A Cost-Efficient Signaling Protocol for Mobility Application Part (MAP) in IMT-2000 Systems *

Wenye Wang Ian F. Akyildiz

Broadband & Wireless Networking Laboratory
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332

{wenye, ian}@ece.gatech.edu

ABSTRACT

An efficient signaling protocol for mobility application part (MAP) is essential to mobility support when mobile terminals roam between different networks in next generation wireless systems such as IMT-2000. In this paper, a new signaling protocol is proposed to reduce the overhead caused by mobility management, alleviating network load and consumption of network resources. Moreover, the new protocol effectively reduces the latency of call delivery and call loss rate due to crossing wireless systems with different standards and signaling protocols. Instead of performing location registration after a mobile user arrives at the new system, the mobile user is required to update its location information prior to its reaching the boundary of two systems. Results in this study demonstrate that the new protocol yields significant benefits in terms of reducing signaling costs, delays, and call loss rates.

1. INTRODUCTION

Next generation (NG) wireless systems, e.g., International Mobile Telecommunications 2000 (IMT-2000), are envisioned as seamless worldwide radio systems [2]. They will enable data transfer, image transfer, video conferencing, and video delivery, regardless of mobile users' locations. On the other hand, the demand to provide wireless multimedia services to an increasing population of mobile customers has placed new requirements on wireless systems. The mobile users require that reliable quality of service (QoS) constraints be maintained throughout the duration of a call as they travel not only from cell to cell, but also from one system to another that uses different technology. Mobile subscribers use mobile terminals (MTs) to communicate with others through the base station via radio links when they change their locations over time in a mobile environment. When an MT moves within the service area of a stand-alone system, e.g., global system for mobile communication (GSM) system, the MT's location information can be obtained by querying a centralized home location register (HLR) and visitor location registers (VLRs) within the system. In case of *inter-system roaming*, MTs move between different systems. Unlike roaming in a stand-alone system, the MT's location information may not be retrieved from a centralized database, instead, it may need to access databases associated with two adjacent networks. Therefore, a location management scheme for inter-system roaming is desired to effectively keep track of the MTs and to locate a called MT.

The NG wireless systems will evolve from the mature second generation systems, with the aim of providing universal access and global roaming [5, 10, 12]. However, the existing systems do not have compatibility with each other. Each system has a specific mobile application part (MAP) for mobility management so that an MT's mobility is limited within one system. Thus, the interworking of these systems is critical to support the universal roaming capability. Recently, there are some ongoing standards and research work on designing MAP protocol for inter-system roaming. In [14], a signaling protocol is proposed to provide inter-system roaming to personal handyphone system (PHS) users. Under this scheme, service data function units and service control function units are utilized to provide the roaming numbers to the MTs when they request location registration. The roaming number is then transferred to the visiting system as the routing information, which is conformed to the PHS specifications. After receiving the roaming number, the access protocol is implemented in a service control function unit so as to establish the connection. The interworking GSM with digital enhanced cordless telephone (DECT) systems is discussed in [13]. Two types of network architectures are introduced: dedicated mobile switching center (MSC) and non-dedicated MSC. In case of dedicated MSC for DECT, an MT would have a set of location information within GSM VLR and another set in DECT VLR. For the non-dedicated architecture, the VLR contains two sets of information pointing to the GSM and DECT location areas. In [18], a logical interworking function (IWF) entity is presented to support the roaming between GSM and personal digital cellular (PDC) systems. The configuration of IWF consists of an IWF-Location register an IWF-switch to handle inter-system roaming service. A dual mode home location register (HLR-IIF) is described for interworking and interoperability between IS-41 and PCS 1900 MAPs in [6]. The mobility management procedure is triggered when a system detects the presence of a visiting MT or when an MT sends a registration message.

Also, several vendors have developed gateways for interworking IS-41 with GSM. For instance, an interworking service gateway (ISG) is

* This work is supported by NSF under grant NCR-97-04393 and by Korea Telecom – Wireless Communications Research Laboratory (WCRL).

ACM SIGMOBILE 7/01 Rome, Italy
© 2001 ACM ISBN 1-58113-422-3/01/07…$5.OO

introduced in [4], which is responsible for converting messages from an IS-41 VLR into GSM HLR messages and vice versa. In order to provide this conversion, the ISG supports data storage, message and parameters mapping, and formatting functions for each of the systems. When a GSM user roams into an IS-41 network, the ISG operates as an HLR to an IS-41 MSC/VLR. Similarly, the ISG also acts as an IS-41 VLR to a GSM HLR. The ISG participates during call establishment to handle functions such as registration and authentication, but it does not participate in the call itself. The interworking on registration and call delivery makes use of some intermediate switch centers, in which the transformation of signaling formats, identity authentication, and retrieval of users profile are accomplished. As suggested in [3], The new entities for inter-system roaming should not replace existing systems, although they may affect some of the functions or signaling in the presence of tremendous installation of PCS systems around the world. Rather, the new interworking units should allow for the exchange of information needed to provide basic mobility management across different systems.

In this paper, we introduce an active location management scheme for the NG wireless networks. Under this scheme, a cache database called boundary location register (BLR) is deployed. When an MT requests an inter-system location registration for the conversion of signaling formats, the BLR records the MT's location and service information. It is assumed that there is only one BLR for each pair of adjacent networks. Accordingly, the MT's latest information can be found in the BLR. When an incoming call arrives, the MT's current network is determined by the information in the BLR; therefore, the call delivery can be processed by querying the BLR instead of accessing the HLR of an MT's home network. By using this protocol, the signaling cost and database access time of location registration and call delivery are greatly reduced. Moreover, the functions of the other network elements, such as the HLR and VLRs, remain primarily unchanged. This greatly facilitates the deployment of this scheme in current and future wireless systems.

This paper is organized as follows. In Section 2, we describe the network architecture and the location management standards for NG wireless systems. In Section 3, we introduce the proposed distributed network architecture and the new BLR concept that contains the up-to-date location information of roaming MTs. Besides, we present the location registration and call delivery procedures for BLR-MAP protocol. An analysis of the signaling and database processing time for the proposed scheme is presented in Section 4. In Section 5, numerical results over a wide range of the parameters are provided to demonstrate the performance of the new protocol. Finally, conclusions are given in Section 6.

2. THE CURRENT MOBILITY GATEWAY REGISTER (GLR) MAP PROTOCOL

In order to support the open environment of inter-system roaming, the mobility *gateway register* (GLR) can be used, which conforms to both commonly used existing mobility management standards IS-41 and GSM [3]. This gateway converts signaling and data format from one network to the other. Therefore, the protocols and interfaces in different networks are similar to the mobility support, although the air-interfaces and physical entities are different. According to universal mobile telecommunications system (UMTS) standard [1], the VLR sees the GLR as an HLR, and the HLR sees the GLR as a VLR. This network architecture is shown in Figure 1. When an MT is moving from a GSM network to an IS-41 network, the user profiles including the service and location information of the MT can be acquired through accessing the GSM HLR. From the point of the VLR in IS-41 networks, the GLR looks like an HLR which can provide the up-to-date location information. When a location updating dialogue initiated by a GLR has been successfully completed, the HLR sees the GLR as the VLR. This protocol is referred to as GLR-MAP in the remainder of the paper.

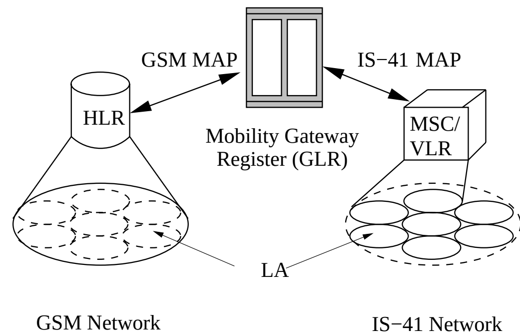


Figure 1: System Architecture for Inter-system Roaming.

2.1 Location Registration/Update Using GLR-MAP

At the stage of location registration, the MTs update their location information with the network so that the network is able to set up call connections for the MTs. The signaling messages are carried out based on the services offered by the signaling connection control part (SCCP) of signaling systems No. 7 (SS7). The signaling diagram of location registration under GLR-MAP is shown in Figure 2 and the corresponding procedure is described as follows:

1. The MT detects that it has entered a new network and sends a location registration/update message to the MSC/VLR through the BS.
2. The MSC/VLR recognizes that the MT is not one of its subscribers and sends a location update request to the GLR.
3. The GLR sends a location update request to the HLR of the MT's home network.
4. The HLR sends a request to insert subscriber data to the GLR.
5. The GLR forwards this message to the VLR.
6. The VLR sends a confirmation message to the GLR for inserting subscriber data.
7. The GLR receives the information and saves it in the user's profile. Then it sends a confirmation message to the HLR.
8. The HLR sends an update location result to the GLR.
9. The GLR sends a location update acknowledgment message to the serving MSC/VLR.
10. The registration complete message is sent by the VLR to the MT through the BS.

2.2 Call Delivery Procedure Using GLR-MAP

During the registration/update procedure, the subscriber data is restored for an unidentified MT (i.e., an unknown user to the VLR). The restore data service is invoked towards the GLR. When the GLR receives a restore data indication, it determines whether it invokes the restore data service towards the HLR, and invokes it if necessary. In

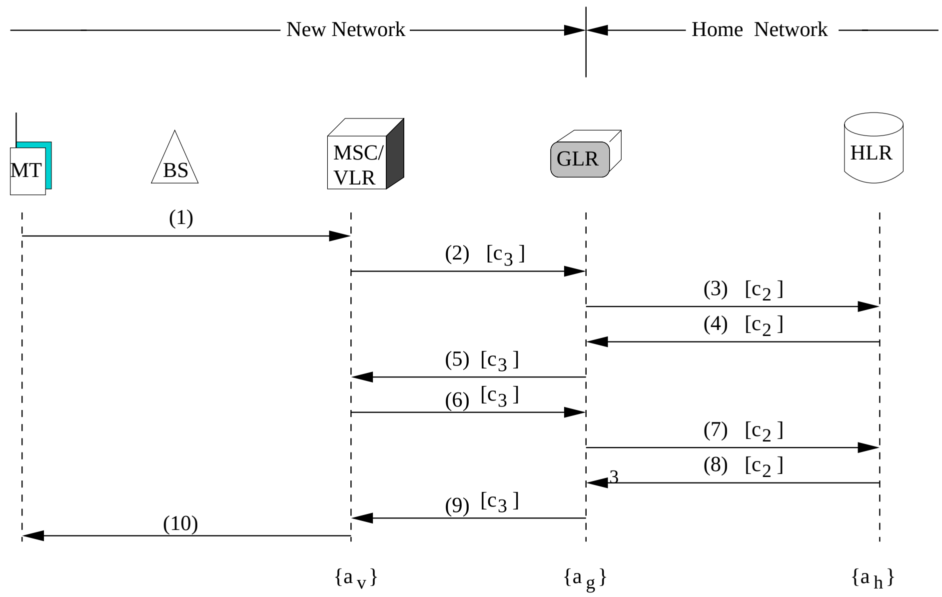


Figure 2: Process of Location Registration/Update Using GLR-MAP.

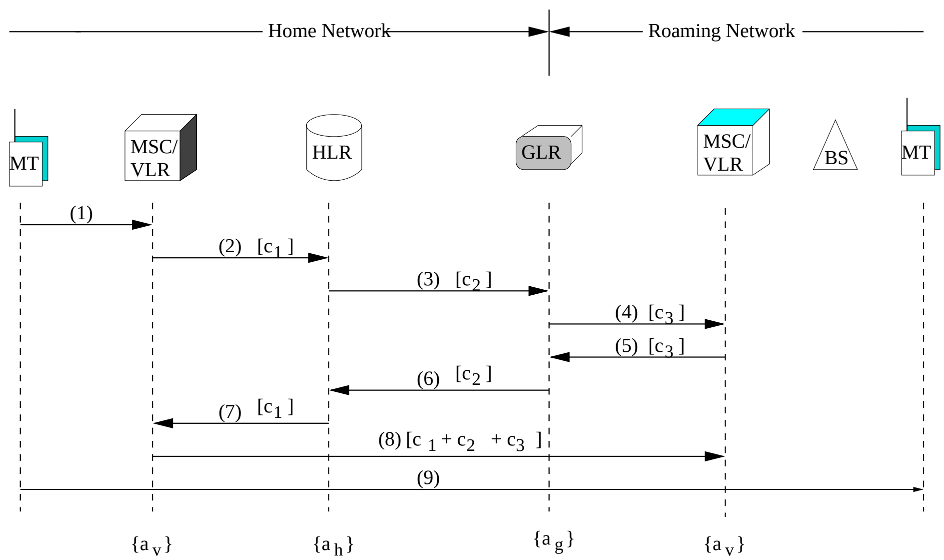


Figure 3: Process of Call Delivery Using GLR-MAP.

Figure 2 and Figure 3, we deploy the similar notation as in [7]. The $(\cdot)$ indicates the sequence number of signaling, the $[\cdot]$ represents the cost for a particular signaling exchange, and the $\{\cdot\}$ at the bottom of the figure indicates the cost for processing in a particular database. These signaling costs and processing time will be discussed in detail in Section 4.

The procedure of call delivery under GLR MAP is described as follows and is shown in Figure 3:

1. A call is initiated by a user at its home mobile network and it is forwarded to its serving MSC through the BS.
2. The MSC/VLR sends a routing information request to the HLR in order to receive a routing number of the called MT.
3. The HLR initiates a request message of routing information towards the GLR.
4. The GLR then sends a routing information request to the serving MSC/VLR of the called MT. The GLR is aware of the MSC/VLR because this information has been stored during the location registration stage.
5. The MSC/VLR responds the roaming number to the GLR.
6. The GLR forwards the roaming number to the HLR as an acknowledgment message with return result.
7. The HLR sends the routing information to the serving MSC/VLR of the calling MT.
8. The call connection is set up between two MSCs.

9. The call is delivered to the called MT through the BS.

If a call is originated from a user in other backbone networks, such as public switching telephone network (PSTN), the call is delivered to the gateway MSC (GMSC) first, then the GMSC sends and receives the routing information rather than an MSC/VLR in the mobile network.

3. A NEW BOUNDARY LOCATION REGISTER (BLR) MAP PROTOCOL

The GLR-MAP protocol is able to identify MTs appearing in a new system and it allows for an MT to initiate a call after it finishes location registration in the new system. However, GLR-MAP protocol is not designed for ongoing call connection during inter-system roaming. When an MT has an active call while crossing the boundary of two systems, the MT must request location registration after it receives signals from the new system. As a result, the existing connection is most probably interrupted or it may be lost. In addition, the incoming calls are always delivered to the old system regardless that an MT has moved to a new system. It is not clearly shown how to avoid this overhead of signaling costs and processing time under GLR-MAP protocol in [1]. Finally, it gives rise to a triangular call routing when the incoming call to a roaming MT is originated by an MT in the same new system. If it is the case, the incoming call is routed to the old system first and then it is delivered to the roaming MT in the new system. It is obvious that this problem can be resolved if the network is aware of the roaming MT's location before call delivery.

In order to solve the above problems, we consider a system architecture which is composed of many different systems. Each system may have its own signaling format, user information, and identification, as well as mobility management protocol. Therefore, locating an MT in the IMT-2000 system becomes more complex because the network may need to search more than one system instead of searching within a stand-alone system. In this section, we present an active location management mechanism, in which the location registration can be finished prior to the arrival of an MT at the new network. Moreover, the call delivery is performed by querying a cache database called *boundary location register* (BLR) first. This method is called BLR-MAP protocol in this paper.

3.1 Boundary Location Register

As an example, we illustrate a system model with two systems X and Y using different protocols in Figure 4. Note that the proposed scheme is applicable to multiple systems scenario by taking pairs of adjacent networks. Each hexagon represents a location area (LA), which consists of many cells. Some LAs may be on the boundary of two adjacent systems, e.g., LA_1^X and LA_2^X of system X and LA_1^Y, LA_2^Y of system Y. We refer to these LAs as *peripheral location areas* (PLAs). It can also be observed that MTs can leave a system only through these PLAs. For example, it is impossible for any MTs in X to leave system X to Y from LA_6^X without going through PLAs. This means that any MT leaving to other systems must cross at least one PLA.

The location registration of inter-system is controlled by a boundary interworking unit (BIU) [15]. BIU is connected to MSCs and VLRs in both systems and it is responsible for retrieving a user's service information and transforming message formats. Also, the BIU is assumed to handle some other issues such as the compatibility of air interfaces and the authentication of mobile users. The configuration of a BIU depends on the two adjacent networks that the BIU is coordinating. More details can be found in [3, 6, 13, 18].

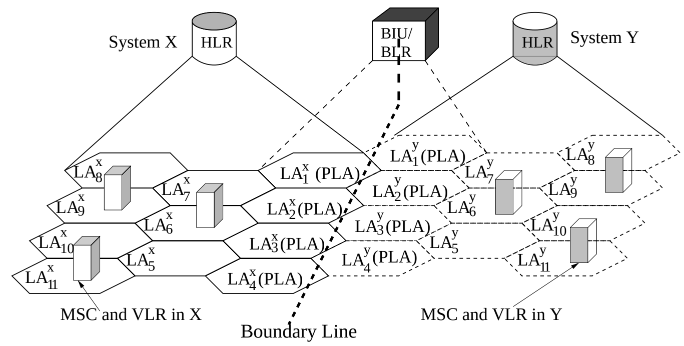


Figure 4: System Model with Boundary Location Register (BLR).

In addition, we designate a boundary location register (BLR) to be embedded in the BIU. A BLR is a cache database so as to maintain the roaming information of MTs moving between different networks. The roaming information is captured when the MT requests a location registration in the BIU. The BLR is involved in tracking the MTs which cross the boundary of two different systems. Therefore, the BLR and the BIU are accessible to the two adjacent networks and they are co-located to handle the inter-system roaming of MTs. Another advantage of the BLR is that it reduces the zigzag effect caused by inter-system roaming. For example, when an MT is moving back and forth on the boundary of two adjacent systems, it only needs to update the information in BLR. On the contrary, the VLR and the MSC are used for registration of MTs crossing the boundaries of LAs within the same system and provide roaming information within a system. Besides, there is only one BLR and one BIU between a pair of neighboring systems, but there may be many VLRs and MSCs within a stand-alone system.

We consider that there is only one BLR between a pair of systems. Each BLR may store the information of MT's crossing the boundary in several PLAs; therefore, the MTs crossing the boundary between systems can be found in the corresponding BLR. If a system has more than one neighboring systems, there are more than one BLRs for this system. Each of these BLRs is also associated with a neighboring system. Since the registrations with any PLA update the MT's location information in HLR, the last LA that an MT registers can be determined by querying the HLR, thus the BLR associated with the PLA can be determined. When a call connection request arrives at system X, the last PAL or LA in which the called MT registered is known by accessing the HLR. Given that the last registered LA within X is a PLA to Y, the system needs to perform following steps to locate the MT:

- Send a query signal to the BLR between X and Y to retrieve the MT's location information. This step is used to ascertain whether the MT has crossed the boundary.

- If the MT has already moved to Y, only the PLA in Y needs to be searched. If the MT has already moved from the PLA to other PLAs or LAs in system Y, the BLR shows the pointer to the HLR in system Y. Then the MT's last registered LA in Y will be searched.

- If the BLR indicates that the MT is still in system X, the last registered LA within X will be searched. Within system X or Y, one or multiple polling messages are sent to the cells in the LA according to some specific paging scheme with delay constraint.

3.2 Location Registration/Update Using BLR-MAP

When an MT moves into the PLA of system X, it receives the location information via the broadcast channel. The basic idea of BLR-MAP is that the MT can request location registration of inter-system roaming when it is in a PLA. As a result, the MT may finish signaling transformation and authentication before it arrives at the new system. This is an *active* mechanism compared to the *passive* scheme of GLR-MAP in which the MT requests location registration after it arrives at the new system [15]. Figure 5 shows the location registration procedure. Each step shown in Figure 5 is described as follows:

1. The MT sends a location update message to the MSC/VLR for inter-system roaming through its serving BS.
2. The MSC/VLR sends a location registration request to the BLR along with the user information.
3. The BLR stores the MT's location in terms of its current MSC/VLR in X and it sends location registration message to the MSC/VLR in Y.
4. The MSC/VLR in Y sends a message of insert subscriber data to the BLR.
5. The BLR sends the user profile of the MT to an MSC/VLR in system Y.
6. The MSC/VLR in Y responds to the BLR with a confirmation message.
7. Then the BLR sends an location update acknowledgment message to the MSC/VLR in the PLA of system X.
8. The registration confirmation message is sent from the serving MSC/VLR to the calling MT through the BS.

3.3 Call Delivery Procedure Using BLR-MAP

In order for the NG wireless system to establish the call connection for an MT during the inter-system roaming, the signaling messages involve HLRs, VLRs, and the BLR associated with the two systems that the MT moves from and to. In Figure 6, the detailed procedure of delivering a call to a called MT of home network X (e.g., mobile-to-mobile) is described as follows.

1. A call is initiated and sent to the MSC/VLR through the serving BS in system X.
2. The MSC/VLR sends a location information request message to the HLR in X.
3. The procedure of locating the called MT depends on the location information indicated in the HLR of X.
   (a) If the HLR shows the last LA with which the called MT registers is an ordinary LA, i.e., non-PLA, it means that the call delivery follows the procedure in a stand-alone system. We call this case as *intra-system call delivery* in which the call connection is established between the two MSCs serving the called and calling MTs within one system.
   (b) If the HLR shows the last LA with which the called MT registers in X is a PLA adjoining to Y, then the HLR sends a query message to the BIU/BLR associated with systems X and Y.
   Then, following procedures are required for *inter-system call delivery*.
4. The BLR is queried first and it shows the serving MSC/VLR of the called MT. The information of the MSC/VLR is available due to the registration process.
   (a) If the BLR indicates that the called MT has moved to a PLA in system Y, the BLR sends a routing request message to the serving MSC/VLR of the called MT in system Y.
   Otherwise,
   (b) If the BLR indicates that the called MT has not moved to network Y, it means that the called MT is still in X. Then the HLR of X will be queried to find the serving MSC/VLR of the called MT as an intra-system call delivery.
5. The MSC/VLR of called MT responds a routing number to the BLR.
6. The BLR forwards the routing number of the called MT to the HLR of the calling MT.
7. The HLR of the calling MT forwards the routing number to the MSC/VLR of the calling MT.
8. The call connection is setup between two MSC/VLRs.
9. The call is delivered to the called MT.

If the BLR is not used, the HLR of system X is always queried first followed by the intra-system call delivery procedure as up to step (3).a in the above description. In the presence that an MT has moved to system Y, this procedure informs a failure. The HLR of X must send a location request information to the HLR in Y. Same procedure is repeated again to find the MSC serving the called MT in system Y, which are followed by the steps (5) to (7) in Figure 6. Therefore, the signaling cost for call delivery is reduced if the called MT is residing in the PLAs of two systems. This benefit is great for those MTs who go back and forth between two systems, thus reducing the signaling cost due to the zigzag effect.

Therefore, the new BLR-MAP protocol is designed for those MTs with ongoing connections during the inter-system roaming. The advantage of this protocol over the GLR-MAP protocol is that it resolves the existing problems left over from GLR-MAP. BLR-MAP protocol enables an MT to update its location and information actively before it arrives at the new system while GLR-MAP performs location registration passively after its arrival. Since the BLR is used to provide the MTs' up-to-date location information, the incoming calls of the inter-system roaming MTs are delivered to them directly, rather than delivering to the old system. Thus, the latency of call delivery and call loss can be reduced, which is discussed in the following section.

4. PERFORMANCE ANALYSIS

In this section, we investigate the overall performance in terms of signaling cost, and latency of location registration and call delivery.

4.1 Assumptions and Parameters

We consider two aspects of signaling costs: the radio resource and the database access. Also we consider transmission delay and processing time in databases in evaluating the latency. The transmission delay may be ignored given that the cell radius is not very large. On the other hand, the processing time consists of two parts. One of them is the retrieval time of database such as HLR/VLR/GLR/BLR, and the other part is the waiting time for service processing.

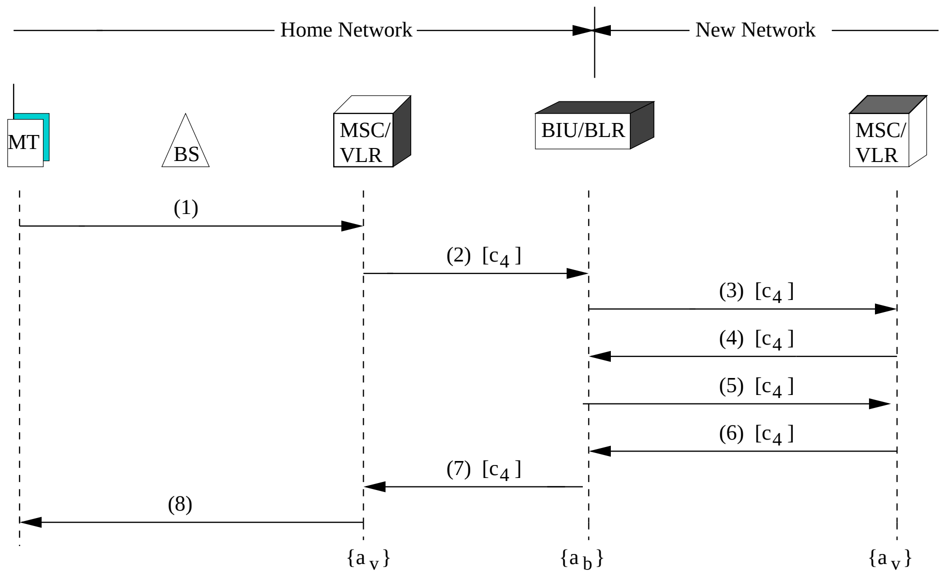


Figure 5: Process of Location Registration/Update Using BLR-MAP.

As described in the previous Section 3.2 and 3.3, the signaling protocol of location registration and call delivery involves the exchange of signaling messages among the network elements. The costs for location management are associated with the traffic of messages between the entities and the accessing cost of database. In order for us to present and evaluate the performance of the signaling protocol, we define the following parameters for the rest of the paper.

c_1 The transmission cost of messages between the HLR and the VLR.

c_2 The transmission cost of messages between the HLR and GLR.

c_3 The transmission cost of messages between the VLR and the GLR.

c_4 The transmission cost of messages between the VLR and the BLR.

c_5 The transmission cost of messages between the HLR and the BLR.

p_0 The probability that an MT leaves its current PLA to another LA (non-PLA).

p_1 The probability that an MT leaves its current PLA to another PLA.

p_2 The probability that an MT leaves its current PLA for another system, i.e., inter-system roaming.

α The weighting factor of the transmission cost.

β The weight factor of the access cost of databases such as HLRs, VLRs, GLRs, and BLRs.

λ The rate of incoming calls in Poisson.

τ The paging delay of finding the called MT by the serving MSC/VLR.

For the sake of simplicity, we assume that the updating, deletion, and retrieval in the database have the same cost, where a_h is the HLR access cost, a_g is the GLR access cost, a_v is the VLR access cost, and a_b is the BLR access cost.

We further assume that each of the HLR, VLR, GLR, and BLR is modeled as a single exponential server with an infinite buffer. The average service time of each of them are $1/\mu_h$ for HLR, $1/\mu_v$ for VLR, $1/\mu_g$ for GLR, and $1/\mu_b$ for BLR, respectively. We consider the average system time in each of the databases is the waiting time in the queue and the service time. The system time is represented by s_h, s_v, s_g, and s_b for the HLR, VLR, GLR, and BLR, respectively. The corresponding waiting times are denoted as w_h, w_v, w_g, and w_b, respectively. The message transmission delay is neglected because the message length of signaling is very short and the transmission rate between the network elements is very high.

4.2 Overhead of Signaling Costs

We analyze six different scenarios for location registration and three cases for call delivery. The signaling cost for each case of location registration is denoted by $\kappa_i^r(\cdot), (i = 0, 1, 2, 3, 4, 5)$ for either GLR or BLR. $\nu_j^d(\cdot), (j = 0, 1, 2)$ is the cost of call delivery for either GLR or BLR.

First, we investigate the location registration cost for different cases. We assume that the last registration of an MT occurred in a PLA which is adjacent to system Y. There are six possible scenarios with regard to the current and next location of an MT whose home network is system X.

- *Case 0*: The MT is currently staying in a PLA of X, but it will send next location registration message in an ordinary LA (i.e., non-PLA) in X.
- *Case 1*: The MT is currently staying in a PLA of X, and it will request next registration in another PLA of X.
- *Case 2*: The MT is currently staying in a PLA of X, and this is the last registration record in X. Then it will move to a PLA in Y.
- *Case 3*: The MT is currently staying in a PLA of Y, and it will request next registration in an ordinary LA (non-PLA) in system Y.
- *Case 4*: The MT is currently staying in a PLA of Y, and it will enter another PLA of Y.

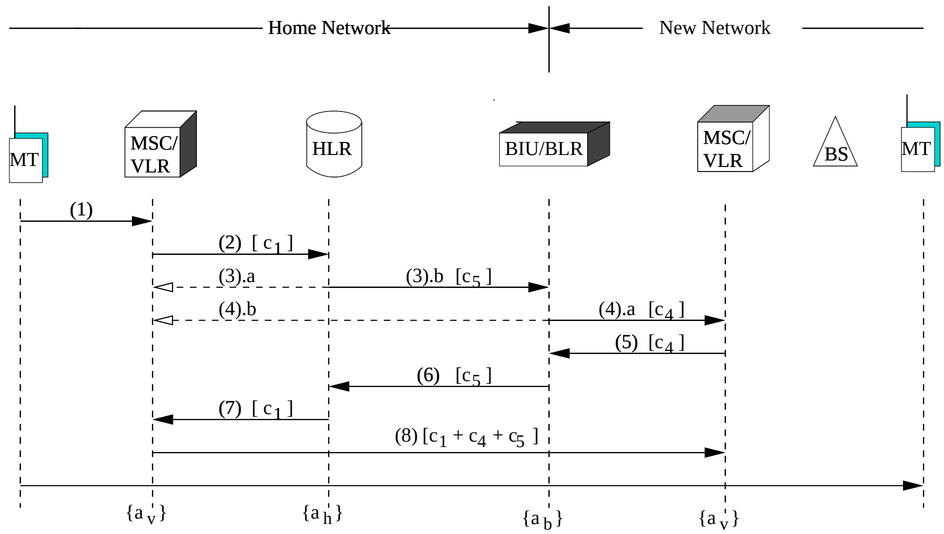


Figure 6: Process of Call Delivery Using BLR-MAP.

- *Case 5*: The MT is currently staying in a PLA of Y, and it is moving to a PLA of system X.

Under the BLR-MAP, the registration procedure of *Case 0* is exactly the same as that in a stand-alone system. The messages are exchanged between the HLR and the VLR for request, confirmation, and update. Therefore, the signaling cost related to the transmission cost is $\alpha \cdot 4c_1$ as shown in Figure 2 and Figure 5, where α is the weighting factor of transmission cost. On the other hand, we consider database access which involves the HLR and the VLR. Accordingly, the cost associated with databases is $\beta \cdot (a_h + a_v)$, where β is the weighting cost of database accessing cost ($\alpha + \beta = 1$). The total cost of this case is then calculated as $\kappa_0^r(BLR) = 4\alpha c_1 + \beta(a_h + a_v)$ as shown in the Table 1 with probability of p_0 as denoted in Section 4.1. *Case 1* is similar to *Case 0* since the MT is moving between different LAs. Thus, the MT must send location registration request to the HLR, old and new MSC/VLRs. The only difference is whether the MT has sent the location update request to the BLR in Figure 5. If the MT sends a location update request to the BLR whenever crossing the boundaries of PLAs, then location registration cost is $\kappa_1^r(BLR) = \alpha(c_4 + c_4 + 4c_4) + \beta(a_b + a_v)$.

In *Case 2*, the MT is experiencing an inter-system roaming. The signaling messages are required between the VLR and the BLR while the HLR is not involved. As shown in Figure 5, the registration cost is $\kappa_2^r(BLR) = \alpha(c_4 + c_4 + 4c_4) + \beta(a_b + a_v)$. However, if the GLR-MAP is used, the HLR is involved in the location registration procedure as shown in Figure 2. The corresponding signaling cost is $\alpha(c_3 + 2c_2 + 2c_3 + 2c_2 + c_3)$ and the cost of accessing database is $\beta(a_g + a_h)$. Furthermore, we assume that an MT keeps the same mobility pattern when it moves from systems Y to X. Therefore, the *Cases 3-5* are very similar to *Cases 0-2*. The registration costs for each case are summarized in Table 1.

Assume the MT is currently staying in a PLA of system X. The average location registration cost, $C^r(BLR)$ and $C^r(GLR)$, can be calculated as:

$$\begin{aligned} C^r(BLR) &= p_0\kappa_0^r(BLR) + p_1\kappa_1^r(BLR) \\ &\quad + p_2\kappa_2^r(BLR) \\ C^r(GLR) &= p_0\kappa_0^r(GLR) + p_1\kappa_1^r(GLR) \\ &\quad + p_2\kappa_2^r(GLR) \end{aligned} \tag{1}$$

Next we investigate the cost of call delivery. There are three possibilities related to the inter-system roaming, given that the MT's last registration occurred in a PLA of X. When the called MT is still in the LAs or PLAs of X, the procedure of call delivery is the same as that of a stand-alone system. If we denote the probability for inter-system roaming by p_2, then the probability that the called MT is still residing in its home network X is $1 - p_2$.

- *Case 0*: The call is initiated by a user in system X and the called MT is also residing in X.
- *Case 1*: The call is initiated by a user in the PSTN or the home mobile network X. The called MT is now residing in the visiting network Y. The incoming calls is Poisson of average rate λ_1.
- *Case 2*: The call is initiated by a user in the visiting network Y while the called MT has moved from its home network X to Y. The incoming calls is Poisson of average rate λ_2.

Similarly, the call delivery for *Case 0* is the same as in a stand-alone system. In *Case 1*, the call is delivered to an MSC/VLR no matter whether the call is initiated by a user from PSTN or from a mobile user in the home network. The signaling messages are exchanged among the HLR, VLR, BLR and the VLR in the new system. This results in the total signaling cost as the summation of costs of steps (2)-(8) in Figure 6. Correspondingly, the access cost of database includes the operation in HLR, VLR, and BLR. In *Case 2*, where the call is initiated by a mobile user in the visiting network, the BLR is queried. If the BLR shows that the called user has moved to the visiting network in which the call is initiated, the connection can be setup directly between the two VLRs in the visiting network. As a result,

Case i		Probability	Signaling Cost	Cost of Database	Cost of Registration ($\kappa_i^r(\cdot)$)
0 (PLA-X → LA-X)	BLR	p_0	$4c_1$	$a_h + a_v$	$4\alpha c_1 + \beta(a_h + a_v)$
	GLR	p_0	$4c_1$	$a_h + a_v$	$4\alpha c_1 + \beta(a_h + a_v)$
1 (PLA-X → PLA-X)	BLR	p_1	$6c_4$	$a_b + a_v$	$6\alpha c_4 + \beta(a_b + a_v)$
	GLR	p_1	$4c_1$	$a_h + a_v$	$4\alpha c_1 + \beta(a_h + a_v)$
2 (PLA-X → PLA-Y)	BLR	p_2	$6c_4$	$a_b + a_v$	$6\alpha c_4 + \beta(a_b + a_v)$
	GLR	p_2	$4c_2 + 4c_3$	$a_g + a_h$	$4\alpha(c_2 + c_3) + \beta(a_g + a_h)$
3 (PLA-Y → LA-Y)	BLR	p_0	$4c_4$	$a_b + a_v$	$4\alpha c_4 + \beta(a_b + a_v)$
	GLR	p_0	$4c_2 + 4c_3$	$a_g + a_h$	$4\alpha(c_2 + c_3) + \beta(a_g + a_h)$
4 (PLA-Y → PLA-Y)	BLR	p_1	$6c_4$	$a_b + a_v$	$6\alpha c_4 + \beta(a_b + a_v)$
	GLR	p_1	$4c_2 + 4c_3$	$a_g + a_h$	$4\alpha(c_2 + c_3) + \beta(a_g + a_h)$
5 (PLA-Y → PLA-X)	BLR	p_2	$6c_4$	$a_b + a_v$	$6\alpha c_4 + \beta(a_b + a_v)$
	GLR	p_2	$4c_1$	$a_h + a_v$	$4\alpha c_1 + \beta(a_h + a_v)$

Table 1: The Signaling Costs and Probabilities for Different Scenarios.

Case j		Probability	Signaling Cost	Cost of Database	Cost of Delivery ($\nu_j^d(\cdot)$)
0	BLR	$1 - p_2$	$6c_1$	$a_h + a_v$	$6\alpha c_1 + \beta(a_h + a_v)$
	GLR	$1 - p_2$	$6c_1$	$a_h + a_v$	$6\alpha c_1 + \beta(a_h + a_v)$
1	BLR	$p_2 \frac{\lambda_1}{\lambda_1+\lambda_2}$	$3c_1 + 3c_4 + 3c_5$	$a_b + a_h + a_v$	$\alpha(3c_1 + 3c_4 + 3c_5) + \beta(a_b + a_h + a_v)$
	GLR	$p_2 \frac{\lambda_1}{\lambda_1+\lambda_2}$	$3c_1 + 3c_2 + 3c_3$	$a_g + a_h + a_v$	$\alpha(3c_1 + 3c_2 + 3c_3) + \beta(a_g + a_h + a_v)$
2	BLR	$p_2 \frac{\lambda_2}{\lambda_1+\lambda_2}$	$6c_4$	$a_b + a_v$	$6\alpha c_4 + \beta(a_b + a_v)$
	GLR	$p_2 \frac{\lambda_2}{\lambda_1+\lambda_2}$	$3c_1 + 3c_2 + 3c_3$	$a_g + a_h + a_v$	$\alpha(3c_1 + 3c_2 + 3c_3) + \beta(a_g + a_h + a_v)$

Table 2: The Signaling Costs and Probabilities for Call Delivery.

the HLR and the VLR of the called MT's home network are not involved in the process of call delivery. The costs of call delivery for each case are summarized in Table 2.

The average call delivery cost for BLR-MAP, $C^d(BLR)$, is obtained by:

$$\begin{aligned} C^d(BLR) &= (1-p_2)\nu_0^d(BLR) \\ &+ p_2 \frac{\lambda_1}{\lambda_1+\lambda_2}\nu_1^d(BLR) \\ &+ p_2 \frac{\lambda 2}{\lambda_1+\lambda_2}\nu_2^d(BLR), \end{aligned} \tag{2}$$

where $\nu_{(\cdot)}^d(BLR)$ is the call delivery cost using BLR-MAP protocol. The first item is the product of probability $(1-p_2)$ and $\nu_0^d(BLR)$ in the second row of Table 2. In the same way, the other two items are obtained by multiplying $\nu_{(\cdot)}^d(BLR)$ and their corresponding probabilities, $p_2 \frac{\lambda_1}{\lambda_1+\lambda_2}$ and $p_2 \frac{\lambda 2}{\lambda_1+\lambda_2}$, respectively in Table 2. Under the GLR-MAP protocol, if the called MT has roamed to system Y, the network will search system X first. If the called MT cannot be found, then system Y will be searched. The average call delivery cost for GLR-MAP, $C^d(GLR)$, is then computed from:

$$\begin{aligned} C^d(GLR) &= (1-p_2)\nu_0^d(GLR) \\ &+ p_2 \frac{\lambda_1}{\lambda_1+\lambda_2}\nu_1^d(GLR) \\ &+ p_2 \frac{\lambda_2}{\lambda_1+\lambda_2}\nu_2^d(GLR), \end{aligned} \tag{3}$$

where $\nu_{(\cdot)}^d(GLR)$ is the call delivery cost using GLR-MAP protocol as shown in Table 2. The most important attribute of the BLR MAP is that it does not only reduce the signaling cost, but it also alleviates the bottleneck problem in the HLR and decreases the traffic load in the signaling network.

4.3 Latency of Location Registration and Call Delivery

With respect to the location registration process, the end-to-end response time is from the time an MT sends a message for registration to a confirmation of the complete message. On the other hand, the end-to-end delay for the call delivery is from the time that an MT initiates a call to the moment that the called MT receives the message. For each case i we described in the previous Section 4.2, we denote the delay for location registration as $\delta_i^r(\cdot)$ and $\phi_j^d(\cdot)$ for call delivery. As mentioned before, the latency is evaluated based on the processing time, which consists of two parts. One of them is the retrieval time of database, and the other part is the waiting time for service. Therefore, we deploy an M/G/1 queuing model to describe the scenario and analyze the performance. Accordingly, the delay of accessing each database, $s_{(\cdot)}$, can be computed as

$$s_{(\cdot)} = \frac{1}{\mu(\cdot)} + w_{(\cdot)}, \tag{4}$$

where $1/\mu(\cdot)$ represents the average processing time for the database such as HLR, VLR, GLR, and BLR. We use $w_{(\cdot)}$ to denote the waiting time for the above databases. As an example, we analyze w_h of HLR, where we assume the average arrival rate of location registration at the HLR is η_h.

By using the well-known Pollaczek-Khinchin (P-K) formula, the average waiting time, w_h is obtained by [8]

$$w_h = \frac{\eta_h \cdot \mu_h^2 + \eta_h \cdot \sigma_h^2}{2 \cdot (1 - \frac{\eta_h}{\mu_h})}, \tag{5}$$

where $\sigma_{(\cdot)}^2$ is variance of processing time in each database. And the processing time or the so-called service time of the HLR, s_h, can be computed from

$$\begin{aligned} s_h &= \frac{1}{\mu_h} + w_h \\ &= \frac{1}{\mu_h} + \eta_h \frac{\mu_h^2 + \sigma_h^2}{2 \cdot (1 - \frac{\eta_h}{\mu_h})}, \end{aligned} \tag{6}$$

where w_h is the result from (5). Similarly, we can obtain the processing time for the VLR, GLR and BLR by substituting the corresponding parameters into (6). Note that the latency of location registration for each case in Table 1 can be calculated by considering the processing time $s_{(\cdot)}$ instead of $a_{(\cdot)}$ of each entity. For example, the delay of location registration for *Case 1* with BLR, $\delta_1^r(BLR)$, is the combination of delay of accessing BLR and the VLR,

$$\begin{aligned} \delta_1^r(BLR) &= s_b + s_v \\ &= \frac{1}{\mu_b} + \eta_b \frac{\mu_b^2+\sigma_b^2}{2\cdot(1-\frac{\eta_b}{\mu_b})} + \frac{1}{\mu_v} + \eta_v \frac{\mu_v^2+\sigma_v^2}{2\cdot(1-\frac{\eta_v}{\mu_v})}, \end{aligned} \tag{7}$$

where the first two items are the processing time of BLR consisting of service time $1/\mu_b$ and waiting time $w_b = \eta_b \frac{\mu_b^2+\sigma_b^2}{2\cdot(1-\frac{\eta_b}{\mu_b})}$. The last two items are the processing time of VLR which are composed of service time $1/\mu_v$ and waiting time $w_v = \eta_v \frac{\mu_v^2+\sigma_v^2}{2\cdot(1-\frac{\eta_v}{\mu_v})}$. These formulas are obtained by the same way as in (6). Therefore, the average delay for location registration using BLR-MAP and GLR-MAP, $D^r(BLR)$, and $D^r(GLR)$ are

$$\begin{aligned} D^r(BLR) &= (1-p_2)\delta_0^d(BLR) + \\ &\quad p_2\frac{\lambda_1}{\lambda_1+\lambda_2}\delta_1^d(BLR) + \\ &\quad p_2\frac{\lambda_2}{\lambda_1+\lambda_2}\delta_2^d(BLR) \\ D^r(GLR) &= (1-p_2)\delta_0^d(GLR) + \\ &\quad p_2\frac{\lambda_1}{\lambda_1+\lambda_2}\delta_1^d(GLR) + \\ &\quad p_2\frac{\lambda_2}{\lambda_1+\lambda_2}\delta_2^d(GLR), \end{aligned} \tag{8}$$

which are computed in a similar way as for (1) to (3), and (refd1blr).

For the call delivery, in addition to the database access time, the paging delay must be considered. Paging delay can be regarded as the required time for an MSC to deliver a call to the called MT. Then the delay of *Case 0* is the same for BLR-MAP and GLR-MAP, which is the summation of s_h, s_v, and τ as shown in Figure 6 and Figure 3. That means

$$\phi_0^d(BLR) = \phi_0^d(GLR) = s_h + s_v + \tau. \tag{9}$$

And the delay of call delivery for *Case 1* is computed by

$$\begin{aligned} \phi_1^d(BLR) &= s_b + s_h + s_v + \tau, \\ \phi_1^d(GLR) &= s_h + s_g + s_v + \tau. \end{aligned} \tag{10}$$

Similarly, the delay for *Case 2* is obtained as

$$\begin{aligned} \phi_2^d(BLR) &= s_b + s_v + \tau, \\ \phi_2^d(GLR) &= s_h + s_g + s_v + \tau. \end{aligned} \tag{11}$$

Therefore, the average delay for call delivery using BLR-MAP and GLR-MAP, $D^d(BLR)$, and $D^d(GLR)$ are

$$\begin{aligned} D^d(BLR) &= (1-p_2)\phi_0^d(BLR) + \\ &\quad p_2\frac{\lambda_1}{\lambda_1+\lambda_2}\phi_1^d(BLR) + \\ &\quad p_2\frac{\lambda_2}{\lambda_1+\lambda_2}\phi_2^d(BLR) \\ D^d(GLR) &= (1-p_2)\phi_0^d(GLR) + \\ &\quad p_2\frac{\lambda_1}{\lambda_1+\lambda_2}\phi_1^d(GLR) + \\ &\quad p_2\frac{\lambda_2}{\lambda_1+\lambda_2}\phi_2^d(GLR), \end{aligned} \tag{12}$$

where $\phi_i^d(\cdot)$ can be obtained in the same way for (9) to (11). $D^d(\cdot)$ can be computed in a similar way as in (1), (2), and (3).

4.4 Call Loss Rate

When an MT moves from one network to another, both new incoming calls and calls in progress must wait for call processing after the inter-system location registration is finished. As a result, the ongoing calls may be blocked or lost due to waiting for the location registration. This occurs for the GLR-MAP protocol. Under the BLR-MAP protocol, the MTs are allowed to request location registration before they arrive at the new network by sending request to the BIU/BLR. We assume that the MTs send their location registration messages at time $t - \Delta t$, where t is the arrival time of an MT at the new system and Δt is the extra time for a call to wait for processing. For the simplicity, we assume that $\Delta t = 0.1 * w_b$, where w_b is the average waiting time for an MT to finish the process of inter-system location registration.

The Laplace transform of the waiting time distribution for the BLR, $W_B^*(s)$, can be expressed as [8]

$$W_B^*(s) = \frac{1-\rho_b}{1-\rho_b\left[\frac{1-B_b^*(s)}{s/\mu_b}\right]}, \tag{13}$$

where $\rho_b = \eta_b/\mu_b$ and $B_b^*(s)$ is the Laplace transform of the probability density function (pdf) of service time. For the special case M/M/1, the corresponding probability distribution function (PDF), $W_b(y)$ is obtained by

$$W_b(y) = 1 - \rho_b e^{-\mu_b(1-\rho_b)\cdot y}. \tag{14}$$

Thus, the call loss rate due to inter-system roaming, $R_l(BLR)$, is obtained by

$$\begin{aligned} R_l(BLR) &= p_c \cdot prob\,[y > \Delta t] \\ &= p_c \cdot [W_b(\infty) - W_b(\Delta t)], \end{aligned} \tag{15}$$

where p_c is the roaming probability. $W_b(\infty)$ and $W_b(\Delta t)$ can be obtained by applying (14). Similarly, the call loss rate for GLR-MAP protocol, $R_l(GLR)$, can be obtained as

$$\begin{aligned} R_l(GLR) &= p_c \cdot prob\,[y > 0\,] \\ &= p_c \cdot [W_g(\infty) - W_g(0)], \end{aligned} \tag{16}$$

where $W_g(\infty)$ and $W_g(\Delta t)$ are obtained from $W_g(y) = 1-\rho_g e^{-\mu_g(1-\rho_g)\cdot y}$ for GLR-MAP protocol.

5. NUMERICAL RESULTS

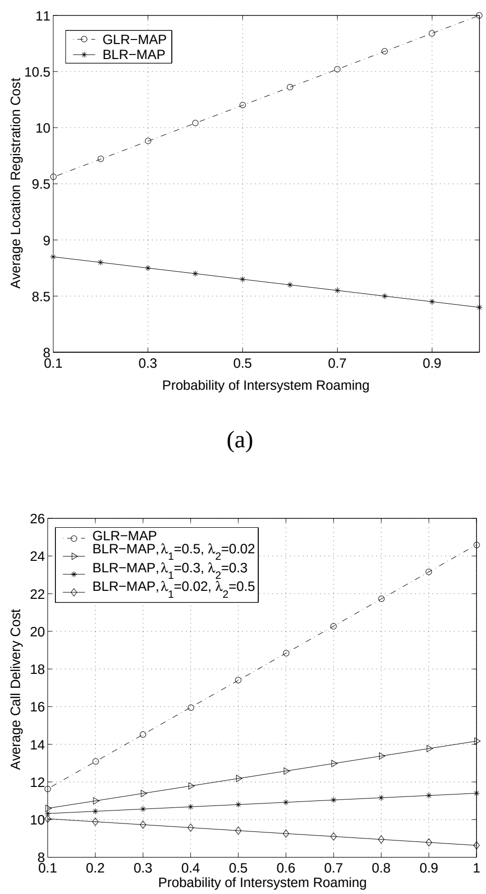
In this section, numerical results are provided to demonstrate the performance of inter-system roaming supported by both GLR-MAP and BLR-MAP. We assume the cost for transmitting signaling messages and the cost for database access are available. Table 3 lists all parameters used in our performance analysis [9]. We compare the average signaling cost and delay for both GLR-MAP and BLR-MAP versus inter-system roaming probability.

5.1 Signaling Cost of Location Registration and Call Delivery

Figure 7(a) shows the average location registration cost as a function of inter-system roaming probability by using (1). We can observe that the average cost of location registration of GLR-MAP is always higher than that of BLR-MAP. Also, as the inter-system roaming probability increases, the location registration cost of BLR-MAP decreases slightly. The reason for decreasing registration cost is that the inter-system location registration only involves BLR and VLR. As we consider that an MT is in a PLA of X, it will either go to other

Database Access Cost				Avg. Arrival Rate for DB Reg. ($msec^{-1}$)			
a_h	a_v	a_g	a_b	η_h	η_v	η_g	η_b
8	5	5	5	0.001	0.001	0.001	0.001
DB Avg. Processing Time($msec$)				Variance of DB Processing Time($msec$)			
$1/\mu_h$	$1/\mu_v$	$1/\mu_g$	$1/\mu_b$	σ_h^2	σ_v^2	σ_g^2	σ_b^2
1.0	0.5	0.5	0.5	0.04	0.01	0.01	0.01
Signaling Transmission Cost					Weighting Factors		Paging Delay($msec$)
c_1	c_2	c_3	c_4	c_5	α	β	τ
1	1	1	1	1	0.4	0.6	3.0

Table 3: Performance Analysis Parameters



(a)

(b)

Figure 7: Average Location Registration and Call Delivery Cost vs. Inter-system Roaming Probability

LAs in system X or to a new system Y. When inter-system roaming probability is small, the registration cost is dominated by intra-system roaming between different LAs, involving HLR and VLR access. Considering the HLR is much larger than the BLR, and the HLR may not be as close to the roaming MT as the BLR, the access and retrieval cost of the HLR is very likely higher than that of the BLR, causing higher registration cost. On the other hand, if the inter-system roaming probability is high, the registration cost is dominated by accessing the BLR, resulting in lower cost. This is different from the case of GLR-MAP with which the cost increases as the roaming probability increases. Therefore, BLR-MAP reduces the location registration cost so that it is more suitable for high probability inter-system roaming environment.

The average call delivery cost from (2) and (3) is shown in Figure 7(b) as a function of inter-system roaming probability. We investigate the cost under three different sets of values of λ_1 and λ_2, which are the average rates of incoming calls for *Case 1* and *Case 2* mentioned in Section 4. It is observed that the average call delivery cost of GLR-MAP is higher than that of BLR-MAP. The cost of BLR-MAP varies under different set of λ_1 and λ_2 values, whereas the cost of GLR-MAP keeps unchanged.

5.2 Delay of Location Registration and Call Delivery

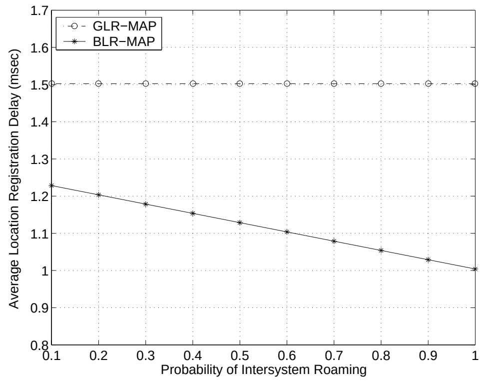
The location registration delay is shown in Figure 8(a), in which we find that the BLR-MAP outperforms the GLR-MAP in terms of the registration delay. Similar to the case of location registration cost, the location registration delay of BLR-MAP decreases when the inter-system roaming probability increases. In the same way as for the registration cost, the delay of inter-system registration and call delivery is associated with BLR and VLR. When inter-system roaming probability is small, the registration delay is mainly determined by accessing the HLR while it is dominated by accessing the BLR when inter-system roaming probability is higher. Considering that the retrieving delay of HLR is higher than that of the BLR, the delays are decreased with the increasing inter-system roaming probabilities. Figure 8(b) demonstrates the average call delivery delay as a function of inter-system roaming probability using (8) and (12) for location registration and call delivery. The performance of the BLR-MAP is also better than that of the GLR-MAP in the sense of decreasing the latency of location management.

5.3 Comparison of Call Loss Rates

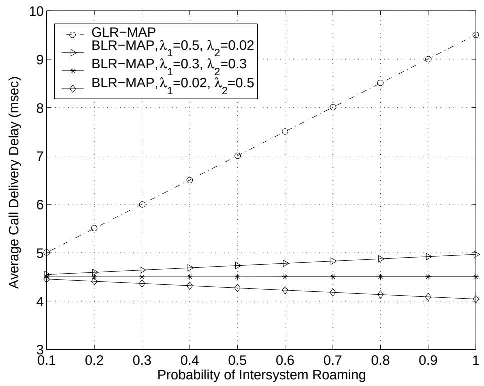
The call loss rates caused by GLR-MAP and BLR-MAP are compared in Figure 9, which are obtained from (15) and (16). We assume that the incoming or outgoing calls would be lost if the MT has not finished its inter-system location registration. Thus, if the GLR-MAP is used, the incoming or outgoing calls may be lost due to the latency of registration process. However, when the BLR-MAP protocol is used, the MTs may initiate the location registration before they arrive at the new network. Thus, the call loss rates can be reduced. The improvement of BLR-MAP can be observed in Figure 9. It is quite visible that the call loss rates decrease as the registration rates of the BLR are reduced for the same processing time.

6. CONCLUSIONS

In this paper, we introduced a new cost-efficient signaling protocol for the mobility application part (MAP), which is based on the new concept of boundary location register (BLR). We proposed the detailed procedure of location registration and call delivery for BLR-MAP protocol. This protocol is specifically developed to maintain



(a)



(b)

Figure 8: Average Location Registration and Call Delivery Delay vs. Inter-system Roaming Probability

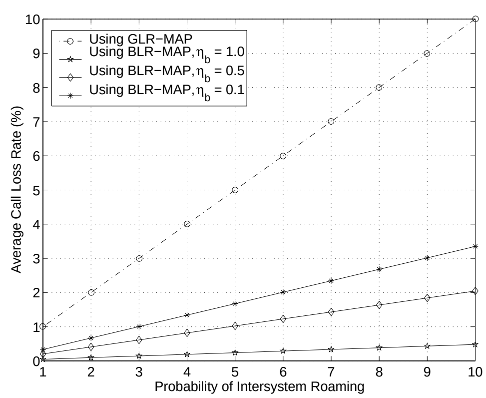


Figure 9: Comparison of Call Loss Rate.

ongoing calls which are not well supported in the current GLR-MAP protocol. We analyzed the overall system performance with respect to the signaling cost of location registration and call delivery, the delay of location management, and the call loss rates due to the location registration from one system to another. The numerical results demonstrate that both the signaling costs and the latency of call delivery, as well as the call loss rates can be reduced for various scenarios.

REFERENCES

[1] ETSI TS 129 120 V3.0.0 (2000-03) *Universal Mobile Telecommunications Systems (UMTS); Mobile Application Part (MAP) specification for Gateway Location Register (GLR); Stage 3*, 3GPP/ETSI 2000.

[2] I.F. Akyildiz, J. McNair, J.S.M. Ho, H. Uzunalioğlu and W. Wang, “Mobility Management in Next-Generation Wireless Systems,” *Proceedings of the IEEE*, Vol. 87, pp. 1347-1384, August, 1999.

[3] A. Bertrand, “Jambala Mobility Gateway – Convergence and Inter-system Roaming,” *Ericsson Review*, pp. 89-93, No. 2, 1999.

[4] U. Black, *Second Generation Mobile and Wireless Networks*, Prentice Hall PTR, New Jersey, 1998.

[5] M. Gallagher and W. Webb, “UMTS–the Next Generation of Mobile Radio,” *IEE Review*, Vol. 45, NO. 2, pp. 59-63, March 1999

[6] V. Garg and J.E. Wilkes, “Interworking and Interoperability Issues for North American PCS,” *IEEE Communications Magazine*, Vol. 34, No. 3, pp. 94-99, March 1996.

[7] J.S. Ho and I.F. Akyildiz, “Dynamic Hierarchical Database Architecture for Location Management in PCS Networks,” *IEEE/ACM Transactions on Networking*, Vol. 5, No. 5, pp. 646-660. October 1997.

[8] L. Kleinrock, “Queueing Systems Volume 1: THEORY,” John Wiley & Sons, 1975.

[9] K.K. Leung and Y. Levy, “Global Mobility Management by Replicated Databases in Personal Communication Networks,” *IEEE Journal on Selected Areas in Communications*, Vol. 15, No. 8, pp. 1582-1595, October 1997.

[10] A.R. Modarressi and S. Mohan, “Control and Management in Next-Generation Networks: Challenges and Opportunities,” *IEEE Communications Magazine*, Vol. 38, No. 10, pp. 94-102, October 2000.

[11] Z. Naor and H. Levy, “Minimizing the Wireless Cost of Tracking Mobile Users: An Adaptive Threshold Scheme,” *IEEE INFOCOM’98*, Vol. 2, pp. 720-727, March 1998.

[12] T. Nillson, “Toward Third-Generation Mobile Multimedia Communication,” *Ericsson Review*, No. 3, pp. 122-131, 1999.

[13] S.G. Niri and R. Tafazoli, “Cordless - Cellular Network Integration for the 3rd Generation Personal Communication Systems,” *IEEE VTC’98*, pp. 402-408, Ottwa Canada, May 1998.

[14] S. Suzuki and T. Shibata, and M. Yoshimi, “PHS Roaming Signaling Protocol Architecture Toward Global Mobility Network,” *IEEE Journal of Selected Areas in Communications*, Vol. 15, No. 8, pp. 1597-1607. October 1997.

[15] W. Wang and I.F. Akyildiz, “Intersystem Location Update and Paging Schemes for Multitier Wireless Networks,” *ACM MobiCom 2000*, pp. 99-109. August 2000.

[16] G. Wan and E. Lin, “Cost Reduction in Location Management Using Semi-Realtime Movement Information,” *ACM-Baltzer Journal of Wireless Networks (WINET)*, Vol 5, No. 4, pp. 245-256, 1999.

[17] S. M. Walters, “Interworking in the Next Millennium,” *IEICE Transactions on Communications*, Vol. E80-B, No. 10, pp. 1383-1385, October 1997.

[18] A. Yamaguchi, S. Ota, Y. Ito, M. Ohashi and F. Watanabe, “Inter-system Mobility and Service Management in GSM/PDC Roaming,” *IEEE GLOBECOM’97*, pp. 694-698, November 1997.

[19] M. Zeng, A. Annamalai, and V.K. Bhargava, “Recent Advances in Cellular Wireless Communications,” *IEEE Communications Magazine*. Vol. 37, No. 9, pp. 128-138, September 1999.