MANAGING TERMINALS MOBILITY FOR PERSONAL COMMUNICATION SYSTEMS

By

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A Thesis

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Abstract

Location update is an indispensible issue on Personal Communication Services (PCS). To realize the high capacity property of PCS's, there should be a large number of cells in the system. Paging by traditional flooding algorithm becomes not desirable. Several kinds of location update protocols, such as geographic and time based schemes, have been developed. A new approach of analysis for these two protocols will be presented. Moreover, a new category of location update scheme which is based on some *hashing* functions is proposed. The proposed Bloom filter based and One-Bit-Reply (OBR) protocols are two examples. A cost function to measure the performance of a location registration scheme is defined and its value for the four location registration schemes considered here will be derived. Moreover, based on a set of practical environment parameters, their performance are compared numerically.

There is a common shortcoming for both geographic and time based schemes: there is an expensive unavoidable overhead in the location update procedure. Since the uplink control channels are mostly randomly accessed, packet collision and retransmission are unescapable. Moreover, to ensure the correct delievery of the update messages, handshaking of signals between base stations (BS's) and mobile units (MU's) is neccessary and it will further affect the efficiency of the

uplink control channel as well as the battery life of the MU's.

Two collision resistant location registration methods, the Bloom filter based and OBR protocol are suggested. The idea of a Bloom filter is commonly used to test set membership by means of a sequence of binary valued test functions with hashing properties. A sequence of predefined test functions are delievered to every cell by BS's. The MU's response by replying with radio pulses, in corresponding time slots to represent their presence. By detecting the presence of pulses in different time slots, the locations of MU's can be estimated by the protocol, without knowing the source of transmission,. Although more than one MU may transmit pulses in the same time slot, the collision will not affect the extraction of location information.

As with the Bloom filter based method, the OBR protocol requires that during an update cycle, MU's only need to transmit radio pulses. By means of a designated algorithm, called *binary cutting algorithm*, MU's are systematically divided into different groups according to their user identity numbers (ID's). The update procedure is done by the transimssion of only one radio pulse from the MU's to the BS in the time slot corresponding to the group they belong to, since each MU belongs to one group only.

The performance of the update schemes is compared in two domains: the common air interface and the backbone network. For the air interface, the performance can be theoretically measured by two variables: U_x, the average data rate for a MU to update its location and P_x, the average data rate required for paging the MU by the system. The total cost functions C_x, defined by the sum of U_x and P_x, of the four location update schemes are derived. By optimizing these functions with respect to suitable variables, the performance

of different schemes can be compared.

Moreover, for the analysis in backbone network, it is proposed to implement the OBR protocol into GSM. The influence of the protocol on the databases (Home Location Register and Vistor Location Register) management will be analysed by means of an numerical example. It is found that compared with the tradition location update protocol for GSM, OBR protocol can reduce the traffic loading in the backbone network.

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Chapter 1

Introduction

1.1 Overview of Personal Communication Systems

According to the definition of [15], the Personal Communication System (or Services) (PCS) is the system by which every user can exchange information with anyone, at anytime, in any place, through any type of devices, using a single personal telecommunication number. This implies that the service should be low-cost and ubiquitous. The key features can be summarized as follows:

- **Multiple Environments**

  PCS should be compatible in a multi-system environment.

- **Multimedia services with high quality**

  Video, speech and data services are provided. The processing delay and the accuracy should have a good guarantee.

- **Muti-user types**

  Different quality of service (QOS) is available for different type of users.

- **Global roaming capability**

  Users can utilize the PCS everywhere in the world.

- **Single personal telecommunication number**

  No matter where the user is or what kind of terminal he is using, services can be provided through a single personal telecommunication number.

- **Very high capacity**

  Capable to accomodate millions of users with acceptable QOS.

- **Universal handset**

  Portable handset can be used anywhere.

- **Service security**

  The loss and leakage of confidential data is prevented.

In order to realize all the above features, the system management is much more complex than that of the traditional cellular systems. Channel allocation, multiple accessing, , handoffs and location management become the critical issues concerning the performance of a PCS.

1.2 Design issues on PCS

1.2.1 Channel allocation

In digital cellular systems, A *Channel* is defined as either a piece of frequency spectrum, a time slot or a pseudo-random code. The channel is allocated to every cell according to the densiy of users. Two kind of allocation strategies, static channel assignment and dynamic channel assignment, have been discussed [29].

- **Static channel assignment**

  Channels are nominally assigned to cells. Every cell has a fixed number of channels. However, this number may be different among every cells due to the difference in traffic intensity.

- **Dynamic channel assignment**

  All the channels are put into a common *resource pool.* They are granted on a call by call basis. When a call is initiated, a channel is requested from the *resource pool.* It is proven to be more efficient than the static channel assignment.

1.2.2 Multiple Access

High throughput and low delay are the goals of a good multiple access protocol. Starting from the invention of ALOHA [1], multiple access has been a controversy issue on wireless communication. However, to suit the multimedia service and high capacity environment, various type of multiple access schemes have been introduced. However, they can be divided into three categories [16]:

- **Fixed Assignment**

  Bandwidth either in frequency or time domain is fixed assigned to every terminals in the system, like Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA). The advantage is that terminals can own a collision free channel and the delay for acquiring a channel is ignored. However, the capacity of the system will be very limited. In addition, when the terminal is idle, the channel assigned for it is wasted.

- **Random Access**

  By this kind of multiple access protocols, channels are contended by the terminals. Examples are ALOHA, Carrier Sense Multiple Access with Collision Detection (CSMA/CD), Code Division Multiple Access (CDMA). All the communication channels are shared by any terminal. This reduces the idle time of the channels. However, collisions are unavoidable. For ALOHA and CSMA/CD, collisions of data cause total loss of data packets so that the throughput and the delay will be deteriorated. For CDMA, the problem of collisions is solved by the orthogonity of pseudo-random codes.

- **Hybrid Schemes**

  These schemes utilize the advantages of the above two so that a high thoughput low delay communication channel can be achieved. Examples are Packet Reservation Multiple Access (PRMA) [9], [10], Resource Auction Multiple Access (RAMA) [2] and Dynamic Reservation Multiple Access (DRMA). By this kind of protocols, an active user is required to contend for a channel. After he successfully captures a channel for the first packet, it is dedicated to him for the rest of his transmission.

1.2.3 Handoffs

Owing to the mobility of the terminals, handoff between two base stations is neccessary when terminals pass across the boundary of two cells during a call

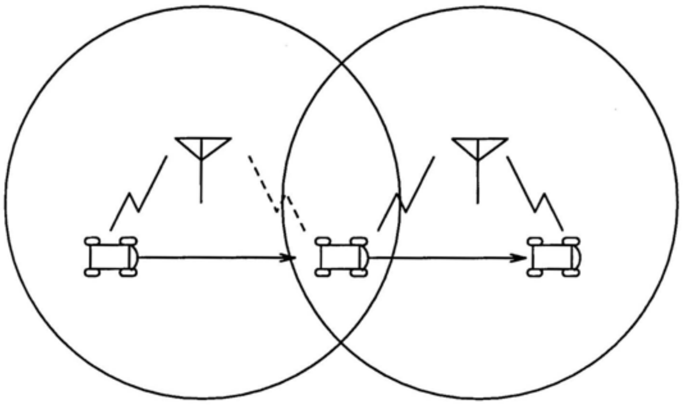


Figure 1.1: Hard handoff

holding period. Some of the handoff algorithms have been discussed and analysed [7], [26]. There are two kind of handoffs: hard and soft handoff.

- **Hard handoff**

  During a call holding period, the terminal detects the power strength from the base station. When the power received by the terminal is lower than a predefined threshold, the terminal seeks another base station to hook on by searching the strongest radio power from the neighboring base stations. Once it is done, the terminal then cut the connection to the old base station and develop a new connection to the new base station. The procedure is shown in figure 1.1

- **Soft handoff**

  This is similar to the hard handoff but after the terminal has setup the connection to the new cell, the old connection is still held for a short period of time, as shown in figure 1.2. However, this kind of handoff is available only in CDMA system.

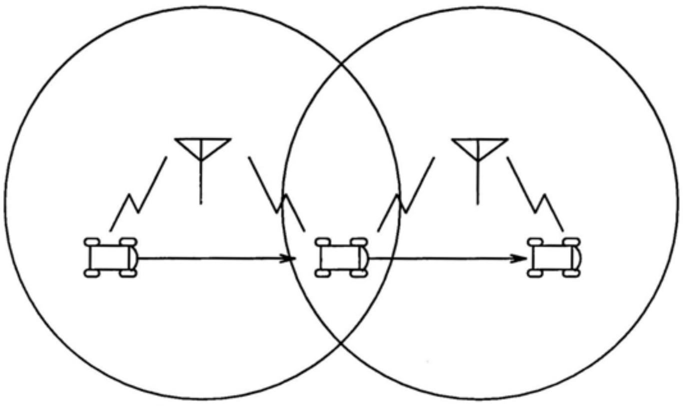


Figure 1.2: soft handoff

1.2.4 Location management

Terminal mobility and User Mobility

The mobility problem of PCS can be classified into *terminal mobility* problem and *personal mobility* problem, (see for example [23].) Typically, personal mobility is managed by means of an identity number, called the personal identity number (PIN), which allows a PCS user to make and receive calls independently of both the network point of attachment and the portable terminal being used. To handle terminal mobility, a common approach is to assign to every portable terminal in the system a unique identity number, called mobile identity number (MIN), which is independent of the point of attachment to the system. The network maintains the terminal location information by means of this number. For example, in GSM [17], a popular European mobile communication standard, every user has a subscriber identity module (SIM), which is physically implemented as a memory card containing a universal PIN. By inserting this module into any GSM compatible terminal which is identified by its own MIN, the user can utilize the sevices provided by the system regardless of where the network attachment point of the terminal is. The location of either the user or the terminal is maintained by different database in the system.

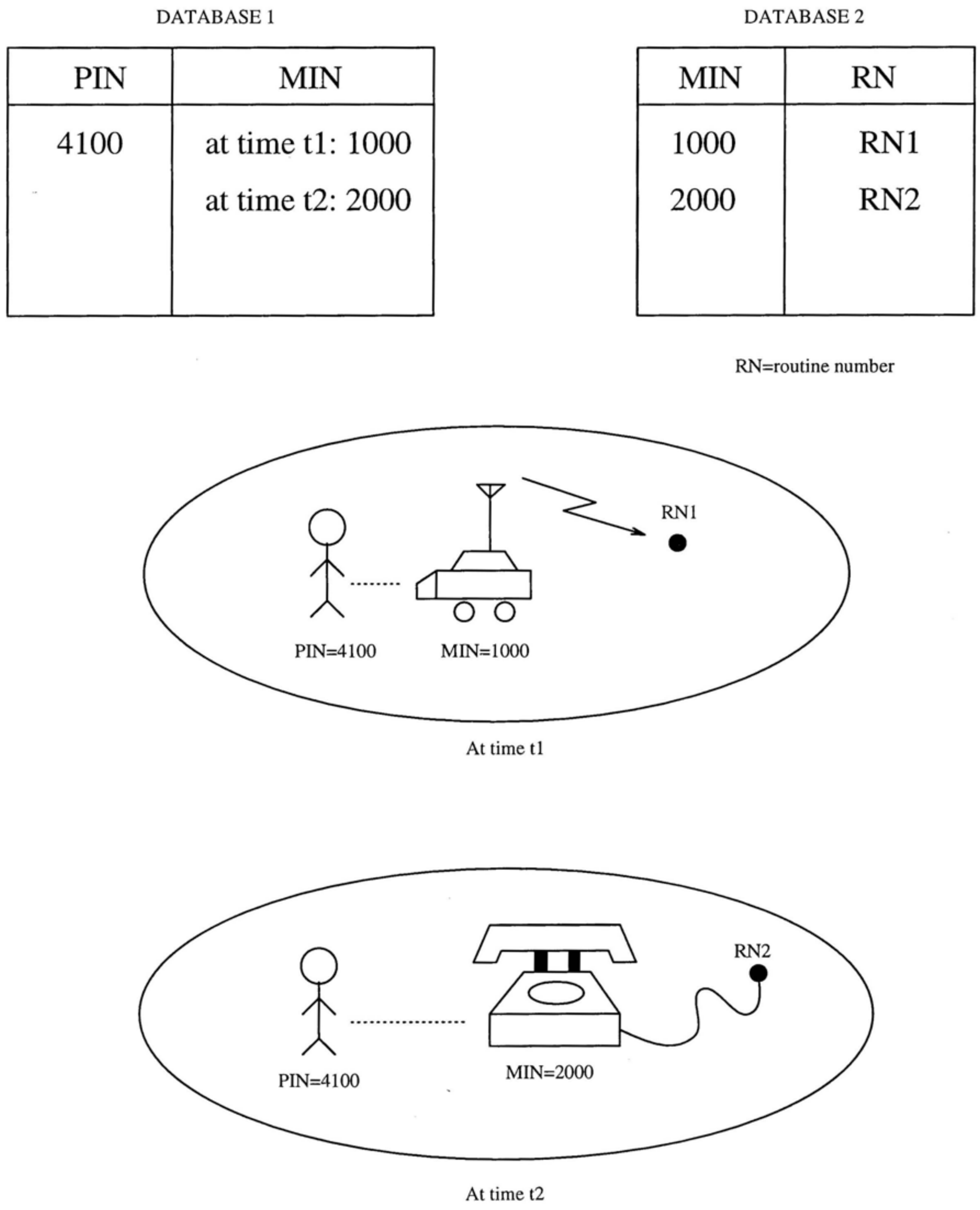
For clearer illustration, let us consider the situation shown in figure 1.3. At time t_1, the GSM user with PIN 4100 was in his car and using the mobile phone with the MIN 1000 which hooked onto the network access point RN1. Therefore, PIN 4100 was mapped to MIN 1000 in DATABASE 1 and in the mean time, MIN 1000 was mapped to RN1 in DATABASE 2. When the user left the car and moved into, say, his office, his SIM was then inserted to the telephone in the office. Afterward, the content of the databases was changed such that PIN 4100 was mapped to MIN 2000 and MIN 2000 was mapped to RN2. When a call comes for PIN 4100, it is routed to the correct destination according to the content of the databases.

The issues of how to manage these two types of mobility are extreme challenging. However, the focus of this thesis is only on terminal mobility.

Location update protocols

The implement of a location update protocol becomes a critical issue for the reason of resources conservation. A desired location update protocol should consider the tradeoff between the among of information required for location update and for call paging. The former one affects the battery life of the mobile unites (MU's) and the traffic of the uplink control channels while the later one affects both the traffic of the backbone network connecting base stations (BS's) and the switching centers as well as the downlink control channels.

Several kinds of the location update protocols have been developed [20], [30], [5], [8]. The location update protocols can be categorized and described as follows:



DATABASE 1

PIN	MIN
4100	at time t1: 1000 at time t2: 2000

DATABASE 2

MIN	RN
1000	RN1
2000	RN2

RN=routine number

Figure 1.3: Illustration of the personal and terminal mobility

- Geographic based: Cells in a cellular system are divided into different location area. Every time a MU moves across the boundary between two different location update areas, it initiates a location update procedure.
- Time based: Regardless of which cell a MU belongs to, a MU updates its location periodically with a constant time period.
- Movement based: After the MU passes across a certain number of cells, it updates its location.
- Stimulus based: A MU performs a location update only after it receives the requests from the base station.
- ON/OFF based: A location update occurs only after MU's are power on or just before they are powered off.

1.3 Motivation of this thesis

For all the above protocols, location updates incur unavoidable contention overheads since the uplink control channels are almost always randomly accessed and contention is unavoidable. Retransmissions required by collision inherently reduce channel throughput. Apart from this basic consideration, in some protocol standards, setting up a connection for location update requires complicated signal handshakes between the MU and the BS. This type of overheads further reduce the efficiency of uplink control channels.

In this thesis, a new category of location update protocol, called Bloom filter based protocol, is introduced and analysed. The basic idea is that mobile users indicate their presence in a cell by transmitting or abstained from transmitting radio pulses at certain time slots. The update procedure is initiated periodically by the base stations. Then terminals send radio pulses in certain time slots to represent their presence. Whether to transmit the radio pulses is determined by the relation between a set of predefined *queries* with two answers and the ID of the terminal. If we use '1' to represent the presence of a radio pulse in a time slot and '0' to represent the absence, by the bit pattern received in a fixed number of time slots for every cell, the location of the terminals can be estimated.

In addition, another scheme related to the Bloom filter based protocol called One-Bit-Reply (OBR) protocol is introduced. By this scheme the terminals only to transmit one radio pulse in each location update period. The set of ID's is first divided into a certain number of ordered groups by means of *binary grouping method*. When the location update procedure is initiated by the base station, each terminal send one pulse in the time slot matching the group to which the terminal belong. The detailed description will be shown in chapter 3.

For the both proposed protocols, collisions of radio pulses which represent the answer '1' do not affect the result of the location information obtained by the base stations. The uplink control channel can be efficiently utilized. This is a positive contribution to the expansion of capacity for a PCS.

1.4 The theme of this thesis

1.4.1 Methodology

The performance of a location update protocol in the common air interface can be measured by the among of data required for MU's to update their position as well as that needed for the system to page a MU when a call comes. For comparison, two cost functions P_x and U_x representing the paging and update costs are defined by equation [1.1] and [1.2]. The subscript x for the functions refers to different location update protocols.

$$\bar{P}_x = \frac{\text{average no of bits transmitted by the system to page a MU when a call comes}}{\text{average inter call arrival time}} \tag{1.1}$$

$$\bar{U}_x = \frac{\text{average no of bits transmitted by a MU when a location update is required}}{\text{average time between two consecutive location updates}} \tag{1.2}$$

It is clear that P_x varies inversely as U_x and vise versa. However, for the sum of the two functions, named as C_x, there exists a minimum value for every location update protocol.

In the analysis of the later chapters, the resultant cost functions for the time based (C_T), geographic based (C_G), Bloom filter based (C_B) and the OBR (C_O)protocols are derived under a reasonable mobility model and system parameters. These functions will be optimized either numerically or analytically with respect to suitable variables. The performance of the location update protocols will be contrasted by comparing each of the optimized cost function under reasonable environment parameters.

In addition, we try to implement the OBR protocol into a European cellular system standart GSM. Compared with the tradition geographic based method, the performance of OBR will then be measured by the traffic loading in the network connecting the location databases of the system.

1.4.2 The system model and assumptions

The environment we consider is a digital packet switch cellular system. The derivation of the cost functions is based upon the following assumptions:

- The coverage area of the whole system is $A\, km^2$.
- The total number of cells is C and each cell is equal size.
- The total number of users M and they are evenly distributed in the system.
- Slotted ALOHA is used as the random access protocol for the uplink control channel and it is assumed to be under maximum throughput condition, i.e. $G = 1$.
- The call arrivals for every MU follows Poisson distribution with average rate μ per second.
- A simple Markovian model is assumed for the mobility such that the mean dwelling time (the residing time in a unit area) for a terminal is exponentially distributed with normalized mean $\frac{1}{\lambda}$ second per square km. Moreover, when a terminal leaves a cell it will enter either neighbouring cell with an equal probability. (Some other mobility models with real time speed estimation have also been proposed [25], [4]).
- The period between successive location updates for time based, OBR and Bloom filter based is τ second.
- The average number of cells in a *location area* for the geographic based scheme is $\bar{n}$.

- The length of the terminal ID's is L bits. In addition, σL is the length of the paging message for any protocol and ρL is the length of update messages for time and geographic based protocols.
- The system is in steady state.
- MU's are always power on.

1.4.3 Outline of the thesis

The content of this thesis will focus on the description, performance analysis and comparisons of four different location update schemes: the geographic based, time based, Bloom filter based and OBR protocols.

In the next chapter, we will first study two traditional location update schemes: geographic and time based schemes. Under the above mentioned system, the cost functions C_G and C_T for geographic and time based respectively are derived. The numerical results match those in previous papers but they are obtained in a different point of view.

After that, the concept of Bloom filter is introduced. It is traditionally used in data retrieval in large databased systems. We try to apply the theory on the location update problem for PCS. Moreover, a related location update scheme called OBR protocol will also be proposed and analysed. C_B and C_O for the Bloom filter based and OBR protocol respectively will also be derived. Then the cost functions for all the four update schemes will be optimized either analytically or numerically with respect to suitable variables. Finally, for different number of cells and mean dwelling time per square km, the performance of the time based, geographic based, Bloom filter based and OBR protocols will be contrasted numerically.

Chapter 2

Overview of the traditional location update schemes

2.1 Why do we need location registration?

Location update is a must if the system complexity is high.

One of the main characters of PCS is the high capacity. To accomodate a large propulation of Mobile Units (MU's), we have to increase the number of cells in the system. In a simple cellular system, it can be shown that

$$m = \frac{B_t}{B_c N}$$

where m is the number of radio channel available in a cell, B_t is the total allocated spectrum for the system, B_c is the channel bandwidth and N is the number of cells in frequency reused area, which is defined as a cluster, for the system. If $\frac{B_t}{B_c}$ is fixed, N must be as small as possible to provide a enough capacity for the system. Then the number of cells in the system will increase.

The traditional flooding algorithm using in call paging is resource wasting. It is clear that by this algorithm, the amount of transmitted information required to deliever a call from the Base Stations (BS's) to MU's increases linearly as the number of cells as well as number of MU's in the system. However, since any MU belongs to only one cell (except those performing a soft handoff), $\frac{C-1}{C}$ fraction of paging information is wasted. (C is the total number of cells in the system.) If both the propulation of MU's and the number of cells increase, not only the downlink paging channel will be heavily loaded but also the wastage of radio resource will increase tremendously.

To alleviate the explosive escalation of transmitted information for paging a MU, location update protocols are introduced. Their common feature is that by the location information provided by the MU's individually, calls are not flooded to the whole system but only delievered to the cell(s) which the target MU may appear. Conceptually, the role of the location update protocol is to share the loading of the system to every MU. Moreover, the performance of a location update protocol is determined by the balance of the information required for both call paging and location registration.

2.2 Location registration by Geographic and Time based methods

2.2.1 Geographic Based Registration Schemes

This is the most common location update protocol employing in practical systems such as GSM. (The detailed protocol of GSM will be described in Chapter

6.) For this kind of scheme, the whole covering area of the system is partitioned into several *location areas* which may consist of different number of cells. When MU's move across the boundary between two *location areas*, they initiate a location update procedure by sending their ID's to the new *location area.* Every time a call arrives, it will be delievered to all the cells in the *location area* where the target MU has recently updated its position. The *location areas* partition method, which have been suggested in various papers [22], [8], [12], [21], can be done in either a fixed or dynamic manner.

- **Fixed partition**

  Cells are grouped permanently into different *location areas.* This is shown in figure 2.1. The partition is based on both the boundary crossing rate of MU's and the effort required for paging them. Optimization of the location area can be done by various method such as the one suggested in [22].

- **Dynamic partition**

  This kind of partition method is suggested for improving the weakness of fixed partition method. In some special scenarios for the fixed partition method, the MU's may bounce back and forth on the boundary between two *location areas* so that the frequency of updating locations will increase drastically. To prevent this occurence, the dynamic partition of *location areas* is proposed [12], [11], [21] . When a MU moves across the boundary of its homing area, it will initiate a location update procedure in the new homing cell which will be the centre of a new *location area.* This is illustrated in figure 2.2. Hence, the problem of bouncing on the boundary can be solved.

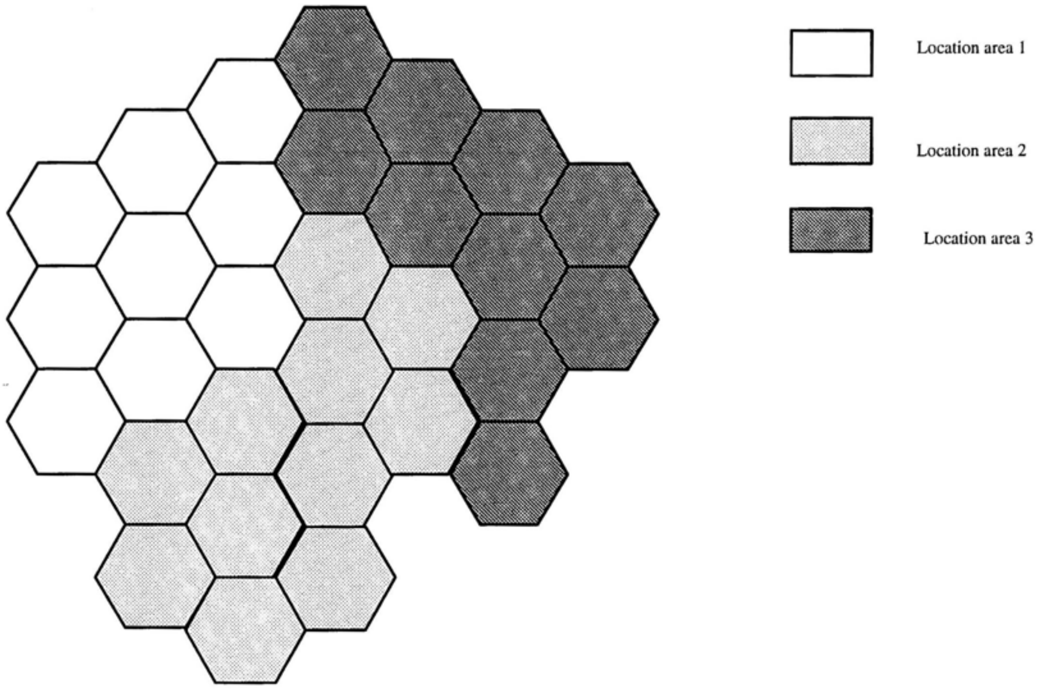


Figure 2.1: An example of fixed partition of location areas

Moreover, for fixed partition, The uplink traffic due to location registration is concentrated in the boundary cells of the *location areas*. This problem can also be solved by dynamic partition method. The traffic intensity due to the location registration is shared by every cells in the system since there is no fixed boundary cells for dynamic partition.

However, if the terminal moves linearly, the performance of the dynamic partition may not be as good as the fixed partition method. It is shown in figure 2.3 that for linear movement of terminals, the distance travelled from one location area to another for dynamic partition is half of that for fixed partition method. In other words, the update frequency for dynamic case is doubled. The detailed comparison has been shown in [32].

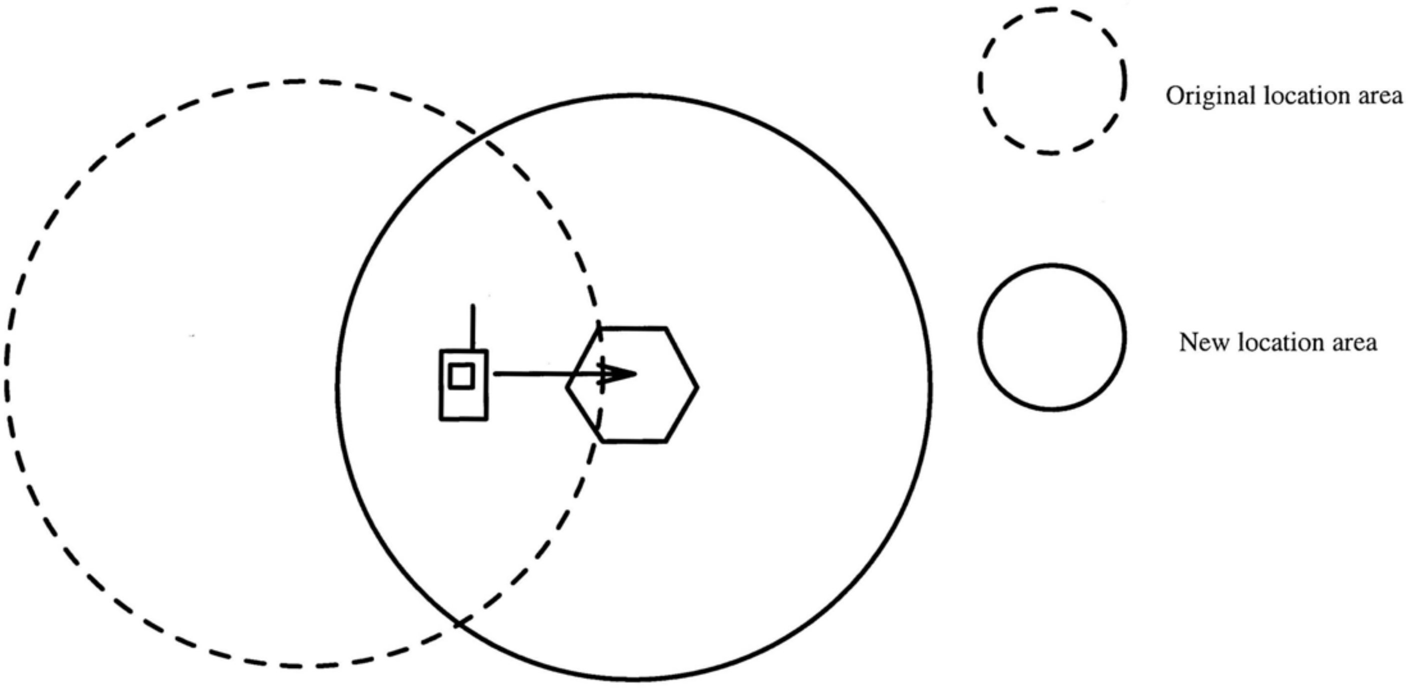


Figure 2.2: An example of dynamic partition of location areas

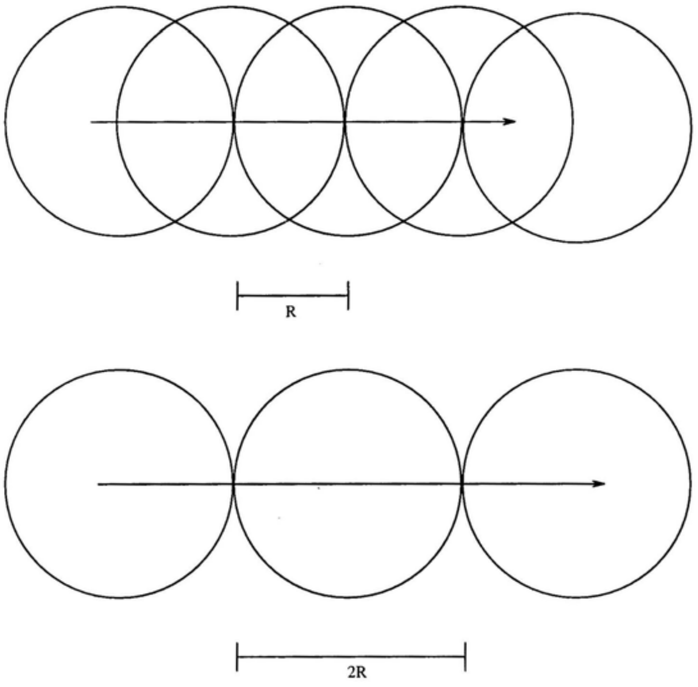


Figure 2.3: Comparison of the fixed and dynamic partition method for linear movement of terminals.

2.2.2 Time Based Registration Scheme

Updating algorithm

For this scheme, MU's independently initiate the location update process periodically. IS-41 [23] is a standard that adopts this approach. The locations of MU's are registered based on the internal timer of the MU's. To minimized the chance of packet collisions, the update periods for the MU's are not synchronized.

Paging algorithm

Since a MU may leave the cell in which it has updated its location in the recent update cycle, the incoming calls may be delievered not only to the cell where the MU has recently updated its position. Two paging strategies are employed:

- **Shooting-then-flooding**
  The incoming call is first delievered to the cell which contains the location information of the target MU. If the base station gets no response, the call is *flooded* to all other cells.
- **Shooting-then-radiating**
  If the BS gets no response for the first time of paging, the call will be delievered to the cells surrounding the paged cell layer by layer as shown on figure 2.4.

2.3 Peformance Analysis of protocols

There are several papers which have shown the analysis of these two protocols such as [3], [28]. Particularly, in [3], the environment considered in the paper

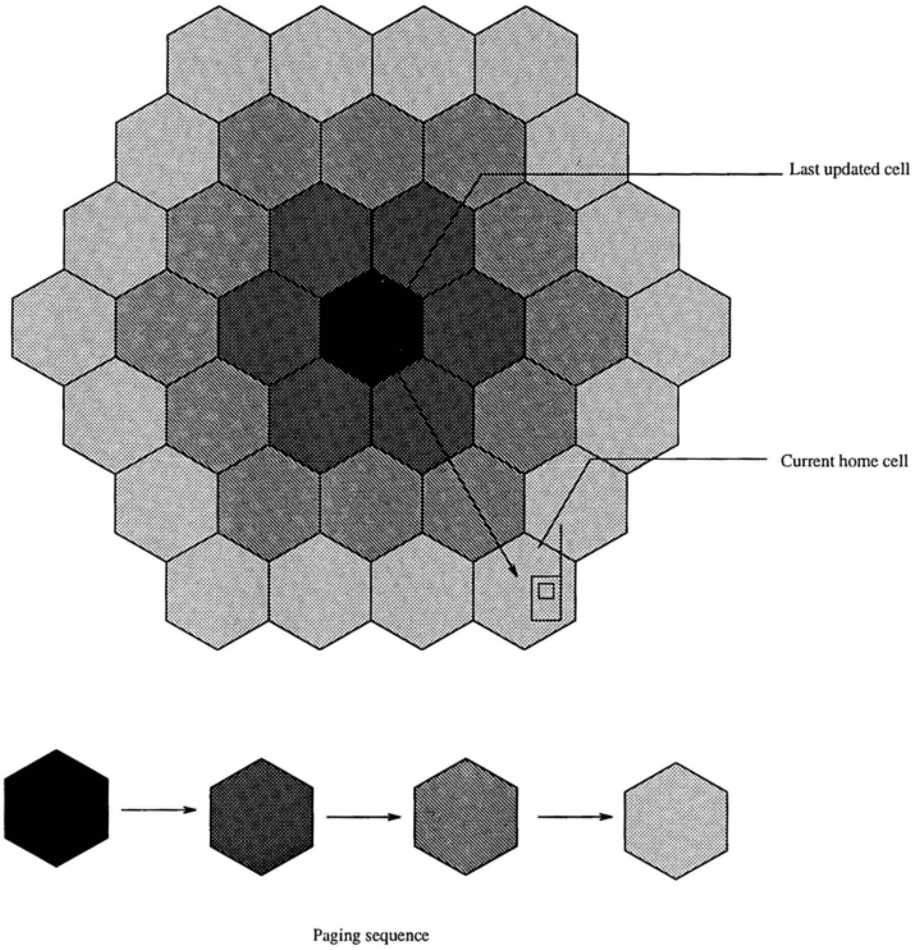


Figure 2.4: Paging by Shooting-then-Radiating

is a ring shape cellular system. The results shows that determined by the average frequency of updating location for MU's and the average number of paged cells for an incoming call, the performance of geographic based location update protocol is better than that of time based.

According to the analysis of this thesis, the results are obtained in a different approach. As mentioned in chapter 1, the measure of the performance employed for different location update protocols is U_x and P_x (the definition refers to 1.1 and 1.2). The most significant difference of the analysis in this thesis compared with the above papers is that the problem of retransmission due to collision is considered as well. Moreover, instead of the ring cellular system, we consider a two dimensional one with close packed hexagonal cells. The detail description of the system model has been mentioned in Chapter 1.

2.3.1 Analytical Results

By the above mentioned system model and assumptions, the cost functions can be obtained as follows:

Geographic based

$$\begin{aligned} P_G &= \sigma L \mu \bar{n} && (2.1) \\ U_G &= \frac{\theta \rho L \lambda C}{\bar{n} A} \left(1 - \frac{C}{M}\right)^{1-\frac{M}{C}} && (2.2) \end{aligned}$$

Time based

$$\begin{aligned} P_T &= \sigma L \cdot \mu \cdot \left\{ C \left(1 - \frac{A(1 - e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}\right) + \left(\frac{A(1 - e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}\right) \right\} && (2.3) \\ U_T &= \frac{\theta \rho L}{\tau} \left(1 - \frac{C}{M}\right)^{1-\frac{M}{C}} && (2.4) \end{aligned}$$

In the cost functions, θ is the factor due to handshaking of messages during location update while other symbols refer to the system model defined in Chapter 1. The proof of these cost functions are shown in Appendix A.

τ and $\bar{n}$ are system parameters that can be adjusted to minimize the sums of the cost functions, i.e. C_G and C_T, for the two protocols. In our comparison study, we optimized each of the protocol by tuning the system parameters accordingly. For the geographic based scheme, the cost function is optimized with respect to the number of cells $\bar{n}$ in a *location area* while for the time based, it is done with respect to the length of the update period τ.

Theorem 1 *The C_G is optimized when*

$$\bar{n} = \sqrt{\frac{\theta\rho\lambda C}{\sigma\mu A}\left(1 - \frac{C}{M}\right)^{(1-\frac{M}{C})}}.$$

And the optimized function $min(C_G)$is obtained below

$$min(C_G) = 2L\sqrt{\frac{\theta\rho\sigma\lambda C\mu}{A}\left(1 - \frac{C}{M}\right)^{(1-\frac{M}{C})}}$$

However, owing to the cumbersome expression, C_T is not optimized analytically but in the following numerical study, it is done numerically by steepest descent method (See Appendix B).

2.3.2 A Numerical Study

The performance of the two traditional location registration protocols is compared numerically. It is shown that the geographic based scheme outperforms the time based scheme.

Description	value
A	$100km^2$
M	131072
$\frac{1}{\mu}$	30 minutes
L	$\log_2 131072$ bits
θ, ρ and σ	1

Table 2.1: Practical values for the system variables

The results shown in figure 2.5 and figure 2.6 are obtained when the dwelling time per unit area varies from 200 to 1200 seconds and the number of cells varies from 50 to 170 respectively. Moreover, the variables are fixed as shown in the following table.

In figure 2.5, the general tendency of the curves is declining as the the dwelling time per unit area increases. The reason is that for geographic based when the dwelling time increases the frequency of location updating for the MU's decreases and it dominates the total cost. For time based, When the dwelling time increases, the probability of paging a MU without flooding is higher.

As the number of cells increases, the total costs for both schemes increase as well as shown in figure 2.6. However, the increasing rate for the geographic based scheme is lower than that for time based.

2.4 Summary of the results for time and geographic based location update protocol

As shown in previous section, the performance, in terms of the average bit rate for location update and call paging, of geographic based is better than that

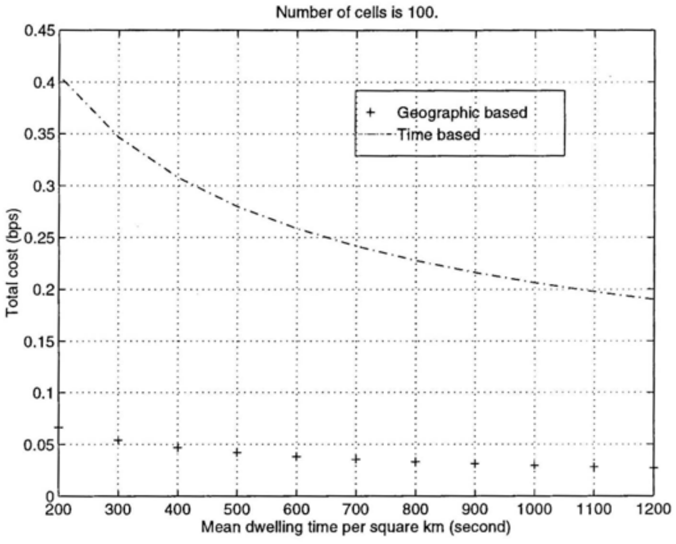


Figure 2.5: Comparison of Time and Geographic based schemes as dwelling time varies

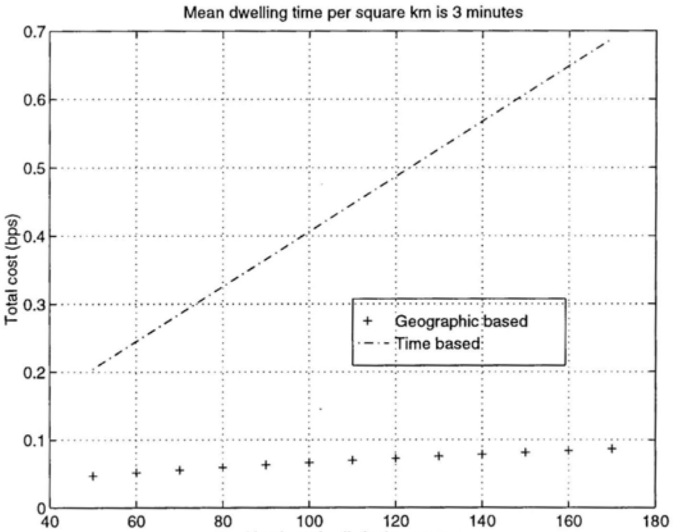


Figure 2.6: Comparison of Time and Geographic based schemes as number of cells varies

of time based scheme. The result matches that in previous papers but it is expressed in a different point of view.

Chapter 3

The Implementation of Bloom filter on location registration

3.1 Introduction

One of the searching method in computer science is by *hashing*. The *key* of a record in a database is defined as an index governing the sorting of the record. To locate a particular record with a *key* K from a database, traditional methods such as binary search, optimal tree search or digital tree search are based on comparing the given K to the *keys* in the database, or using the digits of the argument to govern a branching process [13]. Another possibility is to compute a function which can be interpreted as the location of K and the associated data in the database. However, it is difficult to discover the function such that all the entities in the database can be uniquely located. These leads to a popular class of searching method known as *hashing* or scatter storage techniques. The idea of *hashing* is to chop off some aspects of the *key* and to use this partial information as the basis for searching. The *hashing function*, $h(K)$, is computed for the *address* of the record with *key* K. Since this function truncates the information of the record location, more than 1 records may have the same *address* so that ambiguity may occur when they are retreived. This occurence is called *collision*. However, it can be algorithmically solved [13].

One of the interesting applications of the *hashing* function has been suggested by Burton H. Bloom [6] in 1970. His idea is that it is possible to maintain a bit table, which is called the *Bloom filter*, so that most *keys* not in the file can be recognized as absent without making any references to further search. The bit table is assumed to have M slots containing $b_0, b_1, \ldots, b_{M-1}$, where b_i is either '1' or '0'. For each *key* K_j in the file, compute k independent hash functions $h_1(K_j), h_2(K_j), \ldots, h_k(K_j)$, and set the corresponding k b's equal to 1. Thus $b_i = 1$ if and only if $h_l(K_j) = i$ for some j and l. To determine if a search argument K is in the file, first test whether or not $b_{h_l(K)} = 1$ for $1 \leq l \leq k$. If so, a conventional search will probably find K if k and M have been chosen properly. The use of Bloom filters is not new to databased researchers. Several papers [24], [18], [19]have discussed their performance on databases.

In this chapter, the theory of the Bloom filter is applied on the location registration problem for PCS's. The performance will also be analysed.

3.2 The Implementation of Bloom filter on location registration

3.2.1 Location Update by Bloom filter

The application of Bloom filter on the location registration problem in PCS's was first suggested by [31]. The basic idea is that all the MUs in a cell periodically reply to a series of queries and transmit the answers to the BS via the uplink control data channel. The queries are assumed to be based on the user ID's and a user will reply with a "1" with a certain probability p and a "0" with probability $(1-p)$. If the answer is "1", the MU will send a radio pulse at a specific time slot; otherwise, the MU will remain idle.

This process corresponds to the hashing of each element in a set through a specific transform, that is, the queries. After a query-and-reply session, every BS obtains a bit table which is defined as *location vector* with the length depending on the number of queries which have been broadcasted. In addition, the queries can be predefined to minimize the downlink traffic.

3.2.2 Paging algorithm

It is assumed that the *location vectors* obtained in the most recent location update cycle for C cells is $\mathcal{L} = \{l_1, l_2, \ldots, l_C\}$, where l_j, $1 \leq j \leq C$, is a binary vector. When a call comes, the ID of the callee will be tested by the same series of queries as those used for updating location. The transformed ID t_m, which is also binary vector with the same length as the *location vectors*, is compared with the *location vector* in every cell.

The criterior for delievering a call to cell i is that

$$t_m \odot l_j = t_m \tag{3.1}$$

, where $\odot$ is the bit-by-bit multiplying operator. This operation is like *filtering* out the content of the specific slots from the *location vector* of cell j. If t_m has i "1's" in specific slots, there is no reason to page the cell with the *location vector* having at least a "0" in those i slots. If the *filtered* vector is not equal to t_m, at least it is known that the target MU is not in the cell j during the most recent location update cycle and the call will not be delievered to that cell.

Nevertheless, there may be more than one cells which satisfy the paging criterior due to the property of the *hashing* function. The reason is that more than 1 MU's may have exactly the same transformed ID and they may location at different cells. If a call for any of the MU's with the same transformed ID arrives, it will be delievered to all the cells satisfying 3.1.

Similar to the time based case, the MU's may leave the home cell after a update cycle. It may happen that even though we page the MU to all the cells whose *location vector* satisfying 3.1, the system may not resceive any response. In such case, the call will be flooded to other cells like the *shooting-then-flooding* paging method for time based scheme.

3.2.3 An example

Suppose there are 8 MU's which even distribute to a 3-cell system as shown in figure 3.1. In the most recent update period, terminals are assumed to reply as shown in table 3.1 and *location vectors* for every cell are summarized in table 3.2.

Terminals	transformed ID's (binary)
0	1001
1	1100
2	0101
3	1010
4	1001
5	0110
6	0100
7	0001

Table 3.1: The transformed ID's for the recent location update

Cells	*Location vectors* obtained
1	1101 (=1001+1100+0001)
2	0101 (=0101+0100)
3	1111 (=1001+0110+1010)

Table 3.2: The location vectors obtained in every cell for the recent location update

Cells	*Location vectors* $\odot$ 1001
1	1001
2	0001
3	1001

Table 3.3: The result to check whether to deliever a call

If a call for terminal 0 arrives, the call delievery procedures is done as follows:

1. The ID of the callee (terminal 0 in this case) is tested with the same set of queries. The result will be 1001_b.
2. The condition 3.1 is checked for every cell. The results are shown in table 3.3.
3. According to the operation result in table 3.3, the call will be delievered to cells 1 and 3.
4. If the terminal does not response, the call will also be delievered to cell 1.

3.3 Performance evaluation of the Bloom filter based location update scheme

Using the system model mentioned in Chapter 1, the following results can be obtained.

$$\begin{aligned} P_B &= \sigma L \mu C \left[\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}(1-pq^{\frac{M}{C}})^n + (1-\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}) \right] && (3.2) \\ U_B &= \frac{knp}{\tau} && (3.3) \end{aligned}$$

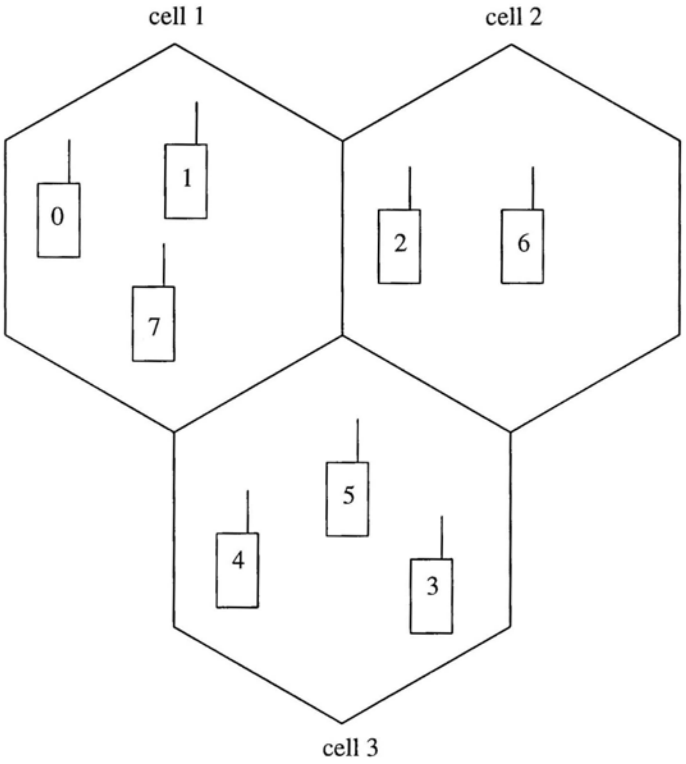


Figure 3.1: An example of the distribution of terminals into a 3-cell system

where n is the length of the *location vector*, p is the probability that a MU will reply a "1" for a certain query and $q = (1 - p)$. The factor k in the update cost function is for the pulse detection. Every time terminals reply the queries, a single tone radio pulse is sent. For secure detection of the radio pulse, the time slot for sending such pulse should be larger than an actual bit time. The detailed derivation of the cost functions can be found in Appendix A. However, the components in the paging and update cost functions can be described as follows. The term $\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}$ is the probability that when a call arrives, the callee still locates at the cell where he updated the location in the recent update period. $(1 - pq^{\frac{M}{C}})^n$ is the average number of cells in which terminals with the same transformed ID's may locate.

The total cost function, $C_B = P_B + U_B$, can be minimized against the query length n and τ independently.

Theorem 2 *C_B is minimized when*

$$n = \frac{\log\left(-\frac{\alpha}{\beta\log\gamma}\right)}{\log\gamma} \tag{3.4}$$

where

$$\begin{aligned}
\alpha &= \frac{kp}{\tau} \\
\beta &= \sigma L\mu\left(\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{\lambda\tau}\right) \\
\gamma &= (1-pq^{\frac{M}{C}}) \text{ where } q\text{=1-}p
\end{aligned} \tag{3.5}$$

For the validity of the optimized solution, the following condition should be satisfed.

$$\frac{p}{\log\left(\frac{1}{1-pq^{\frac{M}{C}}}\right)} \le \frac{\sigma L\mu A(1-e^{-\frac{C\lambda\tau}{A}})}{k\lambda} \tag{3.6}$$

All the proofs for the above theorem and criterior can be refered to Appendix B.

Moreover, the C_B with the query length showing in 3.4 can be further optimized numerically with respect to the update period τ, by means of the steepest descent method described in Appendix B. The performance of the optimized Bloom filter based location update scheme will be numerically compared with others in the next chapter.

3.4 Summary of the results for Bloom filter based scheme

The idea of implementing the Bloom filter into location update problem for PCS has been introduced. The update and paging cost function are derived. The optimization of the total cost function C_B is done analytically and numerically with respect to two variables: the length of the *location vector* and the update period τ respectively.

Chapter 4

One-Bit-Reply protocol

4.1 Introduction

A Bloom filter related location update scheme, called One-Bit-Reply (OBR) protocol, is introduced and analysed. The key idea of this category of protocols is that all MU's homing on to a given BS register their location by sending only one radio pulse after receiving a periodic query broadcast from the base station. The issue of signal collision is algorithmically resolved by the protocol.

The basic idea is that the system divides all its subscribing MU's into groups, called *mobile groups*, according to their ID's. Any kind of grouping can be used theoretically, but for simplicity and efficiency considerations, a modified version of the *binary cutting algorithm* as described in [14] is proposed here.

The idea of the *binary cutting algorithm* is to allow the BS to determine through a sequence of adaptively constructed queries and replies to determine whether the ID's of the MU's homing onto its cell fall within certain numerical ranges. The numerical ranges are constructed recursively by sub-dividing a queried range into two equal subintervals if that range is known to contain ID's of MU's in the cell. If the queried range does not contain any ID of all the MU's in the cell, obviously there is no need to query its sub-intervals. Theoretically, if enough queries are processed, the exact identities of the MU's in any cell can be determined. For practical purposes, the algorithm can stop at certain level of probabilistic certainty. The details of how to implement the stopping rule is discussed in [14] and is not central to the current discussion.

4.2 One-Bit-Reply protocol

The *binary cutting algorithm* can effectively reduce paging costs, however, its requirement of adaptively constructing queries makes it difficult to be implemented in practice. To simplify the algorithm, the *mobile groups* are not constructed adaptively. Instead, a BS can first determine the desirable size of the *mobile groups*. The groups are then defined by partitioning the whole user address space into sub-intervals. Since the size of the whole user address space is a known system parameter, the BS only needs to convey the desired group size to the MU's by means of a *header* packet which also serves the purposes of initiating the query-reply process. The time immediately after the header packet is automatically divided into a number of time slots, called *mobile group slots*, each of which corresponds to an address sub-interval. The MU sends a radio pulse at the *mobile group slots* which contains its ID. For example, a MU belonging to group 1 is required to send a pulse in the first time slot after the *header* packet. This modified protocol possesses both power and bandwidth saving features for the uplink control channel. Since in every location update cycle, each MU only needs to send only one radio pulse. The issue of random collision can also be resolved in a probabilistic sense, by chosing the size of the *mobile group* appropriately to reduce the expected number of paging needed for incoming calls.

4.2.1 Grouping of MU's

Before starting the protocol, all MU's in the system are divided into different groups according to their ID's by means of the *binary cutting method* mentioned above. The reason for employing this method is to simplify the control signal as we will explain in the following subsections. Assume that there are M, where M is supposed to be a power of 2, MU's in the system and they are identified by the set $\{1, 2, ..., M\}$. In figure 4.1, the binary tree represents how the MU's are grouped together. The number of *mobile groups* is determined by the level of the tree, called the *level of grouping*. For example, at level 0, there is only one group and at level 1, MU's 1, 2, ..., $\frac{M}{2}$ are the members of the first group and the rest belongs to the second group, and so on. In fact, by the property of *binary cutting algorithm*, every group in a level, except level 0, bisect the number of MU's in the groups of the previous one. As a result, every group at an arbitrary level n contains $\frac{M}{2^n}$ MU's.

In the MU's point of view, to which *mobile group slot* it should reply a radio pulse for location update can be determined by the digits of its binary ID. Given a *level of grouping* to be l, where $l > 0$, every MU considers the most significant l bits of their binary ID's and converts these l-bit binary word into a decimal number, say, d. Then each MU should reply the radio pulse in the $(d+1)$th slot.

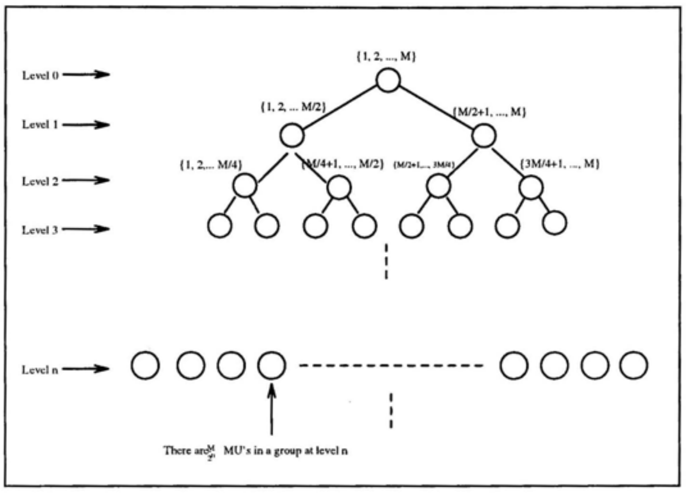


Figure 4.1: Each level indicates how the MU's are grouped together.

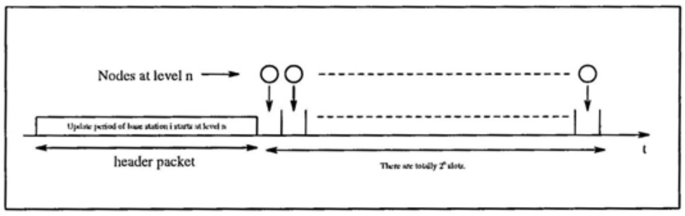


Figure 4.2: The binary tree representation of ID's and the corresponding location update period.

4.2.2 The Update Procedure

The location update procedure is performed in the following order:

1. The procedure is initiated by the broadcast of the *header* packet from base stations. The contents of the *header* packet consist of the ID of the base station and the *level of grouping* at which the *mobile groups* are formed.

2. The *mobile group slots* following the *header* packet correspond sequentially to the nodes at the *level of grouping* specifed (see figure 4.2). Hence, after receiving the *header* packet, every MU should know at which slot to transmit the radio pulse corresponding to its own ID.

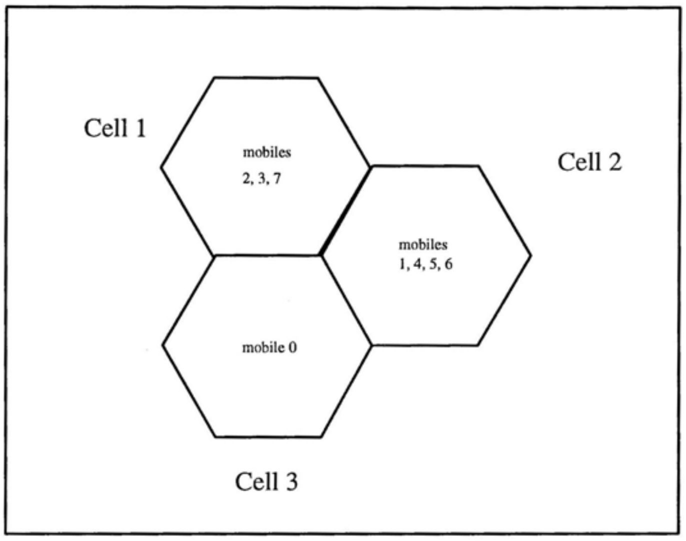


Figure 4.3: A cellular system with 3 cells and 8 mobile units

To cite an example, let us consider a system with 3 cells and 8 MU's which are distributed to the system as shown in figure 4.3. The binary ID's of the MU's are $\{000, 001, 010, 011, 100, 101, 110, 111\}$. By assuming that the *level of grouping* to be 2, the signal flow in the uplink control channel is presented in figure 4.4. The MU's 000, 001 should reply a radio pulse in the first *mobile group slot* and the MU 010, 011 reply at the 2nd *mobile group slot* and so on. Notice that at the second *mobile group slot* in the uplink control channel of cell 1, both MU 010 and MU 011 reply simultaneously. After this location update cycle, the *location vectors* at cell 1, cell 2, cell 3 are respectively (0101), (1011) and (1000).

4.2.3 Paging algorithm

Similar to the Bloom filter based scheme, the paging algorithm is carried out in two stages:

1. The location of the callee is estimated based on the bit pattern received in the *mobile group slots*. Calls are routed to the corresponding cells which

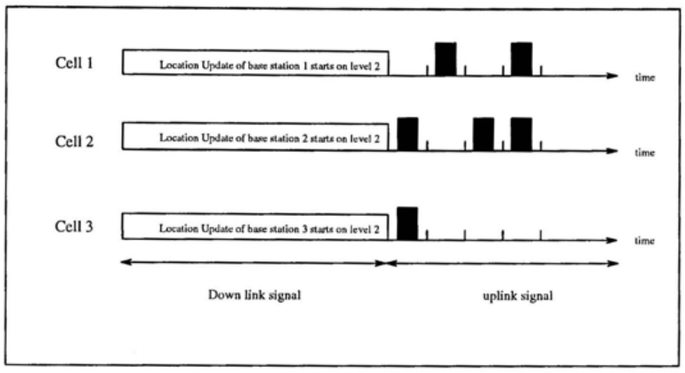


Figure 4.4: The control signal flow for a location update of the system shown in the figure 4.3

satisfies the criterior mentioned in equation 3.1.

2. For the reason that the callee may move away from the cell to which it has updated its position in the previous location update period, calls will then be flooded to the remaining cells.

To illustrate the paging algorithm, let us refer to the above example again. Assume that after the system has received the bit pattern as shown in figure 4.4, a call comes, say, for MU 001. The transformed ID for MU 001 is 1000. The system knows MU 001 may be in Cell 2 or 3 since their *location vectors* and the transformed ID of MU 001 satisfies the condition 3.1. Therefore the paging call is delievered the call to these two cells. However, if there is no response in these cells, the call is routed to the remaining cells, in this case, Cell 1.

4.3 Performance evaluation of the OBR protocol

4.3.1 Analytical Results

Similar to the Bloom filter based scheme, it can be proved that

$$U_O = \frac{k}{\tau}$$

where k is the factor due to the convenience of radio pulse detection.

On condition that MUs are evenly distributed in the system, the probability $Q(i, r)$ of r MU's locating in i $(i < r)$ cells can be obtained as:

$$Q(i,r) = \frac{\binom{C}{i}\Gamma(i,r)}{C^r},$$

where

$$\Gamma(i,r) = \sum_{\substack{j_1+j_2+\cdots+j_i=r \\ j_k \geq 1,\ for\ k=1,2,\ldots,i.}} \binom{r}{j_1, j_2, \ldots, j_i}$$

which is the totally number of combinations that r MU's are locating at i different cells such that at least one of the r MU's are in every cell.

If we start the OBR scheme with *level of grouping* being l, it can be shown that

$$P_O = \sigma L \cdot \mu \cdot \left\{ C \left(1 - \frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \right) + \bar{N} \left(\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \right) \right\}$$

where $\bar{N} = \sum_{k=1}^{\frac{M}{2^l}} kQ\left(k, \frac{M}{2^l}\right)$. The derivation of P_O is similar to that of P_B for Bloom filter based scheme referring to Appendix A.

4.3.2 A Simulation Study

The OBR location update protocol has been simulated using Simscript. Obtained by subsituting the practical values shown in table 2.1 for different variables, the simulation result is shown in figure 4.6. More details for the simulation study will be described in Appendix C.

The following results are concluded from figure 4.6:

1. The result obtained is the relation between the sum of the paging as well as update cost and the update period.

2. There exists a minimum cost value as the update period varies and for our particular system, the minimum point locates at about $\tau = 18\,s$.

3. The simulation result shows that the performance of OBR scheme is generally better than the theoretical one. The reason is that for the theoretical derivation of the cost function, it is assumed that once the target MU leaves the updated cell, the call have to be flooded to other cells no matter which cell it enters afterward. However, it is possible that when it departs from the original home cell, it may enter a cell which is homed by another member of its *mobile group* so that it can also be paged in the first stage of the paging algorithm. For example, as shown in figure 4.5, cells A, B, C and D get positive response for the *mobile group* of MU m in the last update period. When a call for MU m arrives, it is firstly routed to these four cells. If MU m leaves cell A after the last location update and enter any of the cells B, C or D, the call can be prevented from flooding.

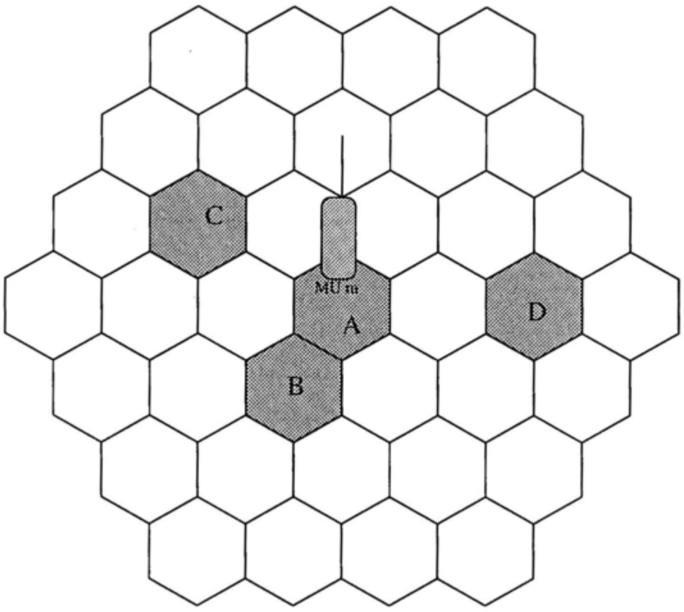


Figure 4.5: Location update by OBR

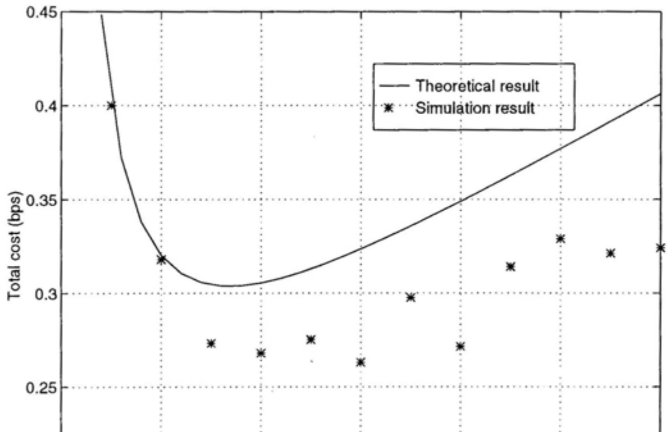


Figure 4.6: Comparison of the theoretical and simulation result.

4.4 Comparison of the location registration schemes - A numerical study

Use the same system model as mentioned in Chapter 1, the performance of the **optimized** location update procotols, geographic based, Bloom filter based and OBR, are contrasted in two different domains: the number of cells in the system and the mean dwelling time per square km for different θ, ρ and σ.

For comparisons, the practical values for the variables shown in table 2.1 in Chapter 2 are employed again here.

Figures 4.7, 4.9, 4.8 and 4.10 show the variation of the total costs for different protocols as the number of cells and the average dwelling time per square km varies. The results show that to determine which kind of protocol outperforms others depends on the factors k, σ, ρ and θ.

In figures 4.7 and 4.8, k, σ, ρ and θ are assumed to be 1 such that the total cost for the geographic based location registration protocol is the lowest. This is an ideal case that to page a mobile terminal, the paging message contains only the ID of the callee. For location update of the Bloom filter and OBR scheme, the time slot for transmitting a radio pulse is of the same length as the bit time of a data packet for other schemes. Moreover, for the geographic based scheme, the update messages is only the ID's of terminals and handshaking is not required in this case.

If σ is 2, and k, ρ, θ are 5, the new proposed schemes, Bloom filter based and OBR, outperforms the geographic based, as shown in figures 4.9 and 4.10. The factors σ and ρ are due to the coding and some control information for the paging and update messages. The reason for ρ being larger than σ is that

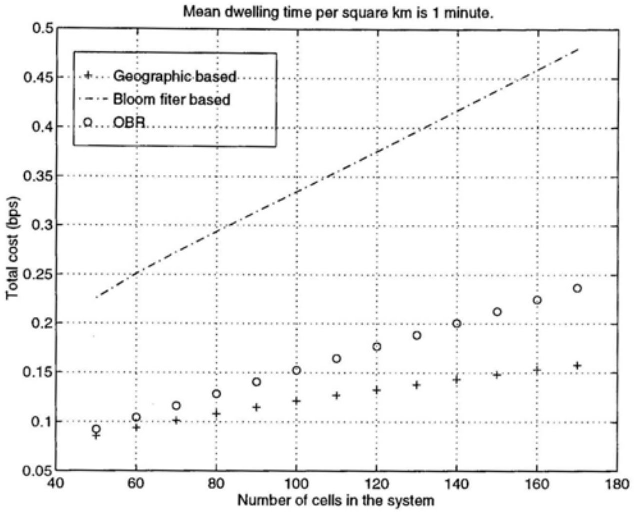


Figure 4.7: $\sigma = \rho = \theta = k = 1$

interference of uplink channels is larger than those of downlink channels.

4.5 Summary

A variation of Bloom filter based scheme called One-Bit-Reply has been described and analysed. Numerical results shows for the optimized cost functions, the performance of the location update scheme depends on the overheads of the update and paging messages due to either coding or handshaking.

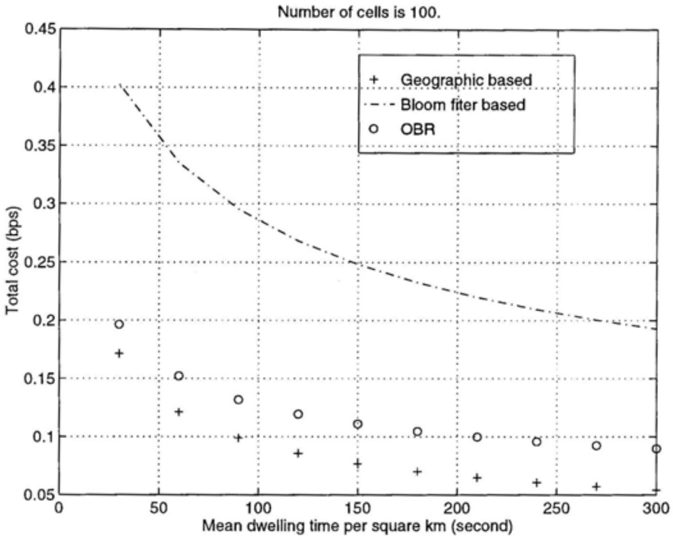


Figure 4.8: $\sigma = \rho = \theta = k = 1$

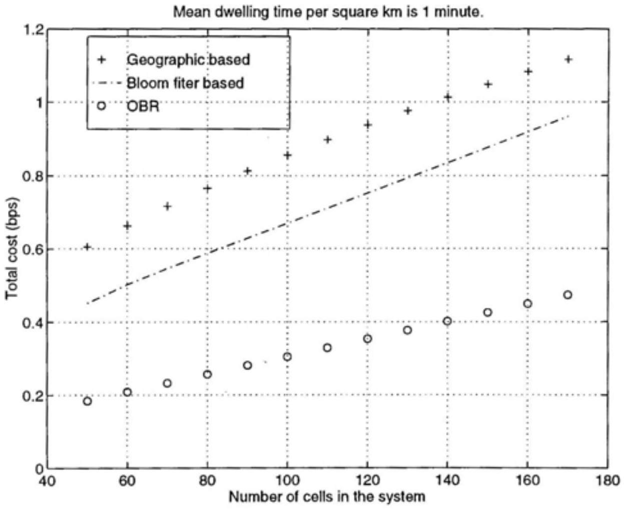


Figure 4.9: $k = 5$, $\sigma = 2$, $\rho = \theta = 5$

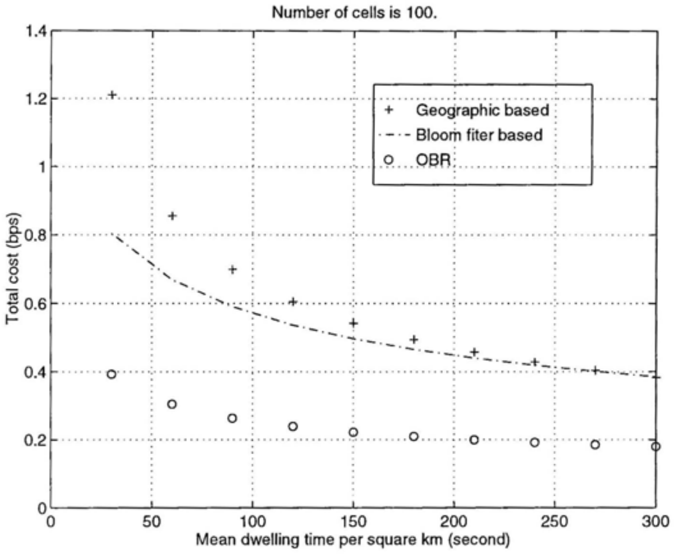


Figure 4.10: $k = 5$, $\sigma = 2$, $\rho = \theta = 5$

Chapter 5

A case study - Implementing the OBR protocol on GSM sytems

5.1 Introduction

We have studied several kind of location update protocols. The most common one utilizing in practical systems is the geographic based scheme. In this chapter, GSM is used as an example illustrating how this kind of location update scheme is practiced. Moreover, we try to suggest how to implement the OBR protocol in to this practical system. The loading of the location databases in the system for the traditional and the new proposed location update scheme will be compared analytically.

5.2 The Architecture of Global System for Mobile Communicaitons (GSM)

GSM is one of the most popular digital cellular telecommunication standards. Beginning from the introduction in 1982, GSM has been not only an European but also a worldwide standard. It can be defined as composed of subsystems which interact between themselves and with the outside world. The subsystems include:

- **Operation Subsystem (OSS)**

  It is the main supervision and maintanence of the whole system.

- **Network and Switching Subsystem (NSS)**

  It provides internetworking for both internal subsystems and external telecommunication network.

- **Base Station Subsystem (BSS)**

  It bridges the radio interface and the backbone wired network.

- **Mobile Station (MS)**

  It is the user interface equipment. Users can give service from GSM through the air interface.

The relations among these subsystems is illustrated in figure 5.1.

The physical architecture of GSM is shown in figure 5.2. The followings are the descriptions for different parts in the network:

- **Mobile Switching Centre (MSC)**

  In the figure, Mobile Switching Centre (MSC) is one of the component of

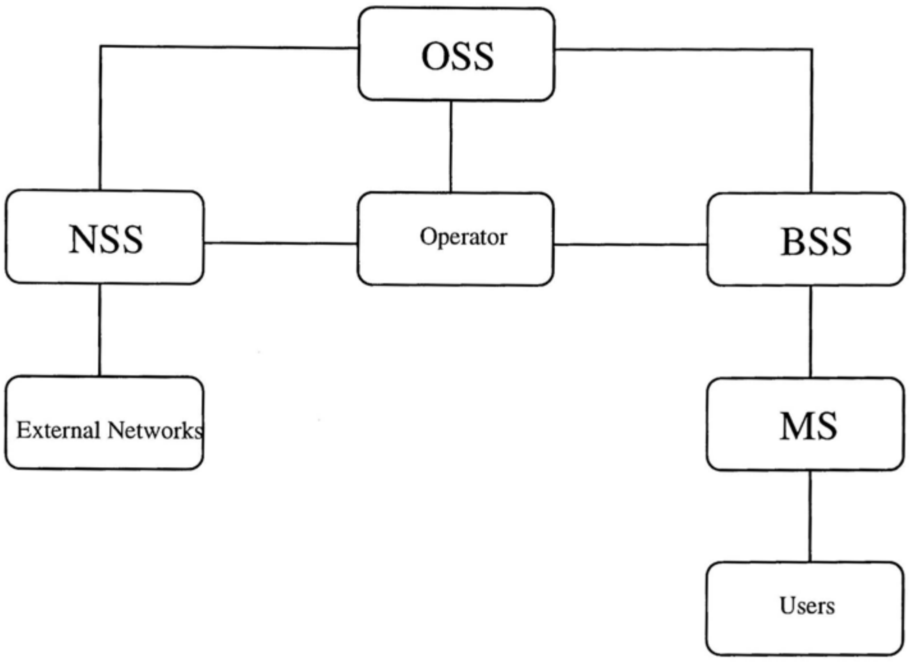


Figure 5.1: The relations of different subsystems, operators and users of GSM

NSS. It is responsible for routing data in the network.

- **Visitor Location Register (VLR)**

  This is a database connecting to a MSC. It contains the information of the MU's in the *location area* controlled by the MSC.

- **Home Location Register (HLR)**

  It is an independent database containing the location information of all MU's in the system.

5.3 Location Update Procedure of GSM

Briefly speaking, the location update protocol utilizing in GSM is the geographic based scheme. A complete location update procedure of GSM is represented in figure 5.3 which comes from [23]. As time runs downward, the update procedure

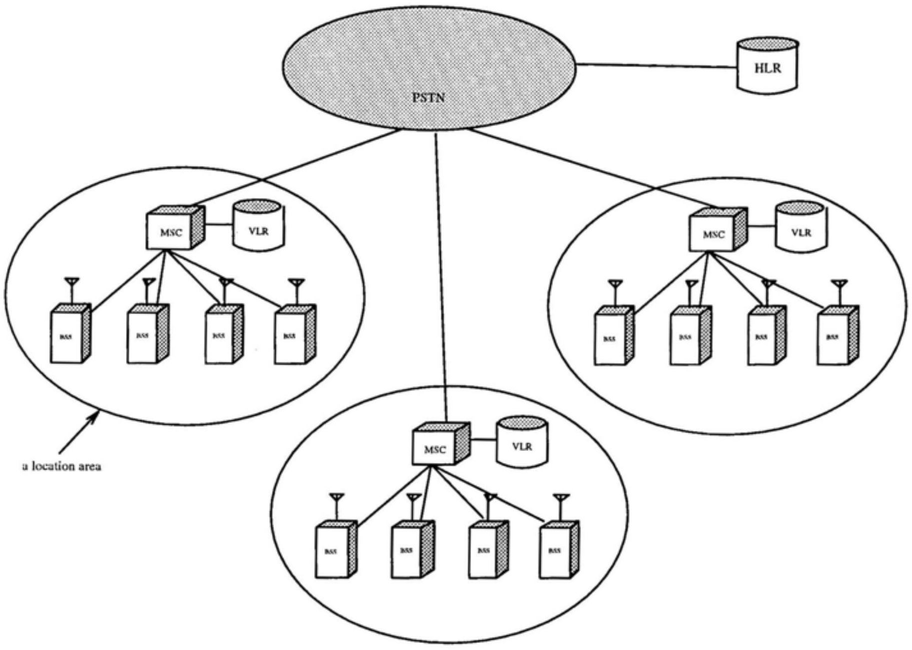


Figure 5.2: The architecture of GSM backbone network

is initiated by a MU entering into a new *location area.* After receiving the request from the MU, the corresponding base station will inform the MSC to update the location database in VLR. However, for security, the MU does not send its internation Mobile Subscriber Identity (IMSI) through the air interface but the Temporary Mobile Subscriber Identity (TMSI) instead. The IMSI will be retreived by the new VLR from that of the old serving *location area.* Following a sequence of updating and clearing procedures in the location databases, the location update is completed.

5.4 Implementing OBR protocol on GSM

One of the method implementing OBR protocol to GSM is shown in figure 5.4. The location update procedures are the following:

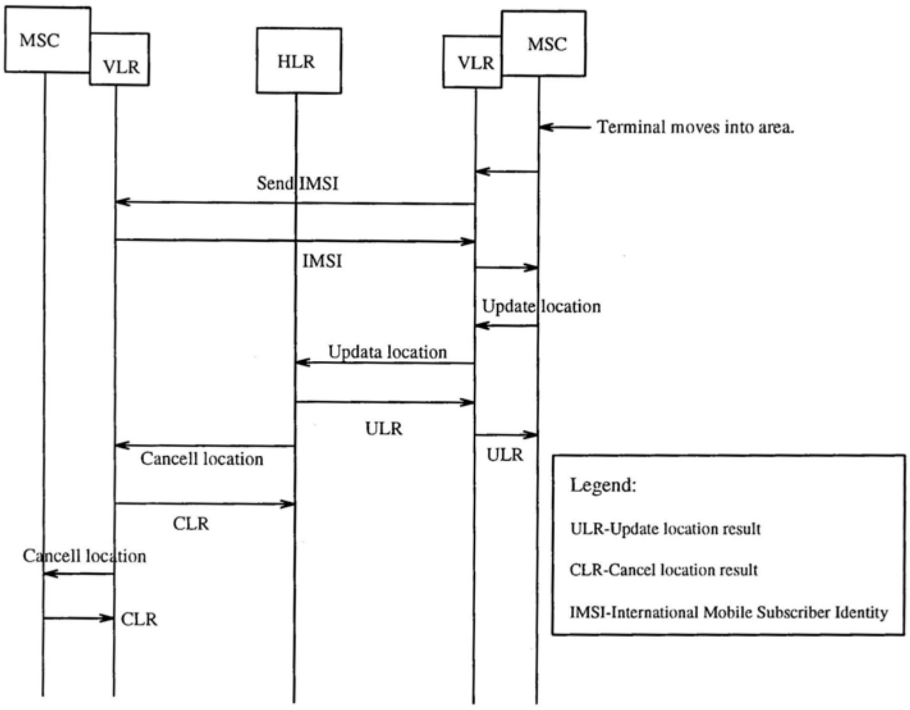


Figure 5.3: Flow diagram for the original registration protocol in GSM

1. The location update as mentioned before is initiated periodically by the MSC's.
2. Every base station will obtain a *location vector*.
3. The corresponding *location vectors* for different cells are then stored in the VLR. After combining the *location vectors* from all the base stations by means of the OR operation, the location information in the HLR is updated by the resultant *location vectors* from different MSC's.

Moreover, the paging procedure is proposed to be done hierarchically. When a call comes, the target MU is paged by the following steps:

1. When a call arrives, the IMSI of the callee is transformed by the OBR protocol resulting a n bit vector , which is named as I_{test}, with only a '1' in a particular position.

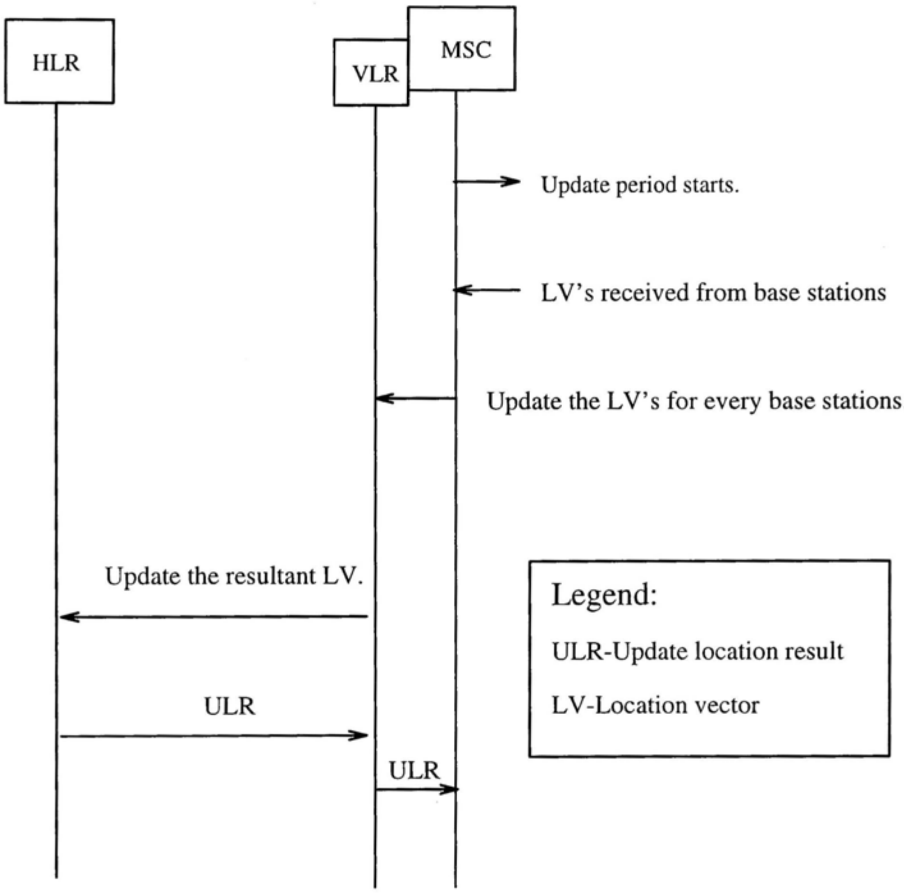


Figure 5.4: Flow diagram for implementation of OBR in GSM

2. Deliever the call to the MSC's so that the bitwise multiplication of its *location vector* and I_{test} is again I_{test}.
3. The above procedure is done again for the base staions managed by possible MSC's.
4. If procedure 3 gets negative response, the call is flooding to other base stations.

The advantages of the implementation can be summarized as follows:

- The signal flow for the proposed protocol is simpler due to the facts:
  - For this kind of protocol, the MU's are not directly identified by either IMSI or TMSI. The security problem is automatically solved and the handshaking of the new and old serving MSC can be omitted.
  - The location cancellation procedure for the original protocol is not neccessary.
- The memory size required in both HLR and VLR is reduced. Instead of storing millions of IMSI or TMSI for all MU's, each of the HLR and VLR only keep a *location vector.*

5.5 Influence of the OBR on the VLR's and HLR

By the proposed implementation of the OBR scheme, the traffic, due to location update and call paging, on VLR's and the HLR in the system will be analysed.

For the sake of comparison with the analysis in [23], the system and mobility assumptions made in that paper are employed in the following analysis.

- 128 total registration areas.
- 10 cells for each registration area.
- Square registration area size = $57.4\,km^2$.
- Average call origination rate = average call delivery rate = 1.4/hr/terminal.
- Mean density of mobile terminals=ρ=$390/km^2$.
- Average dwelling time per user per square km is 1 minute

The following notations are also specified:

- $R_{reg,VLR}$: The rate of registering location information in VLR.
- $R_{Dereg,VLR}$: The rate of deregistering location information in VLR.
- $R_{reg,HLR}$: The rate of updating location information in HLR.
- $R_{CallOrig,VLR}$: The rate of quering the VLR due to call origination.
- $R_{CallDeliv,VLR}$: The rate of quering the VLR due to call arrival.
- $R_{CallDeliv,HLR}$: The rate of quering the HLR due to call arrivals.

The average number of terminals in a registration area is $57.4 \times 390 = 22386$. The average dwelling time per user per cell and per location area can be obtained as $\frac{60\times57.4}{10} = 344.4s$ and $60 \times 57.4 = 3444s$

5.5.1 Analysis of traditional method

$$\begin{aligned} R_{reg,VLR} &= \frac{22386}{57.4 \times 60} \\ &= 6.5/s \end{aligned}$$

Once a terminal registers its location, the old record will be cleared, so that

$$R_{Dereg,VLR} = 6.5/s$$

The HLR has to handle the registration come from all location areas. Therefore,

$$\begin{aligned} R_{reg,HLR} &= 6.5 \times 128 \\ &= 832/s \end{aligned}$$

When a call is generated, the caller will be authenticated by querying the VLR. The rate of such queries can be derived as:

$$\begin{aligned} R_{CallOrig,VLR} &= \frac{1.4 \times 22386}{3600} \\ &= 8.7/s \qquad (5.1) \end{aligned}$$

Once the call is routed to the home MSC of the callee, it is also authenticated before the call is delievered. The rate of queries needed to authenticate the callee is equal to $R_{CallOrig,VLR}$. Therefore,

$$R_{CallDeliv,VLR} = 8.7/s$$

In addition, HLR will be queried once a call is generated. The rate of such queries can be calculated as:

$$\begin{aligned} R_{CallDeliv,HLR} &= 128 \times R_{CallOrig,VLR} \\ &= 1113.6/s \end{aligned}$$

5.5.2 Analysis of OBR

It is assumed that the *level of grouping* for the update algorithm to be 18 so that each *mobile group* contains 10 terminals. By the above mentioned, method, the optimal update period should be about 20 s. Therefore,

$$\begin{aligned} R_{reg,VLR} &= \frac{\text{number of base stations in the location area}}{\text{update period}} \\ &= \frac{10}{20} = 0.5/s \end{aligned}$$

Consequently,

$$\begin{aligned} R_{reg,HLR} &= 128 \times R_{reg,VLR} \\ &= 64/s \end{aligned} \tag{5.2}$$

Since the proposed protocol does not require deregistration, $R_{Dereg,VLR} = 0$. When a call is generated, it may be routed to different location area according to the mobility of the terminals in the same *mobile group*. Assuming that in the worst case, each member in the *mobile group* locate in different location area. In other words, a new generated call will be routed to at most 10 location area. However, the terminal may leave the updated cell. In that case, the call have to be flooded to the whole system. By equation A.3 and A.2, the probability that a

	Traditional scheme	OBR scheme
$R_{CallDeliv,HLR}$	1113.6 /s	1113.6 /s
$R_{CallOrig,VLR}$	8.7 /s	8.7 /s
$R_{CallDeliv,VLR}$	8.7 /s	116.3 /s
$R_{reg,HLR}$	832 /s	64 /s
$R_{reg,VLR}$	6.5 /s	0.5 /s
$R_{Dereg,VLR}$	6.5 /s	0
Total	1976 /s	1303.1 /s

Table 5.1: Comparison of the traffic loading for databases

call arrives before and after the terminal leave the updated cell can be calculated to be 0.9715 and 0.2815 respectively. By the previous derived formulas, the rate of querying VLR's can be derived as follows.

$$\begin{aligned} R_{CallDeliv,HLR} &= 1113.6/s \\ R_{CallOrig,VLR} &= 8.7/s \text{ (Refer to equation 5.1)} \\ R_{CallDeliv,VLR} &= 8.7 \times (.9715 \times 10 + .0285 \times 128) \\ &= 116.3/s \end{aligned} \tag{5.3}$$

The results is summarized in table 5.1.

5.6 Summary

The methodology of how to implement the OBR location update protocol to GSM has been suggested. The signal flow in between MSC's and databases can be simplified. The loading of the databases HLR and VLR in the system is also analysed for both location update protocols. The results show that the new proposed protocol can alleviate the traffic loading in the backbone network.

Chapter 6

Conclusion

6.1 Summaries of Results

6.1.1 Cost functions

The cost functions for time based, geographic based, Bloom filter based and OBR protocols are summarized as follows:

Location update schemes	Cost functions
Time based	$P_T = \sigma L \cdot \mu \cdot \left\{ C \left(1 - \frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \right) + \left(\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \right) \right\}$ $U_T = \frac{\theta\rho L}{\tau} \left(1 - \frac{C}{M} \right)^{1-\frac{M}{C}}$
Geographic based	$P_G = \sigma L \mu \bar{n}$ $U_G = \frac{\theta\rho L\lambda C}{\bar{n}A} \left(1 - \frac{C}{M} \right)^{1-\frac{M}{C}}$
Bloom fiter based	$P_B = \sigma L \mu C \left[\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} (1 - pq^{\frac{M}{C}})^n + (1 - \frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}) \right]$ $U_B = \frac{knp}{\tau}$
OBR	$*P_O = \sigma L \cdot \mu \cdot \left\{ C \left(1 - \frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \right) + \bar{N} \left(\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \right) \right\}$ $U_O = \frac{k}{\tau}$

$*\bar{N} = \sum_{k=1}^{\frac{M}{2^l}} k \frac{\binom{C}{k}\Gamma(k, \frac{M}{2^l})}{C^{\frac{M}{2^l}}}$. in which l is the *level of grouping* and,

$$\Gamma(i, r) = \sum_{\substack{j_1 + j_2 + \cdots + j_i = r \\ j_k \geq 1,\ for\ k = 1, 2, \ldots, i.}} \binom{r}{j_1, j_2, \ldots, j_i}$$

.

6.1.2 Optimization of the cost functions

Each of the above protocols is characterized by its own key variables such as the $\bar{n}$ of geographic based, τ of time based, n, p, τ of Bloom filter based and l, τ of OBR protocol. For our system model, the cost functions of the protocols have been optimized with respect to some of the corresponding key variables either analytically or numerically.

Geographic based scheme

The function C_G is optimized against the average number of cells $\bar{n}$ of a *location area* and the result is

$$min(C_G) = 2L\sqrt{\frac{\theta\rho\sigma\lambda C\mu}{A}\left(1-\frac{C}{M}\right)^{(1-\frac{M}{C})}}.$$

Bloom filter based scheme

C_B is minimized against the length of the *location vector* n and also the update period τ. While keeping τ to be constant, the optimized function is obtained when

$$n = \frac{\log\left(-\frac{\alpha}{\beta\log\gamma}\right)}{\log\gamma} \tag{6.1}$$

where

$$\begin{aligned} \alpha &= \frac{kp}{\tau} \\ \beta &= \sigma L\mu(C-1)\left(\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}\right) \\ \gamma &= (1-pq^{\frac{M}{C}}) \end{aligned} \tag{6.2}$$

Apart from that, the function C_B is further optimized numerically by the steepest descent algorithm against the update period τ.

Time based and OBR schemes

Similar to C_B, C_T and C_O are optimized numerically with respect to the update period τ.

6.1.3 Implementation of OBR into GSM

It has been shown, by means of a numerical example, that by implementing the OBR protocol into GSM, the effect on the traffic due to data retreival from databases is analysed. The result shows that the traffic loading on the databases due to location registration of terminals reduces a lot (see table 5.1. However, it may be tolerated by the increase of traffic loading due to call paging.

6.2 Suggestions for further researches

Two new location update protocols of the same catagory have been analysed. Based on the property of a certain kind of query function with *hashing* property, the locations of MU's are estimated by limited amount of information. The characteristic is that the collision of the transmitted radio pulses can be resolved.

Further research can be done on the relation of transformed ID and the mobility of the MU's. The MU ID's are transformed by a series of query functions. Owing to the *hashing* property of the query functions, the system may locate the target MU at more than one cell, say K cells. According to the suggested paging algorithm, all these K cells are paged, then if the system gets no response, the call will be flooded to other cells. One of method to reduce the probability of flooding the calls is to fit the distribution of the K cells to the mobility of MU's. The reason is that the flooding of his incoming call can be prevented if when he is paged, he is located at the $K-1$ other cells after he leaves the current home cell. This can be done by relating the transformed ID to the inertia and mobility of the MU's.

In addition, the performance of the proposed protocols is neccessary to be tested in different mobility models and different kinds of system environment. It is believed that the new kind of the protocols is more robust than the traditional one but more proofs are required.

Appendix A

Derivation of cost functions

A.1 Geographic based scheme

Since the MU will update its position once it enters a new *location area*, the incoming call can always be delievered to the correct *location area* of the callee provided it is powered on. Therefore the average number of paged cells is $\bar{n}$. To page a cell, the base station transmits L bits. As a result, the total number of transmitted bits for paging a MU is $\bar{n}L$. Since the average interarrival time of the calls is $\frac{1}{\mu}$,

$$P_G = \sigma L \mu \bar{n}$$

The mean dwelling time for a MU to spend in a *location area* is $\frac{A\bar{n}}{C\lambda}$ second. Once the MU leaves a *location area*, it will update its location. Thus, the mean inter-registration time is the same as the mean dwelling time to spend in the *location area*. By slotted ALOHA, for finite population of users, the average number of retransmission in maximum throughput condition [27] is $\left(1 - \frac{C}{M}\right)^{1-\frac{M}{C}}$ in which $\frac{M}{C}$ is the average number of MU's in a cell. Also, it is assumed that due to the handshaking of signals, a factor θ is added to the update cost function.

Therefore,

$$\begin{aligned} U_G &= \frac{\theta\rho L}{\frac{A\bar{n}}{C\lambda}}\left(1-\frac{C}{M}\right)^{1-\frac{M}{C}} \\ &= \frac{\rho L\lambda C}{\bar{n}A}\left(1-\frac{C}{M}\right)^{1-\frac{M}{C}} \end{aligned} \tag{A.1}$$

A.2 Time based scheme

For this part of analysis, we define the following terms:

- $P_{l,c}$: the probability that a MU leaves a cell in which it has recently updated its location before a call comes.
- $P_{c,l}$: the probability that a MU leaves a cell in which it has recently updated its location after a call comes.
- N: the average number of cells to which an incoming call is to be delievered.

By the property of exponential distribution, if a call arrives between successive location update period, the arrival time can be shown to be uniformly distributed from $[0, \tau]$. By conditioning on the call arrival time, $P_{l,c}$ can be obtained as follows.

$$\begin{aligned} P_{l,c} &= \int_0^{\tau}(1-e^{-\frac{C\lambda}{A}t})\frac{1}{\tau}dt \\ &= 1-\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \end{aligned} \tag{A.2}$$

Since $P_{c,l}$ is the complement of $P_{l,c}$,

$$\begin{aligned} P_{c,l} &= 1 - P_{l,c} \\ &= \frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \end{aligned} \tag{A.3}$$

According to the **shooting-then-broadcast** paging algorithm mentioned in Chapter, $\bar{N}$ can be expressed as:

$$\begin{aligned} \bar{N} &= 1 \cdot P_{c,l} + C \cdot P_{l,c} \\ &= C\left(1 - \frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}\right) + \left(\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}\right) \end{aligned} \tag{A.4}$$

Hence, the paging cost function can be derived as the following.

$$\begin{aligned} P_T &= \sigma L \cdot \mu \cdot \bar{N} \\ &= \sigma L \cdot \mu \cdot \left\{ C\left(1 - \frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}\right) + \left(\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}\right) \right\} \end{aligned} \tag{A.5}$$

For update cost, since terminals register their location once every τ seconds and the average number of retransmission as shown in previous section is $\left(1-\frac{C}{M}\right)^{1-\frac{M}{C}}$, it is obvious that

$$U_T = \frac{\theta\rho L}{\tau}\left(1 - \frac{C}{M}\right)^{1-\frac{M}{C}}. \tag{A.6}$$

where θ is the factor due to the handshaking of messages.

A.3 Bloom filter based scheme

By assuming that the probability that a MU replies a "1" for any of the predefined hashing function is p, the expected number of radio pulses transmitted in a location update is np. For the security of the radio pulse detection, the time slot for transmitting a radio pulse should be longer than a normal bit time. Therefore, the factor k is introduced and the update cost function can be obtained as.

$$U_B = \frac{knp}{\tau}$$

To find the expected number of cells to which an incoming call should be delievered, $P_{l,c}$ and $P_{c,l}$ defined in the previous section are employed again. For Bloom filter based scheme, they have the same expression as in A.2 and A.3.

Let the probability of replying i "1's" in particular positions of the *location vector* be p_i and let the probability that the answer "1" received in any position of the *location vector* be η. It is obvious that $p_i = p^i(1-p)^{n-i}$. For the value in any position of the *location vector* to be "0", none of the MU's in the cell does not reply for that hashing function and the probability of this is $(1-p)^{\frac{M}{C}}$. Hence, $\eta = 1-(1-p)^{\frac{M}{C}}$

According to the paging algorithm defined in Chapter 3, a cell should be paged if $l_j \odot t_{id} = t_{id}$, where $\odot$ is the exclusive-OR operation, l_j is the *location vector* stored in cell j and t_{id} is the resulting hashed vector with the same length as the *location vector* for the callee's ID. In this calculation, we ignore the probability that after the callee has left the home cell, it enters into one of the cells with *location vectors* satisfying the paging criterior.

$$\begin{aligned} P_{page} &= \sum_{i=0}^{n} \binom{n}{i} p_i \eta^i \\ &= \sum_{i=0}^{n} \binom{n}{i} p^i (1-p)^{n-i} [1-(1-p)^{\frac{M}{C}}]^i \end{aligned}$$

$$\begin{aligned} &= \left[(1-p) + p(1-(1-p)^{\frac{M}{C}})\right]^n \\ &= (1-pq^{\frac{M}{C}})^n \end{aligned} \tag{A.7}$$

where $q = 1 - p$.

Denote C_{page} as the average number of cells being paged when a call comes provided the MU is in the updated cell after the call arrives.

$$C_{page} = C(1-pq^{\frac{M}{C}})^n \tag{A.8}$$

Combining equations A.3, A.2 and A.7,

$$\begin{aligned} P_G &= \sigma L\mu \left[C_{page} \cdot P_{c,l} + C \cdot P_{l,c}\right] \\ &= \sigma L\mu C \left[\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}(1-pq^{\frac{M}{C}})^n + (1 - \frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau})\right] \end{aligned} \tag{A.9}$$

Appendix B

On the optimality of the cost functions

B.1 Steepest Descent Algorithm for various protocols

The cost function C_T, C_B and C_O are optimized numerically with Steepest Descent Algorithm described as follows.

This is an iterative optimization method. Let f be a function depending on t. To optimize f with respect to t, the following iterative algorithm is peformed.

$$t_i = t_{i-1} + \triangle \cdot f'(t_{i-1})$$

where f' is the derivative of f and $\triangle$ is a predefined constant which is negative if f is minimized and positive if it is maximized. $\triangle$ should not be too large or too small: if it is too large, the algorithm may not converge even though the optimal point exist; if it is too small, the rate of convergency will be very slow. Under the environment parameters described in chapter 2, the $\triangle$ for minimizing the cost functions of different protocols is chosen to be -100.

B.2 Bloom filter based scheme

The parameter n can be tuned to minimized the total of the paging and update cost functions. By the result of Appendix A,

$$C_B = \frac{knp}{\tau} + \sigma L\mu C\left[\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau}(1-pq^{\frac{M}{C}})^n + (1-\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau})\right]$$

To optimize C_B with respect to n, the function can be represented by the following form.

$$C_B = \alpha n + \beta\gamma^n + \eta \tag{B.1}$$

where

$$\begin{aligned}
\alpha &= \frac{kp}{\tau} \\
\beta &= \sigma L\mu C\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau} \\
\gamma &= 1-pq^{\frac{M}{C}} \\
\eta &= \sigma L\mu C(1-\frac{A(1-e^{-\frac{C\lambda}{A}\tau})}{C\lambda\tau})
\end{aligned}$$

By assuming n to be a continuous variable, B.2 can be differentiated with respect to n.

Put $\frac{\partial C_G}{\partial n} = 0$.

We obtain

$$n = \frac{\log(-\frac{\alpha}{\beta\log\gamma})}{\log\gamma}$$

.

Therefore, C_B is minimized when $n = \left[\frac{\log(-\frac{\alpha}{\beta\log\gamma})}{\log\gamma}\right]$ where $[*]$ takes the nearest integer value of the expression.

For the validity of the optimized solution, that is, $n \geq 0$, the condition mentioned in Theorem 3 should be satisfied. Since it is obvious that $\gamma \leq 1$, $\log\gamma \leq 0$. Hence, $n \geq 0$ if and only if

$$\begin{aligned} \log\left(-\frac{\alpha}{\beta\log\gamma}\right) &\leq 0 \\ -\frac{\alpha}{\beta\log\gamma} &\leq 1 \\ \frac{p}{\log\left(\frac{1}{1-pq^{\frac{M}{C}}}\right)} &\leq \frac{\sigma L\mu A(1-e^{-\frac{C\lambda\tau}{A}})}{k\lambda} \end{aligned} \tag{B.2}$$

In addition, C_B is then optimized against the update period τ using steepest descent algorithm. The deriative of C_B with respect to τ is required. For the optimization the following derivatives are obtained.

$$\begin{aligned} \frac{\partial\alpha}{\partial\tau} &= -\frac{kp}{\tau^2} \\ \frac{\partial\beta}{\partial\tau} &= \frac{\sigma L\mu A}{\lambda}\left[-\frac{(1-e^{-\frac{C\lambda\tau}{A}})}{\tau^2} + \frac{C\lambda e^{-\frac{C\lambda\tau}{A}}}{\tau A}\right] \\ \frac{\partial\gamma}{\partial\tau} &= 0 \\ \frac{\partial\eta}{\partial\tau} &= -\frac{\partial\beta}{\partial\tau} \\ \frac{\partial n}{\partial\tau} &= \frac{1}{\log\gamma}\left[-\frac{\beta\log\gamma}{\alpha}\cdot\frac{\partial\left(-\frac{\alpha}{\beta\log\gamma}\right)}{\partial\tau}\right] \end{aligned}$$

$$\begin{aligned}
&= \frac{\beta}{\alpha} \cdot \frac{\partial\left(\frac{\alpha}{\beta \log \gamma}\right)}{\partial \tau} \\
&= \frac{\beta}{\alpha \log \gamma} \cdot \frac{\partial\left(\frac{\alpha}{\beta}\right)}{\partial \tau} \\
&= \frac{\beta}{\alpha \log \gamma} \cdot \left[\frac{1}{\beta}\frac{\partial \alpha}{\partial \tau} - \frac{\alpha}{\beta^2}\frac{\partial \beta}{\partial \tau}\right] \\
\frac{\partial C_B}{\partial \tau} &= \left[n \cdot \frac{\partial \alpha}{\partial \tau} + \alpha \cdot \frac{\partial n}{\partial \tau}\right] + \left[\gamma^n \cdot \frac{\partial \beta}{\partial \tau} + \beta \gamma^n \log \gamma \cdot \frac{\partial n}{\tau}\right] + \frac{\partial n}{\partial \tau}
\end{aligned} \tag{B.3}$$

Therefore, the iterative function for the steepest descent algorithm is the following:

$$\tau_i = \tau_{i-1} - 100 \cdot \frac{\partial C_B}{\partial \tau}\Big|_{\tau=\tau_{i-1}}.$$

B.3 Time Based Scheme

Similar to the optimization of C_B, C_T is also minimized by steepest descent algorithm. The update cost U_T and the paging cost P_T for time based location update scheme have been derived. The corresponding derivatives can be obtained as follows:

$$\begin{aligned}
\frac{\partial U_T}{\partial \tau} &= -\frac{\theta \rho L}{\tau^2}\left(1 - \frac{C}{M}\right)^{1-\frac{M}{C}} \\
\frac{\partial P_T}{\partial \tau} &= \sigma L \mu (1 - C)\left[\frac{e^{-\frac{C\lambda\tau}{A}}}{\tau} - \frac{A}{C\lambda\tau^2}(1 - e^{-\frac{C\lambda\tau}{A}})\right]
\end{aligned} \tag{B.4}$$

Also, $\frac{\partial C_T}{\partial \tau} = \frac{\partial U_T}{\partial \tau} + \frac{\partial P_T}{\partial \tau}$ and the iterative function for the steepest descent algorithm is:

$$\tau_i = \tau_{i-1} - 100 \cdot \frac{\partial C_T}{\partial \tau}|_{\tau=\tau_{i-1}}$$

B.4 One-Bit-Reply scheme

The optimization method for this protocol is similar to the above two. The derivatives of U_O, P_O and C_O can be derived as follow:

$$\begin{aligned}
\frac{\partial U_O}{\partial \tau} &= -\frac{1}{\tau^2} \\
\frac{\partial P_O}{\partial \tau} &= \sigma L \mu (\bar{N} - C) \left[\frac{e^{-\frac{C\lambda\tau}{A}}}{\tau} - \frac{A}{C\lambda\tau^2}(1 - e^{-\frac{C\lambda\tau}{A}}) \right] \\
\frac{\partial C_O}{\partial \tau} &= \frac{\partial U_O}{\partial \tau} + \frac{\partial P_O}{\partial \tau}
\end{aligned} \tag{B.5}$$

where $\bar{N} = \sum_{k=1}^{\frac{M}{2^l}} k \frac{\binom{C}{i}\Gamma(i, \frac{M}{2^l})}{C^{\frac{M}{2^l}}}$.

B.5 Geographic Based Scheme

It has been shown that

$$C_G = \sigma L \bar{n} \mu + \frac{\theta \rho L \lambda C}{\bar{n}_j A} \left(1 - \frac{C}{M}\right)^{1 - \frac{M}{C}}.$$

By assuming $\bar{n}$ to be continuous, C_G is differentiate with respect to $\bar{n}$ such that

$$\frac{\partial C_G}{\partial \bar{n}} = \sigma L \mu - \frac{\theta \rho L \lambda C}{A \bar{n}^2} \left(1 - \frac{C}{M}\right)^{1 - \frac{M}{C}}$$

C_G is minimized when $\bar{n} = \sqrt{\frac{\theta \rho \lambda C}{\sigma \mu A} \left(1 - \frac{C}{M}\right)^{1 - \frac{M}{C}}}$ which is done by putting $\frac{\partial C_G}{\partial \bar{n}} = 0$.

Therefore, $min(C_G) = 2L\sqrt{\frac{\theta\rho\sigma C\lambda\mu}{A}\left(1-\frac{C}{M}\right)^{1-\frac{M}{C}}}$.

Appendix C

Simulation of OBR

The details of the simulation program are summarized as follows:

1. The simulation of the OBR is written by Simscript II.5.
2. The system model of the simulation is based on that mentioned in Chapter 1. However, some of the values are chosen as follows:
    - The model of the cellular system is shown in figure C.1.
    - Total number of terminals is $2^{17} = 131072$.
    - Total number of cells is 100.
    - *Level of grouping* is 14. Therefore, each *mobile group* contains 8 terminals.
    - Mean dwelling time per square km per user is 5 minutes.
    - The average call arrival time is 1 hour.
    - The factor k for the update cost is 1.
    - $\sigma = 5$;

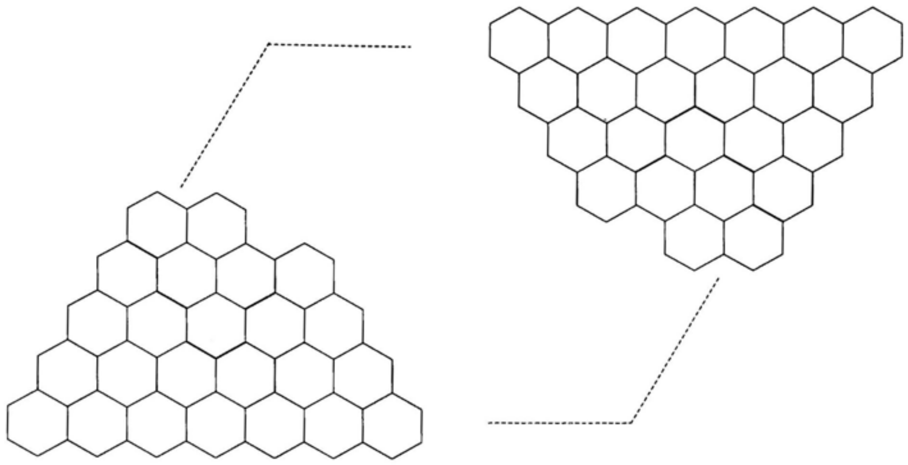


Figure C.1: The cellular system used in the simulation program for OBR protocols

- If the MU leaves its home cell, it will enter one of the neighbouring cells with probability $\frac{1}{6}$.
- The mobility of the MU's in the same *mobile group* is uncorrelated.

3. The system has been simulated as soon as 48 hours in real time.

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