MOBILITY MANAGEMENT
IN
WIRELESS CELLULAR SYSTEMS

BY

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A THESIS

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Abstract

In new generation of wireless cellular systems called Personal Communications Systems (PCS), integrated services (voice, data, multimedia) are provided for mobile subscribers. Microcells and picocells are used to provide extra capacity for the large increase in air traffic. The deployment of small cells, however, makes the mobility management problem critical. New protocols should be designed to alleviate the loading on the terrestrial network and the radio link. In this thesis, the signalling traffic on the radio link is investigated. We contribute a set of algorithms for efficient location tracking of users, squeezing out bandwidth for revenue generating voice and data traffic.

In the first part of the thesis, we examine a location registration algorithm based on a novel multi-accessing technique. Instead of random accessing the uplink control channel during location update, each mobile could sends its specially assigned identity vector on the uplink channel without contention. Our algorithm outperforms other members in this family of protocols. It also performs better than the geographic based strategy when the mobility of the population is high.

In the second part of the thesis, a dynamic strategy for location area assignment is introduced and analysed. New location area is assigned for each

mobile user whenever it leaves the previous location area. The real-time mobility record of a mobile user is retrieved in the assignment of a new location area. Our algorithm has the advantage when the mobile population has diverse mobility characteristics which is also time varying. The strategy outperforms both the geographic based and the distance based strategy under all mobility scenarios.

In the third and final part of this thesis, we propose that the Bloom filter location update algorithm could be used as an auxilliary strategy on top of other standard location tracking strategies. Both random accessed and periodic contention free location updates are allowed on the uplink control channel. When a call is placed to a mobile, only a fraction of the cells in a targeted location area are paged. Thus, the Bloom filtering operation could be viewed as a *selective paging mechanism* to reduce paging traffic.

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Chapter 1

Introduction

1.1 Design Issues in Wireless Cellular Systems

The cellular communication industry has been experiencing a rapid growth in recent years, thanks to the development of small, low cost and low power transceivers. Fueled by the growth in the number of mobile subscribers, researches all over the world involved in the genesis of a new generation of wireless cellular systems - *personal communication systems* (PCS).

With PCS, a plethora of new services will be provided. Simultaneous transmission of voice, data, video traffic, and etc. is supported. The successful implementation of the PCS depends on the *quality* and the *bandwidth availability* of the wireless channel.

The wireless channel, however, is known to be subject to severe conditions [14]. Mobile subscribers experience time and spatial varying fading - rapid fluctuation of signal strength due to multi-path effect. This makes the wireless channel very unreliable. Advanced modulation technologies, diversity combination schemes, error control and retransmission techniques are among those strategies developed to combat the fading problem intrinsic to wireless communications.

By nature, radio bandwidth is a scarce resource. A cellular operator is allocated with limited radio spectrum. The cellular concept [12] offers a means for efficient use of the spectrum. *Frequency reuse* (reuse of same frequency over space) is adopted as a *media access control* (MAC) layer operation to increase the bandwidth availability. In order to squeeze out more capacity to accommodate more mobile users, small cells must be deployed in new PCS.

The provision of small cells in PCS systems have important implications on design issues like channel assignment, handoff, multiple accesses and mobility management. Efficient system management is critical to the performance of the wireless communication system.

1.1.1 Channel Assignment

In static channel assignment, channels are nominally assigned to cells. Every cell has a fixed number of channels. Depending on the multiple accessing technology employed, a channel may refer to frequency, time slots or a *pseudo-noise* (PN) sequence. The static channel assignment works reasonably well for systems with large cells.

In new systems with small cells, traffic intensity is subject to high variability. This makes frequency planning with fixed assignment ineffective. With dynamic channel allocation strategies, all channels are put in a common resource pool. Channels are allocated on a call by call basis. The need for frequency planning is removed. Various assignment strategies have been proposed [4], and [5]. These proposed algorithms are adaptive to traffic patterns, having a capacity gain relative to the static channel assignment. Because of the complexity of the problem, assignment of channels is suboptimal in general.

1.1.2 Handoff

As a mobile unit (MU) moves from one cell to another, any active call needs to be allocated a channel in the destination cell. This event, termed the handover or handoff, must be transparent to the MU. If there is no available channel in the destination cell, the on-going call is terminated. The disconnection of call during handoff is disrupting and probability of this occurence should be minimized. This is done by reserving a number of channels for handoff MU's in each cell. The reservation of channels increases the blocking probability of new arrival calls. Thus there is a tradeoff between handoff blocking and call blocking.

As cell size becomes smaller, the frequency for handoff increases. Efficient protocols should be designed to minimize the signalling overhead and processing delay during handoff. Since there is a close relationship between handoff and channel assignment, these problems are usually coupled together [15], [16] in algorithm design and performance analysis.

1.1.3 Multiple Accesses

In traditional cellular systems, the wireless connection for voice traffic is circuit-oriented. There are three well known MAC layer protocols used, namely, *frequency division multiple access* (FDMA), *time division multiple access* (TDMA) and *code division multiple access* (CDMA). In PCS, the wireless system supports integrated traffic coming from different sources, each with specific *quality of service* (QoS) requirements and diverse traffic characteristics. It is well known that the circuit oriented approach is inefficent when the sources have bursty arrival statistics. Packet oriented connectionless approach offers statistical multiplexing and efficiently utilize the radio bandwidth.

Pure ALOHA, also known as random accessing, is the first protocol designed for multiple users to access a single common channel. Since individual users have no co-ordination in transmissions, the channel efficiency is very low. Starting from the seminal paper on *packet reservation multiple access* (PRMA) [17], many new accessing algorithms RAMA[19], D-TDMA[20], DRMA[18] are proposed to integrate voice and data traffic efficiently. It is expected new accessing schemes will be proposed to multiplex a variety of sources with multiple QoS requirements.

1.1.4 Mobility Management

In mobile systems, the mobile units (MU's) have no fixed point of attachment with the terrestrial network. The network interfaces of the MU's change from time to time. The network has no information on the whereabouts of the roaming MU's. Location tracking of users is accomplished through a combination of *location registration* (*location update*) and *terminal paging* activities. By location registration each MU decides when to report its location to the local base station. The network reserves a hierarachy of location databases, storing the location information of all MU's. When a call is placed to a targeted MU, the corresponding location data is retrieved. The network sends a polling signal to those cells which have high probability to locate the targeted MU. This is called terminal paging. After the targeted MU receives the paging message, it will request for a call connection with the network.

The location registration strategy used in most systems currently is the geographic based strategy. Random accessing is employed as the uplink MAC protocol during call connection setup, location registration and other control messages transmission. As cell size becomes smaller in newer systems, the frequency of location registration increases. This dramatically decreases the efficiency in accessing the uplink control channel.

1.2 Motivation of the thesis

Under the rubric of mobility management, a number of algorithms have been proposed to resolve the coupled problem of location update and paging. The signalling overhead of these control messages must be minimized. Algorithms have been proposed to provide means to avoid unneccessary location updates and paging. There are also some other issues. In particular, new protocols must be designed to resolve the inefficiencies associated with random accessing during location update. The general methodology is to distribute the location update traffic into a larger number of cells. This reduces the offered load on the uplink control channel in each cell, enhancing the efficiency of random accessing.

In [35], a time based Bloom filter location update algorithm is proposed. This belongs to a new category of algorithms characterized by contention free access of uplink control channels during location update. The new multiple access technique provides an alternative to traditional random accessing during location update. Nevertheless, due to the time based nature of the protocol, the proposed algorithm has not been compared favourably with the geographic based strategy. In this thesis, we propose a hybrid Bloom filter algorithm. The algorithm is hybrid in the sense that location updates could be temporally or geographically triggered. Our algorithm outperforms the geographic based counterpart except in low mobility scenarios.

As stated in [21], most recent research efforts focus on the development of dynamic location update and paging schemes. Dynamic schemes allow on-line adjustments based on the characteristics of each individual MU. For instance, when the distance based location update scheme is used, a different distance threshold could be assigned to each MU based on its real-time mobility and call arrival records. The provisioning of a dynamic scheme adapting to *user-varying* and *time-varying* mobility behaviour is highly desirable. It has important implications in new systems where users have vastly different mobility patterns, and the mobility fluctuation with time is large. We contribute a dynamic algorithm in which location area is assigned to each individual MU based on its recent mobility records. The operation of this scheme requires simple computation and data logging. Implementation of the scheme distributely on the MU's is feasible.

1.3 Outline of the thesis

In this thesis, the issue of mobility management is addressed. In particular we focus on strategies that minimize the control bandwidth usage on the radio link. Since the performance of location management schemes is largely independent to the network architecture, we decouple the problem of location management to the network part and the radio link part. Unless otherwise stated, we assume a hierachical databases structure consisting of HLR's and VLR's on the fixed network. The next three chapters present a set of location registration protocols designed to optimize performance on the radio link.

Chapter 2 gives an overview of related literature. The chapter begins with an introduction of the current standards in mobility management. In section 2 commonly used mobility models are discribed. We then categorize the pools of location registration strategies in literature into different class. The relative merits and demerits of different class of location management strategies are discussed.

Chapter 3 presents the Hybrid Bloom Filter Location Update Algorithm. Unlike the traditional location strategies where pure ALOHA is used, our update algorithm belongs to a new family of multi-accessing protocols. Three paging schemes are proposed. Our algorithm is superior to other members of this family of protocols. A comparison of our algorithm with the well known time based and geographic based strategies is also given.

In Chapter 4, a dynamic location area assignment strategy is described. New location area is assigned for each mobile user whenever he leaves the previous location area. The real-time mobility record of a mobile user is retrieved in the assignment of a new location area. Our algorithm has the advantage when the mobile population has diverse mobility characteristics which is also time-varying. The strategy outperforms both the geographic based and the distance based strategy under all mobility scenarios.

In Chapter 5, we examine the possibility that the Bloom filter Location Update algorithm is used as an auxilliary strategy on top of traditional location tracking strategies. When a call arrives, a cell would be paged if it is in the targeted location area and is not excluded by the Bloom filtering operation. A case study is given when both the Hybrid Bloom filter algorithm and the Dynamic location area assignment algorithm are jointly used on the same system.

Finally, chapter 6 gives some concluding remarks and suggestions for future research.

Chapter 2

Background Studies

2.1 Current Standards

There are two standards for location management currently available [23], namely the Electronic/Telecommunications Industry Associations (EIA/TIA) Interim standard 41 (IS-41) and the Global System for Mobile Communications (GSM) mobile application part (MAP). The IS-41 scheme is commonly used in systems like analog AMPS (IS-41) and North America Digital AMPS (IS-54), while the GSM MAP is mostly used in Europe for GSM and DCS-1800. Both standards are strikingly similar in the specifications for fixed network and radio link.

On the fixed network, a two-level data hierarchy is maintained. The operator keeps a *home location register* (HLR) in which information of all mobile subscribers is stored. Collocated with the mobile switching centre (MSC) of every location area there is one or more *visitor location registers* (VLR). With reference to fig.2.1, when a MU departs to a new location area, it sends a registration request to the local base station. This request stimulates a complex

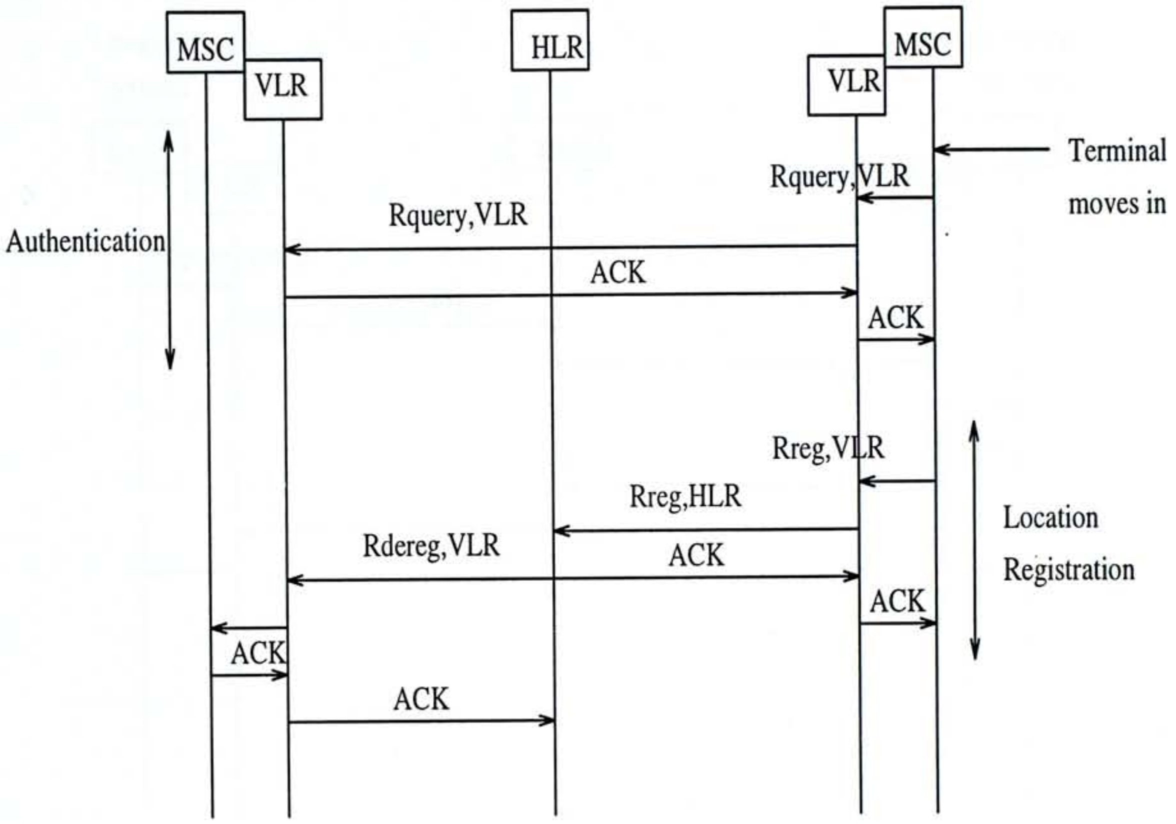


Figure 2.1: Network signalling flow for terminal registration

sequence of network operations including database updates at the current VLR, the HLR of the MU, and the VLR of the previous location area. As seen from the diagram, the VLR registration rate $R_{reg,VLR}$, the HLR registration rate $R_{reg,HLR}$ and the VLR deregistration rate $R_{dereg,VLR}$ are equal. Whereas the VLR query rate $R_{query,VLR}$ is twice the VLR registration rate $R_{reg,VLR}$. The sum of these rates represent the total signalling overhead in the fixed network for terminal registration.

Refer to fig.2.2 when a call is placed for a targeted MU. The calling party queries the database for the address of the HLR, where the autentication and billing information of the targeted MU is stored. The HLR is queried for the VLR of the targeted MU. The Route request message is then sent to the VLR of the called party. At the *mobile switching office* (MSC) of the called party, a

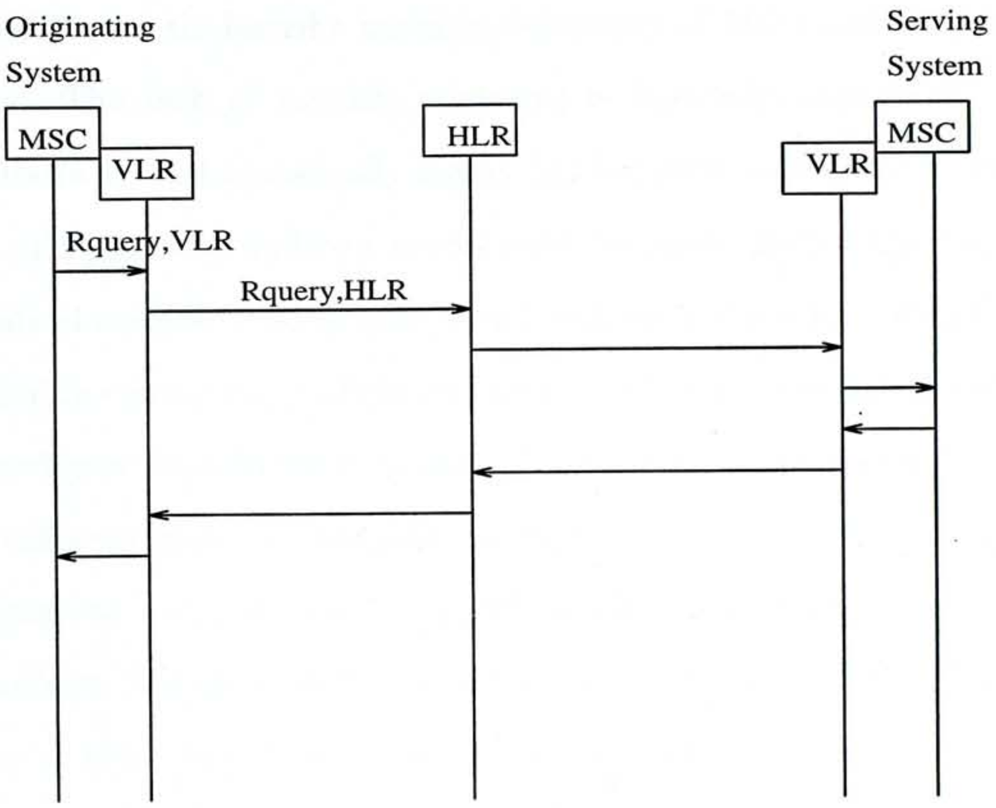


Figure 2.2: Network signalling flow for call delivery

temporary identity number is allocated, which is then sent back to the calling MU. The calling MU will request a call setup through the SS7 network. Associated with the task of call delivery are two querying operations: one querying at the VLR of the calling party and one querying at the HLR. Thus, the total signalling load for call delivery is the sum of $R_{query,VLR}$ and $R_{query,HLR}$.

2.2 Mobility Models

Teletraffic models are invaluable tools for network planning and design. They are useful in areas such as network architecture comparisons and network resource allocations. In the context of mobility management, teletraffic models are generally used to describe mobility behaviour of MU's and call arrival distributions. The task of *mobility modelling* is especially important. In order to quantitatively and realistically assess any location management scheme, an accurate and plausible mobility model must be used. Both empirical [13] and mathematical mobility models have been proposed in literature. Empirical models are used in conducting realistic simulations while mathematical models offer basic paradigms for performance analysis, allowing comparisons to be drawn between different location management strategies.

In analysing the performance of different location management protocols, simple mobility models must be applied to ensure the tractability of the analysis. However these models must be sophisticated enough to reflect the mobility characteristics of the MU's. Among all the analyitical models, the *fluid flow* and the *Markovian model* are the most popular. More sophisticated analytical mobility models do exist [7],[8]. Nevertheless,the two simplistic models has their merits.

2.2.1 Fluid Flow Model

As the name implies, the model conceptualizes traffic flow as the flow of a fluid. It is usually used to model aggregate traffic of vehicles. In its simplest form [6], the number of zone crossings per unit time N is related to the population density ρ, perimeter of the area L and v, the average velocity of the aggregate traffic.

$$N = \frac{\rho v L}{\pi} \tag{2.1}$$

The model assumes uniform distribution of vehicle locations, thus the fluid flow model is also known as uniform traffic model.

Beside the simplicity of the relationships, the model could be extended to include additional features such as capacity constraints and the interdependence between velocity and vehicular desity. However, there are limitations to this model. The model approximates the zone with uniform densities of vehicles, neglecting the street layout. Moreover, since only aggregate traffic is considered, the model could not be used to trace individual MU. In general, it is inappropriate to use this mobility model in the performance evaluation of dynamic location strategies.

2.2.2 Markovian model

The Markovian model describes movement behaviour of individual MU's. By this model, each MU will either remain in a cell or move to other cells according to a transition probability distribution. The Markovian model captures the stochastic fluctuations of each individual MU, and enables location probability distributions to be calculated. The *a priori* knowledge of these location probabilities allows the comparison of different selective paging schemes. The erratic random walking itinerary is usually used to model pedestrian movements. However, there is one major limitation of this modeling. The concept of *trips* is not supported since markovian movements are memoryless.

2.3 Dynamic versus Static Location Strategy

Before we have an overview of different categories of location registration strategies, here we give precise definitions for the static and dynamic location registration strategies.

By *static location strategy*, the location areas are defined for the whole system. Each mobile unit has a fixed set of location area boundaries which do not change with time.

By *dynamic location strategy* location areas are tailored for each MU specifically. Thus, the assignment of location areas take into consideration of user varying mobility behaviour. In our context, we describe a strategy be dynamic when the assignment strategy reacts to time varying mobility behaviour with adjustment.

2.4 Location Registration Strategies

There are numerous algorithms proposed in literature. Broadly speaking, location strategies could be classified as *time based*, *geographic based*, or *distance based* according to the mechanism that triggers a location update. Below is a brief summary of various location strategies. Their relative strength and weakness are highlighted.

2.4.1 Time Based Strategy

Pure Time Based Strategy

By the time based strategy, each MU independently performs location updates. Each MU maintains an internal timer and perform registration periodically. In order to minimize the chance of packet collisions, there is no synchronization of the MU's in location update.

When a call is placed for a targeted MU, the network polls the most recently registered cell. If the MU is not located, the surrounding tier of cells will be polled. It is done recursively until the MU is found. With this paging strategy, the polling delay is not bounded.

The complexity of time based strategy on the MU is very low. Each MU needs only to keep an internal timer. As opposed to other location strategies, time based schemes do not require the MU to record and process location information during the time between location updates. This feature is desirable for minimizing mobile transceiver use during idle periods. However, the time based strategy is generally inefficient. The polling delay, as well as the number of cells paged until a MU is found are large when the MU has high mobility. For a MU with low mobility, there will be excessive location updates.

Time Based Bloom Filter Algorithm

In [35], the time based Bloom filter algorithm is proposed. This belongs to a new category of location update algorithms, characterized by contention free access of uplink control channels for all MU's. Every MU has a unique mobile unit identity vector (MUID) for identification purpose. It is also assigned a

n-bit Bloom filter identity vector(BFID). This n-bit vector is used to perform contention free LU. Periodically, each MU performs a LU by sending its BFID vector to the cell it is camping on. When the corresponding bit in the BFID is a '1', a pulse is sent. Otherwise, the MU sends nothing. A cell receives the superimposition of pulses from all MU's camping on the cell, store it as a *cell vector.* We assume that the maximum propagation delay of pulses from the MU's to a base station is much smaller than the bit time of an updating message so that there is no bit synchronization problem. If the base station detects one or more pulses in the i^{th} bit interval, it knows that at least one MU in the cell contains a '1' in the i^{th} bit. On the other hand, if the base station detects no pulse in the i^{th} bit, it concludes that all MU's inside the cell have BFID's which are zeros at the i^{th} bit. The zero in the i^{th} bit in the cell vector provides significant information. One can infer that a MU with an ID of '1' in the i^{th} bit is not in the cell.

Denote $l_j, j \in [1, M]$, as the cell vector obtained in the most recent location update cycle in cell j from a system of M cells. When a call arrives for the MU with ID t_m, the system will page the call to cell j if $t_m \otimes l_j = t_m$, where $\otimes$ denotes bit by bit multiplication. This operation is called Bloom filtering [31]. The aim of the Bloom filter operation is to reduce the number of paging cells. Only the cells whose cell vectors match to the targeted MU will be paged. The MUID of the called MU is then broadcasted on the paging channels of the matched cells. Assume each bit of an arbitrary ID vector is independent and is '1' with probability p, it is shown in [32] that the proportion of cells needed to be paged is $(1-pq)^n$, where $q = (1-p)^k$ and k is the number of MU's in a cell.

In [33], a location update scheme based on Bloom filter approach, called the

One-Bit-Reply (OBR) protocol, is proposed. Both algorithms use contention-free, temporally triggered updates which contribute to a small LU bandwidth cost, at the expense of higher paging cost.

2.4.2 Geographic Based Strategy

Pure Geographic Based

This is the strategy employed in the specifications of the IS-41 and IS-54 standards. By the geographic based stategy, the whole network is partitioned into non-overlapping location areas. Each MU performs a location update when it enters a new location area. Thus at any time the system keeps track of the location of all MU's at the resolution of one location area. When a call is placed to a targeted MU, the location information stored on the fixed network is retrieved. All cells in the registered location area are paged. There are three major problems associated with the geographic based strategy, namely:

- Location areas are assigned such that the combined control bandwidth usage is minimized globally. The chosen location area size is not optimal for all MU's.
- If a MU moves back-and-forth frequently between two location areas, there is excessive location updates.
- The load of location registration is concentrated in the boundary cells of the location areas.

Location Area Partitioning

Modifications of the geographic based strategy have been proposed to overcome these problems. In [43],[41],[42], the location area assignment problem is formulated as the classical graph partitioning problem. Since this problem is NP-complete [3], an exact search for the optimal solution is impractical for a large-scale system due to its exponentially growing computation time. These heuristic algorithms are proposed to find approximately optimal solutions in location area partitioning. The assigned location areas have arbitrary shapes. These assignments yield better control bandwidth saving than regular tesselation of location areas.

Overlaid Location Area Layers

In [40], the location area size of a MU is dynamically determined according to its call arrival and mobility pattern. In [30], a multi-layer location area structure is proposed. The overlapping layers provide hysteresis against frequency switching between two location areas. In both [30] and [40], more cells perform the job of location registration. Thus, the offered load of location registration in these cells are smaller, maintaining the efficiency of random accessing.

2.4.3 Distance Based Strategy

By the distance based strategy, the concept of a static location area is removed. Each MU is assigned a location area consisting of d tiers of cells, where d is known as the *location area radius.* When the MU exits a location area, a location update is performed. The *updating cell* becomes the centre cell of the new location area.

The *location area radius* could be dynamically adjusted adapting to different mobility patterns [44]. Since a MU Selective paging schemes could be used in the polling of cells. The distance based strategy is an attractive alternative to the geographic based counterpart because:

- The distance based strategy is dynamic in the sense that *location area radius* could be tailored for each MU individually .
- By the nature of the distance based strategy, a newly assigned location area is overlapped with the previous location area, thus providing hysteresis.
- The burden of location updating is fully distributed to all cells within the system. Every cell may become the location area boundary of a MU as time evolves.

Further variations of the distance based strategy have been proposed. In [11], the distance based strategy is combined with a paging scheme which guarantees a pre-defined maximum delay requirement. In [10], a MU determines when to perform a location update based on the distance from the most recent registered cell and the call arrival probability. It has the advantage of time based schemes and the efficiencies of distance based schemes.

2.4.4 Miscellaneous Strategies

There are a number of location management schemes which do not fall into any of the above categories. In [1], a novel tracking strategy in which a subset of all base stations is selected and designated as reporting centers. Mobile users transmit update messages only upon entering cells of reporting centers, while every search for a MU is restricted to the vicinity of the reporting center to which the MU last reported. In [9], a mobility tracking mechanism that combines a movement-based location update policy with a selective paging scheme is proposed. Movement based location update is selected for its simplicity. Each MU only keeps a counter of the number of cells visited, without the need to know the network topology. A location update is performed when the counter exceeds a predefined threshold value. Selective paging of cells are used at the expense of paging delay.

2.5 Summary

In this chapter, we have described two location management standards which are used in current systems. The importance of mobility modelling in performance analysis of location algorithms is highlighted. The Markovian and Fluid Flow models are described. We have given a condensed notes on well known location tracking strategies.

Chapter 3

Hybrid Bloom Filter Location Update Algorithm

3.1 Introduction

An efficient location tracking scheme should reduce the overall signalling load on the radio link. As highlighted in the previous chapter, the problem associated with random accessing the uplink channel for location updates is prominent in new generation wireless communication systems. New protocols are designed to minimize the impact of location updates. There are two major approaches. The most common methodology is to distribute location update traffic to a larger number of cells. This is achieved through the adoption of various dynamic location update protocols. Each MU is assigned a different location area tailored for its mobility and call arrival behaviour. The assignment may also be adjusted to account for time varying mobility behaviour of specific MU's. Another approach to bypass the inefficiency of random access is the use of alternative multiple accessing options. The time based Bloom filter location update algorithm described in chapter 2 is one of those algorithms which do not rely on random accessing during location update.

In this chapter, a Hybrid Bloom Filter Location Update Algorithm is proposed. The proposed algorithm belongs to the same family as the time based Bloom filter location update algorithm [32]. It is hybrid in the sense that location updates could be either temporally or geographically triggered. It is a static strategy since each MU is assigned with the same timeout irrespective of its mobility behaviour. The Bloom filter algorithm is characterized by contention free access of uplink control channels during location update. Two or more mobile units are permitted to register with a base station simultaneously without contention on the uplink channel. The location updating procedure is hybrid in the sense that it could be temporally or geographically triggered. Based on the location information stored in all base stations, Bloom filtering is used to select cells to be paged to locate the targeted mobile unit. The performance of this scheme is compared with the well known Time Based, Geographic Based, and its predecessor, Time Based Bloom Filter Location Update Algorithm. Our numerical results show that the new algorithm requires the least combined location update and paging bandwidth when average mobility of MU's is not too small.

3.2 System Model

Consider a wireless cellular system consisting of M cells with total population of N MU's. Since we characterize mobility in terms of cell crossing rate, the choice of shape and layout of the cells have no consequences in the subsequent analysis. Nevertheless, for illustration purpose, we assume the system is regularly tesselated with square cells. The dwell time in a cell of each MU is assumed to be exponentially distributed with mean $\frac{1}{\mu}$. Individual call interarrival time is also exponentially distributed with mean $\frac{1}{\lambda}$. Since the interarrival time of calls is generally much larger than update period τ_g, it is reasonable to assume that there can be at most one incoming call during one update cycle. We also assume that LU messages are received instantaneously, i.e. propagation delay is ignored. The number of users in a cell is denoted by k_0. The average value of k_0 is assumed to be $\frac{N}{M}$.

Besides an unique MUID for identification purpose, each MU is assigned a BFID of length n. We assume each bit of this vector is independent, and is '1' with probability p. Note that these n-bit vectors need not to be unique.

3.3 Hybrid Bloom Filter Algorithm

In this section, we present a new location tracking strategy for MU's and the algorithms used by the fixed network in tracking the MU's. We discuss both the location update and the paging protocols.

3.3.1 Location Update Protocol

As shown in fig.3.1, the uplink control channel consists of periodic *registration slots* with period τ_g. Only LU messages are allowed in these slots. The duration of each slot is very small compared with τ_g, so we assume any location update message sent is received by the local cell instantaneously. All other control messages such as call setup negotiations can contend for the channel in other unreserved time slots. When a MU crosses a cell boundary at time t_a, it attempts to register to the new cell. However, it can do so only at the next registration slot. In the meantime, the system loses track of the MU temporarily, as shown by the shaded area in the diagram. At time t_b, the MU sends its ID vector on the uplink channel. The cell is informed of the presence of the MU's immediately. If more than one MU's enter the given cell since the last update, the received cell vector is a superimposition of several BFID's, coming from each of the newly arrived MU's. The registration information is valid for a period of $r\tau_g$. If a MU remains in the same cell at the end of this period, a temporally triggered LU will be performed to re-register with the cell. If the cell does not receive any re-registration from a MU which registered at a time $r\tau_g$ before, the system infers that the MU has left the cell and deregisters it. Viewed from the base station, a bit in the cell vector will be reset if no pulse is received in the corresponding bit time for the r most recent registration slots. At any time t, label the end of the most recent registration slot by $T_r(t)$. Label the end of the immediately preceding registration slot by $T_{r-1}(t)$ and so on. The time interval $T_r(t) - T_1(t)$ is called the *registration memory window* at time t. If no confusion arises, $T_i(t)$ could be simply denoted as T_i. Label the cell vector received by the base station at time T_i by S_i.

The updating algorithm described above is hybrid in the sense that both temporally triggered and geographically triggered LU are used in the location tracking. This hybrid update scheme is advantageous because an inactive MU will need to register only once every r slots. Hence, the expected number of MU's participating in the location update process for the hybrid scheme is smaller than

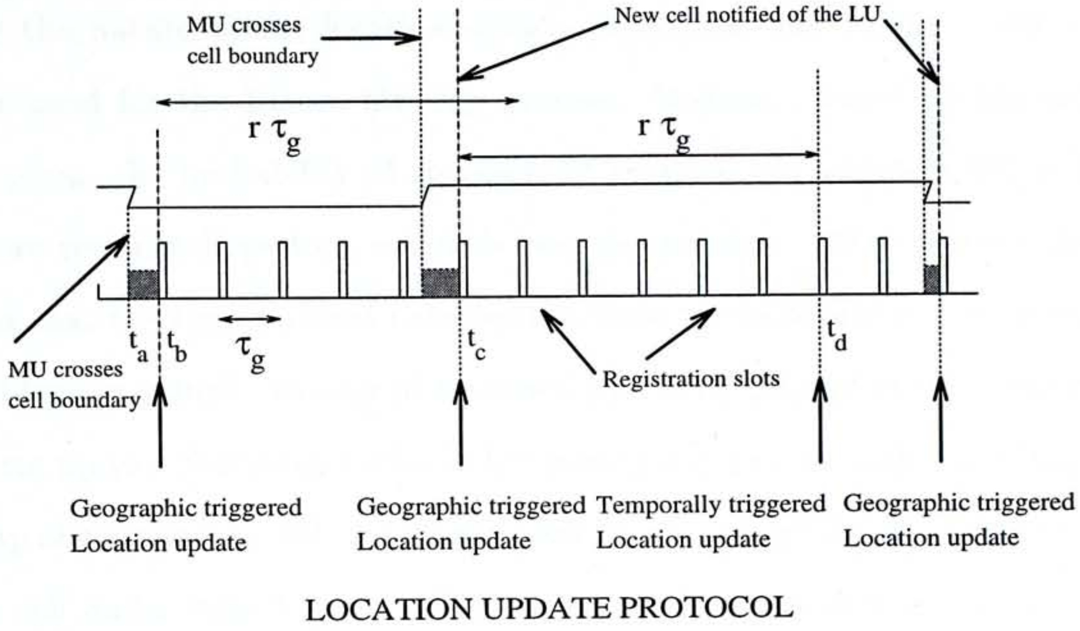


Figure 3.1: Illustration of location update on uplink control channel for an arbitrary MU

the original Bloom filter scheme. As the number of MU's required to register becomes smaller, the MU's can be tracked more accurately. Moreover, as MU will not register as frequently as that in the TBBF algorithm, battery power in the handset can be saved.

3.3.2 Paging Protocol

When a MU is called, the system retrieves the most recent r location vectors from all cells. These location vectors are used to locate a MU via Bloom filtering. There is a finite probability $P_{L,C}$ that the targeted MU has just left the cell when the call arrives. In this case the system will not be able to locate the MU without flooding the whole system. With probability $P_{C,L} = 1 - P_{L,C}$ the targeted MU is still in the registered cell when the call arrives. This MU is registered in at least one of the r most recent cell vectors stored at the base station.

By the nature of the location update algorithm, any of the r cell vectors can be used for the Bloom filtering process. However, based on our mobility assumption, the probability of successfully locating the targeted MU is higher for more recent cell vectors, which is counter-intuitive. (We argue in the next section that the time interval between the most recent location update and call arrival time is actually the *age* of a renewal process.) To exploit this property, we institute up to r *matching cycles* in the paging process. In each matching cycle, a group of consecutive cell vectors are used to decide whether the targeted MU is in the cell under consideration. The first matching cycle uses the most recently received group of cell vectors. The second matching cycle uses the next most recently received group and so on. If the targeted MU is found, the matching cycle stops immediately. If the users cannot be identified with this process, the system will flood all yet unpaged cells in the system to locate the targeted MU.

It is shown in [24] that the paging cost would be minimum if cells are paged sequentially in order of decreasing probability. More probable cells should be paged first. Under our mobility model, a MU is more likely to be registered in a more recent time slot. Thus, the use of more recent cell vectors for matching first is analogous to the optimal paging scheme.

Three types of matching cycle groupings are considered here for comparison. In paging scheme 1, there is only one matching cycle. That is, all r cell vectors in each cell are used to match the BFID of the incoming MU. The system sends a polling signal to all cells that match the BFID of the MU. In paging scheme 2, there are two matching cycles. In the first pass, the w most recent cell vectors from each cell are used for matching. In the second pass, the remaining $r - w$ vectors are used. In paging scheme 3, there are r matching cycles starting with the most recent cell vector. In all three cases, if the targeted MU cannot be located after all the matching cycles, the remaining cells will be flooded.

3.4 Performance Evaluation

Since the radio bandwidth is a more critical resource than the bandwidth of a fixed network, we define here the cost function to be the weighted sum of LU and paging data rate per MU per hour on the air interface. The expected value of the cost function for the proposed algorithm is derived in Theorem 1.

Consider a system with M square cells. Assume a call arrives at time t and the targeted MU is located at cell 0. Consider the registration memory window of cell 0 at time t. Assume the targeted MU has not changed cell during the time interval $[T_r, t]$. Define $Z = t - T_r$. In steady state, Z is uniformly distributed between $[0, \tau_g]$. The targeted MU must register at least once with cell 0 during the registration memory window at time t. Let I be the most recent registration slot in the window when the targeted MU updates at cell 0. Denote the probability $I = i$ by P_i, conditioned on the event that the MU has not changed cell during $[T_r, t]$.

Let X_j be the time instants at which the targeted MU changes cell. Let t fall in the interval defined by X_j and X_{j+1}. By renewal theory, the *age* of the arrival defined by $T = t - X_j$ is known to be exponential distributed with mean μ [25]. With this assumption, P_i is derived in the following lemma.

Lemma 1

$$P_i = P_{C,L} \frac{e^{-\mu(r-i)\tau_g} - e^{-\mu(r-i+1)\tau_g}}{1 - e^{-\mu r \tau_g}} \tag{3.1}$$

Proof:

The event $I = i$ is equivalent to having a geographically or temporally triggered registration at T_i. This in turn is equivalent to the age T falling in the intervals, $[lr-i, lr-i+1]\tau_g$ for some $l = 1, 2, \ldots$. (Refer to fig. 3.2.) Since T is exponential distributed with mean $\frac{1}{\mu}$, we have:

$$\begin{aligned}
P_i &= \sum_{l=1}^{\infty} P\left[(lr-i+1)\tau_g + Z > T > (lr-i)\tau_g + Z\right] && (3.2)\\
&= P[T-(lr-i+1)\tau_g > Z]\sum_{l=1}^{\infty}\{P[T > (lr-i)\tau_g] && (3.3)\\
&\qquad -P[T > (lr-i+1)\tau_g]\} && (3.4)\\
&= P_{C,L}\sum_{l=1}^{\infty}\left\{e^{-\mu(lr-i)\tau_g} - e^{-\mu(lr-i+1)\tau_g}\right\} && (3.5)\\
&= P_{C,L}\frac{e^{-\mu(r-i)\tau_g} - e^{-\mu(r-i+1)\tau_g}}{1-e^{-\mu r\tau_g}} && (3.6)
\end{aligned}$$

If the MU is not lost in the system, it must register in at least one of the registration slots T_i, $i \in [1, r]$ in the local cell with probability P_i. It is stratightforward to verify that

$$\sum_{i=1}^{r} P_i = 1 \tag{3.7}$$

For any cell, define $P_l(i)$ as the probability that the i^{th} cell vector matches to the BFID of the targeted MU. Define $P[page]$ to be the probability that a cell is paged.

Theorem 1 *The combined paging and update radio bandwidth usage per MU per unit time is given by the following equation:*

$$C_{HBF} = \frac{c_1 n M}{\tau_g N} + c_2\lambda\log_2 N\left[P_{C,L}(P[page]M) + P_{L,C}M\right] \tag{3.8}$$

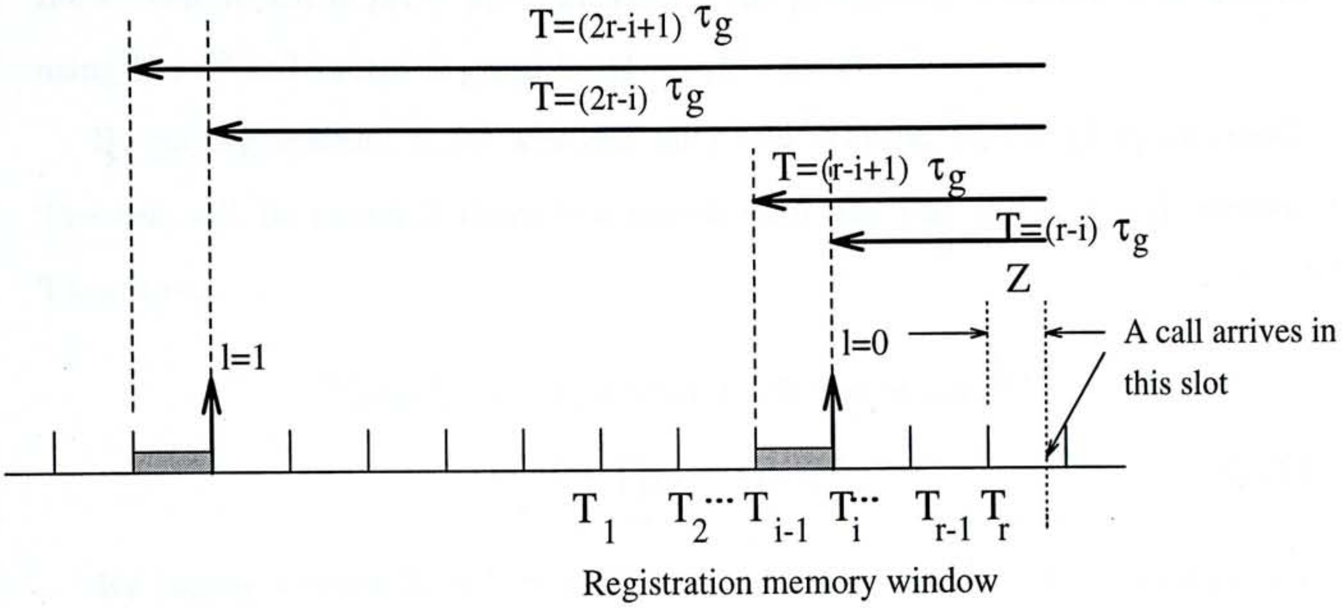


Figure 3.2: When a MU is registered in slot i, the dwell time may take the above values

where $P[page]$ *for the paging schemes are given by:*

$$\begin{cases} P[page]_1 = 1 - \prod_{i=1}^{r}(1 - P_l(i)) \\ P[page]_2 = \left[1 - \prod_{i=r-w+1}^{r}(1 - P_l(i))\right] \\ \qquad + \sum_{i=1}^{r-w} P_i \left[1 - \prod_{i=1}^{r-w}(1 - P_l(i))\right] \\ \\ P[page]_3 = \sum_{i=1}^{r}\sum_{j=i}^{r} P_i P_l(j) \end{cases} \tag{3.9}$$

and

$$P_l(i) = (1 - p(1-p)^{v_i})^n \tag{3.10}$$

$$P_{C,L} = \frac{1-e^{-\mu\tau_g}}{\mu\tau_g} \qquad P_{L,C} = 1 - P_{C,L} \tag{3.11}$$

Proof:

Define v_i to be the number of MU's sending updates in registration slot i in cell 0. The probability that there is no match in a given bit between the BFID the i^{th} cell vector is $p(1-p)^{v_i}$. Therefore, the probability a match is identified using the i^{th} cell vector is given by $(1-p(1-p)^{v_i})^n$.

By paging scheme 1, for any cell all r cell vectors, $S_i, i \in [1,r]$ are used. The cell will be paged if there is a match with any one of the r cell vectors. Therefore,

$$\begin{aligned} P[page]_1 &= P[\text{at least 1 cell vector match}] \\ &= 1-\prod_{i=1}^{r}(1-P_l(i)) \end{aligned} \tag{3.12}$$

By paging scheme 2, cell vectors from slot $S_i, i \in [r-w+1, r]$ are used for matching in the first pass. With probability $\sum_{i=1}^{r-w} P_i$ the MU is not located in first matching cycle. Therefore, $P[page]$ is given by

$$\begin{aligned} & P[page]_2 \\ = & \left[1-\prod_{i=r-w+1}^{r}(1-P_l(i))\right] \\ + & P[\text{2nd cycle is needed}]\left[1-\prod_{i=1}^{r-w}(1-P_l(i))\right] \end{aligned} \tag{3.13}$$

$$\begin{aligned} = & \left[1-\prod_{i=r-w+1}^{r}(1-P_l(i))\right] \\ + & \sum_{i=1}^{r-w} P_i\left[1-\prod_{i=1}^{r-w}(1-P_l(i))\right] \end{aligned} \tag{3.14}$$

By paging scheme 3, a cell vector is used only if the intended MU cannot be located by preceeding cell vectors. Therefore,

$$\begin{aligned} P[page]_3 &= P_r P_l(r) + P_{r-1}(P_l(r)+P_l(r-1)) \\ &+ P_{r-2}(P_l(r)+P_l(r-1)+P_l(r-2)) + \ldots \end{aligned} \tag{3.15}$$

$$= \sum_{i=1}^{r}\sum_{j=i}^{r} P_i P_l(j) \tag{3.16}$$

Since $v_i, i \in [1, r]$ are intricately inter-dependent random variables, it is intractable to compute cost C_{HBF} exactly. For the purpose of comparison with other algorithms in our numerical studies, we have chosen to use average values of v_i for the computation of C_{HBF}. In steady state, all $\bar{v}_i$'s are identical. We denote the average as $\bar{v}$. $\bar{v}$ is equal to sum of the mean number of temporally triggered registrations and the mean number of geographically triggered registrations in an update cycle.

By symmetry, we assume the mean number of incoming MU's in a cell during an update cycle is equal to the mean number of departures of MU's in a cell in the same cycle. Therefore, the mean number of geographically triggered registrations is given by:

$$k_0 \, Pr[T < \tau_g] = k_0 \, (1 - e^{-\mu \tau_g}) \tag{3.17}$$

The mean number of temporally triggered updates is given by:

$$\bar{v} \, Pr[T > r\tau_g] = \bar{v} \, e^{-\mu r \tau_g} \tag{3.18}$$

Hence,

$$\bar{v} \, e^{-\mu r \tau_g} + k_0 \, (1 - e^{-\mu \tau_g}) = \bar{v} \tag{3.19}$$

$$\bar{v} = \frac{k_0 (1 - e^{-\mu \tau_g})}{1 - e^{-\mu r \tau_g}} \tag{3.20}$$

Substitute all v_i for $\bar{v}$, $P_l(i) = P_l \;\; \forall i$. The average probability of paging a cell for the proposed paging schemes are respectively:

$$\begin{cases} P[page]_1 &= 1-(1-P_l)^r \\ P[page]_2 &= [1-(1-P_l)^w] \\ & \quad + \sum_{i=1}^{r-w} P_i[1-(1-P_l)^{r-w}] \\ P[page]_3 &= \sum_{i=1}^{r} P_i(r+1-i)P_l \end{cases} \tag{3.21}$$

3.4.1 Comparison of the hybrid and time based Bloom filter algorithms

Suppose the BFID length n, period of registration slot τ_i, $i \in \{g,t\}$ and p is the same for both the hybrid and time based Bloom filter schemes. Note that when $r=1$, the hybrid algorithm reduces back to the time based Bloom filter algorithm. This is obvious since every MU must re-register again in the next registration slot. Number of update messages expected in each registration slot v equals to the average number of MU's in each cell k_0. The probability of paging a cell $P[page]_1$ when $r=1$ is thus given by:

$$1-(1-P_l)^1 = P_l \tag{3.22}$$

$$= [1-p(1-p)^v]^n \tag{3.23}$$

$$= [1-p(1-p)^{k_0}]^n \tag{3.24}$$

Suppose a MU has very low mobility. For the hybrid algorithm, the MU performs mostly temporally triggered location updates once every r registration slots. Assuming the mobile population consists solely of low mobility MU's, that is, $\mu \to 0$. The number of expected updates per registration slot v is given by:

$$\bar{v} = \frac{k_0(1-e^{-\mu\tau_g})}{1-e^{-\mu r\tau_g}} \tag{3.25}$$

$$\approx \frac{k_0(1-1+\mu\tau_g)}{1-1+r\mu\tau_g} \tag{3.26}$$

$$= \frac{k_0}{r} \tag{3.27}$$

Thus the expected number of location updates received per registration slot is r times smaller for the hybrid Bloom filter algorithm. The presence of more zero bits in cell vectors decrease the probability of a match during the Bloom filtering operation, which in turn improves the accuracy in the paging process. For this reason, the hybrid algorithm outperforms the time based counterpart under all paging schemes when the average mobility is low.

3.5 Numerical Studies

In this section, numerical studies are carried out to compare the performance of four different location tracking strategies, namely, time based(TB), geographic based(GB), time based Bloom filter(TBBF), and hybrid Bloom filter(HBF) algorithms. The cost functions are computed for each algorithm using the system parameters shown on table 3.1.

System Parameter	Numerical value
Area of each cell	$0.25km^2$
Number of cells in the system	$M = 900$
Number of users in the system	$N = 2^{15}$
Avg. cell crossing rate per MU	$\mu = 50$ cells/hr
Avg. call arrival rate per MU	$\lambda = 1$ calls/hr
weight factor for location update cost	$c_1 = (5, 10)$
weight factor for paging cost	$c_2 = 1$
penalty factor for random accessing and overhead	$\gamma = 4e$

Table 3.1: System parameters adopted in the numerical studies

For practical considerations, preference is given to minimize location update traffic. This is because uplink traffic requires more co-ordination between MU's than that in the downlink, which is simple broadcasting. The weight factors, c_1 and c_2, in the cost functions are chosen so that $c_1 = 5c_2$ in the first study and $c_1 = 10c_2$ in the second study. For geographic based strategy, there is an extra penalty factor γ in the update component in the cost function to account for conflicts due to random uplink access and packet overheads. The exact value varies from applications to applications. It is chosen to be $4e$ in both studies.

With reference to [35], the cost functions for GB, TB and the TBBF algorithms per hour per MU are given by respectively,

$$\begin{cases} C_{GB} &= \dfrac{c_1\gamma\mu\log_2(N)}{m} + c_2\lambda m^2 log_2(N) \\ C_{TB} &= \dfrac{c_1\log_2(N)}{\tau_t} + c_2\lambda\log_2(N)\left[P_{L,C}M + P_{C,L}\right] \\ \\ C_{TBBF} &= \dfrac{c_1 nM}{\tau_t N} + c_2\lambda\log_2(N)\left\{P_{L,C}M + P_{C,L}\lceil M(1-p(1-p)^{k_0})^n\rceil\right\} \end{cases} \tag{3.28}$$

where m^2 is number of cells in a square location area.

The performance of the *optimized* location update protocols, time based, geographic based, time based Bloom filter, and hybrid Bloom filter, are compared. The optimized parameter for various strategies are shown on table 3.2 for study 1 and table 3.3 for study 2.

3.5.1 Cost versus mobility

Refer to fig. 3.3, the costs of the optimized algorithms are plotted against different values of average mobility for numerical study 1. The costs of all algorithms

Strategy	τ	n	r	w	m	p
TB	0.0207529	-	-	-	-	-
GB	-	-	-	-	$\left[\left(\frac{c_1\gamma\mu}{2c_2\lambda}\right)^{\frac{1}{3}}\right]$	-
TBBF	0.01190701	208	-	-	-	$\frac{1}{1+k_0}$
HBF paging scheme 1	0.004227	112	13	-	-	$\frac{1}{1+v}$
HBF paging scheme 2	0.00413976	98	15	5	-	$\frac{1}{1+v}$
HBF paging scheme 3	0.00367644	80	31	-	-	$\frac{1}{1+v}$

Table 3.2: Optimized values of parameters for various strategies: Numerical study 1

Strategy	τ	n	r	w	m	p
TB	0.03729662	-	-	-	-	-
GB	-	-	-	-	$\left[\left(\frac{c_1\gamma\mu}{2c_2\lambda}\right)^{\frac{1}{3}}\right]$	-
TBBF	0.01723422	174	-	-	-	$\frac{1}{1+k_0}$
HBF paging scheme 1	0.01066761	161	13	-	-	$\frac{1}{1+v}$
HBF paging scheme 2	0.00908246	129	6	2	-	$\frac{1}{1+v}$
HBF paging scheme 3	0.00815481	106	11	-	-	$\frac{1}{1+v}$

Table 3.3: Optimized values of parameters for various strategies: Numerical study 2

increases with increasing average cell crossing rate. The cost of the hybrid algorithms are lower than the time based Bloom filter algorithm in low mobility scenarios. This is because a slowly moving MU mostly performs temporally triggered re-registrations in the hybrid algorithms. This decreases the number of updates in each registration slot, which improves the accuracy of the Bloom filter.

Unless the system is operated with very high average mobility MU's, the hybrid algorithms outperform all other time based schemes. This shows that

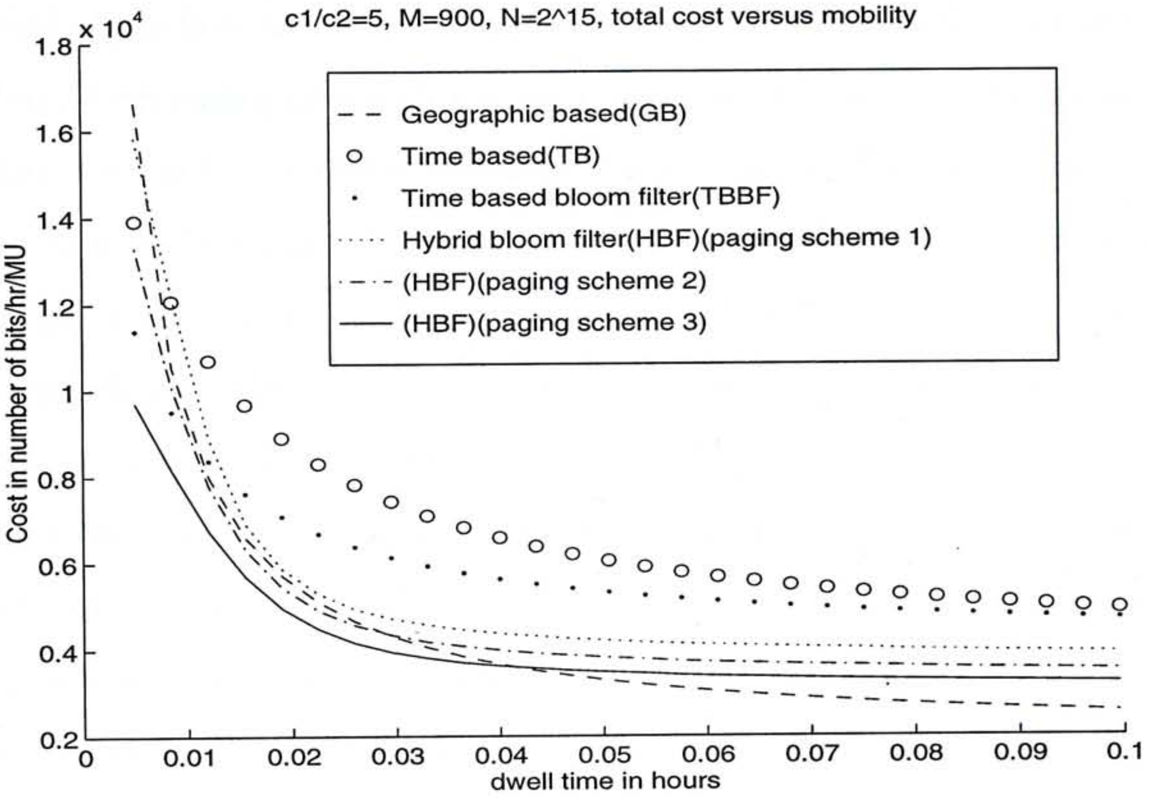


Figure 3.3: Combined costs under different average dwell time of MU: c1/c2=5

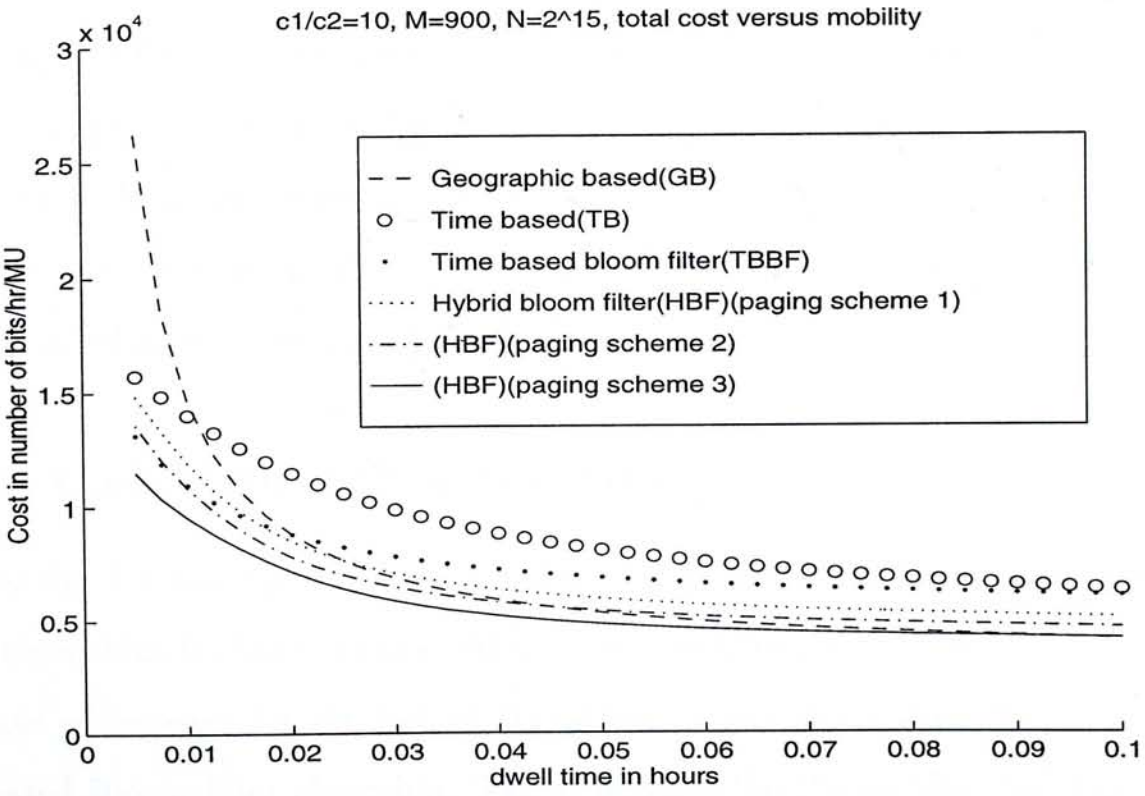


Figure 3.4: Combined costs under different average dwell time of MU: c1/c2=10

our hybrid algorithms are better alternatives than the time based Bloom filter algorithm. With paging scheme 3, our algorithm outperforms other time based algorithms even in high mobility scenarios. This is because for a highly mobile MU, the chance of locating it in the first few matching cycles is high. Compared with the geographic based algorithm, the proposed algorithms always have lower cost except when mobility is very low. This is obvious because most registration slots will be wasted in low mobility scenarios.

Refer to fig. 3.4, the costs of the optimized algorithms are plotted against different values of average mobility for numerical study 2. In this case, the location update cost is weighted more. The parameters for various strategies are tuned such that location update cost is smaller than that in study 1, at the expense of more paging cost. Since the optimized values r for our hybrid algorithms are smaller, the cost difference between the time based Bloom filter and the hybrid Bloon filter algorithm is less. We also observe that the geographic based strategy performs more badly in this case study. The hybrid algorithms under any of the paging schemes outperform the geographic based strategy even when the actual average mobility of the system is several times smaller than the nominal value used to optimize the system.

3.5.2 Cost versus call arrival rate

Refer to fig. 3.5 and fig. 3.6, costs are plotted against different call arrival rate of the algorithms for both studies. When λ increases, paging cost also increases. The rate of increase for the hybrid algorithms is less steep than that of the time based Bloom filter algorithm. This is because the Bloom filter has higher accuracy in locating a targeted MU for the hybrid algorithms.

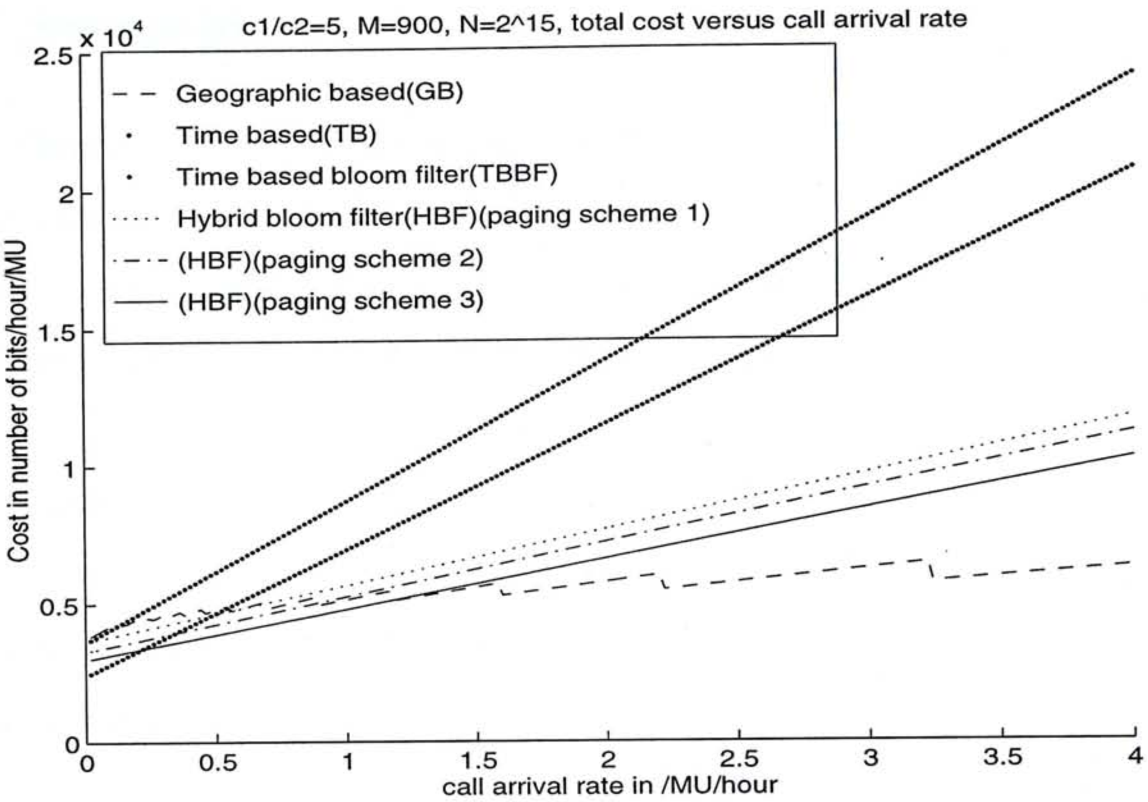


Figure 3.5: Combined costs under different average call arrival rate: c1/c2=5

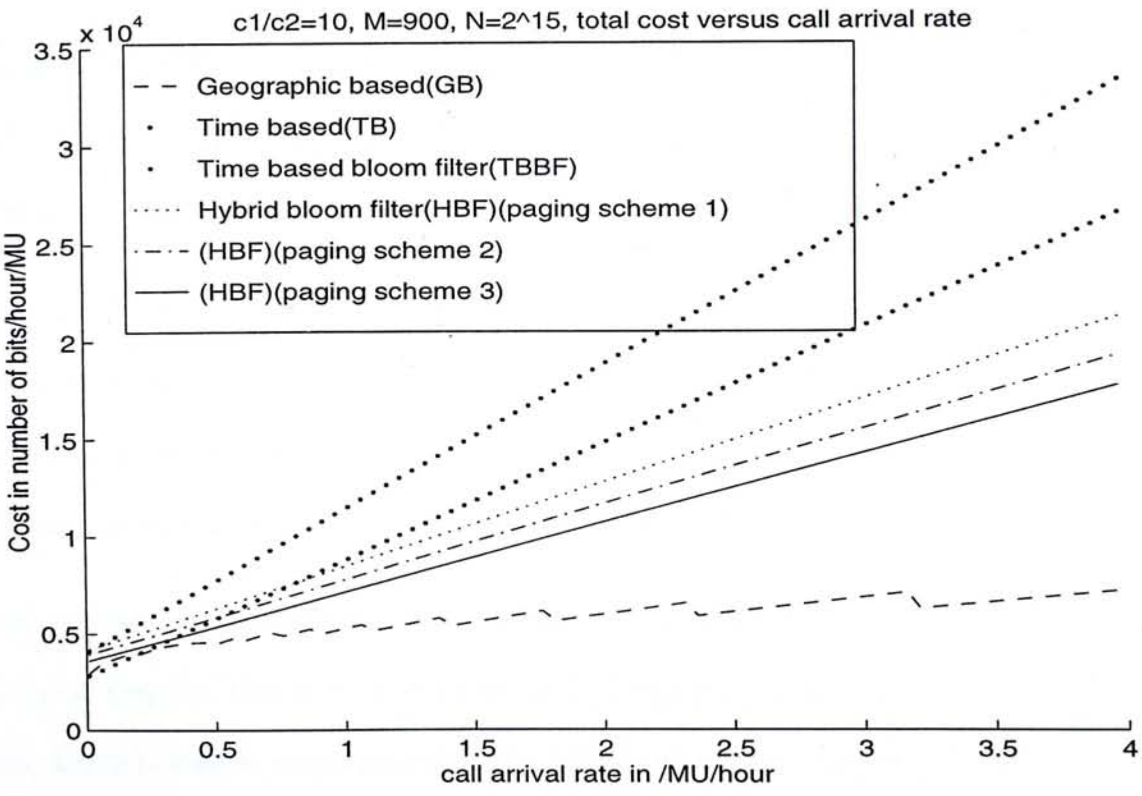


Figure 3.6: Combined costs under different average call arrival rate: c1/c2=10

3.6 Summary

In this chapter, a new contention free location update algorithm is proposed and analysed. The novel multiple access technique eliminates contention in LU messages. Location updates could be either temporally or geographically triggered. The hybrid approach reduces the number of location updates performed, which boosts the accuracy of the Bloom filtering in the paging process. This will be significant in new generation systems in which location update traffic is heavy. Beside lower overall cost on the air interface, the hybrid algorithms also generates less control traffic on the fixed network. To end this chapter we summarize the advantages of the Hybrid Bloom Filter Algorithm.

- The new multiple accessing technique is a feasible alternative to random accessing in PCS networks.
- Network traffic is reduced considerably because there is no need for the MU to deregister explicitly with the previous location. Deregistration is carried out implicitly automatically by a timeout.
- Each cell needs to store r cell vectors only, which is usually much smaller than the number of MU's in a cell k. Ordinary strategies require storage of ID's of all subscribers in the location database. Thus number of memory elements in the location database could be reduced.
- As opposed to geographic based strategy, the hybrid Bloom filter algorithm do not require the user to record and process location information during the time between registration slots. This minimizes mobile transceiver use during idle periods, saving battery power.

Chapter 4

A Dynamic Location Area Assignment Algorithm

In the previous chapter, we have investigated a novel location update algorithm based on a new multi-accessing technique. Our location update protocol is *static* since it disregards the user-varying and time-varying mobility characteristics of MU's. A dynamic version of this protocol is infeasible because the optimized parameters must be computed using numerical methods. The prohibitive computational complexity involved limits its application to the static scenario. Nevertheless, in new PCS systems, the use of dynamic location update and paging protocols is highly desirable. In this chapter, we present another location management strategy, the Dynamic Location Area Assignment Algorithm, as a candidate for the new PCS system. Location areas are assigned according to real-time mobility records of individual MU's. The computational burden is sufficiently low that a MU could effectively implement the algorithm distributively on the handset.

4.1 Geographic versus Distance Based Strategies

As briefed in chapter 2, the underlying update protocols used in many standards rely on the geographic based strategy. We pointed out that the geographic based strategy is unsuitable for PCS networks, where cells size are likely to be small. To alleviate the resulting location update traffic due to small cells, algorithms have been proposed to distribute location update traffic into a larger group of cells, thereby reducing the inefficiencies of random access during location update. Among other variants of geographic based strategies, the distance based strategy is an attractive alternative to the traditional geographic based strategy.

It is shown in [29] and [36] that distance based strategy outperforms geographic based strategy. Random walking is used for modelling mobility of individual MU's. This demonstrates the inefficiency of the geographic based strategy for MU's assuming a non-directional trajectory. This model can be arguably applied to characterize pedestrian mobility behaviour. On the other hand, vehicular traffic is characterized by high directionality of trajectory, which is more appropriately modelled by the fluid flow approach. Following a directional trajectory, a MU has to update more frequently under the fabric of distance based strategy. Thus, the geographic based strategy outperforms the distance based strategy when vehicular users are dominant in the mobile population.

In this chapter, we propose a location tracking strategy which combines the merits of both the geographic based and the distance based strategy. If the trajectory of a MU shows some directionality, the overlapping region of the newly assigned location area and the original location area is smaller. The updating cell is not necessarily the centre cell of the newly assigned location area. Each MU maintains a *time-varying* record of mobility statistics, namely the number of cell transitions in each direction in the original location area. These data are used in the assignment of a new location area. Our approach to the problem is similar to that in [2]. Specifically we want to assigned a location area to a MU such that the expected dwell time is maximized. The effort required to compute expected dwell time, however, is extremely high in [2]. This limits the application to static planning scenarios like [30]. We have decoupled the problem into the maximization of expected dwell time in two orthogonal directions. Simple analytical expressions are derived. Distributive implementation on MU's in real time is feasible.

The chapter is organized as follows. In section 2, we describe the system model and the performance metric. The proposed location area assignment algorithm is given in section 3. The optimality of our algorithm is shown. Numerical examples are given in section 4. Our algorithm are compared with the geographic based and the distance based strategy under different mobility scenarios. Section 5 contains some concluding remarks.

4.2 System Model

4.2.1 cell layout

Consider a wireless cellular system consisting of square cells. A location area with location area size k defines a square location area of $k \times k$ cells. Refer to fig.4.1, the layout of a planar cellular system is shown. Each cell of a location area is labelled by a coordinate. The cell on the downward left of the assigned

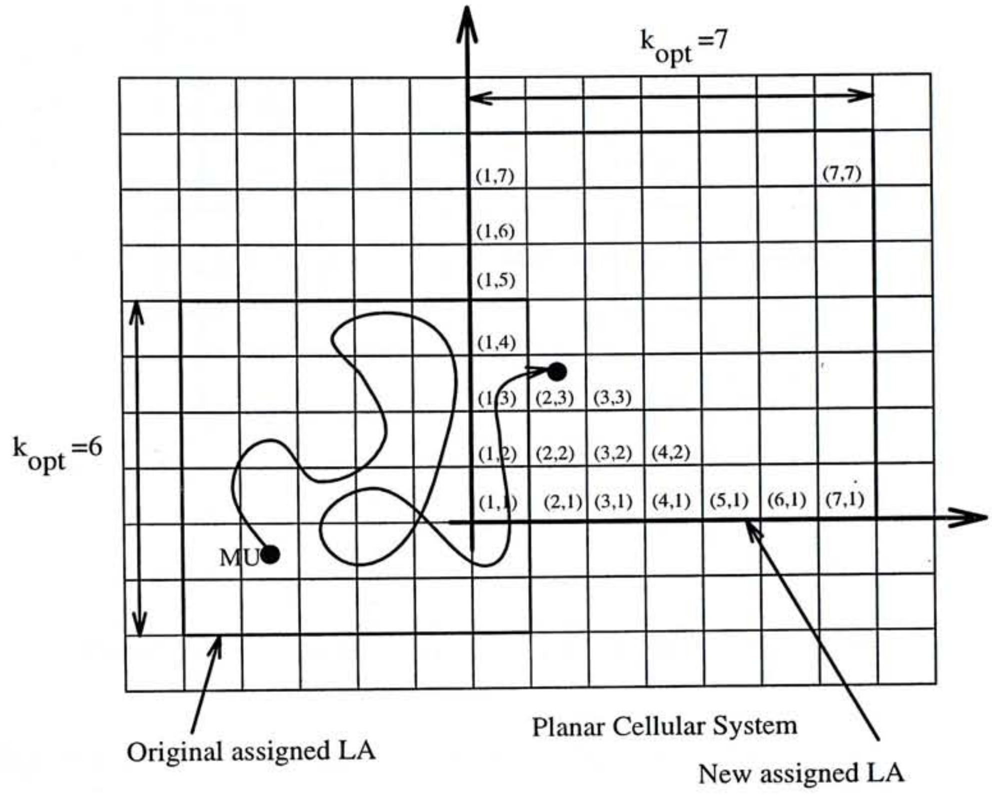


Figure 4.1: Illustration of the cell layout

location area is labelled cell $(1,1)$. The cell located on the i^{th} column in the right and j^{th} row upward to cell $(1,1)$ is labelled cell (i,j). For instance, the *updating cell* is labelled $(2,3)$ with reference to the newly assigned location area in fig.4.1.

4.2.2 mobility model

Since the dynamic location area assignment algorithm is performed distributively by individual MU's, we focus on the mobility behaviour of a single MU. A discrete-time Markovian model is used to characterize the mobility of individual MU's. Time is discretized into steps of duration Δt. In each step, a MU may transit to another cell in the horizontal direction, vertical direction, or diagonally. We assume the independence of the vertical and horizontal motion

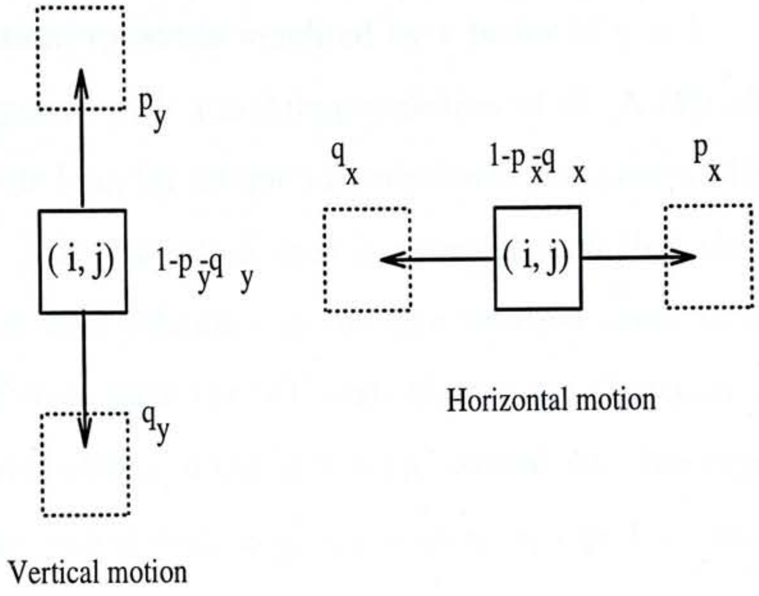


Figure 4.2: Illustration of cell transition probabilities

to simplify subsequent analysis. Suppose a MU is initially located in cell (i, j), as shown on fig.4.2. In the next step, a MU may transit rightward or leftward with probability p_x and q_x respectively. With probability $1 - p_x - q_x$, there is no cell transition in the x direction. In the y direction, a MU has the probabilities p_y and q_y to transit upward and downward respectively. With probability $1 - p_y - q_y$ there is no cell transition in the y direction. Thus, at any step, a MU may stay in the same cell or transits to one of the eighth neighbouring cells. The individual *cell transition probabilities* (p_x, q_x, p_y, q_y) are time dependent. Their values are estimated from real-time measurements taken by individual MU's.

4.2.3 cost function

In cellular systems, the control traffic over radio link should be minimized. In general, we prefer more downlink traffic over uplink traffic due to the inherent inefficiencies of uplink random accessing. To indicate our preference we define the cost function C_X as weighted sum of location update and paging data rate.

The cost of location update is weighted by a factor of $\gamma > 1$.

Consider a system with a mobile population of N. A MU identifier must be at least $\log_2 N$ bits long for unique identification. Suppose a MU has just exited a location area. A new location area is assigned such that the updating cell is labelled cell (i, j) with reference to the new location area. Define $\mathbf{E}\, T_{i,j}$ as the mean number of steps until the MU exits the assigned location area. Define c as the call arrival probability of the MU in an interval Δt. The expected number of steps between two call arrivals is $\frac{1}{c}$. C_X is given by eqn.4.1, expressed in number of bits per unit time Δt:

$$C_X = \gamma \frac{\log_2 N}{\mathbf{E}\, T_{i,j}} + ck^2 \log_2 N \tag{4.1}$$

where X denotes distance based, geographic based and our proposed strategies. Note that $\mathbf{E}\, T_{i,j}$ depends on the cell transition probabilities (p_x, p_y, q_x, q_y), location area size k and the co-ordinates (i, j) of the updating cell.

4.3 Dynamic Location Area Assignment Algorithm

As depicted in fig.4.1, a MU is roaming in an assigned location area. The MU keeps track of its location by retrieving the cell identifier of the local cell on the broadcasting control channel. When a MU detects that it exits the original location area, the algorithm is performed to assign a new location area for the MU. The algorithm is divided into 3 procedures.

4.3.1 Measurement

In order to assign location areas based on time-varying mobility statistics, a MU should be capable of making measurement that accurately characterizes its mobility behaviour. Refer to fig.4.1, suppose a MU leaves the original location area at time t. Each MU keeps track of the number of cell transitions made in each direction in the original location area up to time t. The data are used as estimates for the time-varying ratio of cell transition probabilities, namely:

$$\frac{q_x(t)}{p_x(t)} = \frac{\text{number of cell transitions to leftward}}{\text{number of cell transitions to rightward}} \tag{4.2}$$

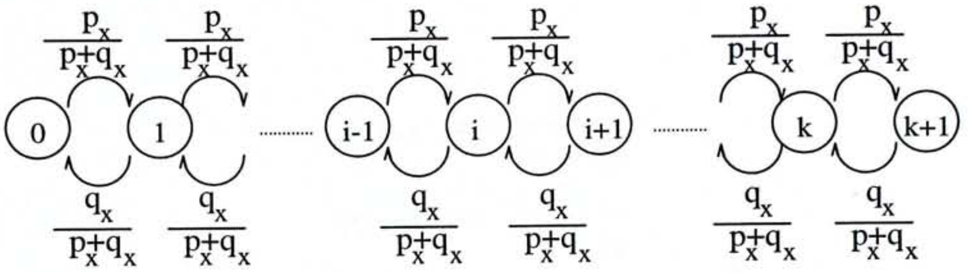
and

$$\frac{q_y(t)}{p_y(t)} = \frac{\text{number of cell transitions to downward}}{\text{number of cell transitions to upward}} \tag{4.3}$$

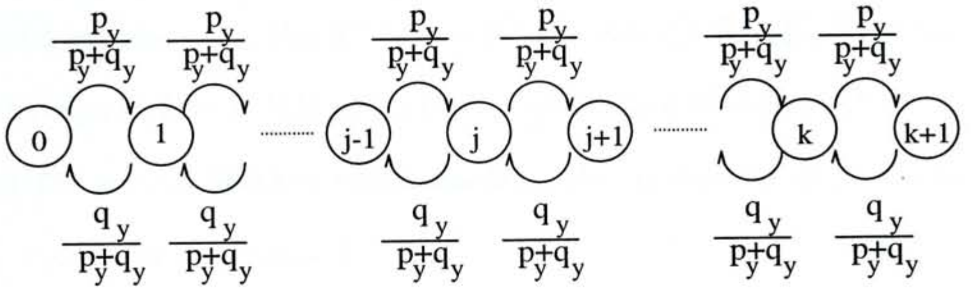
The estimated ratios of cell transition probabilities are accurate if there is a small change of mobility behaviour between location areas. This is a reasonable assumption because a subscriber has a drastic change of mobility statistics only when it is altering its mode between a pedestrain and a vehicular user. The measurement of cell transition probabilities involves simple counting, which is readily accomplished using simple hardware.

4.3.2 Computation of (i_{opt}, j_{opt})

At time t, the pre-computed location area size $k(t)$, the estimates for $\frac{q_x(t)}{p_x(t)}$ and $\frac{q_y(t)}{p_y(t)}$ are retrieved for the computation of new location area boundaries. In section 2, we defined $(i(t), j(t))$ as the co-ordinates of the *updating cell* with reference to the new location area. Our objective is to find the co-ordinates



(a) Horizontal motion



(b) Vertical motion

Figure 4.3: Markov chain models in computation of expected time leaving a location area (a)for horizontal motion (b)for vertical motion

(i_{opt}, j_{opt}) such that the cost metric defined by eqn.4.1 is minimized. Since location area size $k(t)$ is fixed, the paging cost is constant. We minimize the cost metric by maximizing the expected dwell time of the MU in a location area.

Fig.4.3(a) shows the Markov chain model when the location area size is k. A MU is in state i when it is in cell column i. The transition probabilities of the discrete-time Markov chain are given as:

$$p_{i,i+1} = \frac{p_x}{p_x + q_x} \tag{4.4}$$

$$p_{i,i-1} = \frac{q_x}{p_x + q_x} \tag{4.5}$$

Similarly, we setup another Markov chain model in the vertical direction. A MU is in state j when it is in cell row j. Refering to fig.4.3(b), the transition probabilities of the discrete-time Markov chain are given as:

$$p_{j,j+1} = \frac{p_y}{p_y + q_y} \tag{4.6}$$

$$p_{j,j-1} = \frac{q_y}{p_y + q_y} \tag{4.7}$$

We further define $\mathbf{E_x}T_i$ as the expected number of steps before a MU exits to the absorbing states at the 0^{th} or $k+1^{th} column$. Define $\mathbf{E_y}T_j$ as the expected number of steps before a MU exits to the absorbing states at the 0^{th} or $k+1^{th}$ row. With the use of Markov chain models, the analytical expressions for $\mathbf{E_x}T_i$ and $\mathbf{E_y}T_j$ are given in lemma 1.

Lemma 1

$$\mathbf{E_x}T_i = \begin{cases} \dfrac{1}{p_x+q_x}\, i\,(k+1-i) & p_x = q_x \\ \dfrac{i}{q_x-p_x} - \dfrac{k+1}{q_x-p_x}\dfrac{1-\left(\frac{q_x}{p_x}\right)^i}{1-\left(\frac{q_x}{p_x}\right)^{k+1}} & p_x \neq q_x,\ p_x \neq 0,\ q_x \neq 0 \\ \dfrac{i}{q_x} & p_x \neq q_x,\ p_x = 0 \\ \dfrac{k+1-i}{p_x} & p_x \neq q_x,\ q_x = 0 \end{cases} \tag{4.8}$$

$$\mathbf{E_y}T_j = \begin{cases} \dfrac{1}{p_y+q_y}\, j\,(k+1-j) & p_y = q_y \\ \dfrac{j}{q_y-p_y} - \dfrac{k+1}{q_y-p_y}\dfrac{1-\left(\frac{q_y}{p_y}\right)^j}{1-\left(\frac{q_y}{p_y}\right)^{k+1}} & p_y \neq q_y,\ p_y \neq 0,\ q_y \neq 0 \\ \dfrac{j}{q_y} & p_y \neq q_y,\ p_y = 0 \\ \dfrac{k+1-j}{p_y} & p_y \neq q_y,\ q_y = 0 \end{cases} \tag{4.9}$$

Proof:

Since the case of horizontal and vertical motions are similar, we consider only horizontal motion for illustration. Suppose initially a MU is in state i. Define random variable $N^{(i)}, i \in [1, k]$ as the number of cell transitions before absorbed to states 0 or $k+1$. We also define $X_r, r \in [1, N^{(i)}]$ as the number of steps between the $r-1^{th}$ and r^{th} cell transition. The expected number of steps before the MU exits to the absorbing states 0 or $k+1$ is given by:

$$\begin{aligned} \mathbf{E_x} T_i &= \mathbf{E} \sum_{r=1}^{N^{(i)}} X_r \\ &= \mathbf{E} X_r \mathbf{E} N^{(i)} \\ &= \frac{1}{p_x + q_x} \mathbf{E} N^{(i)} \end{aligned} \tag{4.10}$$

Refer to fig.4.3(a), we get the expression for $\mathbf{E}N^{(i)}$ by conditioning on the first transition to other states.

$$\begin{aligned} \mathbf{E}N^{(i)} &= 1 + p_{i,i+1}\mathbf{E}N^{(i+1)} + p_{i,i-1}\mathbf{E}N^{(i-1)} \\ &= 1 + \frac{p_x}{p_x + q_x}\mathbf{E}N^{(i+1)} + \frac{q_x}{p_x + q_x}\mathbf{E}N^{(i-1)} \end{aligned} \tag{4.11}$$

The Markov chain should satisfy boundary conditions $\mathbf{E}N^{(0)} = \mathbf{E}N^{(k+1)} = 0$. The defined Markov chain is similar to the gambler ruins problem in literature [27]. Using the method of substitution, the general and the particular solutions for the non-homogeneous difference equation eqn.4.11 are found. $\mathbf{E_x}T_i$ are obtained by substituting $\mathbf{E}N^{(i)}$ back in eqn.4.10.

△

In our system model, we have assumed the independence of horizontal and vertical motion. A MU exits a location area in either the horizontal or the vertical direction, whichever occurs sooner. To maximize the expected dwell time in a location area, we decouple the problem into the maximization of expected dwell time in the horizontal and the vertical direction, i.e. $\max_i \mathbf{E_x} T_i$ and $\max_j \mathbf{E_y} T_j$.

We consider $\mathbf{E_x} T_i$ for illustration. It could be readily verified that the first two expressions in eqn.4.8 have only one global maximum. Denote $\overline{i_{opt}}$ as the continuous value such that $\frac{d}{di}\mathbf{E_x} T_i\Big|_{i=\overline{i_{opt}}} = 0$. Denote $\left\langle \overline{i_{opt}} \right\rangle$ as $\{i : \arg\max\left(\lfloor \overline{i_{opt}} \rfloor, \lceil \overline{i_{opt}} \rceil\right)\}$. The analytical expressions for the optimal integer vlaue i_{opt} are given by eqn.4.12.

$$i_{opt} = \begin{cases} \left\langle \dfrac{k+1}{2} \right\rangle & p_x = q_x \\ \left\langle \dfrac{\ln\left[\frac{\left(\frac{q_x}{p_x}\right)^{k+1} - 1}{(k+1)\ln\left(\frac{q_x}{p_x}\right)}\right]}{\ln\left(\frac{q_x}{p_x}\right)} \right\rangle & p_x \neq q_x,\ p_x \neq 0,\ q_x \neq 0 \\ k & p_x \neq q_x,\ p_x = 0 \\ 1 & p_x \neq q_x,\ q_x = 0 \end{cases} \tag{4.12}$$

Similarly, j_{opt} is given by eqn.4.13.

$$j_{opt} = \begin{cases} \left\langle \dfrac{k+1}{2} \right\rangle & p_y = q_y \\ \left\langle \dfrac{\ln \left[\dfrac{\left(\frac{q_y}{p_y}\right)^{k+1} - 1}{(k+1)\ln\left(\frac{q_y}{p_y}\right)} \right]}{\ln\left(\frac{q_y}{p_y}\right)} \right\rangle & p_y \neq q_y,\ p_y \neq 0,\ q_y \neq 0 \\ k & p_y \neq q_y,\ p_y = 0 \\ 1 & p_y \neq q_y,\ q_y = 0 \end{cases} \tag{4.13}$$

4.3.3 Computation of location area size k

In the previous subsection, we minimize the cost metric by finding the optimal co-ordinates (i_{opt}, j_{opt}) for the updating cell. The pre-computed location area size k is retrieved at time t when (i_{opt}, j_{opt}) is computed. The location area size k is renewed periodically (with period $\tau_k \gg \frac{1}{\mathbf{E}\, T_{i_{opt}, j_{opt}}}$) to adapt to changes in mobility statistics of a MU. Suppose k is computed at time $\bar{t}$. Rewrite the cost function C_{DLA} as a function of k (eqn.4.14).

$$\begin{aligned} C_{DLA}(k) &= \frac{\gamma \log_2 N}{\mathbf{E}\, T_{i_{opt}(\bar{t}), j_{opt}(\bar{t})}(k)} + c\, k^2 \log_2 N & (4.14) \\ &\leq \frac{\gamma \log_2 N}{\min\left(\mathbf{E_x}\, T_{i_{opt}(\bar{t})}(k), \mathbf{E_y}\, T_{j_{opt}(\bar{t})}(k)\right)} + c\, k^2 \log_2 N & (4.15) \end{aligned}$$

Starting from initial value $k = 2$, we substitute consecutive increasing values of k to eqn.4.14. k is kept increased until there is no further decrease in cost with increased k. Mathematically, we define:

$$\Delta(k) = C_{DLA}(k) - C_{DLA}(k-1) \tag{4.16}$$

$$k_{opt} = \begin{cases} 1 & \text{if} \Delta(2) > 0 \\ \max\{k : \Delta(k) \leq 0\} & \text{o.w.} \end{cases} \tag{4.17}$$

Unless for highly mobile MU's, k_{opt} rarely exceeds 15. Thus the number of iterations needed to compute k_{opt} is upper-bounded by 14 in most cases.

The value of k is renewed *periodically* because of the following reasons:

- The value of k_{opt} depends on the order of magnitudes of the cell transition probabilities. The magnitude changes seldomly in practical situations. A pedestrian has low mobility and the assigned value of k is small. This value need not to be changed unless the pedestrian alters its mode from a pedestrian to a vehicular user.
- Consider the case when a MU alters its mode from a vehicular user to a pedestrian. The assigned location area size is too large for the MU then. If the location area size is re-computed when the MU exits the location area, it takes a long time before the MU is assigned a smaller location area size. This incurs extraneous paging cost on the MU.

4.4 Numerical Studies

Consider the distance based strategy. When a MU exits a location area, the updating cell becomes the centre cell of the new location area. Suppose the current location area size is k. The co-ordinate for the updating cell is $\left(\left[\frac{k+1}{2}\right], \left[\frac{k+1}{2}\right]\right)$. Hence, the cost function C_{DB} for the distance based strategy is given by eqn.4.18:

$$C_{DB} \leq \gamma \frac{\log_2 N}{\min\left(\mathbf{E_x}\, T_{\left[\frac{k+1}{2}\right]}, \mathbf{E_y}\, T_{\left[\frac{k+1}{2}\right]}\right)} + c\, k^2 \log_2 N \tag{4.18}$$

By the nature of geographic based strategy, the updating cell is located on the boundary of a location area. Since the mobility behaviour of a MU is time-varying, the limiting probabilities of a MU updating in specific cells do not exist in general. For comparison with other strategies, we investigate the special case that a MU enters a new location area at an arbitrary cell labelled $(1, \left[\frac{k+1}{2}\right])$. The cost function C_{GB} for the geographic based strategy is given by eqn.4.19:

$$C_{GB} \;\leq\; \gamma \frac{\log_2 N}{\min\left(\mathbf{E}_{\mathbf{x}}\, T_1, \mathbf{E}_{\mathbf{y}}\, T_{\left[\frac{k+1}{2}\right]}\right)} + c\, k^2 \log_2 N \tag{4.19}$$

Comparing the three cost functions eqn.4.14,4.18 and 4.19, eqn.4.14 is minimum for all values of k. This is obvious because for a fixed value k, an assigned location area with updating cell (i_{opt}, j_{opt}) maximizes the expected dwell time $\mathbf{E}T_{i,j}(k)$ in the new location area. In the following examples, we investigate how much performance gain is possible with our algorithm under different mobility scenarios.

We consider a cellular system with a mobile population $N = 2^{15} = 32768$. The call arrival probability in an interval Δt is $c = 0.001$. The weighting factor for location update is given by $\gamma = 16$.

Example 1.

Suppose the cell transition probabilities are given by $p_x = q_x = q_x = q_y = 0.005$. The relative position of the new and orginal location areas for various strategies are shown on fig.4.4. By the proposed algorithm, the expected dwell time in a location area is maximized when i_{opt} and j_{opt} are equal to $\left[\frac{k+1}{2}\right]$.

Refer to figure 4.5, the cost functions are plotted against location area size k. The distance based strategy has identical performance with the proposed strategy in the random walking scenario. This conforms with the intuition that the distance based strategy is optimal when the mobility behaviour of a MU is purely random. The two algorithms outperforms the geographic based strategy for all values of k. The optimal location area size for all three strategies is $k = 4$. Costs of the proposed strategy and geographic based strategy are respectively 0.64 and 0.84 bits per unit time. For practical considerations, the global location area size assigned by the geographic based strategy is not optimal for individual MU's. The performance gain of the dynamic algorithm is higher. This amounts to more than 30% decrease in cost. The results of example 1 is summarized in table 4.1.

$(p_x, q_x, p_y, q_y) = (0.05, 0.05, 0.05, 0.05)$

Strategy	k_{opt}	cost (number of bits/step)
Distance based	4	0.64
Geographic based	4	0.84
Dynamic location area strategy	4	0.64

Table 4.1: Results of example 1

Example 2.

In this example, we compare the performance of the three strategies in the vehicular traffic scenario. A MU follows a highly directional trajectory. The order of magnitude in mobility is also higher. This translates to a large dominant component term in the cell transition probabilities. We simulate a vehicular traffic scenario by setting $(p_x, q_x, p_y, q_y) = (0.05, 0, 0.01, 0.005)$.

The relative position of the new and orginal location areas for various strategies are shown on fig.4.6. Compared with the last example, the assigned location area sizes are greater because the MU has higher mobility. The assigned location area has no overlapping with the original location area under the proposed algorithm. This demonstrates that no hysteresis is needed when the trajectory of a MU is highly directional . The distance based strategy is inferior in this scenario. The overlapping regions between location areas lead to more frequent location updates.

Refer to fig.4.7, the cost function for the distance based strategy is not smooth. This is because the co-ordinates of the updating cell are rounded off for different location area sizes. The optimal location area size for the distance based strategy is 7, with a cost of 3.735 bits per unit time. Both the geograhpic based and the proposed algorithm have identical cost 2.4493 bits per unit time when the location area size k is 7. Our algorithm leads to a cost reduction of 52.5% over the distance based strategy. The results are summarized in table 4.2.

$(p_x, q_x, p_y, q_y) = (0.05, 0, 0.01, 0.005)$

Strategy	k_{opt}	cost (number of bits/step)
Distance based	7	3.735
Geographic based	7	2.4493
Dynamic location area strategy	7	2.4493

Table 4.2: Results of example 2

For the proposed algorithm, the assigned location area is shifted upward from that under geographic based strategy. The shift in the assigned location area reflects the tendency of the MU to move upward. Although the geographic based algorithm has identical performance with our algorithm in this example, it is more costly in general. If the direction of the vehicle is neither in the x nor

y direction, our algorithm yields better performance than the geographic based strategy. This is illustrated in the next example.

Example 3.

Suppose a MU is heading in a direction at an angle +45° with the x-axis. We set (p_x, q_x, p_y, q_y) to $(0.04, 0.005, 0.035, 0.003)$ to simulate the trajectory. The relative position of the new and orginal location areas for various strategies are shown on fig.4.8.

As depicted in figure 4.9, the distance based strategy gives the highest cost for all location area size. The cost is minimal when $k = 7$, with 2.836 bits per unit time. Our algorithm outperforms the geographic based strategy for all location area sizes. When k is equal to 7, both algorithms have minimum costs, with $C_{DLA} = 2.135$ and $C_{GB} = 2.6552$ bits per unit time. Our strategy leads to a 33% cost reduction compared with the distance based strategy and a 24% cost reduction compared with the geographic based strategy. The results are summarized in table 4.3.

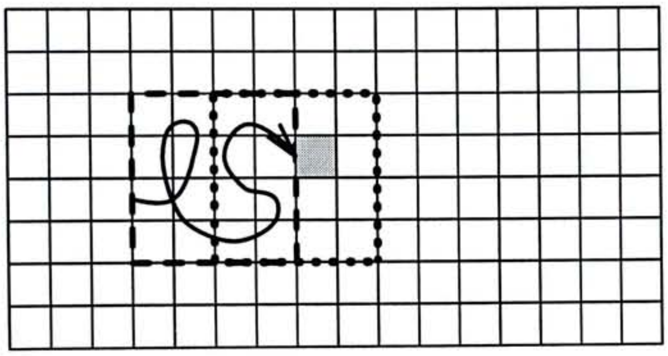
$(p_x, q_x, p_y, q_y) = (0.04, 0.005, 0.035, 0.003)$

Strategy	k_{opt}	cost (number of bits/step)
Distance based	7	2.836
Geographic based	7	2.6552
Dynamic location area strategy	7	2.135

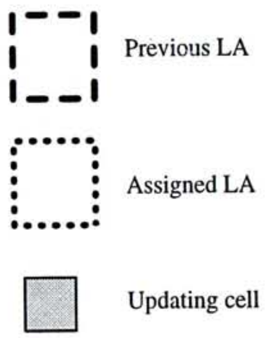
Table 4.3: Results of example 3

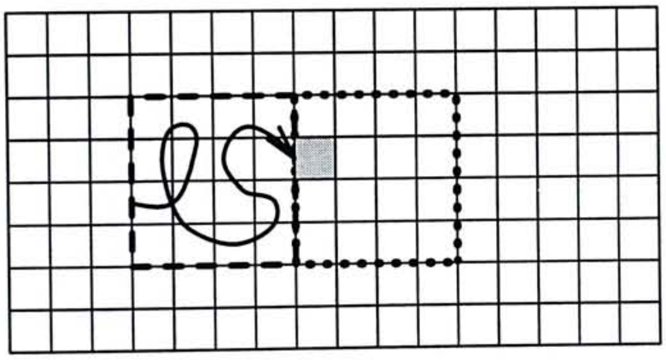
4.5 Summary

In this chapter, we first reiterate the inefficiencies of the geographic based and the distance based strategies towards certain mobility patterns. A dynamic location area assignment algorithm is then introduced. New location area is assigned based on the recent mobility record maintained by individual MU's. The degree of overlapping of an assigned location area with the previous one, and the location area size, could be adjusted dynamically. For any given location area size, our algorithm is optimal such that the expected dwell time in an assigned location area is maximized. The performance of our algorithm is compared with the geographic based and the distance based strategy. Numerical results shows that the new algorithm requires the least combined location update and paging bandwidth under *all* mobility scenarios. Nevertheless, the computational complexity of our algorithm is low. A MU could efficiently implement the algorithm distributively. Hence, our algorithm is a promising candidate as a location tracking strategy in wireless systems with diverse user mobility characteristics which is also varying with time.

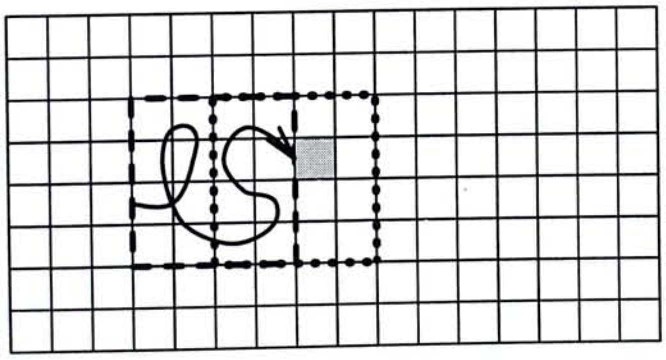


Distance Based Strategy





Geographic Based Strategy



Dynamic Location Area Assignment Strategy

Figure 4.4: Example 1. Assigned Location areas for various strategies

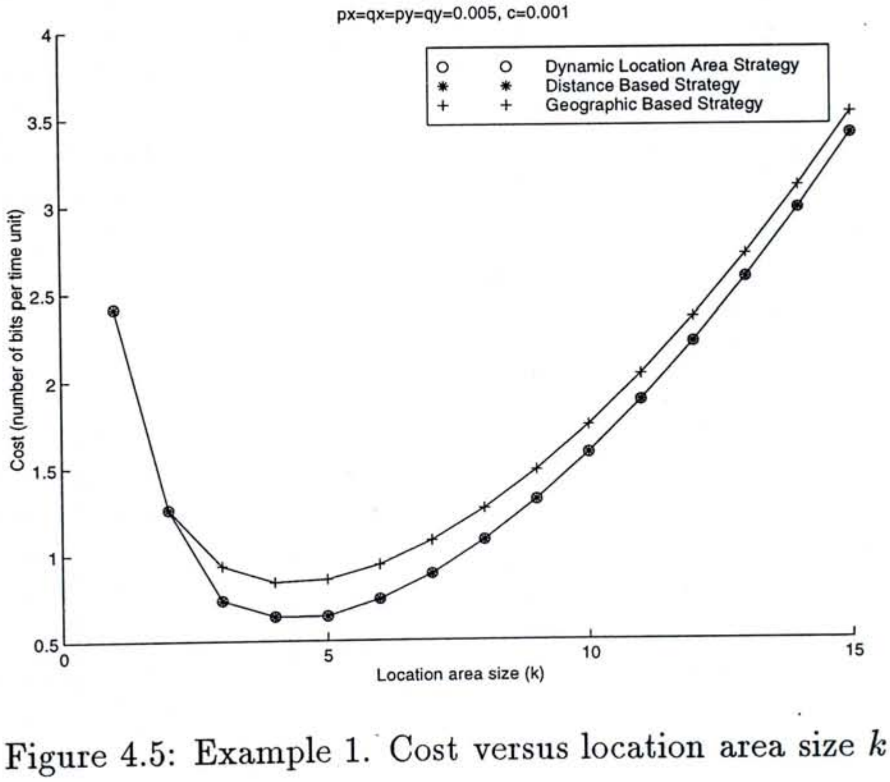
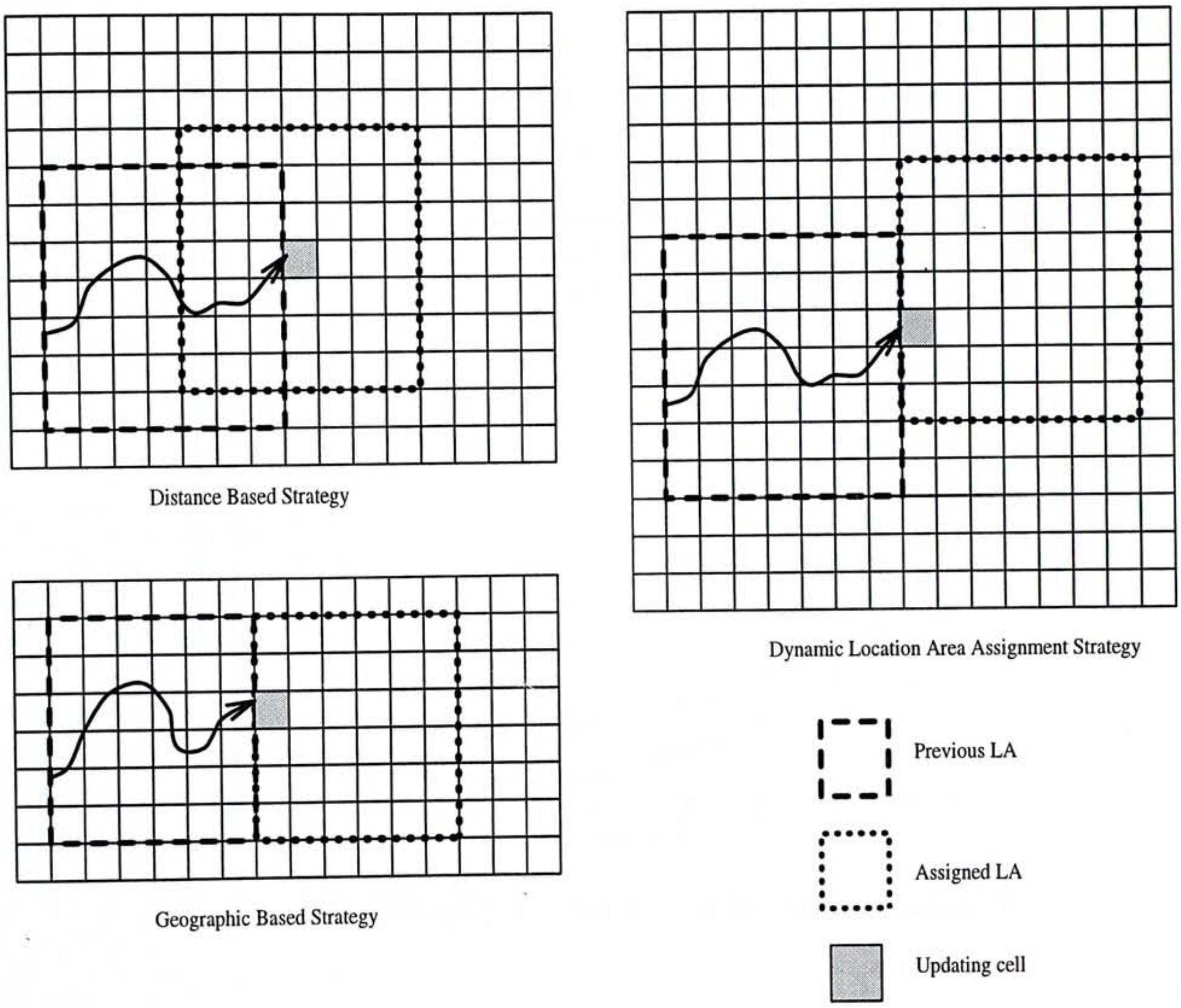


Figure 4.5: Example 1. Cost versus location area size k


Distance Based Strategy

Geographic Based Strategy

Dynamic Location Area Assignment Strategy

Figure 4.6: Example 2. Assigned Location areas for various strategies

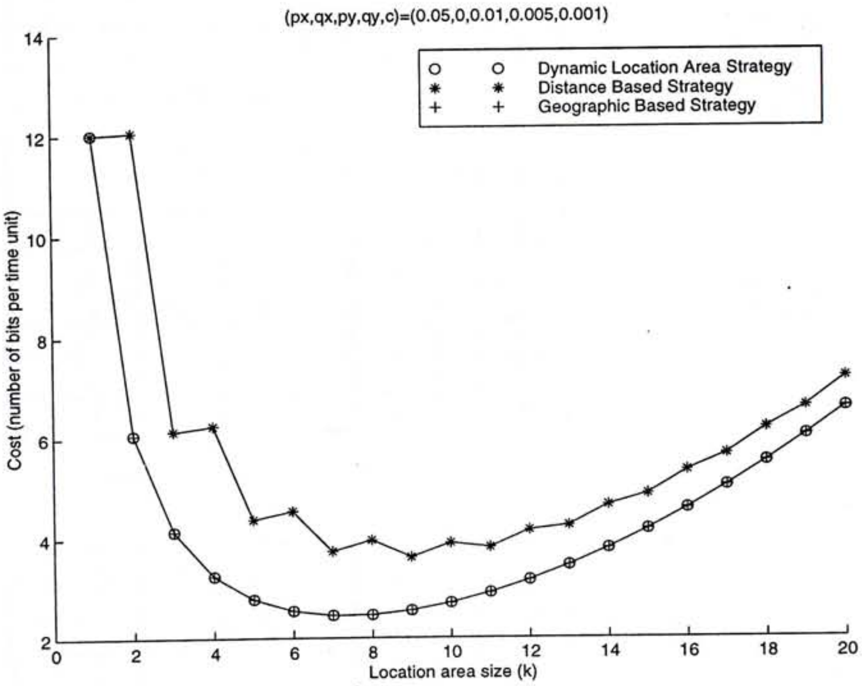
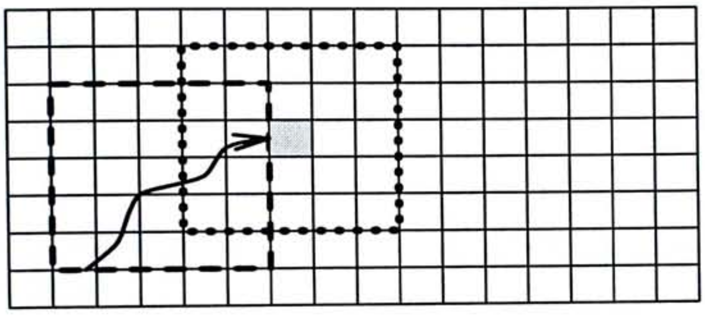
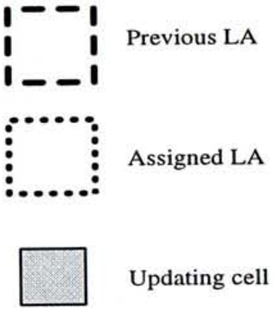
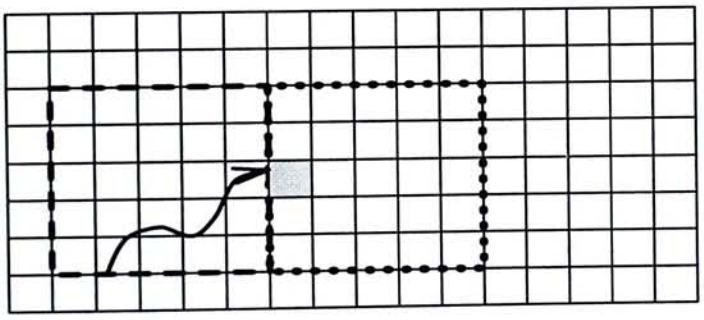


Figure 4.7: Example 2. Cost versus location area size k

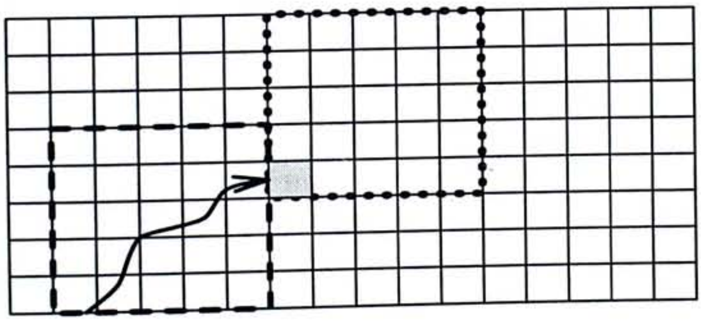


Distance Based Strategy





Geographic Based Strategy



Dynamic Location Area Assignment Strategy

Figure 4.8: Example 3. Assigned Location areas for various strategies

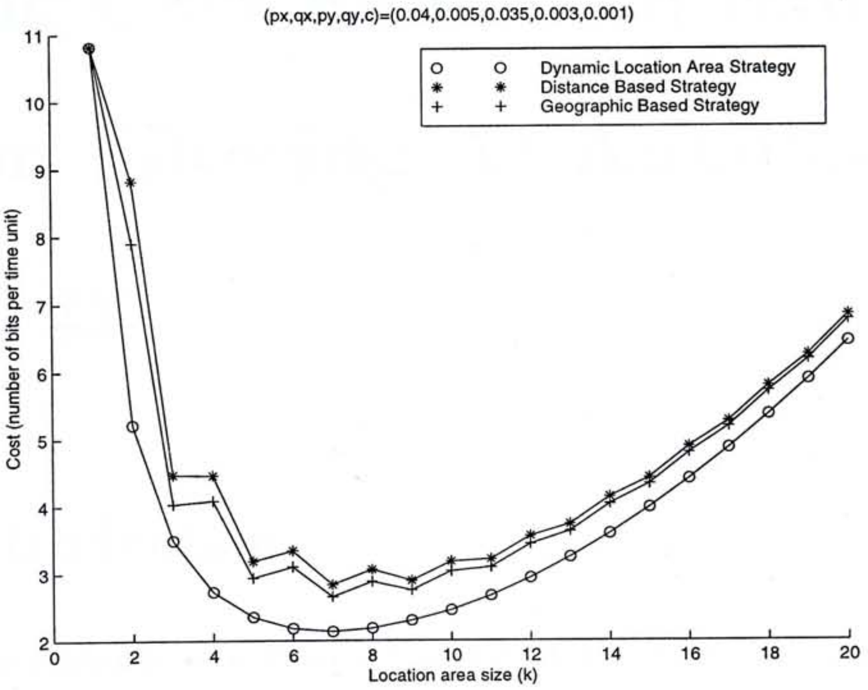


Figure 4.9: Example 3. Cost versus location area size k

Chapter 5

Paging Cost Reduction Using Bloom Filtering As Auxilliary Strategy

5.1 Introduction

This chapter presents a composite location update protocol. The protocol is composite in the sense that a Bloom filter location update algorithm is jointly used with any other non-time based location tracking strategy on a single system. More specifically, if Bloom filtering is used in conjunction with a strategy in which location areas are defined, the Bloom filtering operation could be viewed as a selective paging mechanism. For instance, Bloom filtering could be combined with the geographic based strategy, distance based strategy and the dynamic location area assignment algorithm described in the previous chapter. Besides the hybrid Bloom filter algorithm proposed in this thesis, other algortihms based on the Bloom filter concept [33],[35] could be used as the auxilliary strategy. Nevertheless, the hybrid Bloom filter algorithm should be chosen in general for its better power in selection paging.

When a call is arrived for a targeted MU, the registered location area is determined first. A cell in the location area would be paged if there is a match of BFID's between the cell vector and the called MU. Since only a fraction of cells in a location area are paged, paging bandwidth reduction is achieved. In conventional selective paging schemes, *a priori* location distributions of individual MU's must be obtained in order to find an optimal polling sequence in selective paging. The location probabilities of individual MU's are computed in advance using past mobility statistics. Therefore the predetermined polling sequence is suboptimal under fluctuating mobility characteristics.

In the following section, we present a case study in which the hybrid Bloom filter algorithm is used jointly with the dynamic location area assignment algorithm. We show that the composite algorithm should give better performance to either of the component algorithms. This is a promising result and the topic is subject to further research. New quantitative results and comparisons with standard selective paging schemes are reported in subsesquent papers.

5.2 A Case Study - Joint DLA-HBF Algorithm

5.2.1 The Algorithm

The Dynamic Location Area (DLA) Algorithm is the primary location management scheme used by all MU's in the system. Location areas are assigned to each MU based on real-time mobility behaviour. Every MU has an unique mobile unit identity vector (MUID) for the purpose of location update. Each MU is also assigned a n-bit Bloom filter identity vector (BFID).

According to individual mobility characterisitcs, the whole mobile population is differentiated into two groups . Group 1 MU's have low mobility characteristics, which consists mainly of pedestrians. Group 2 MU's have high mobility, which consists mainly of vehicular users. Periodically, the system re-groups the status of individual MU's to reflect changes of mobility characteristics with time. Under our composite strategy, group 1 MU's perform only the DLA strategy, while group 2 MU's perform both the DLA strategy and the HBF location update algorithm.

The advantage of these mobility differentiations is obvious. The group 1 MU's have low mobility, the number of cells in an assigned location area is small. The reduction in paging cost by Bloom filtering is insignificant. Thus no overlaying Bloom filter location update is required for group 1 MU's. For group 2 MU's, the assigned location area is large owing to the high mobility. When a call is placed to a group 2 MU, the system first determines the registered location area. Bloom filtering is then used to locate all cells which need to be paged within the location area. Suppose the location area consists of k^2 cells. With the composite strategy, the system polls only $Pr[page]k^2$ cells most of the time. Thus, paging cost reduction is achieved at the expense of extra location update.

Despite the difference in the adopted multi-accessing technology, both location update strategies require usage of the same uplink control channel. The channel structure of an arbitrary cell is depicted in fig. 5.1. Special slots are reserved periodically to MU's for Bloom filter location update. The MU's are

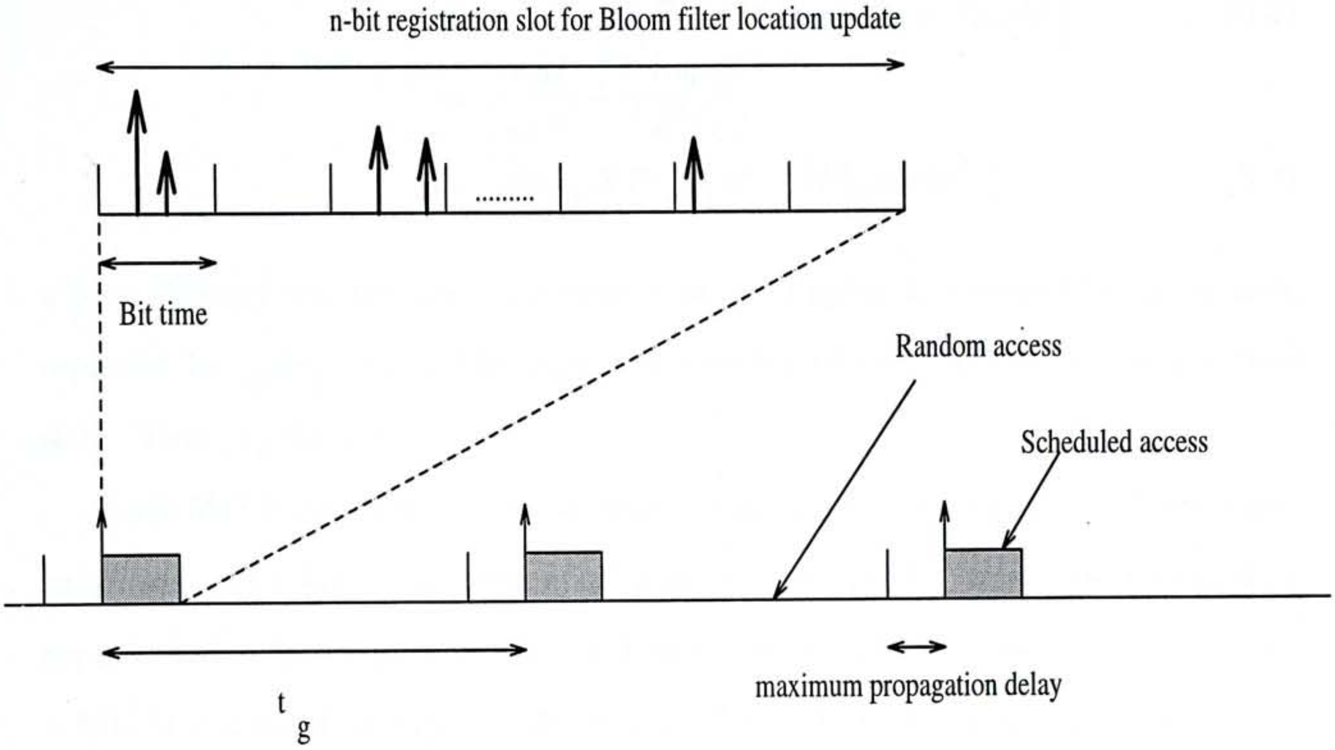


Figure 5.1: Illustration of the uplink control channel structure

free to perform random accesses the cell base station in the rest of the time. In order to prevent the random access update from garbling in the Bloom filter update messages, a guard time is added before every reserved slot.

5.2.2 Performance Evaluation

We define the cost functions as weighted sum of location update and paging cost. The cost for location update is weighted by a factor γ. For type 1 MU's, only the DLA strategy is performed, the objective cost function is given by:

$$C_{joint,type1} = \gamma \frac{log_2 N}{E\left[T_{i,j}\right]} + c\log_2 Nk^2 \tag{5.1}$$

For type 2 MU's,

$$C_{joint,type2} = \frac{nM}{\tau_{\Delta} N} + \gamma \frac{log_2 N}{E[T_{i,j}]}$$

$$\begin{aligned} &+ \; c\log_2 N\left\{P_{C,L}\left[P[page]k^2\right] + P_{L,C}k^2\right\} && (5.2) \\ &= \; \frac{nM}{\tau_\Delta N} + \gamma\frac{log_2 N}{E[T_{i,j}]} \\ &+ \; c\log_2 N P_{C,L}\left\{k^2 - \left[P[page]k^2\right]\right\} && (5.3) \end{aligned}$$

where $P[page]$ has the same expression as in chapter 3, except that $\mu\tau$ is now replaced by $\frac{\tau_\Delta}{E[T_{i,j}]}$. τ_Δ is the expected number of steps between two reserved slots. Thus, $\tau_\Delta \Delta t = \tau$

Each MU keeps track of its mobility statistics by taking intermittent measurement. The MU's are regrouped periodically. A MU would be grouped as type 1 if the first equation gives a lower cost for the specific MU. Otherwise a MU is classified as type 2. Note that the cost function of type 1 MU's are exactly the same as the primary algorithm used, i.e. the dynamic location area assignment algorithm. A MU would be classified as type 2 MU's only if the total bandwidth cost is lower when both update algorithms are used jointly. It follows that the joint use of both update algorithms must give better performance than the primary location tracking strategy.

5.3 Summary

We present a composite location update strategy. The Bloom filtering operation is used as a selective paging mechanism to reduce paging cost. In a following mini case study, the DLA and the HBF algorithms are jointly used in tracking location of MU's. We show that the joint use of both algorithms leads to a further decrease in total system cost, at the expense of increased system complexity in location update. The hybrid Bloom filter location update algorithm could be used as an auxiliary selective paging strategy to other location tracking algorithms. Comparisons with traditional selective paging schemes are interesting and is subject to ongoing research.

Chapter 6

Conclusion

6.1 Summary of Results

Traditional systems use random accessing as the multiple accessing technology in location update. In new generation of high capacity cellular systems, the location update rate is very high, making random access inefficient. In literature, attempts have been made to modify the inefficiencies of the geographic based strategy. New algorithms are designed to distribute the location update traffic to a larger number of cells, providing hysteresis against frequent switching of location areas. Surprisingly little effort is paid in devising a new multiple accessing technology for location registration. The thesis presents an algorithm which belongs to a new family of contentionless update protocol. Our algorithm is found to outperform other members in the family of protocols and, in high mobility scenario, the geographic based strategy.

In the second part of the thesis, a dynamic location area assignment algorithm is introduced. Location areas are assigned for each MU dynamically, with consideration on the real-time mobility record of individual MU. The update traffic is distributed to all cells. The degree of overlapping between location areas could be adjusted to adapt for different traffic patterns. In the scenario when the movement pattern is highly directional, as in vehicular traffic, few overlapping between location areas is needed to reduce location update rate. If the trajectory follows an erratic pattern, more hysteresis is needed against frequent switching of location areas. We have proven that our strategy brings a significant saving on bandwidth compared with the geographic and the distance based strategy.

We have also proposed that the Bloom filtering location update algorithm could be used in conjunction with other standard location tracking strategies in a single system. When a call arrives, the Bloom filtering algorithm is used as an auxilliary strategy that would selectively page cells in a targeted location area. A case study is given which the Bloom filter algorithm are jointly used with the dynamic location area assignment algorithm. Comparison with traditional selective paging schemes are interesting and is subjected to further research.

6.2 Future Research Directions

In this thesis, a set of three protocols for location tracking has been proposed, offering solutions to the problem of random accessing in location update.

Throughout the analysis, we model individual mobility by the Markovian assumption. This model is appealing for its computational simplicity. However, this approach ignores the concept of *trips* through a series of regions. The trip is an important modeling aspect in the analysis of location registration schemes.

Thus, the Markovian mobility model is not generalized into the framework in evaluating the overall performance of the different mobility management strategies.

We have shown that the performance of various location management schemes depends highly on the underlying mobility model. Thus comparison between various location management strategies will be biased and incompleted if a simple mobility model is used. A desired model must be sophisticated enough to emulate different mobility patterns for the individual MU's, yet simple enough to make performance analysis tractable. A framework for mobility management should be setup to allow fair comparison for the large pool of mobility protocols in literature.

Appendix A

Optimality of the Hybrid Bloom Filter Algorithm

In this appendix, the optimal values of the parameters for the hybrid Bloom filter algorithm is derived such that the cost function is minimized. The cost function is given by:

$$C(n, \tau_g, r, p) = \frac{c_1 n M}{\tau_g N} + c_2 \lambda \log_2 N \left\{ P_{C,L} P[page]_i M + P_{L,C} M \right\}$$

where and $i = 1, 2, 3$ represents three paging schemes. We assume steady state value $\bar{v}_i = \bar{v}$ for computation. With reference to chapter 3, the expression $P[page]_i$ for the three paging schemes are given by the following:

$$\begin{cases} P[page]_1 & = & 1 - (1 - P_l)^r \\ P[page]_2 & = & [1 - (1 - P_l)^w] \\ & + & \sum_{i=1}^{r-w} P_i [1 - (1 - P_l)^{r-w}] \\ P[page]_3 & = & \sum_{i=1}^{r} P_i (r + 1 - i) P_l \end{cases}$$

In all the three paging schemes,

$$P_l = \left(1 - p(1-p)^{\bar{v}}\right)^n$$

and

$$\bar{v} = \frac{k(1 - e^{-\mu\tau_g})}{1 - e^{-\mu r \tau_g}}$$

To minimize the cost function, the optimal parameters $(n, \tau_g, r, p)_{opt}$ are chosen such that

$$\nabla C(n, \tau_g, r, p)\Big|_{n,\tau_g,r,p_{opt}} = \left[\frac{\partial C}{\partial n}\ \frac{\partial C}{\partial \tau_g}\ \frac{\partial C}{\partial r}\ \frac{\partial C}{\partial p}\right] = \vec{0}$$

Note however that the expressions for $\frac{\partial C}{\partial n}$, $\frac{\partial C}{\partial \tau_g}$ and $\frac{\partial C}{\partial r}$ involves sum of polynomial and transcendental terms. Thus there are no analytical expressions for the optimal parameter values. Algorithms like the steepest descent algorithm is needed to obtain the parameter values numerically. Here the analytical expression of p_{opt} is derived for the three paging schemes.

$$\frac{\partial C}{\partial p} = \frac{\partial}{\partial p}\left[P_{C,L} c_2 \log_2 N P[page]_i M\right] \qquad i \in [1, 3]$$

Setting $\frac{\partial C}{\partial p} = 0$

$$\frac{\partial}{\partial p}\Big[P[page]_i\Big] = 0$$

Case 1: Paging scheme 1

$$\begin{aligned} & \frac{\partial}{\partial p}\Big[P[page]_1\Big] = 0 \\ \Rightarrow\quad & r\left(1 - P_l(p)\right)^{r-1} n \left[1 - p(1-p)^{\bar{v}}\right]^{n-1} \Big[(1-p)^{\bar{v}} - p\bar{v}(1-p)^{\bar{v}-1}\Big] = 0 \end{aligned}$$

Since p could not takes value 0 and 1, the equality holds only when

$$(1-p)^{\bar{v}-1}[1-p-\bar{v}p]=0$$

That is ,

$$p_{opt,HBF}=\frac{1}{1+\bar{v}}$$

Note that when $r=1$,

$$\bar{v}=\frac{k(1-e^{-\mu\tau_g})}{1-e^{-\mu\tau_g}}=k$$

$$p_{opt,TBBF}=\frac{1}{1+k}$$

which could be readily verified by taking the partial derivative of the cost function C_{TBBF}.

Case 2: Paging scheme 2

$$\frac{\partial}{\partial p}\Big[P[page]_2\Big]=(f_1(p)+f_2(p))\left[(1-p)^{\bar{v}}-p\bar{v}(1-p)^{\bar{v}-1}\right]$$

Since both $f_1(p)$ and $f_2(p)$ are greater than zeroes for all valid values of p, equality holds only when

$$\left[(1-p)^{\bar{v}}-p\bar{v}(1-p)^{\bar{v}-1}\right]$$

That is,

$$p_{opt}=\frac{1}{1+\bar{v}}$$

Case 3: Paging scheme 3

$$\frac{\partial}{\partial p}\Big[P[page]_3\Big] = \sum_{i=1}^{r} P_i \frac{\partial P_l}{\partial p}$$

Setting $\frac{\partial P_l}{\partial p} = 0$,

$$p_{opt} = \frac{1}{1+\bar{v}}$$

Appendix B

Derivation of the Expected First Passage Time $\mathbf{E}_{\mathbf{x}}T_i$ and $\mathbf{E}_{\mathbf{y}}T_j$

This appendix gives the solution of the Markov chain equations for the DLA algorithm in chapter 4, where $\mathbf{E}_{\mathbf{x}}T_i$ and $\mathbf{E}_{\mathbf{y}}T_j$ are respectively *first passage time* to the boundary states in the horizontal and the vertical direction. Since the equations for $\mathbf{E}_{\mathbf{x}}T_i$ and $\mathbf{E}_{\mathbf{y}}T_j$ are similar, here we solves for $\mathbf{E}_{\mathbf{x}}T_i$ for illustration purpose.

The balanced equation for $\mathbf{E}_{\mathbf{x}}T_i$ is given by:

$$\mathbf{E}_{\mathbf{x}}T_i = 1 + \frac{p_x}{p_x + q_x}\mathbf{E}_{\mathbf{x}}T_{i+1} + \frac{q_x}{p_x + q_x}\mathbf{E}_{\mathbf{x}}T_{i-1}$$

Boundary conditions for the Markov chain are $\mathbf{E}_{\mathbf{x}}T_0 = 0$ and $\mathbf{E}_{\mathbf{x}}T_{k+1} = 0$. We solve the Markov chain using the method of difference equations. Let $x = \frac{q_x}{p_x}$. The balance equation is rewritten as follows:

$$\mathbf{E}_{\mathbf{x}}T_{i+1} - \mathbf{E}_{\mathbf{x}}T_i = x\left(\mathbf{E}_{\mathbf{x}}T_i - \mathbf{E}_{\mathbf{x}}T_{i-1}\right) - (1 + x)$$

We obtain from the preceeding line that:

$$\begin{aligned}
\mathbf{E_x}T_2 - \mathbf{E_x}T_1 &= x\left(\mathbf{E_x}T_1 - \mathbf{E_x}T_0\right) - (1+x) \\
\mathbf{E_x}T_3 - \mathbf{E_x}T_2 &= x\left(\mathbf{E_x}T_2 - \mathbf{E_x}T_1\right) - (1+x) \\
\mathbf{E_x}T_4 - \mathbf{E_x}T_3 &= x\left(\mathbf{E_x}T_3 - \mathbf{E_x}T_2\right) - (1+x) \\
&\vdots \\
\mathbf{E_x}T_i - \mathbf{E_x}T_{i-1} &= x\left(\mathbf{E_x}T_{i-1} - \mathbf{E_x}T_{i-2}\right) - (1+x) \\
&\vdots \\
\mathbf{E_x}T_{k+1} - \mathbf{E_x}T_k &= x\left(\mathbf{E_x}T_k - \mathbf{E_x}T_{k-1}\right) - (1+x)
\end{aligned}$$

From the first eqeuation,

$$\begin{aligned}
\mathbf{E_x}T_2 - \mathbf{E_x}T_1 &= x\mathbf{E_x}T_1 - (1+x) \\
\Rightarrow \qquad \mathbf{E_x}T_2 &= \mathbf{E_x}T_1(1+x) - (1+x)
\end{aligned}$$

From the second equation,

$$\begin{aligned}
\mathbf{E_x}T_3 - \mathbf{E_x}T_2 &= x\left(\mathbf{E_x}T_2 - \mathbf{E_x}T_1\right) - (1+x) \\
&= [\mathbf{E_x}T_1 x - (1+x)]x - (1+x) \\
&= \mathbf{E_x}T_1 x^2 - (1+x)x - (1+x) \\
\Rightarrow \qquad \mathbf{E_x}T_3 &= \mathbf{E_x}T_1(1+x) - (1+x) + \mathbf{E_x}T_1 x^2 - (1+x)x - (1+x) \\
&= \mathbf{E_x}T_1\left(x^2 + x + 1\right) - (1+x)(2+x)
\end{aligned}$$

From the third equation,

$$\begin{aligned}
\mathbf{E_x}T_4 - \mathbf{E_x}T_3 &= x\left(\mathbf{E_x}T_3 - \mathbf{E_x}T_2\right) - (1+x) \\
&= [\mathbf{E_x}T_1 x^2 - (1+x)^2]x - (1+x) \\
\Rightarrow \qquad \mathbf{E_x}T_4 &= \mathbf{E_x}T_1(x^3 + x^2 + x + 1) - (1+x)(3 + 2x + x^2)
\end{aligned}$$

Thus, in general,

$$\begin{aligned}
\mathbf{E_x}T_i &= \mathbf{E_x}T_1(x^{i-1} + x^{i-2} + \cdots + 1) \\
&- (1+x)[(i-1) + (i-2)x + \cdots + x^{i-2}] \\
&= \mathbf{E_x}T_1 \sum_{s=0}^{i-1} x^s - (1-x) \sum_{s=0}^{i-2}\sum_{r=0}^{s} x^r
\end{aligned} \qquad \text{(B.1)}$$

$$= \begin{cases} \mathbf{E_x}T_1 \left(\dfrac{1-x^i}{1-x}\right) - (1-x)\left[\dfrac{x^i - 1}{(x-1)^2} - \dfrac{i}{x-1}\right] & x \neq 1 \\ i\mathbf{E_x}T_1 - (i-1)\, i & x = 1 \end{cases} \qquad \text{(B.2)}$$

Substitute $i = k+1$, and note that $\mathbf{E_x}T_{k+1} = 0$,

$$\begin{cases} \mathbf{E_x}T_1 \left(\dfrac{1-x^{k+1}}{1-x}\right) - (1-x)\left[\dfrac{x^{k+1} - 1}{(x-1)^2} - \dfrac{k+1}{x-1} = 0\right] & x \neq 1 \\ (k+1)\mathbf{E_x}T_1 - (k+1-1)\,(k+1) = 0 & x = 1 \end{cases}$$

or,

$$\mathbf{E_x}T_1 = \begin{cases} \dfrac{(1+x)\left[k + 1 - \frac{1-x^{k+1}}{1-x}\right]}{1 - x^{k+1}} & x \neq 1 \\ k & x = 1 \end{cases}$$

Substitute $\mathbf{E_x}T_1$ back into eqn. B.2, $\mathbf{E_x}T_i$ is given as follows:

$$\mathbf{E_x}T_i = \begin{cases} \left(\dfrac{1+x}{1-x}\right)\left[(k+1)\left(\dfrac{1-x^i}{1-x^{k+1}}\right) - i\right] & x \neq 1 \\ i\,(k+1-i) & x = 1 \end{cases}$$

$$= \begin{cases} (p_x + q_x)\left[\dfrac{i}{q_x - p_x} - \dfrac{k+1}{q_x - p_x}\dfrac{1-\left(\frac{q_x}{p_x}\right)^i}{1-\left(\frac{q_x}{p_x}\right)^{k+1}}\right] & x \neq 1 \\ i\,(k+1-i) & x = 1 \end{cases}$$

Appendix C

Optimality of the Dynamic Location Area Algorithm

For a square location area with location area size k, the degree of overlapping with the previous assigned location area could be adjusted to provide hysteresis. Given the mobility characteristics of the MU, an optimally assigned location area should maximize the expected dwell time in the horizontal $\mathbf{E_x}T_i$ and the vertical $\mathbf{E_y}T_j$ directions. Specifically, when a MU is making a location update at the *updating cell*, we compute the optimal co-ordinates of the *updating cell* with respect to the newly assigned location area such that both terms are maximized. The location area is completely specified with the co-ordinate of the *updating cell.*

In chapter 4, we have setup two Markov chains to derive the anayltical formulae for $\mathbf{E_x}T_i$ and $\mathbf{E_y}T_j$ respectively, where $\mathbf{E_x}T_i$ and $\mathbf{E_y}T_j$ are given by:

$$\mathbf{E_x}T_i = \begin{cases} \dfrac{1}{p_x+q_x}\, i\,(k+1-i) & p_x = q_x \\ \dfrac{i}{q_x-p_x} - \dfrac{k+1}{q_x-p_x}\,\dfrac{1-\left(\frac{q_x}{p_x}\right)^i}{1-\left(\frac{q_x}{p_x}\right)^{k+1}} & p_x \neq q_x,\ p_x \neq 0,\ q_x \neq 0 \\ \dfrac{1}{q_x}\, i & p_x \neq q_x,\ p_x = 0 \\ \\ \dfrac{1}{p_x}\,(k+1-i) & p_x \neq q_x,\ q_x = 0 \end{cases}$$

$$\mathbf{E_y}T_j = \begin{cases} \dfrac{1}{p_y+q_y}\, j\,(k+1-j) & p_y = q_y \\ \dfrac{j}{q_y-p_y} - \dfrac{k+1}{q_y-p_y}\,\dfrac{1-\left(\frac{q_y}{p_y}\right)^j}{1-\left(\frac{q_y}{p_y}\right)^{k+1}} & p_y \neq q_y,\ p_y \neq 0,\ q_y \neq 0 \\ \dfrac{1}{q_y}\, j & p_y \neq q_y,\ p_y = 0 \\ \\ \dfrac{1}{p_y}\,(k+1-j) & p_y \neq q_y,\ q_y = 0 \end{cases}$$

Here we derive the optimal values (i_{opt}, j_{opt}) such that $\mathbf{E_x}T_i$ and $\mathbf{E_y}T_j$ are minimized. Note that the formulae for $\mathbf{E_x}T_i$ and $\mathbf{E_y}T_j$ are similar. For illustration purpose we show below how $\mathbf{E_x}T_i$ is optimized.

Case 1: $p_x = q_x$

$$\begin{aligned} f(i) &= i(k+1-i) \\ f'(i) &= (k+1-i) + (-i) \\ &= k+1-2i \end{aligned}$$

$$f'(i)\big|_{i=\frac{k+1}{2}} = 0$$
$$\Rightarrow i_{opt} = \frac{k+1}{2}$$

Case 2: $p_x \neq q_x,\ p_x \neq 0,\ q_x \neq 0$

$$\begin{aligned} f(i) &= \frac{i}{q_x - p_x} - \frac{k+1}{q_x - p_x}\,\frac{1 - \left(\frac{q_x}{p_x}\right)^i}{1 - \left(\frac{q_x}{p_x}\right)^{k+1}} \\ f'(i) &= \frac{1}{q_x - p_x} - \frac{k+1}{q_x - p_x}\,\frac{-\ln\left(\frac{q_x}{p_x}\right)\left(\frac{q_x}{p_x}\right)^i}{1 - \left(\frac{q_x}{p_x}\right)^{k+1}} \end{aligned}$$

put $f'(i) = 0$

$$\frac{k+1}{\left(\frac{q_x}{p_x}\right)^{k+1} - 1}\ln\left(\frac{q_x}{p_x}\right)\left(\frac{q_x}{p_x}\right)^{i_{opt}} = 1$$

Hence,

$$i_{opt} = \frac{\ln\left[\frac{\left(\frac{q_x}{p_x}\right)^{k+1} - 1}{(k+1)\ln\left(\frac{q_x}{p_x}\right)}\right]}{\ln\left(\frac{q_x}{p_x}\right)}$$

Case 3: $p_x \neq q_x,\ p_x = 0$

$$\begin{aligned} f(i) &= \frac{i}{q_x} - \frac{k+1}{q_x}\,\frac{(p_x^{k+1} - q_x^i p^{k+1-i})}{(p_x^{k+1} - q_x^{k+1})} \\ &= \frac{i}{q_x} - \frac{k+1}{q_x}(0) \\ &= \frac{i}{q_x} \end{aligned}$$

Hence,

$$\begin{aligned} i_{opt} &= \left\{ i \,\middle|\, f(i) = \max_j(f(j)), j \in [1,k] \right\} \\ &= k \end{aligned}$$

Case 4: $p_x \neq q_x,\ q_x = 0$

$$\begin{aligned} f(i) &= \frac{i}{-p_x} - \frac{k+1}{-p_x} \, \frac{1-\left(\frac{q_x}{p_x}\right)^i}{1-\left(\frac{q_x}{p_x}\right)^{k+1}} \\ &= \frac{i}{-p_x} - \frac{k+1}{-p_x}\,(1) \\ &= \frac{k+1-i}{p_x} \end{aligned}$$

Hence,

$$\begin{aligned} i_{opt} &= \left\{ i \,\middle|\, f(i) = \max_j(f(j)), j \in [1,k] \right\} \\ &= 1 \end{aligned}$$

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