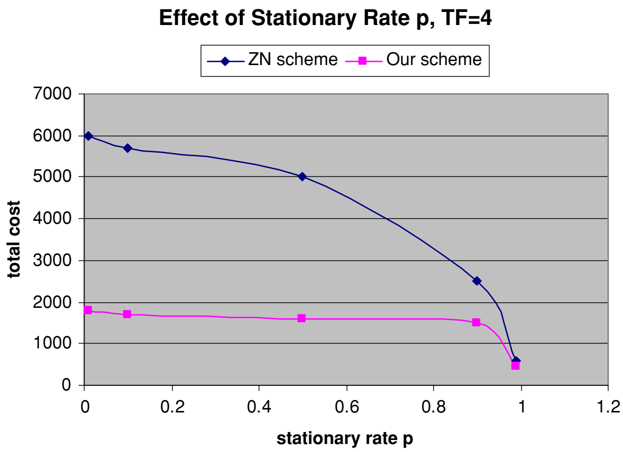


Fig. 8 Performance comparison with TF = 4 and call arrival interval being 100

Figure 8 shows the cost as a function of the stationary rate *p*. In this figure, the average incoming call interval is 100 time units. As we can see from the figure, when the stationary rate increases, the performance of the two schemes becomes closer. When *p* is close to 1, the speed-adaptive scheme and the ZN scheme have about the same performance. However, in other cases, the proposed scheme performs much better that the ZN scheme. The proposed scheme is able to adapt to the stationary rate, which indicates the speed of movement.

3.4. Validation of simulation results in real networks

Although the simulation is done in honeycomb networks, the results presented above are still valid in real networks. In a real network, the base stations may not be uniformly distributed. As described in Section 2.2, a virtual uniform network can be introduced such that each virtual cell contains at most one base station. If each virtual cell has a base station, the simulation results can be directly extended to the real network. We will show our proposed scheme still exhibits similar behavior even if not every virtual cell has a base station.

The main difference between our scheme and the ZN scheme is the look-up tables used. After the critical time, both tables use the same distances. Before the critical time, ZN's distance is larger than ours. A larger distance means a larger paging area. In fact, ZN's paging area always contains ours. A larger paging area includes more base stations whether or not the base stations are uniformly distributed. Therefore the ZN scheme has more paging cost than ours. The difference will be big when the call arrival rate is high. If the call arrival rate is high, a call can arrive shortly after a location update. At that time, our paging area is much smaller than ZN's. Therefore, the paging cost can be greatly reduced using our scheme. By using the paging angle, the paging cost can be further reduced.

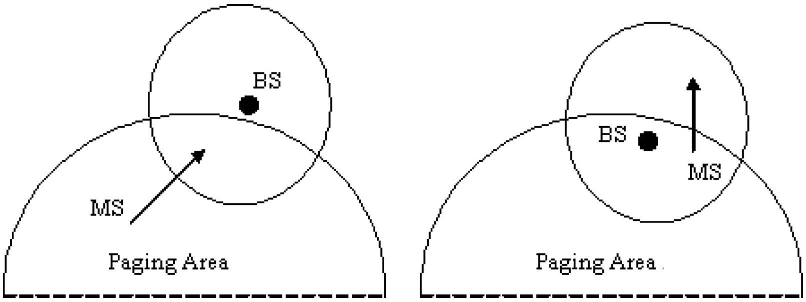
Intuitively, if the paging area is smaller, the chance for the mobile station to move out of the paging area is bigger, which leads to a higher location update cost. However, the paging area in our scheme is designed based on the movement of the mobile station. Therefore the chance for the mobile station to move out of the paging area is not much bigger. Sometimes, when a mobile station (MS) moves into a cell whose base station (BS) is located outside the paging area as shown at the left side of Fig. 9, the distance and speed will be over-calculated. That may lead to more location update cost. Sometimes, a mobile station may under-calculate its distance and speed, which leads to less location update cost. As shown at the right side of the figure, although the mobile station moves out of the circular paging area, but it is still in the actual paging area because it is still in the cell whose base station is located within the circular paging area. In this case, no location update is initiated.

Figure 9 shows that the irregularity of cell sizes and shapes may cause more location updates in some cases and less locations updates in other cases. The total location update costs will be about the same or at least similar statistically.

4. Summary and future work

This paper proposed a new speed-adaptive location management scheme. This work was enlightened by Naor's distance- and time-based location management scheme presented in his original work [12]. Our scheme has utilized the speed

Fig. 9 Over- and under-calculation of the distance and speed



information of the mobile stations, both the magnitude and the direction. Unlike the ZN scheme, an enhanced look-up table was used in our scheme. The table consists of two parts: the distance in the first part increases while the time increases; in the second part, the distance decreases with the increasing time. The first part was introduced for two purposes. First, it is to deal with high incoming call rates. While the call rate is high, our scheme uses the first part that has a smaller radius. Second, the first part of the table reflects the current speed mode of a mobile station. By associating a paging polar angle with a speed mode, our scheme is able to reduce the paging cost for a high-speed mobile station. It has been shown that under the activity-based model and the random walk model, the proposed scheme performs well for mobile stations traveling at a high speed, as well as for those traveling at a low speed. We also argued in the paper that the proposed scheme could be implemented with real networks, and the simulation results were valid with real networks as well. However, the implementation details on top of real networks remain to be worked out. It is anticipated that changes to the current control protocols are necessary in order to apply the proposed scheme to the current network. The cost of changes also remains to be a future research topic. Finally, a large network may have a large variance in cell size in reality. How to reduce the location management cost in such a network is another interesting topic for future study.

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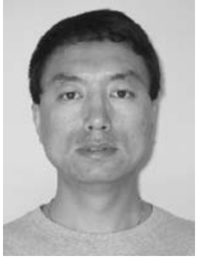

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