Handbook of Wireless Networks and Mobile Computing, Edited by Ivan Stojmenović
Copyright © 2002 John Wiley & Sons, Inc.
ISBNs: 0-471-41902-8 (Paper); 0-471-22456-1 (Electronic)

CHAPTER 2

Location Management in Cellular Networks

JINGYUAN ZHANG
Department of Computer Science, University of Alabama

2.1 INTRODUCTION

It has been known for over one hundred years that radio can be used to keep in touch with people on the move. However, wireless communications using radio were not popular until Bell Laboratories developed the cellular concept to reuse the radio frequency in the 1960s and 1970s [31]. In the past decade, cellular communications have experienced an explosive growth due to recent technological advances in cellular networks and cellular telephone manufacturing. It is anticipated that they will experience even more growth in the next decade. In order to accommodate more subscribers, the size of cells must be reduced to make more efficient use of the limited frequency spectrum allocation. This will add to the challenge of some fundamental issues in cellular networks. Location management is one of the fundamental issues in cellular networks. It deals with how to track subscribers on the move. The purpose of this chapter is to survey recent research on location management in cellular networks. The rest of this chapter is organized as follows. Section 2.2 introduces cellular networks and Section 2.3 describes basic concepts of location management. Section 2.4 presents some assumptions that are commonly used to evaluate a location management scheme in terms of network topology, call arrival probability, and mobility. Section 2.5 surveys popular location management schemes. Finally, Section 2.6 summarizes the chapter.

2.2 CELLULAR NETWORKS

In a cellular network, a service coverage area is divided into smaller hexagonal areas referred to as cells. Each cell is served by a base station. The base station is fixed. It is able to communicate with mobile stations such as cellular telephones using its radio transceiver. The base station is connected to the mobile switching center (MSC) which is, in turn, connected to the public switched telephone network (PSTN). Figure 2.1 illustrates a typical cellular network. The triangles represent base stations.

The frequency spectrum allocated to wireless communications is very limited, so the

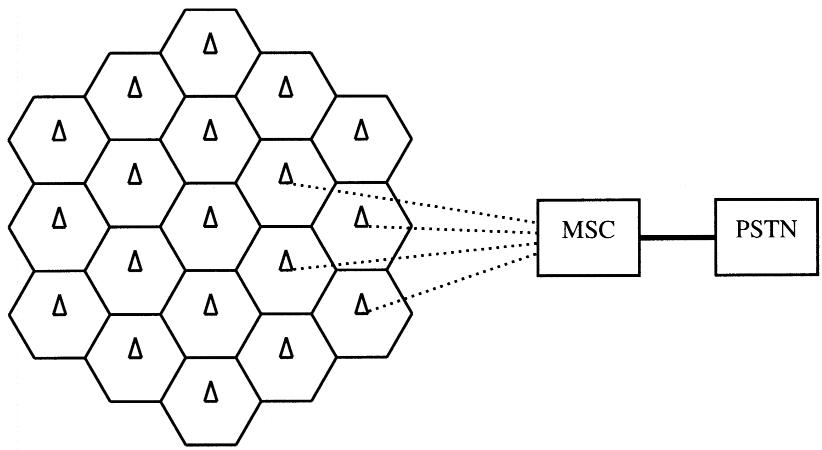

Figure 2.1 A typical cellular network.

cellular concept was introduced to reuse the frequency. Each cell is assigned a certain number of channels. To avoid radio interference, the channels assigned to one cell must be different from the channels assigned to its neighboring cells. However, the same channels can be reused by two cells that are far apart such that the radio interference between them is tolerable. By reducing the size of cells, the cellular network is able to increase its capacity, and therefore to serve more subscribers.

For the channels assigned to a cell, some are forward (or downlink) channels that are used to carry traffic from the base station to mobile stations, and the others are reverse (or uplink) channels that are used to carry traffic from mobile stations to the base station. Both forward and reverse channels are further divided into control and voice (or data) channels. The voice channels are for actual conversations, whereas the control channels are used to help set up conversations.

A mobile station communicates with another station, either mobile or land, via a base station. A mobile station cannot communicate with another mobile station directly. To make a call from a mobile station, the mobile station first needs to make a request using a reverse control channel of the current cell. If the request is granted by the MSC, a pair of voice channels will be assigned for the call. To route a call to a mobile station is more complicated. The network first needs to know the MSC and the cell in which the mobile station is currently located. How to find out the current residing cell of a mobile station is an issue of location management. Once the MSC knows the cell of the mobile station, it can assign a pair of voice channels in that cell for the call. If a call is in progress when the mobile station moves into a neighboring cell, the mobile station needs to get a new pair of voice channels in the neighboring cell from the MSC so the call can continue. This process is called handoff (or handover). The MSC usually adopts a channel assignment strategy that prioritizes handoff calls over new calls.

This section has briefly described some fundamental concepts about cellular networks such as frequency reuse, channel assignment, handoff, and location management. For detailed information, please refer to [6, 7, 20, 31, 35]. This chapter will address recent research on location management.

2.3 LOCATION MANAGEMENT

Location management deals with how to keep track of an active mobile station within the cellular network. A mobile station is active if it is powered on. Since the exact location of a mobile station must be known to the network during a call, location management usually means how to track an active mobile station between two consecutive phone calls.

There are two basic operations involved in location management: location update and paging. The paging operation is performed by the cellular network. When an incoming call arrives for a mobile station, the cellular network will page the mobile station in all possible cells to find out the cell in which the mobile station is located so the incoming call can be routed to the corresponding base station. The number of all possible cells to be paged is dependent on how the location update operation is performed. The location update operation is performed by an active mobile station.

A location update scheme can be classified as either global or local [11]. A location update scheme is global if all subscribers update their locations at the same set of cells, and a scheme is local if an individual subscriber is allowed to decide when and where to perform the location update. A local scheme is also called individualized or per-user-based. From another point of view, a location update scheme can be classified as either static or dynamic [11, 33]. A location update scheme is static if there is a predetermined set of cells at which location updates must be generated by a mobile station regardless of its mobility. A scheme is dynamic if a location update can be generated by a mobile station in any cell depending on its mobility. A global scheme is based on aggregate statistics and traffic patterns, and it is usually static too. Location areas described in [30] and reporting centers described in [9, 18] are two examples of global static schemes. A global scheme can be dynamic. For example, the time-varying location areas scheme described in [25] is both global and dynamic. A per-user-based scheme is based on the statistics and/or mobility patterns of an individual subscriber, and it is usually dynamic. The time-based, movement-based and distance-based schemes described in [11] are three excellent examples of individualized dynamic schemes. An individualized scheme is not necessarily dynamic. For example, the individualized location areas scheme in [43] is both individualized and static.

Location management involves signaling in both the wireline portion and the wireless portion of the cellular network. However, most researchers only consider signaling in the wireless portion due to the fact that the radio frequency bandwidth is limited, whereas the bandwidth of the wireline network is always expandable. This chapter will only discuss signaling in the wireless portion of the network. Location update involves reverse control channels whereas paging involves forward control channels. The total location management cost is the sum of the location update cost and the paging cost. There is a trade-off between the location update cost and the paging cost. If a mobile station updates its location more frequently (incurring higher location update costs), the network knows the location of the mobile station better. Then the paging cost will be lower when an incoming call arrives for the mobile station. Therefore, both location update and paging costs cannot be minimized at the same time. However, the total cost can be minimized or one cost can be minimized by putting a bound on the other cost. For example, many researchers try to minimize the location update cost subject to a constraint on the paging cost.

The cost of paging a mobile station over a set of cells or location areas has been studied against the paging delay [34]. There is a trade-off between the paging cost and the paging delay. If there is no delay constraint, the cells can be paged sequentially in order of decreasing probability, which will result in the minimal paging cost. If all cells are paged simultaneously, the paging cost reaches the maximum while the paging delay is the minimum. Many researchers try to minimize the paging cost under delay constraints [2, 4, 17].

2.4 COMMON ASSUMPTIONS FOR PERFORMANCE EVALUATION

2.4.1 Network Topology

The network topology can be either one-dimensional or two-dimensional. As demonstrated in Figure 2.2, in one-dimensional topology, each cell has two neighboring cells if they exist [17]. Some researchers use a ring topology in which the first and the last cells are considered as neighboring cells [11]. The one-dimensional topology is used to model the service area in which the mobility of mobile stations is restricted to either forward or backward direction. Examples include highways and railroads.

The two-dimensional network topology is used to model a more general service area in which mobile stations can move in any direction. There are two possible cell configurations to cover the service area—hexagonal configuration and mesh configuration. The hexagonal cell configuration is shown in Figure 2.1, where each cell has six neighboring cells. Figure 2.3 illustrates a mesh cell configuration. Although eight neighbors can be assumed for each cell in the mesh configuration, most researchers assume four neighbors (horizontal and vertical ones only) [2, 3, 5, 22]. Although the mesh configuration has been assumed for simplicity, it is not known whether the mesh configuration, especially the one with four neighbors, is a practical model.

2.4.2 Call Arrival Probability

The call arrival probability plays a very important role when evaluating the performance of a location management scheme. If the call arrival time is known to the called mobile station in advance, the mobile station can update its location just before the call arrival time. In this way, costs of both locate update and paging are kept to the minimum. However, the reality is not like this. Many researchers assume that the incoming call arrivals to a mobile station follow a Poisson process. Therefore, the interarrival times have indepen-

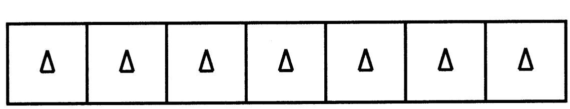

Figure 2.2 One-dimensional network topology.

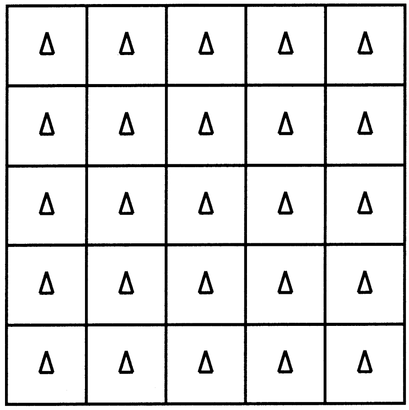

Figure 2.3 Two-dimensional network topology with the mesh configuration.

dent exponential distributions with the density function $f(t) = \lambda e^{-\lambda t}$ [2, 19, 22]. Here λ represents the call arrival rate. Some researchers assume the discrete case. Therefore, the call interarrival times have geometric distributions with the probability distribution function $F(t) = 1 - (1 - \lambda)^t$ [1, 17, 24]. Here λ is the call arrival probability.

2.4.3 Mobility Models

The mobility pattern also plays an important role when evaluating the performance of a location management scheme. A mobility model is usually used to describe the mobility of an individual subscriber. Sometimes it is used to describe the aggregate pattern of all subscribers. The following are several commonly used mobility models.

Fluid Flow Model

The fluid flow model has been used in [43] to model the mobility of vehicular mobile stations. It requires a continuous movement with infrequent speed and direction changes. The fluid flow model is suitable for vehicle traffic on highways, but not suitable for pedestrian movements with stop-and-go interruption.

Random Walk Model

Many researchers have used the discrete random walk as the mobility model. In this model, it is assumed that time is slotted, and a subscriber can make at most one move during a time slot. Assume that a subscriber is in cell i at the beginning of time slot t. For the one-dimensional network topology, at the beginning of time slot $t + 1$, the probability that the subscriber remains in cell i is p, and the probability that the subscriber moves to cell $i + 1$ or cell $i - 1$ is equally $(1 - p)/2$ [11, 24].

The discrete random walk model has also been used in the two-dimensional network topology [2, 17]. For the hexagonal configuration, the probability that the subscriber remains in the same cell is p, and the probability that the subscriber moves to each neighboring cell is equally $(1 - p)/6$. The concept of *ring* has been introduced to convert the two-dimensional random walk to the one-dimensional one. A simplified two-dimensional random walk model has been proposed in [5].

Markov Walk Model

Although the random walk model is memoryless, the current move is dependent on the previous move in the Markov walk model. In [11], the Markov walk has been used to model mobility in the one-dimensional ring topology. Three states have been assumed for a subscriber at the beginning of time slot t: the stationary state (S), the left-move state (L), and the right-move state (R). For the S state, the probability that the subscriber remains in S is p, and the probability that the subscriber moves to either L or R is equally $(1 - p)/2$. For the L (or R) state, the probability that the subscriber remains in the same state is q, the probability that the subscriber moves to the opposite state is v, and the probability that the subscriber moves to S is $1 - q - v$. Figure 2.4 illustrates the state transitions.

In [12], the authors split the S state into SL and SR—a total of four states. Both SL and SR are stationary, but they memorize the most recent move, either leftward (for SL) or rightward (for SR). The probability of resuming motion in the same direction has been distinguished from that in the opposite direction.

Cell-Residence-Time-Based Model

While one group of researchers uses the probability that a mobile station may remain in the same cell after each time slot to determine the cell residence time implicitly, another group considers the cell residence time as a random variable [2, 19, 22]. Most studies use the exponential distribution to model the cell residence time because of its simplicity. The Gamma distribution is selected by some researchers for the following reasons. First, some important distributions such as the exponential, Erlang, and Chi-square distributions are special cases of the Gamma distribution. Second, the Gamma distribution has a simple Laplace–Stieltjes transform.

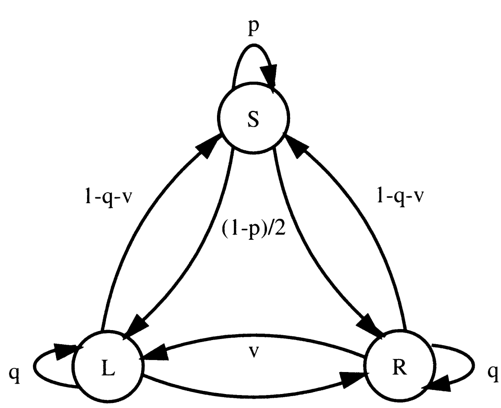

Figure 2.4 The state transitions of the Markov walk model.

Gauss–Markov Model

In [21], the authors have used the Gauss–Markov mobility model, which captures the velocity correlation of a mobile station in time. Specifically the velocity at the time slot n, v_n, is represented as follows:

$$v_n = \alpha v_{n-1} + (1 - \alpha)\mu + \sqrt{1 - \alpha^2} x_{n-1}$$

Here $0 \leq \alpha \leq 1$, μ is the asymptotic mean of v_n when n approaches infinity, and x_n is an independent, uncorrelated, and stationary Gaussian process with zero mean. The Gauss–Markov model represents a wide range of mobility patterns, including the constant velocity fluid flow models (when $\alpha = 1$) and the random walk model (when $\alpha = 0$ and $\mu = 0$).

Normal Walk Model

In [41], the authors have proposed a multiscale, straight-oriented mobility model referred to as *normal walk*. They assume that a mobile station moves in unit steps on a Euclidean plane. The ith move, Y_i, is obtained by rotating the $(i - 1)$th move, Y_{i-1}, counterclockwise for θ_i degrees:

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

Here θ_i is normally distributed with zero mean. Since the normal distribution with zero mean is chosen, the probability density increases as the rotation angle approaches zero. Therefore, a mobile station has a very high probability of preserving the previous direction.

Shortest Path Model

In [3], the authors have introduced the shortest path model for the mobility of a vehicular mobile station. The network topology used to illustrate the model is of the mesh configuration. They assume that, within the location area, a mobile station will follow the shortest path measured in the number of cells traversed, from source to destination. At each intersection, the mobile station makes a decision to proceed to any of the neighboring cells such that the shortest distance assumption is maintained. That means that a mobile station can only go straight or make a left or right turn at an intersection. Furthermore, a mobile station cannot make two consecutive left turns or right turns.

Activity-Based Model

Instead of using a set of random variables to model the mobility pattern, an actual activity-based mobility model has been developed at the University of Waterloo [38, 39]. The model is based on the trip survey conducted by the Regional Municipality of Waterloo in 1987. It is assumed that a trip is undertaken for taking part in an activity such as shopping at the destination. Once the location for the next activity is selected, the route from the current location to the activity location will be determined in terms of cells crossed. The activity-based mobility model has been used to test the performance of several popular location management schemes [39]. It has shown that the scheme that performs well in a random mobility model may not perform as well when deployed in actual systems.

2.5 LOCATION MANAGEMENT SCHEMES

2.5.1 Location Areas

The location areas approach has been used for location management in some first-generation cellular systems and in many second-generation cellular systems such as GSM [30]. In the location areas approach, the service coverage area is partitioned into location areas, each consisting of several contiguous cells. The base station of each cell broadcasts the identification (ID) of location area to which the cell belongs. Therefore, a mobile station knows which location area it is in. Figure 2.5 illustrates a service area with three location areas.

A mobile station will update its location (i.e., location area) whenever it moves into a cell that belongs to a new location area. For example, when a mobile station moves from cell B to cell D in Figure 2.5, it will report its new location area because cell B and cell D are in different location areas. When an incoming call arrives for a mobile station, the cellular system will page all cells of the location area that was last reported by the mobile station.

The location areas approach is global in the sense that all mobile stations transmit their location updates in the same set of cells, and it is static in the sense that location areas are fixed [11, 33]. Furthermore, a mobile station located close to a location area boundary will perform more location updates because it moves back and forth between two location areas more often. In principle, a service area should be partitioned in such a way that both the location update cost and the paging cost are minimized. However, this is not possible

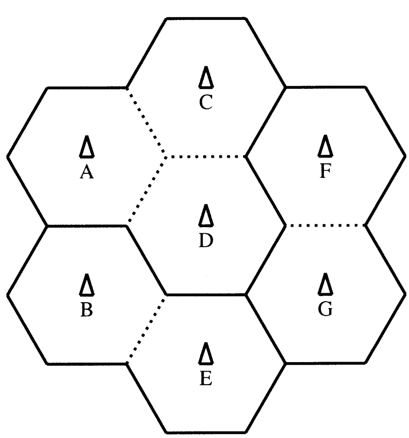

Figure 2.5 A service area with three location areas.

because there is trade-off between them. Let us consider two extreme cases. One is known as "always-update," in which each cell is a location area. Under always-update, a mobile station needs to update its location whenever it enters a new cell. Obviously, the cost of location update is very high, but there is no paging cost because the cellular system can just route an incoming call to the last reported cell without paging. The other is known as "never-update," in which the whole service area is a location area. Therefore there is no cost of location update. However, the paging cost is very high because the cellular system needs to page every cell in the service area to find out the cell in which the mobile is currently located so an incoming call can be routed to the base station of that cell.

Various approaches for location area planning in a city environment, the worst-case environment, are discussed in [25]. The simplest approach is the use of heuristic algorithms for approximating the optimal location area configuration. The approach collects a high number of location area configurations and picks up the best one. Although the approach does not guarantee the optimal location area configuration, the optimal solution can be approximated when the number of experiments is high. A more complex approach is based on area zones and highway topology. A city can have area zones such as the city center, suburbs, etc. Moreover, population movements between area zones are usually routed through main highways that connect the area zones. Naturally, the size of a location area is determined by the density of mobile subscribers, and the shape is determined by the highway topology. Location updates due to zig-zag movement can be avoided if location areas with overlapping borders are defined. The most complex approach is to create dynamic location area configurations based on the time-varying mobility and traffic conditions. For example, when the network detects a high-mobility and low-traffic time zone, it decides to reduce the number of location areas to reduce location updates. When the network detects an ordinary mobility and high-traffic time zone, it decides to increase the number of location areas to reduce paging. The above approaches are based on the mobility characteristics of the subscriber population.

The authors in [25] also discussed location area planning based on the mobility characteristics of each individual mobile subscriber or a group of mobile subscribers. Another per-user dynamic location area strategy has been proposed in [43]. Their strategy uses the subscriber incoming call arrival rate and mobility to dynamically determine the size of a subscriber's location area, and their analytical results show their strategy is better than static ones when call arrival rates are subscriber- or time-dependent.

In the classical location area strategy, the most recently visited location area ID is stored in a mobile station. Whenever the mobile station receives a new location area ID, it initiates a location update. In [19], the author has proposed a two location algorithm (TLA). The two location algorithm allows a mobile station to store the IDs of two most recently visited location areas. When a mobile station moves into a new location area, it checks to see if the new location is in the memory. If the new location is not found, the most recently visited location is kept and the other location is replaced by the new location. In this case, a location update is required to notify the cellular system of the change that has been made. If the new location is already in the memory, no location update is performed. When an incoming call arrives for a mobile station, two location areas are used to find the cell in which the mobile station is located. The order of the locations selected to locate the mobile station affects the performance of the algorithm. The possible strategies include random selection and the most recently visited location area first. This study shows that TLA significantly outperforms the classical location area strategy when the call-to-mobility ratio is low (i.e., the subscriber moves more frequently than calls are received) or when the location update cost is high. When the location update cost is low, the performance of TLA degrades if the variance of the residence times is small. It has been mentioned that TLA can be easily implemented by modifying the existing IS-41 system [14].

In [37], the authors have proposed a selective location update strategy. Their proposal is based on the location areas approach. The idea behind their proposal is that it is a waste of scarce wireless bandwidth to do a location update at a location in which a mobile station stays for a very short interval of time and has an extremely low probability of receiving a call. In their proposal, each subscriber updates only in certain preselected location areas, called update areas, based on his/her own mobility pattern. To determine update areas, a genetic algorithm is used to optimize the total location management cost, which is the weighted average of the location management costs in the individual location areas, which are functions of the subscriber's update strategy. The corresponding paging cost will be higher because the cellular system needs to track a mobile station down to the current location area from the last known location area. The tracking-down can be based on the location area interconnection graph in which the node set represents the location areas and the edge set represents the access paths (roads, highways, etc.) between pairs of location areas. Their experiments have shown that for low user location probability, low to moderate call arrival rate, and/or comparatively high update cost, skipping updating in several location areas leads to a minimization of the location management cost.

In [3], the authors have proposed a dynamic location area strategy that minimizes the cost of location update subject to a constraint on the number of cells in the location area. They have proposed and used the shortest distance mobility model for vehicular subscribers, instead of the independent and identically distributed model. They have proved the location update optimal problem is NP-complete [16], and have provided a heuristic greedy algorithm to generate an approximate solution, which consists of location areas of irregular shape. They have also shown that the optimal rectangular location update areas are very close approximations to the irregular areas generated by the greedy algorithm. To page a subscriber within a location area, the authors have considered the trade-off between the paging cost and the paging delay. They have proposed a dynamic selective paging strategy, which is to minimize the paging cost subject to a constraint on the paging delay [4]. They use the subscriber's mobility pattern and incoming call rate to partition the location area, then page the partition sequentially until the subscriber is found.

2.5.2 Reporting Cells

Another location management strategy is to use reporting cells or reporting centers [9, 18]. In the reporting cells approach, a subset of cells have been selected from all cells. Those selected cells are called reporting cells, and the other cells are called nonreporting cells. The base station of each cell broadcasts a signal to indicate whether the cell is a reporting cell or not. Therefore, a mobile station knows whether it is in a reporting cell or not. Figure 2.6 illustrates a service area with four reporting cells, marked by solid black triangles. For each reporting cell *i*, its vicinity is defined as the collection of all nonreporting cells that are reachable from cell *i* without crossing another reporting cell. The reporting cell belongs to its own vicinity. For example, the vicinity of cell C includes cells A, C, and F in Figure 2.6.

A mobile station will update its location (i.e., cell ID) whenever it moves into a new reporting cell. For example, when a mobile station moves from cell B to cell A then to cell C in Figure 2.6, it will report its new location because cell B and cell C are two different reporting cells. However, if a mobile station moves from cell B to cell A then move back into cell B, no location update is necessary. When an incoming call arrives for a mobile station, the cellular system will page all cells within the vicinity of the reporting cell that was last reported by the mobile station.

The reporting cells approach is also global in the sense that all mobile stations transmit their location updates in the same set of reporting cells, and it is static in the sense that reporting cells are fixed [11, 33]. The reporting cells approach also has two extreme cases, always-update and never-update. In the always-update case, every cell is selected as reporting. Therefore, a mobile station needs to update its location whenever it enters a new cell. As before, the cost of location update is very high, but there is no paging cost. In the never-update case, every cell is nonreporting. Therefore, there is no cost of location update. However, the paging cost is very high because the cellular system needs to page every cell in the service area to find out the cell in which the mobile station is currently located. The goal here is how to select a subset of reporting cells to minimize the total location management cost, which is the sum of the location update cost and the paging cost.

The idea of reporting centers/cells has been first proposed in [9]. In [9], the authors define the cost of paging based on the largest vicinity in the network because the cost of paging increases with the size of the vicinity in which the paging is performed. Associating with each reporting cell a weight that reflects the frequency that mobile subscribers enter into that cell, they define the cost of location update as the sum of the weights of all the reporting cells. The problem is to select a set of reporting centers to minimize both the size

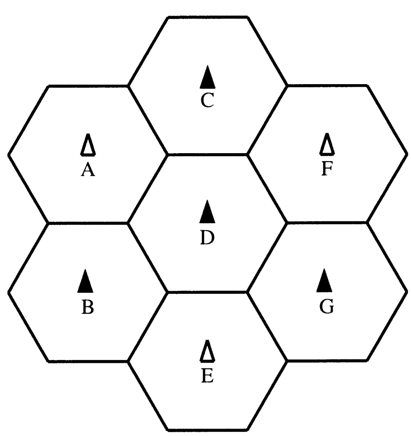

Figure 2.6 A service area with four reporting cells.

of the largest vicinity and the total weight of the reporting centers. Considering those two contradicting goals, they try to bound the size of the largest vicinity and to minimize the total weight of the reporting centers, which is reflected in their formal definition of the reporting centers problem. The reporting centers problem is defined on a mobility graph in which the vertex corresponds to a cell, and two vertices are connected by an edge if and only if the corresponding cells overlap. In addition, each vertex is assigned a weight to reflect the frequency that mobile subscribers update their locations at that cell. They have shown that for an arbitrary topology of the cellular network, finding the optimal set of reporting centers is an NP-complete problem [16]. For the case of unweighted vertices, they have presented an optimal solution for ring graphs and near optimal solutions for various types of grid graphs, including the topology of the hexagonal cellular network. For the case of weighted vertices, they have presented an optimal solution for tree graphs and a simple approximation algorithm for arbitrary graphs.

Although the results in [9] are excellent but theoretical, the results in [18] are more practical. In [18], the authors use the topology of a hexagonal cellular network with weighted vertices. They redefine the reporting centers problem, which is to select a subset of reporting cells to minimize the total signaling cost, which is the sum of both the location update and paging costs. A procedure has been given to find an approximate solution to the reporting centers problem. Simulations have shown that their scheme performs better than the always-update scheme and the never-update scheme.

A per-user dynamic reporting cell strategy has been proposed in [12]. Their strategy uses the direction information at the time of location update to derive optimal "asymmetric" reporting boundaries. In addition, they have used the elapsed time since the last update to choose the cell order in which a mobile station is paged in the event of an incoming call. Their ideas have been evaluated using a Markovian model over a linear topology. Although it is listed here as a variant of the reporting cells approach, it also can be considered as a variant of the distance-based approach.

2.5.3 Time-Based Location Update Strategies

The simplest time-based location update strategy is described in [11]. Given a time threshold T, a mobile station updates its location every T units of time. The corresponding paging strategy is also simple. Whenever there is an incoming call for a mobile station, the system will first search the cell the mobile station last reported, say i. If it is not found there, the system will search in cells $i + j$ and $i - j$, starting with $j = 1$ and continuing until the mobile station is found. Here a ring cellular topology is assumed. The time-based strategy is dynamic in the sense that the cells for reporting are not predefined. The time threshold T can be determined on a per-user basis. The advantage of this strategy is its simplicity. The disadvantage is its worst overall performance compared to the other dynamic location update strategies. This is mainly because a mobile station will keep updating its location regardless of its incoming call arrival probability and its mobility pattern.

In [1], the authors have proposed a time-based strategy in which a mobile station dynamically determines when to update its location based on its mobility pattern and the incoming call arrival probability. Whenever a mobile station enters a new cell, the mobile station needs to find out the number of cells that will be paged if an incoming call arrives and the resulting cost for the network to page the mobile station. The weighted paging cost at a given time slot is the paging cost multiplied by the call arrival probability during that time slot. A location update will be performed when the weighted paging cost exceeds the location update cost.

Another time-based strategy has been proposed in [32]. The strategy is to find the maximum amount of time to wait before the next location update such that the average cost of paging and location update is minimized. The author has shown that the timer-based strategy performs substantially better than a fixed location area-based strategy.

The location update scheme proposed in [44] is modified from the time-based approach. The time-based location update starts with setting the timer to a given time threshold t. When the timer expires, the mobile station reports its current location. It is hard to know the distance covered by a mobile station during the time period t, which makes the paging job hard. In order to make the paging job easier, the location update scheme in [44] keeps track of the maximal distance traveled since the last update. When it is time for location update, the mobile station reports both its current cell and the traveled maximal distance R. The location update occurs either when the timer expires or when the traveled maximal distance exceeds the last reported maximal distance. The paging operation is based on the last reported cell and the maximal distance R. The system will search all R rings surrounding the last reported cell. In order to keep the paging operation under the delay constraint, a distance threshold is imposed on the possible R a mobile station can report. The scheme is speed-adaptive. When the mobile station is decelerating, the reported maximal distance will become smaller and smaller. The distance becomes 0 when it stops at the destination, such as home. In this case, there is absolutely no location update or paging costs.

2.5.4 Movement-Based Location Update Strategies

In the movement-based location update strategy [11], each mobile station keeps a count that is initialized to zero after each location update. Whenever it crosses the boundary between two cells, it increases the count by one. The boundary crossing can be detected by comparing the IDs of those two cells. When the count reaches a predefined threshold, say M, the mobile station updates its location (i.e., cell ID), and resets the count to zero. The movement-based strategy guarantees that the mobile station is located in an area that is within a distance M from the last reported cell. This area is called the residing area of the mobile station. When an incoming call arrives for a mobile station, the cellular system will page all the cells within a distance M from the last reported cell. The movement-based strategy is dynamic, and the movement threshold M can be determined on a per-user basis, depending on his/her mobility pattern. The advantage of this strategy is its simplicity. The mobile station needs to keep a simple count of the number of cell boundaries crossed, and the boundary crossing can be checked easily.

Due to its simplicity, the movement-based location update strategy has been used to study the optimization of the total location update and paging cost. In [2], the authors have proposed selective paging combined with the movement-based location update. In the movement-based strategy, when an incoming call arrives, the cellular system will page all the cells within a distance of M, the movement threshold, from the last reported cell of the called mobile station. Here the paging is done within one polling cycle. However, if the system is allowed to have more than one polling cycle to find the called mobile station, the authors propose to apply a selective paging scheme in which the system partitions the residing area of the called mobile station into a number of subareas, and then polls each subarea one after the other until the called mobile station is found. Their result shows that if the paging delay is increased from one to three polling cycles, the total location update and paging cost is reduced to halfway between the maximum (when the paging delay is one) and the minimum (when the paging delay is not constrained). They also show that although increasing the allowable paging delay reduces the total cost, a large paging delay does not necessarily translate into a significant total cost reduction. The authors also introduce an analytical model for the proposed location tracking mechanism that captures the mobility and the incoming call arrival pattern of each mobile station. The analytical model can be used to study the effects of various parameters on the total location update and paging costs. It can also be used to determine the optimal location update movement threshold.

In [22], the authors have proposed a similar analytical model that formulates the costs of location update and paging in the movement-based location update scheme. Paging is assumed to be done in one polling cycle. The authors prove that the location update cost is a decreasing and convex function with respect to the movement threshold, and the paging cost is an increasing and convex function with respect to the threshold. Therefore, the total costs of location update and paging is a convex function. An efficient algorithm has been proposed to obtain the optimal threshold directly. It has been shown that the optimal threshold decreases as the call-to-mobility ratio increases, an increase in update cost (or a decrease in polling cost) may cause an increase in the optimal threshold, and the residence time variance has no significant effect on the optimal threshold.

An enhanced version of the movement-based location update with selective paging strategy has been proposed in [13]. The difference is that when a subscriber moves back to the last reported cell, the movement count will be reset to zero. The effect is that the total location update and paging cost will be reduced by about 10–15%, with a slightly increased paging cost.

In [42], the authors have proposed two velocity paging schemes that utilize semireal-time velocity information of individual mobile stations to dynamically compute a paging zone for an incoming call. The schemes can be used with either the movement- (or distance-) based location update. The basic velocity paging scheme uses the speed without the direction information at the time of last update, and the resulting paging zone is a smaller circular area. The advanced velocity paging scheme uses both speed and direction information at the time of last update, and the resulting paging zone is an even smaller sector. Their analysis and simulation have shown that their schemes lead to a significant cost reduction over the standard location area scheme.

2.5.5 Distance-Based Location Update Strategies

In the distance-based location update strategy [11], each mobile station keeps track of the distance between the current cell and the last reported cell. The distance here is defined in terms of cells. When the distance reaches a predefined threshold, say D, the mobile station updates its location (i.e., cell ID). The distance-based strategy guarantees that the mobile station is located in an area that is within a distance *D* from the last reported cell. This area is called the residing area of the mobile station. When an incoming call arrives for a mobile station, the cellular system will page all the cells within a distance of *D* from the last reported cell. The distance-based strategy is dynamic, and the distance threshold *D* can be determined on a per-user basis depending on his/her mobility pattern. In [11], the authors have shown that the distance-based strategy performs significantly better than the time-based and movement-based strategies in both memoryless and Markovian movement patterns. However, it has been claimed that it is hard to compute the distance between two cells or that it requires a lot of storage to maintain the distance information among all cells [2, 22]. In [28, 44], the authors have shown that if the cell IDs can be assigned properly, the distance between two cells can be computed very easily.

In [17], the authors have introduced a location management mechanism that incorporates the distance-based location update scheme with the selective paging mechanism that satisfies predefined delay requirements. In the distance-based strategy, when an incoming call arrives, the cellular system will page all the cells within a distance of *D*, the distance threshold, from the last reported cell of the called mobile station within one polling cycle. If the system is allowed to have more than one polling cycle to find the called mobile station, the authors propose to apply a selective paging scheme in which the system partitions the residing area of the called mobile station into a number of subareas, and then polls each subarea one after the other until the called mobile station is found. Their result shows that the reduction in the total cost of location update and paging is significant even for a maximum paging delay of two polling cycles. They also show that in most cases, the average total costs are very close to the minimum (when there is no paging delay bound) when a maximum paging delay of three polling cycles is used. The authors also have derived the average total location update and paging cost under given distance threshold and maximum delay constraint. Given this average total cost function, they are able to determine the optimal distance threshold using an iterative algorithm.

A similar distance-based location update strategy has been independently developed in [24]. In [24], the authors have derived the formula for the average total cost, which captures the trade-off between location update and paging costs. They have shown that the optimal choice can be determined by dynamic programming equations that have a unique solution. Solution of the dynamic programming equations for the one-dimensional Markov mobility model can be found using two approaches. One approach is to solve the equations explicitly; the other uses an iterative algorithm. It has been shown the iterative algorithm will converge geometrically to the unique solution.

In [21], the authors have introduced a predicative distance-based mobility management scheme that uses the Gauss–Markov mobility model to predict a mobile station's position at a future time from its last report of location and velocity. When a mobile station reaches some threshold distance *d* from the predicated location, it updates its location. That guarantees that the mobile station is located in an area that is within a distance *d* from the predicated location. When an incoming call arrives for the mobile station, the system is able to find the mobile station at and around its predicated location in descending probability until the mobile station is found. Their simulation results show that the predictive distance-based scheme performs as much as ten times better than the regular one.

In [41], the authors have introduced the look-ahead strategy for distance-based location tracking. In the regular distance-based strategy, the mobile station reports its current cell at location update. The look-ahead strategy uses the mobility model to find the optimal future cell and report that cell at location update. In this way, the rate of location update can be reduced without incurring extra paging cost. Their strategy is based on a multiscale, straight-oriented mobility model, referred to as "normal walk." Their analysis shows that the tracking cost for mobile subscribers with large mobility scales can be effectively reduced.

Recall that the distance information is not available in the current cellular network. However, in [28] the authors have pointed out that the distance between two cells can be computed easily if the cell address can be assigned systematically using the coordinate system proposed for the honeycomb network in [36]. The coordinate system has three axes, x, y, and z at a mutual angle of 120° between any two of them, as indicated in Figure 2.7. These three axes are, obviously, not independent. However, this redundancy greatly simplifies cell addressing. The origin is assigned (0, 0, 0) as its address. A node will be assigned an address (a, b, c) if the node can be reached from the origin via cumulative a movements along the x axis, b movements along the y axis, and c movements along the z axis.

In [28], the authors first show that if (a, b, c) is an address for cell A, all possible addresses for cell A are of form $(a + d, b + d, c + d)$ for any integer d. Starting from the nonunique addressing, they propose two forms of unique cell addressing schemes, referred to as the shortest path form and the zero-positive form.

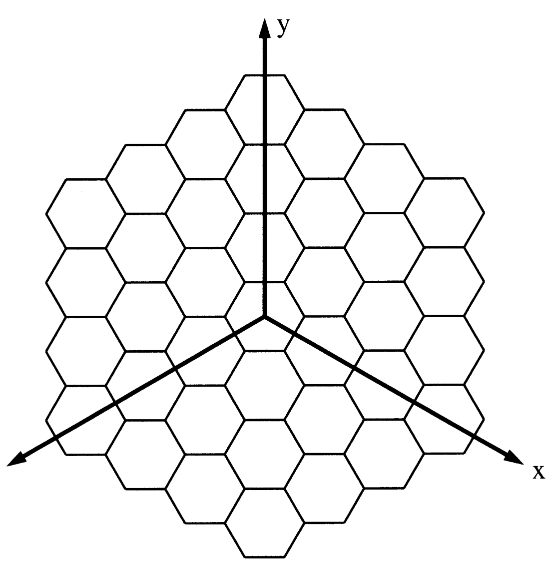

Figure 2.7 The x-y-z coordinate system for cell addressing.

A node address (a, b, c) is of the shortest path form if and only if the following conditions are satisfied:

1. At least one component is zero (that is, $abc = 0$)
2. Any two components cannot have the same sign (that is, $ab \leq 0$, $ac \leq 0$, and $bc \leq 0$)

A node address (a, b, c) is of the zero-positive form if and only if the following conditions are satisfied:

1. At least one component is zero (that is, $abc = 0$)
2. All components are nonnegative (that is, $a \geq 0$, $b \geq 0$, and $c \geq 0$)

If node A has (a, b, c) as the address of the shortest path form, the distance between node A and the origin is $|a| + |b| + |c|$. If node A has (a, b, c) as the address of the zero-positive form, the distance between node A and the origin is $\max(a, b, c)$. To compute the distance, i.e., the length of the shortest path, between two cells S and D, first compute the address difference between S and D. Assume that $D - S = (a, b, c)$, then distance $|D - S| = \min(|a - c| + |b - c|, |a - b| + |c - b|, |b - a| + |c - a|)$.

To compute the distance between two cells in a cellular network with nonuniformly distributed base stations, the authors in [15] have shown how to design an optimal virtual hexagonal networkwith a uniform virtual cell size such that each virtual cell will contain at most one base station. An address can be assigned to a base station based on the position of the base station in the virtual hexagonal network. Therefore the distance between two cells can also be computed as shown in the above paragraph.

2.5.6 Profile-Based Location Management Strategies

In the profile-based location management strategy, the cellular system keeps the individual subscriber's mobility pattern in his/her profile. The information will be used to save the costs of location update and paging. A profile-based strategy has been proposed in [40] to save the cost of location update. The idea behind his strategy is that the mobility pattern of a majority of subscribers can be foretold. In [40], the author has proposed two versions of the alternative strategy (alternative to the classic location area strategy). The first version uses only long-term statistics, whereas the second version uses short or medium events as well as the long-term statistics with increased memory. In the first version, a profile for each individual subscriber is created as follows. For each time period $[t_i, t_j)$, the system maintains a list of location areas, (A_1, p_1), (A_2, p_2), . . . , (A_k, p_k). Here A_f is the location area and p_f is the probability that the subscriber is located in A_f. It is assumed that the location areas are ordered by the probability from the highest to the lowest, that is, $p_1 > p_2 > \ldots > p_k$. If the subscriber moves within the recorded location areas, $A_1, A_2, \ldots, A_k$ during the corresponding period $[t_i, t_j)$, the subscriber does not need to perform location update. Otherwise, the subscriber reports its current location, and the system will track the subscriber as in the classical location area strategy. Therefore, location updates can be significantly reduced. When an incoming call arrives for the subscriber at time t_g (with $t_i \leq t_g < t_j$), the system will first page the subscriber over the location area A_1. If not found there, the system will page A_2. The process will repeat until the location area A_k. In order to save the paging cost, the author has introduced a second version. The second version takes advantage of the short or medium events and requires more memory. One is paging around the last connection point if the time difference is short enough. The other is reordering the set of location areas based on the short or medium events. Both analytical and simulation results show that the alternative strategy has better performance than the classical strategy in radio bandwidth utilization when the subscribers have high or medium predictable mobility patterns.

In [29], the authors have adopted a similar profile based location strategy and studied its performance more thoroughly. Specifically, they have studied the performance in terms of radio bandwidth, fixed network SS7 traffic, and the call set-up delay. After investigating the conditions under which the profile-based strategy performs better than the classical one, they have concluded that the profile-based strategy has the potential to simultaneously reduce the radio link bandwidth usage and fixed network SS7 load at the expense of a modest increase in paging delay.

Another profile-based location management algorithm has been proposed in [38]. The profile used in their algorithm contains the number of transitions a subscriber has made from cell to cell and the average duration of visits to each cell. The profile can be represented as a directed graph, where the nodes represent visited cells and the links represent transition between cells. The weight of link (a, b), $N_{a,b}$, is the number of transitions from cell a to cell b, and the weight of node b, T_b, is the average time of visits in cell b. The profile is built and stored in the mobile station. Their algorithm uses individual subscriber profiles to dynamically create location areas for individual subscribers and to determine the most probable paging area. A location update is triggered when a subscriber enters a cell that is not part of the previous location area. The mobile station first looks up the new cell in the subscriber profile. If it is not found, a classical location update is performed. If the subscriber profile contains the new cell, the list of its neighbors previously visited is read together with the number of times the subscriber has moved to those cells from the new cell. The average weight W of the links to neighboring cells is calculated. The cells corresponding to the links whose weight is greater than or equal to the average weight W are added to the new location area in decreasing link weight order. Once selected cells from the first ring of neighboring cells have been added to the personal location area, the above steps are repeated using the newly selected cells by decreasing link weight order. Those steps are repeated until the personal location area size has reached its limit or until no other cells are left for inclusion. During a location update, all T_n values for the cells of the new location area are transmitted to the network to be used for subsequent paging attempts. When an incoming call arrives for the subscriber, the average value of T_n among all cells in the current location area is calculated, and cells whose T_n value is greater or equal to the average form the paging area to be used in the first round of paging. If the first attempt is not successful, all cells in the location area are paged in the second round. They have built an activity based mobility model to test the proposed algorithm. Their test results show that their algorithm significantly outperforms the fixed location area algorithms in terms of total location management cost at a small cost of additional logic and memory in the mobile station and network.

2.5.7 Other Tracking Strategies

Topology-Based Strategies

Topology-based tracking strategies have been defined in [10]. A topology-based strategy is a strategy in which the current location area is dependent on the following: the current cell, the previous cell, and the location area that the subscriber belonged to while being in the previous cell. Here location areas can be overlapped. Whenever the current location area is different from the previous location area, a location update is needed. In fact, topology-based strategies are very general. Location areas, overlapping location areas, reporting cells (or centers), and distance-based strategies belong to the topology-based group. However, the time-based and movement-based strategies are not topology-based strategies.

LeZi-Update Strategy

In [8], the authors have proposed the LeZi-update strategy, in which the path of location areas a mobile station has visited will be reported instead of the location area. For every mobile station, the system and the mobile station will maintain an identical dictionary of paths, which is initially empty. A path can be reported if and only if there is no such path in the dictionary. This guarantees that every proper prefix of the reported path is in the dictionary. The path to be reported can be encoded as the index of the maximal proper prefix plus the last location area. This will dramatically reduce the location update cost. The dictionary is stored as a "trie," which can be considered as the profile. When an incoming call arrives, the system will look up the trie of the called mobile station and compute the blended probability of every possible location area based on the history. Those location areas can be paged based on the blended probability from the highest to the lowest.

Load-Sensitive Approaches

Recently, load-sensitive approaches have been proposed. The idea behind these approaches is that nonutilized system resources can be used to improve the system knowledge about the subscriber location. In [23], the authors have proposed an active tracking strategy in which nonutilized system resources are used for queries. A query is applied to each cell by the system when the system detects that the load on the local control channel drops below a predefined threshold. A query is similar to paging. However, paging is conducted when a call arrives to the subscriber and its objective is to set up a call while a query is initiated when there are nonutilized system resources; its objective is only to increase the knowledge about the subscriber location. Queries are initiated to complement location updates, not to replace them. Queries are virtually cost-free, yet have the benefit of reducing the cost of future paging.

In [27], the authors have proposed a load adaptive threshold scheme (LATS for short) in which nonutilized system resources are used to increase the location update activity. The system determines a location update threshold level based on the load for each cell and announces it to the subscribers. Each subscriber computes its own location update priority and performs a location update when its priority exceeds the announced threshold level. Therefore, whenever the local cell load on the cell is low, the location update activity will increase. That will reduce the cost of future paging. The authors' analysis shows that the LATS strategy offers a significant improvement not only at lightly loaded cells, but also at heavily loaded cells. Both active tracking and LATS can be used in addition to any other dynamic tracking strategy.

In [26], the author has proposed an interactive tracking strategy in which the rate of location update is based on the dynamic activity of an individual subscriber as well as the local system activity. Both the system and the mobile station will keep a look-up table $(T_1, d_1), (T_2, d_2), \ldots, (T_k, d_k)$. Here T_i is a time threshold and d_i is a distance threshold. In addition, $T_1 \geq T_2 \geq \ldots \geq T_k$ and $d_1 \leq d_2 \leq \ldots \leq d_k$. The look-up table specifies that a mobile station that travels within a smaller area should report its position less frequently. Starting from the last location update, the mobile station will track the traveled distance d, in cells, and the elapsed time t. Whenever the traveled distance d reaches d_i and the elapsed time t reaches T_i, the mobile station performs its location update. If an incoming call arrives at time t for the subscriber, the system checks the look-up table, and performs the following calculations. If $t \geq T_1$, the area to be searched has a radius of d_1, and if $T_{i-1} > t > T_i$, the area to be searched has a radius of d_i. A mobile station may maintain several look-up tables for different locations and load conditions. The network determines and announces which look-up table is to be used. It has been shown that the interactive tracking strategy is superior to the existing tracking methods used in the current system, and performs better than the distance-based strategy, which is considered the most efficient tracking strategy.

2.6 SUMMARY

Radio can be used to keep in touch with people on the move. The cellular network was introduced to reuse the radio frequency such that more people can take advantage of wireless communications. Location management is one of the most important issues in cellular networks. It deals with how to track subscribers on the move. This chapter has surveyed recent research on location management in cellular networks.

Location management involves two operations: location update and paging. Paging is performed by the network to find the cell in which a mobile station is located so the incoming call for the mobile station can be routed to the corresponding base station. Location update is done by the mobile station to let the network know its current location. There are three metrics involved with location management: location update cost, paging cost, and paging delay.

Network topology, call arrival probability, and mobility patterns have a great impact on the performance of a location management scheme. This chapter has presented some assumptions that are commonly used to evaluate a location management scheme. Finally, this chapter has surveyed a number of papers on location management in cellular networks that have been published recently in major journals and conference proceedings.

ACKNOWLEDGMENTS

The author would like to thank Guangbin Fan for drawing the figures in this chapter. The author would also like to thank Paul Schwartz of Ampersand Grapics Ltd. and Susan Vrbsky of the University of Alabama for suggesting changes that improved the presentation.

REFERENCES

1. I. F. Akyildiz and J. S. M. Ho, Dynamic mobile user location update for wireless PCS networks, *Wireless Networks, 1,* 187–196, 1995.
2. I. F. Akyildiz, J. S. M. Ho, and Y.-B. Lin, Movement-based location update and selective paging for PCS networks, *IEEE/ACM Transactions on Networking, 4,* 4, 629–638, 1996.
3. A. Abutaleb and V. O. K. Li, Location update optimization in personal communication systems, *Wireless Networks, 3,* 205–216, 1997.
4. A. Abutaleb and V. O. K. Li, Paging strategy optimization in personal communication systems, *Wireless Networks, 3,* 195–204, 1997.
5. I. F. Akyildiz, Y.-B. Lin, W.-R. Lai, and R.-J. Chen, A new random walk model for PCS networks, *IEEE Journal on Selected Areas in Communications, 18,* 7, 1254–1260, 2000.
6. U. Black, *Mobile and Wireless Networks,* Upper Saddle River, NJ: Prentice Hall, 1996.
7. U. Black, *Second Generation Mobile and Wireless Networks,* Upper Saddle River, NJ: Prentice Hall, 1999.
8. A. Bhattacharya and S. K. Das, *LeZi-Update: An Information-Theoretic Approach to Track Mobile Users in PCS Networks,* MOBICOM, Seattle, 1999, pp. 1–12.
9. A. Bar-Noy and I. Kessler, Tracking mobile users in wireless communications networks, *IEEE Transactions on Information Theory, 39,* 6, 1877–1886, 1993.
10. A. Bar-Noy, I. Kessler, and M. Naghshineh, Topology-based tracking strategies for personal communication networks, *Mobile Networks and Applications, 1,* 49–56, 1996.
11. A. Bar-Noy, I. Kessler, and M. Sidi, Mobile users: To update or not to update? *Wireless Networks, 1,* 175–185, 1995.
12. Y. Birk and Y. Nachman, Using direction and elapsed-time information to reduce the wireless cost of locating mobile units in cellular networks, *Wireless Networks, 1,* 403–412, 1995.
13. V. Casares-Giner and J. Mataix-Oltra, On movement-based mobility tracking strategy—An enhanced version, *IEEE Communications Letters, 2,* 2, 45–47, 1998.
14. EIA/TIA, *Cellular Radio-Telecommunications Intersystems Operations* (Revision C), Technical Report IS–41, EIA/TIA, 1995.
15. G. Fan and J. Zhang, Virtual cellular networks for non-uniformly distributed base stations, in *Proceedings of the 30th Annual International Conference on Parallel Processing,* Valencia, Spain, September 2001.

16. M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness,* San Francisco: W. H. Freeman, 1979.
17. J. S. M. Ho and I. F. Akyildiz, Mobile user location update and paging under delay constraints, *Wireless Networks, 1,* 413–425, 1995.
18. A. Hac and X. Zhou, Locating strategies for personal communication networks: A novel tracking strategy, *IEEE Journal on Selected Areas in Communications, 15,* 8, 1425–1436, 1997.
19. Y.-B. Lin, Reducing location update cost in a PCS network, *IEEE/ACM Transactions on Networking, 5,* 1, 25–33, 1997.
20. Y.-B. Lin and I. Chlamtac, *Wireless and Mobile Network Architectures,* New York: Wiley, 2001.
21. B. Liang and Z. J. Haas, *Predictive Distance-Based Mobility Management for PCS Networks,* INFOCOM, New York, 1999.
22. J. Li, H. Kameda and K. Li, Optimal dynamic mobility management for PCS networks, *IEEE/ACM Transactions on Networking, 8,* 3, 319–327, 2000.
23. H. Levy and Z. Naor, Active tracking: Locating mobile users in personal communication service networks, *Wireless Networks, 5,* 467–477, 1999.
24. U. Madhow, M. L. M. Honig, and K. Steiglitz, Optimization of wireless resources for personal communications mobility tracking *IEEE/ACM Transactions on Networking, 3,* 6, 698–707, 1995.
25. J. G. Markoulidakis, G. L. Lyberopoulos, D. F. Tsirkas, and E. D. Sykas, Evaluation of location area planning scenarios in future mobile telecommunication systems, *Wireless Networks, 1,* 17–25, 1995.
26. Z. Naor, *Tracking Mobile Users with Uncertain Parameters,* MOBICOM, Boston, 2000.
27. Z. Naor and H. Levy, LATS: A load-adaptive threshold scheme for tracking mobile users, *IEEE/ACM Transactions on Networking, 7,* 6, 808–817, 1999.
28. F. G. Nocetti, I. Stojmenovic, and J. Zhang, Addressing and routing in hexagonal networks with applications for location update and connection rerouting in cellular networks, submitted for publication.
29. G. P. Pollini and C.-L. I, A profile-based location strategy and its performance, *IEEE Journal on Selected Areas in Communications, 15,* 8, 1415–1424, 1997.
30. M. Rahnema, Overview of the GSM systems and protocol architecture, *IEEE Communications Magazine, 43,* 92–100, 1993.
31. T. S. Rappaport, *Wireless Communications—Principles and Practice,* Upper Saddle River, NJ: Prentice Hall, 1996.
32. C. Rose, Minimizing the average cost of paging and registration: A timer-based method, *Wireless Networks, 2,* 109–116, 1996.
33. S. Ramanathan and M. Steenstrup, A survey of routing techniques for mobile communication networks, *Mobile Networks and Applications, 1,* 89–104, 1996.
34. C. Rose and R. Yates, Minimizing the average cost of paging under delay constraints, *Wireless Networks, 1,* 211–219, 1995.
35. J. Schiller, *Wireless Communications,* Boston: Addison-Wesley, 2000.
36. I. Stojmenovic, Honeycomb networks: Topological properties and communication algorithms, *IEEE Transactions on Parallel and Distributed Systems, 8,* 10, 1036–1042, 1997.
37. S. K. Sen, A. Bhattacharya, and S. K. Das, A selective location update strategy for PCS users, *Wireless Networks, 5,* 313–326, 1999.
38. J. Scourias and T. Knuz, A Dynamic individualized location management algorithm, in *Pro-*

ceedings 8th IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications, Helsinki, Finland, September 1997, pp. 1004–1008.

39. A. A. Siddiqi and T. Kunz, *The Peril of Evaluating Location Management Proposals through Simulations,* Dial M, Seattle, 1999, pp. 78–85.
40. S. Tabbane, An alternative strategy for location tracking, *IEEE Journal on Selected Areas in Communications, 13,* 5, 880–892, 1995.
41. I-F. Tsai and R.-H. Jan, The look ahead strategy for distance-based location tracking in wireless cellular networks, *ACM Mobile Computing and Communications Review, 3,* 4, 27–38, 1999.
42. G. Wan and E. Lin, Cost reduction in location management using semi-realtime movement information, *Wireless Networks, 5,* 245–256, 1999.
43. H. Xie, S. Tabbane, and D. J. Goodman, Dynamic location area management and performance analysis, in *Proceedings 43rd IEEE Vehicular Technology Conference,* Secaucus, NJ, May 1993, pp. 536–539.
44. J. Zhang, A Cell ID Assignment scheme and its applications, in *Proceedings ICPP Workshop on Wireless Networks and Mobile Computing,* Toronto, Canada, August 2000, pp. 507–512.