A New Signaling Protocol for Intersystem Roaming in Next-Generation Wireless Systems

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***Abstract*—In next-generation wireless systems, one of the major features that is different from the current personal communication service systems is the seamless global roaming. The mobile subscribers will be allowed to move freely across different networks while maintaining their quality of service for a variety of applications. To meet this demand, the signaling protocol of mobility management must be designed, supporting location registration and call delivery for roaming users who move beyond their home network. In this paper, a new signaling protocol is proposed, emphasizing the active location registration for ongoing services during the mobile subscribers' movement. Another important goal of this new protocol is to reduce the overhead caused by mobility management so that the signaling traffic load and consumption of network resources can be reduced. The new protocol efficiently reduces the latency of call delivery and call loss rate due to crossing wireless systems with different standards or signaling protocols. The numerical results reveal that the proposed protocol is effective in improving the overall system performance.**

***Index Terms*—Call delivery, delays, location registration, mobility management, signaling costs, wireless systems.**

I. INTRODUCTION

THE FORESEEABLE deployment of next-generation (NG) wireless systems, e.g., International Mobile Telecommunications 2000 (IMT-2000) and 4G systems will lead to an enormous increase in both the number of mobile subscribers and mobile applications. The distinguished features of NG wireless systems can be highlighted as quality of service (QoS) provisioning for various applications and global roaming [2], [5], [11]. The demand to provide wireless multimedia services to an increasing population of mobile users has placed new requirements on wireless systems. The mobile users require that QoS constraints be maintained throughout the duration of an application, even though they roam not only from cell to cell but also from one system to another with different technologies. Among many challenges for the NG wireless systems, the mobility management is the focus of this paper [10], [16]. In particular, the mobility application part (MAP) protocol is investigated, which is concerned with a set of messages involving in the location registration and call delivery.

Manuscript received December 1, 2000; revised June 1, 2001. This work was supported by the NSF under Grant NCR-97-04393, by Korea Telecom, Wireless Communications Research Laboratory (WCRL), and by the NSF under Grant CCR-99-88532. A preliminary version of the paper appeared at ACM/IEEE MobiCom'01.

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Publisher Item Identifier S 0733-8716(01)08470-0.

When a mobile terminal (MT) roams within the service area of a stand-alone system, e.g., Global System for Mobile Communication (GSM), the MT requests location registration whenever it crosses the boundary of location areas (LAs), also known as registration areas (RAs). Each LA consists of a group of cells; thus, the system is always aware of the MT's position in an LA. Accordingly, the MT's location information can be obtained by querying a home location register (HLR) and visitor location registers (VLRs) within a system. However, the existing systems may not have compatibility with each other, i.e., each system may have a specific MAP protocol for mobility management so that an MT's mobility is limited within one system. Unlike roaming in a stand-alone system, the MT's location information may not be retrieved from a centralized database in NG systems; instead, it may need to access databases associated with two adjacent networks. Thus, the interworking of these systems is critical to support the universal roaming capability. Recently, there have been some ongoing standards and research work on designing a signaling protocol for *intersystem roaming*.

The new interworking units should support the exchange of information needed to provide basic mobility management across different systems. Several vendors have developed gateways for the interworking of the Interim Standard (IS-41) with GSM [4], [6]. For instance, a dual mode home location register (HLR-IIF) is described in [6] for interworking and interoperability between IS-41 and PCS 1900 MAPs. The mobility management procedure is triggered when a system detects the presence of a visiting MT or when an MT sends a registration message. The interworking of GSM with Digital Enhanced Cordless Telephone (DECT) system is discussed in [12]. The VLR may contain two sets of information pointing to the GSM and DECT location areas or one set of information with a flag pointing to GSM or DECT. In [13], a signaling protocol is proposed to provide intersystem roaming to Personal Handy-Phone System (PHS) users. Under this protocol, service data and 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 in order to establish a connection. In [17], 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 and an IWF-switch to handle intersystem roaming.

In this paper, a new signaling protocol is introduced which is specifically designed to maintain the connection of ongoing

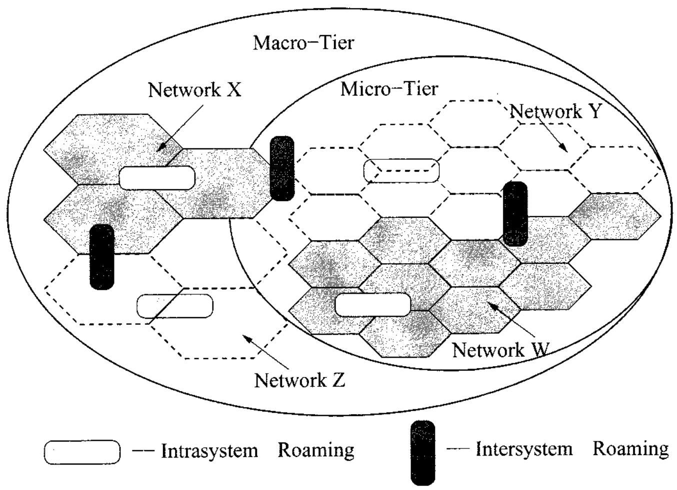


Fig. 1. System architecture of intrasystem and intersystem roaming.

services during an MT's global roaming. Instead of performing location registration after an MT arrives at the new system, the MT is allowed to update its location information prior to its reaching the boundary of two systems. The updated information is contained in a cache database called boundary location register (BLR). Therefore, the MT's latest information can be found in the BLR. The incoming call can then be processed by querying the BLR instead of accessing the HLR of an MT's home network.

The remainder of the paper is organized as follows. In Section II, we describe the system architecture and the existing protocol using the gateway location register (GLR). In Section III, we introduce the new concept of BLR. In addition, we present the location registration and call delivery procedures for BLR protocol. An analysis of the signaling and database processing time for the proposed scheme is presented in Section IV. In Section V, numerical results are provided to demonstrate the performance of the new protocol. Finally, we conclude the paper in Section VI.

II. Current Mobility Gateway Location Register (GLR) Protocol

In the service area of the NG wireless systems, it is very likely for MTs to roam between heterogeneous networks which may affect the continuity of radio connection. For example, the signaling formats for microcell and macrocell tiers may be different. Even in the same tier, the signaling format, user information, and identification authorization may be different for systems using different protocols. As shown in Fig. 1, there are two systems, W and Y in the microcell tier, which may use different protocols such as PHS and PCS1900. Each hexagon represents an LA within a stand-alone system and each LA is composed of a cluster of microcells. The MTs are required to update their location information with the system whenever they enter a new LA; therefore, the system knows the residing LA of an MT all the time. In Fig. 1 there are also two systems, X and Z in the macrocell tier, in which different protocols (e.g., GSM and IS-41) are used. For macrocell systems, one entire LA can be one macrocell. It is possible that systems W and X, although in different tiers, may employ protocols such as IS-95, GSM, or any other protocol. We consider only two adjacent systems throughout our paper; however, our proposed scheme is applicable to multiple systems by using it on each pair of adjacent systems consecutively.

There are two types of roaming as shown in Fig. 1: *intrasystem* and *intersystem* roaming. Intrasystem roaming refers to an MT's movement between the LAs within a system such as Y and Z. Intersystem roaming refers to the MTs that roam between different systems. For example, mobile users may travel from a macrocell system within an IS-41 network to a region that uses the GSM standard.

In order to support the intersystem roaming, the mobility *gateway location register* (GLR) is developed [1]. The GLR converts signaling and data formats from one network to another. Therefore, the mobility support can be provided at the network layer although the air-interfaces may be diferent. 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. When an MT roams from a GSM to an IS-41 network, the user profiles including the service and location information of the MT can be acquired from the GSM HLR. From the point of the VLR in IS-41 network, the GLR looks like an HLR which provides the up-to-date location information. When a location update initiated by a GLR has been successfully completed, the HLR sees the GLR as a VLR. This protocol is referred to as GLR protocol in the remainder of the paper.

A. Location Registration/Update Using GLR Protocol

During 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 the signaling system No. 7 (SS7). The signaling diagram of location registration under the GLR protocol is shown in Fig. 2, assuming the MT's home network is X and the visiting network is Y. This GLR protocol also applies to General Packet Radio Service (GPRS) system in which the Serving GPRS Support Node (SGSN) is used instead of the mobile switching center (MSC). In Figs. 2 and 3, we deploy a similar notation as in [7]. The $(\cdot)$ indicates the sequence number of a signaling message, 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 IV.

The signaling messages of the corresponding procedure are described as follows [15].

1) The MT detects that it has entered a new network and sends a location registration/update message to the MSC/VLR (or SGSN) through the serving base station (BS).
2) The MSC/VLR recognizes that the MT is not one of its subscribers and sends a location registration request to the GLR.

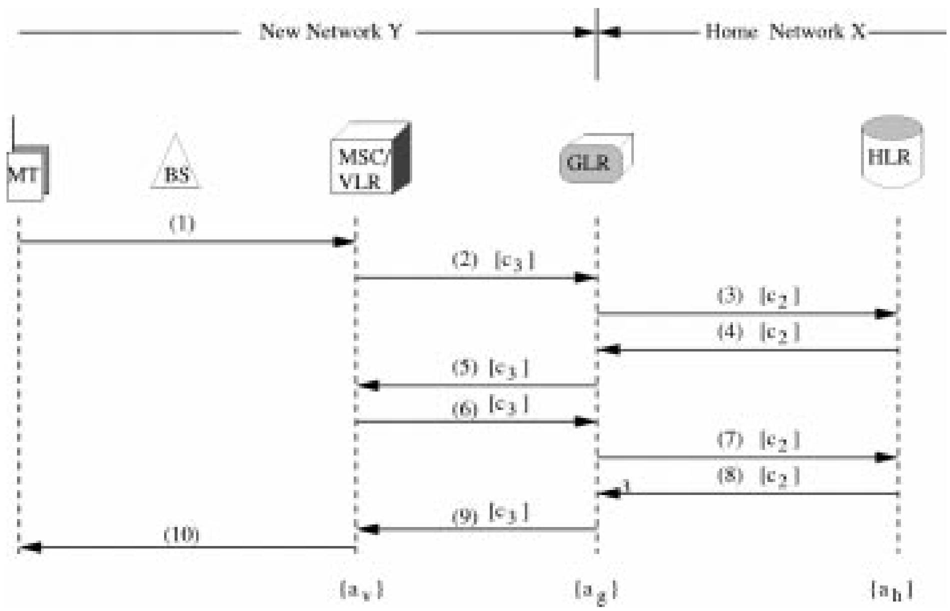


Fig. 2. Process of location registration/update using GLR protocol.

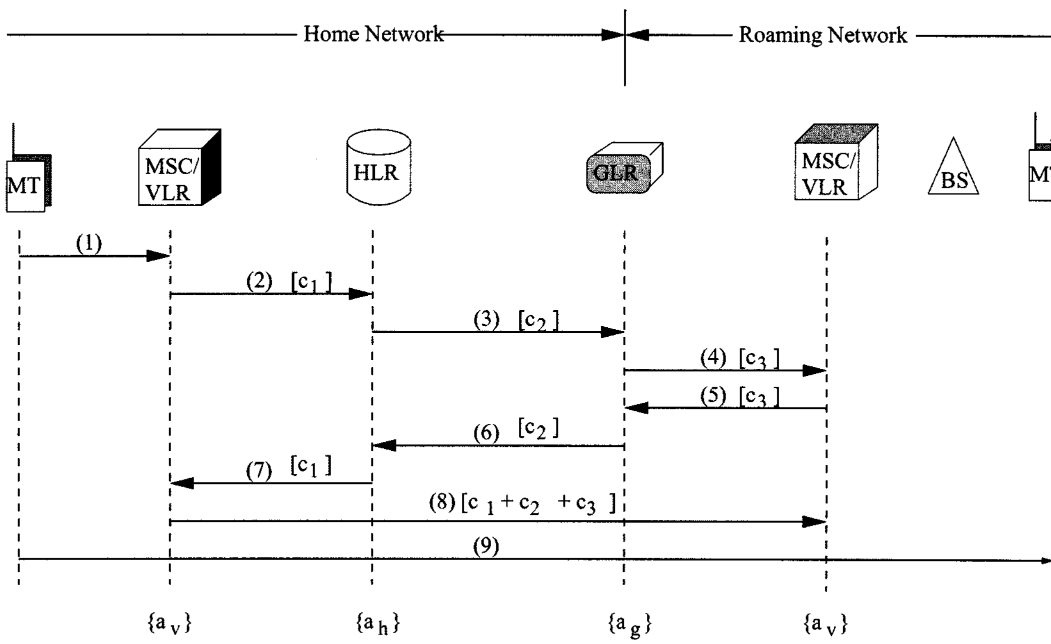


Fig. 3. Process of call delivery using GLR protocol.

3) The GLR transforms this registration message into a location update message, which can be identified by the MT's home network X. The GLR then sends this update request to the HLR in network X.
4) The HLR regards the message from the GLR as a message from a VLR in its home network, sending a request message of insert subscriber data to the GLR.
5) After the GLR receives the update location result from the HLR in X, it generates a message of registration notification and returns it to the serving MSC/VLR.
6) The MSC/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 message to the GLR with security check information.
9) The GLR sends a location update acknowledgment message to the serving MSC/VLR.
10) The registration complete message is sent by the MSC/VLR to the MT through the serving BS.

B. Call Delivery Procedure Using GLR Protocol

The procedure of call delivery under the GLR protocol is described as follows and is shown in Fig. 3.

1) A call is initiated by a user at its home mobile network X and it is forwarded to its serving MSC/VLR through the serving BS.

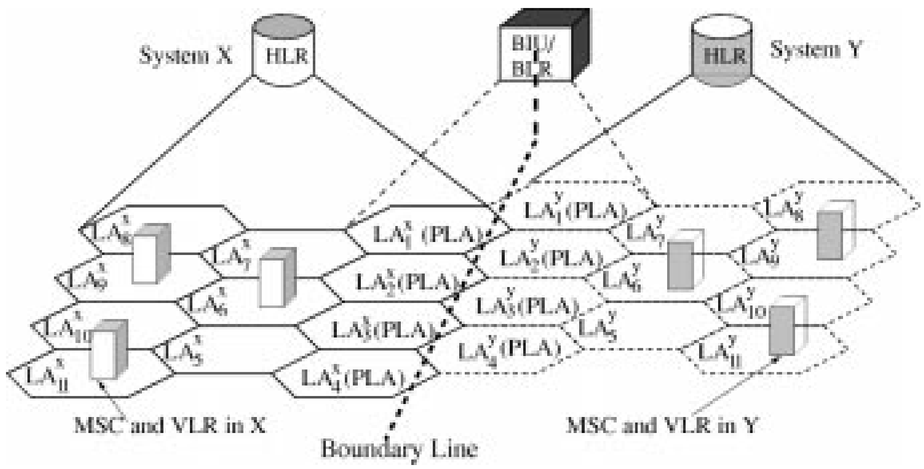


Fig. 4. System model with boundary location register (BLR).

2) The MSC/VLR sends a routing information request to the HLR asking for the routing number of the called MT.
3) The HLR reviews its records and recognizes that the called MT has moved to another network Y during the called MT's registration. Then the HLR initiates a request message of routing information to 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 to the GLR with the roaming number.
6) The GLR forwards the roaming number to the HLR as an acknowledgment message.
7) The HLR sends the routing information to the serving MSC/VLR of the calling MT in network X.
8) The call connection is set up between two MSCs in two networks X and Y.
9) The call is delivered to the called MT through the BSs.

As discussed in [4], the subscribers' data are available in the GLR and can be accessed by the VLRs in network Y. Thus, when the MT moves from the service area of an MSC/VLR to another, it does not need to access HLR each time. If a call is originated from a user in a wired network, e.g., Public Switched Telephone Network (PSTN), the call is delivered to the Gateway MSC (GMSC) first, then the GMSC sends and receives the routing information instead of an MSC/VLR in the mobile network.

III. The New Signaling Protocol for Intersystem Roaming

The existing GLR protocol is a passive signaling protocol for location registration because the presence of a roaming MT from other networks is indicated by receiving an update message at the GLR. In other words, the MTs send location registration after they arrive at the new system and request a location update. The GLR protocol is capable of establishing the registration procedure and allows for an MT to initiate a call after it finishes location registration in the new system. However, the GLR protocol is not suitable for ongoing call connections during intersystem roaming. When an MT has an active call while crossing the boundary of two networks, the MT still needs to request location registration after it receives signals from the new system. As a result, the existing connection is very likely to be interrupted or it may be lost. In addition, the incoming calls are always delivered to the old system regardless of whether an MT has moved to a new system or not. It is not clearly shown in [1] how to avoid this overhead of signaling costs and processing time under the GLR protocol. Moreover, it may cause the triangular call routing problem, i.e., an incoming call for a roaming MT from another MT in the same network will be routed to the previous network first and then it will be delivered to the roaming MT in the new network. It is obvious that this problem can be resolved if the network is aware of the roaming MT's location before the call delivery.

In order to solve the above problems, we present a new location registration scheme, called the BLR protocol, in which the location registration can be finished prior to the arrival of an MT at the new system.

A. Boundary Location Register (BLR)

As an example, we illustrate two systems X and Y using different protocols in Fig. 4. Note that some LAs may be on the boundary of two adjacent systems, e.g., LA_1^X, 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 be observed that the MTs can move from system X to Y only through these PLAs. For example, if there are four PLAs in system X with regard to system Y, an MT must go through one of these PLAs to arrive at system Y. Since we are focusing on the intersystem roaming problem, an MT of X is assumed in one of the PLAs so that it is possible to proceed to system Y.

In each system, there is an HLR with which an MT is permanently associated. The location registration of the intersystem is controlled by a *boundary interworking unit* (BIU) [14]. The 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 coordi-

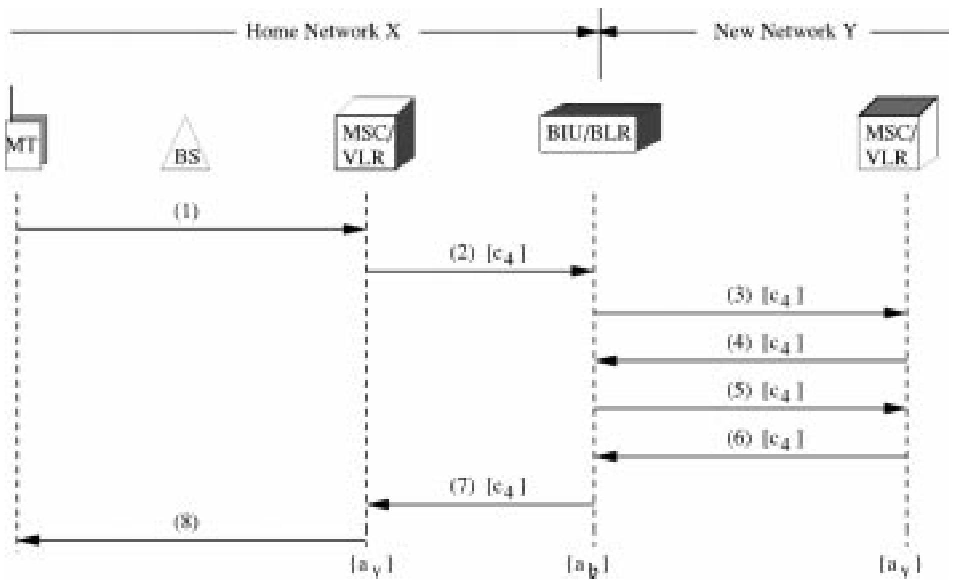


Fig. 5. Process of location registration/update using BLR protocol.

nating. Also, 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 colocated to handle the intersystem roaming of MTs. Another advantage of the BLR is that it reduces the zigzag effect caused by intersystem 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 the BLR. On the other hand, 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.

Each BLR may store the information of MTs crossing the boundary in several PLAs; therefore, the MTs crossing between different systems can be found in the corresponding BLR. If a system has more than one neighboring system, there are more than one BLRs for this system. Each of these BLRs is associated with one neighboring system. Since the registrations with any PLA update the MT's location information in the HLR, the last LA that an MT registers with 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 PLA 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 the 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 make sure that 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 [2].

B. Location Registration/Update Using BLR Protocol

When an MT moves into a PLA of system X, it receives the location information via the broadcast channel. The basic idea of BLR protocol is that the MT can request location registration of intersystem 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 GLR protocol in which the MT requests location registration after it arrives at the new system [14]. Fig. 5 shows the location registration procedure. Each step shown in Fig. 5 is described as follows.

1) The MT sends a location update message to the serving MSC/VLR for intersystem roaming through its serving BS.
2) The serving MSC/VLR sends a location registration message to the BLR along with the user information.
3) The BLR stores the MT's user data and it sends location registration message to the MSC/VLR of the adjacent PLA in Y.
4) The MSC/VLR which covers the PLA in Y sends a message of insert subscriber data to the BIU/BLR.
5) The BLR sends the user profile of the MT to the MSC/VLR in system Y.
6) The MSC/VLR in Y responds to the BLR with a confirmation message.
7) Then the BLR sends a location update acknowledgment message to the MSC/VLR in the PLA of system X.

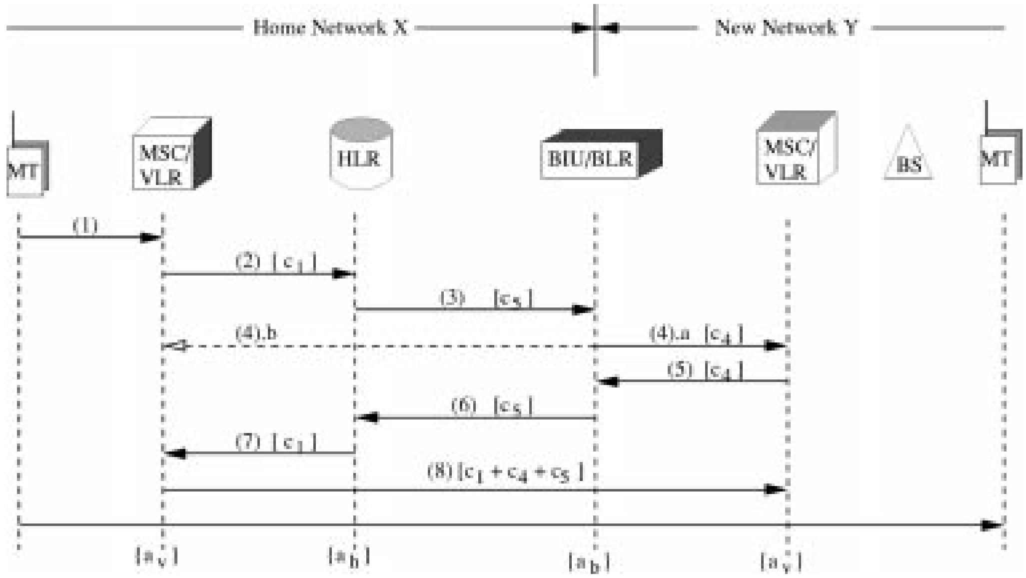


Fig. 6. Process of call delivery using BLR protocol.

8) The registration confirmation message is sent to from the serving MSC/VLR to the roaming MT.

C. Call Delivery Procedure Using BLR Protocol

According to the active location registration procedure of the BLR protocol, the roaming MT's location information is updated in the HLR of its home network. In order for the NG wireless system to establish the call connection for an MT during its intersystem roaming, the signaling messages involve HLRs, VLRs, and the BLR associated with the two systems that the MT goes through. In Fig. 6, the detailed procedure of call delivery is described as follows.

1) A call is initiated by an MT in X and it is sent to the MSC/VLR through the serving BS.
2) The MSC/VLR sends a request of routing number of the called MT to the HLR in X.
3) The procedure of locating the called MT depends on the location information indicated in the HLR of X.

   If the HLR shows that 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 *intrasystem call delivery* in which the call connection is established between the two MSCs serving the called and calling MTs within one system, which is not indicated in Fig. 6.

   If the HLR shows that 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.
4) The BLR shows the serving MSC/VLR of the called MT because the information of the serving MSC/VLR is available due to the registration process.
   a) If the BLR indicates that the called MT has moved to a PLA in Y, the BLR sends a routing request message to the serving MSC/VLR of the called MT in system Y. Otherwise, we have b).
   b) If the BLR indicates that the called MT has not moved to 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 intrasystem call delivery. The signaling (4).b in Fig. 6 does not mean that the called MT and the calling MT are in the coverage area of the same MSC/VLR; instead, it points to any MSC/VLR in system X.
5) The MSC/VLR of called MT responds a routing number to the BLR.
6) The BLR sends 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 serving MSC/VLR of the calling MT.
8) The call connection is set up between two MSC/VLRs.
9) The call is delivered to the called MT.

Although the existing GLR protocol is able to reduce the signaling costs of call delivery, the BLR protocol will be better in the sense of reducing signaling load of location registration while not increasing the signaling costs of call delivery. Moreover, the HLR of the MT's home network must be informed by the GLR when a roaming MT changes its location which is different from the previous MSC/VLR. Under the BLR protocol, the HLR is not involved unless the MT goes through from one PLA to a non-PLA. 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. The new BLR protocol is designed for those MTs with ongoing connections during the intersystem roaming. It enables an MT to update its location and information actively before it arrives at the new system while GLR protocol 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 intersystem roaming MTs are delivered to the serving MSC/VLR 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.

IV. Performance Analysis

In this section we investigate the overall performance in terms of signaling cost and latency of location registration and call delivery, as well as the call losses due to intersystem roaming.

A. 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 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. On the other hand, the processing time consists of two parts. One of them is the retrieval time of a database such as HLR/VLR/GLR/BLR, and the other part is the waiting time for service processing.

As described in the previous Sections III-B and III-C, 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 databases. 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 transmission cost of messages between the HLR and the VLR;
- c_2 transmission cost of messages between the HLR and the GLR;
- c_3 transmission cost of messages between the VLR and the GLR;
- c_4 transmission cost of messages between the VLR and the BLR;
- c_5 transmission cost of messages between the HLR and the BLR;
- p_0 probability that an MT leaves its current PLA to another LA (non-PLA);
- p_1 probability that an MT leaves its current PLA to another PLA;
- p_2 probability that an MT leaves its current PLA for another system, i.e., intersystem roaming. Thus, the probability that an MT remains in the same PLA is $(1-p_0-p_1-p_2)$;
- α weight factor of the transmission cost;
- β weight factor of the access cost of databases such as HLRs, VLRs, GLRs, and BLRs;
- λ rate of incoming calls in Poisson;
- τ 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.

Further, we 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 is $1/\mu_h$ 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 total time including 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.

B. Overhead of Signaling Costs

We analyze different scenarios for location registration and call delivery. The signaling cost for each case of location registration is denoted by $\kappa_i^r(\cdot)$, $(i = 0, 1, 2, 3, 4, 5, 6)$ 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.
- *Case 5*: The MT is currently staying in a PLA of Y, and it is moving to a PLA of system X.
- *Case 6*: The MT remains in the same PLA so there is no extra registration cost.

Under the BLR protocol, 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. Authentication and cancellation are not accounted in the tables. Therefore, the signaling cost related to the transmission cost is $\alpha \cdot 4c_1$, where α is the weight factor of transmission cost. We also 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 weight cost of database access ($\alpha + \beta = 1$). The total cost of this case is then calculated as $\kappa_0^r(\text{BLR}) = 4\alpha c_1 + \beta(a_h + a_v)$ as shown in Table I with probability of p_0 as denoted in Section IV-A. Under *Case 1*, the MTs are moving from a PLA in X to another PLA. Thus, the MT must send location registration request to the BLR. If the MT sends a location update request to the BLR whenever crossing the boundaries of PLAs, then location registration cost is $\kappa_1^r(\text{BLR}) = \alpha 4c_4 + \beta(a_b + a_v)$.

TABLE I
SIGNALING COSTS AND PROBABILITIES FOR LOCATION REGISTRATION

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

TABLE II
SIGNALING COSTS AND PROBABILITIES FOR CALL DELIVERY

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	$p_2 \frac{\lambda_2}{\lambda_1+\lambda_2}$	$3c_1 + 3c_2 + 3c_3$	$a_g + a_h + a_v$	$\alpha(3c_1 + 3c_2 + 3c_3) + \beta(a_g + a_h + a_v)$

In *Case 2*, the MT is experiencing an intersystem roaming. The signaling messages are required between the VLR and the BLR while the HLR is not involved. As shown in Fig. 5, the registration cost is $\kappa_2^r(\text{BLR}) = \alpha(c_4 + c_4 + 4c_4) + \beta(a_b + a_v)$. However, if the GLR protocol is used, the HLR is involved in the location registration procedure as shown in Fig. 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, *Cases 3–5* are very similar to *Cases 0–2* because either the BLR or the GLR has the user profile; thus, the HLR is not involved if the MTs only move within the system Y. The registration costs for each case are summarized in Table I in which the messages involving HLR are marked. Note that the BLR protocol is basically independent of the HLR except the MTs' registration for the first time. Therefore, the traffic load in the HLR is effectively alleviated because the traffic relating to the intersystem roaming is moved to the BLR.

Assume that an MT is currently staying in a PLA of system X, then the average location registration cost, $C^r(\text{BLR})$ and $C^r(\text{GLR})$, can be calculated as

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

Next, we investigate the cost of call delivery. There are three possibilities related to the intersystem roaming, given that the MT's last registration occurs 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 intersystem 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 vffisiting network Y. The incoming calls is Poisson with 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 are Poisson with the 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 in X, BLR, and the VLR in the new system. This results in the total signaling cost as the sum of costs of steps 2)–8) in Fig. 6. Correspondingly, the access cost of databases 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, 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 II.

The average call delivery cost for BLR protocol, $C^d(\mathrm{BLR})$, is obtained by

$$C^d(\mathrm{BLR}) = (1-p_2)\nu_0^d(\mathrm{BLR}) + p_2\frac{\lambda_1}{\lambda_1+\lambda_2}\,\nu_1^d(\mathrm{BLR}) + p_2\frac{\lambda_2}{\lambda_1+\lambda_2}\,\nu_2^d(\mathrm{BLR}) \quad (2)$$

where $\nu_{(\cdot)}^d(\mathrm{BLR})$ is the call delivery cost using BLR protocol. The first item is the product of probability $(1-p_2)$ and $\nu_0^d(\mathrm{BLR})$ in the second row of Table II. In the same way, the other two items are obtained by multiplying $\nu_{(\cdot)}^d(\mathrm{BLR})$ and their corresponding probabilities, $p_2(\lambda_1/(\lambda_1+\lambda_2))$ and $p_2(\lambda_2/(\lambda_1+\lambda_2))$, respectively, in Table II. Under the GLR 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 protocol, $C^d(\mathrm{GLR})$, is then computed from

$$C^d(\mathrm{GLR}) = (1-p_2)\nu_0^d(\mathrm{GLR}) + p_2\frac{\lambda_1}{\lambda_1+\lambda_2}\,\nu_1^d(\mathrm{GLR}) + p_2\frac{\lambda_2}{\lambda_1+\lambda_2}\,\nu_2^d(\mathrm{GLR}) \quad (3)$$

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

C. Latency of Location Registration and Call Delivery

With respect to the location registration process, the end-to-end response time is from the time that 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 IV-B, 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

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

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 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]

$$w_h = \frac{\eta_h\cdot\mu_h^2 + \eta_h\cdot\sigma_h^2}{2\cdot\left(1-\dfrac{\eta_h}{\mu_h}\right)} \quad (5)$$

TABLE III
LATENCY OF LOCATION REGISTRATION

Case i		Probability	Latency $\delta_i^r(\cdot)$
0	BLR	p_0	s_h+s_v
	GLR	p_0	s_h+s_v
1	BLR	p_1	s_b+s_v
	GLR	p_1	s_h+s_v
2	BLR	p_2	s_b+s_v
	GLR	p_2	s_g+s_h
3	BLR	p_0	s_b+s_v
	GLR	p_0	s_g+s_v
4	BLR	p_1	s_b+s_v
	GLR	p_1	s_g+s_v
5	BLR	p_2	s_b+s_v
	GLR	p_2	s_h+s_v
6	BLR/ GLR	$1-p_0-p_1-p_2$	0

TABLE IV
LATENCY OF CALL DELIVERY

Case j		Probability	Latency $\phi_j^d(\cdot)$
0	BLR	$1-p_2$	$s_h+s_v+\tau$
	GLR	$1-p_2$	$s_h+s_v+\tau$
1	BLR	$p_2\frac{\lambda_1}{\lambda_1+\lambda_2}$	$s_b+s_h+s_v+\tau$
	GLR	$p_2\frac{\lambda_1}{\lambda_1+\lambda_2}$	$s_g+s_h+s_v+\tau$
2	BLR	$p_2\frac{\lambda_2}{\lambda_1+\lambda_2}$	$s_b+s_v+\tau$
	GLR	$p_2\frac{\lambda_2}{\lambda_1+\lambda_2}$	$s_g+s_h+s_v+\tau$

where σ_h^2 is the variance of processing time in the HLR. The processing time or the so-called service time of the HLR, s_h, can be computed from

$$s_h = \frac{1}{\mu_h} + w_h = \frac{1}{\mu_h} + \eta_h\frac{\mu_h^2+\sigma_h^2}{2\cdot\left(1-\dfrac{\eta_h}{\mu_h}\right)} \quad (6)$$

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 I can be calculated by considering the processing time $s_{(\cdot)}$ instead of $a_{(\cdot)}$ of each entity as shown in Tables III and IV. For example, the delay of location registration for *Case 1* with the BLR protocol, $\delta_1^r(\mathrm{BLR})$, is the combination of delay of accessing BLR and the VLR

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

where the first two items are the processing time of the BLR consisting of service time $1/\mu_b$ and waiting time $w_b = \eta_b(\mu_b^2+\sigma_b^2)/(2\cdot(1-(\eta_b/\mu_b)))$. The last two items are the processing time of a VLR which are composed of service time $1/\mu_v$ and waiting time $w_v = \eta_v(\mu_v^2+\sigma_v^2)/(2\cdot(1-(\eta_v/\mu_v)))$. These formulas are obtained by the same way as (6). Therefore, the

TABLE V
PERFORMANCE ANALYSIS PARAMETERS

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

average delay for location registration using BLR protocol and GLR protocol, $D^r(\text{BLR})$, and $D^r(\text{GLR})$ are

$$\begin{aligned} D^r(\text{BLR}) &= p_0\,\delta_0^r(\text{BLR}) + p_1\delta_1^r(\text{BLR}) \\ &\quad + p_2\delta_2^r(\text{BLR}) \\ D^r(\text{GLR}) &= p_0\,\delta_0^r(\text{GLR}) + p_1\delta_1^r(\text{GLR}) \\ &\quad + p_2\delta_2^r(\text{GLR}) \end{aligned} \tag{8}$$

which are computed in a similar way as for (1)–(3) and (7).

For 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 the BLR and GLR protocols, which is the sum of s_h, s_v, and τ as shown in Figs. 3 and 6. That means

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

In the same way, the latency of call delivery for *Cases 1* and *2* can be computed. Therefore, the average delay for call delivery using BLR protocol and GLR protocol, $D^d(\text{BLR})$, and $D^d(\text{GLR})$ are

$$\begin{aligned} D^d(\text{BLR}) &= (1-p_2)\phi_0^d(\text{BLR}) + p_2\frac{\lambda_1}{\lambda_1+\lambda_2}\,\phi_1^d(\text{BLR}) \\ &\quad + p_2\frac{\lambda_2}{\lambda_1+\lambda_2}\,\phi_2^d(\text{BLR}) \\ D^d(\text{GLR}) &= (1-p_2)\phi_0^d(\text{GLR}) + p_2\frac{\lambda_1}{\lambda_1+\lambda_2}\,\phi_1^d(\text{GLR}) \\ &\quad + p_2\frac{\lambda_2}{\lambda_1+\lambda_2}\,\phi_2^d(\text{GLR}) \end{aligned} \tag{10}$$

where $\phi_j^d(\cdot)$ can be obtained in the same way for (9). Then $D^d(\cdot)$ can be computed in a similar way as in (1)–(3).

D. 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 intersystem 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 protocol. Under the BLR protocol, the MTs are allowed to request location registration before they arrive at the new network by sending requests 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 simplicity, we assume that $\Delta t = \gamma * w_b$, where w_b is the average waiting time for an MT to finish the process of intersystem location registration. γ is a constant, which can be changed upon the requirements of QoS. However, if Δt is too large, which means that an MT requests a location update long before it arrives at the new system, the MT may change its location again, resulting in the waste of location registration. The details of determining Δt can be found in [3].

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

$$W_B^*(s) = \frac{1-\rho_b}{1-\rho_b\left[\dfrac{1-B_b^*(s)}{s/\mu_b}\right]} \tag{11}$$

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 M/G/1 model. For the special case M/M/1, the corresponding probability distribution function (PDF), $W_b(y)$ is obtained by

$$W_b(y) = 1 - \rho_b e^{-\mu_b(1-\rho_b)\cdot y}. \tag{12}$$

Thus, the call loss rate due to intersystem roaming, $R_l(\text{BLR})$, is obtained by

$$R_l(\text{BLR}) = p_2 \cdot \text{prob}[y > \Delta t] = p_2 \cdot [W_b(\infty) - W_b(\Delta t)] \tag{13}$$

where p_2 is the roaming probability, relating the system architecture of the home network of an MT and the MT's current velocity and so on [3]. $W_b(\infty)$ and $W_b(\Delta t)$ are obtained by applying (12). Similarly, the call loss rate for GLR protocol, $R_l(\text{GLR})$, are computed from

$$R_l(\text{GLR}) = p_2 \cdot \text{prob}[y > 0] = p_2 \cdot [W_g(\infty) - W_g(0)] \tag{14}$$

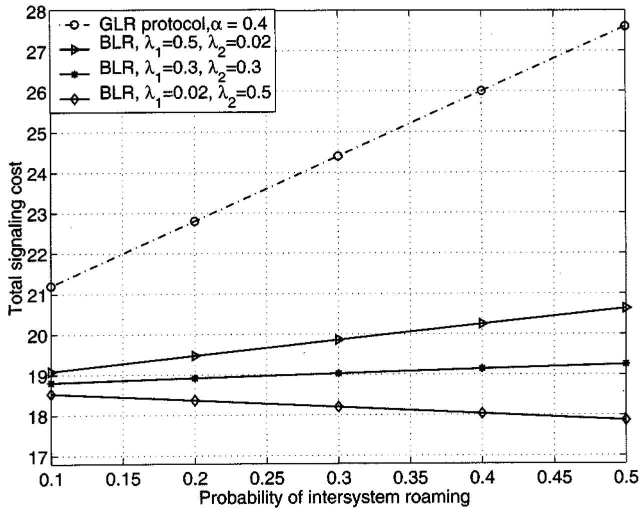
where $W_g(\infty)$ and $W_g(0)$ are calculated from $W_g(y) = 1 - \rho_g e^{-\mu_g(1-\rho_g)\cdot y}$ for the GLR protocol.

V. NUMERICAL RESULTS

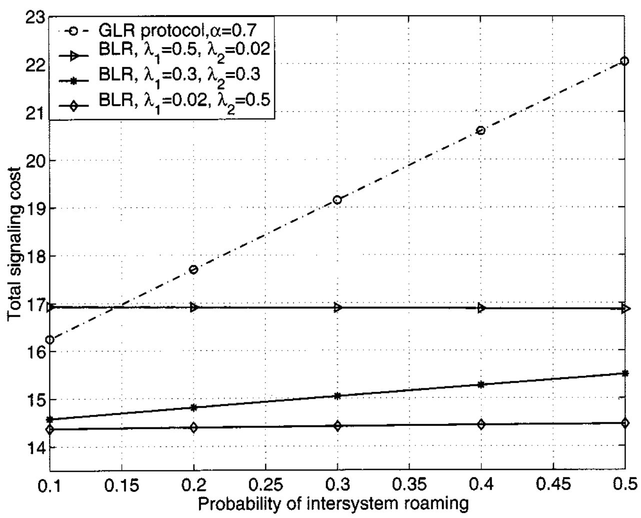
In this section, numerical results are provided to demonstrate the performance of intersystem roaming supported by the GLR protocol and the BLR protocol. We assume that the cost for transmitting signaling messages and the cost for database access are available. Table V lists all parameters used in our performance analysis [9], [18]. We compare the average signaling cost and delay dependent on intersystem roaming probabilities for GLR and BLR protocols.

A. Total Signaling Cost

Fig. 7 shows the comparison of total signaling cost as a function of intersystem roaming probability by using (1)–(3). The total signaling cost is composed of average cost of location



(a)



(b)

Fig. 7. Total cost of location registration and call delivery versus intersystem roaming probability.

registration and that of call delivery. To compare the effect of weight factor α and β, two cases of $\alpha = 0.4$ and $\alpha = 0.7$ are shown in Fig. 7(a) and (b), respectively. When the access cost of database dominates the total cost, the BLR protocol yields less signaling cost than the GLR protocol regardless of the origination of incoming calls to a roaming user as shown in Fig. 7(a), where we assume that $p_0 = p_1 = (1 - p_2)/2$ in the calculation.

We can also observe that, as the intersystem roaming probability increases, the total signaling cost of BLR protocol increases or decreases slightly, depending on the distribution of incoming calls. Sometimes, the registration cost decreases because we consider that if an MT is in a PLA of X, which will either go to other LAs in system X or to a new system Y. When the intersystem roaming probability is small, the registration cost is dominated by intrasystem roaming between different LAs, involving HLR and VLR access. On the other hand, the intersystem location registration only involves BLR and VLR. 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

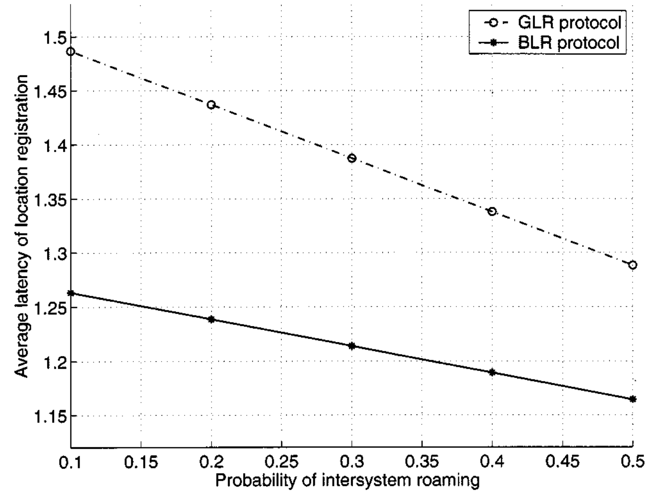


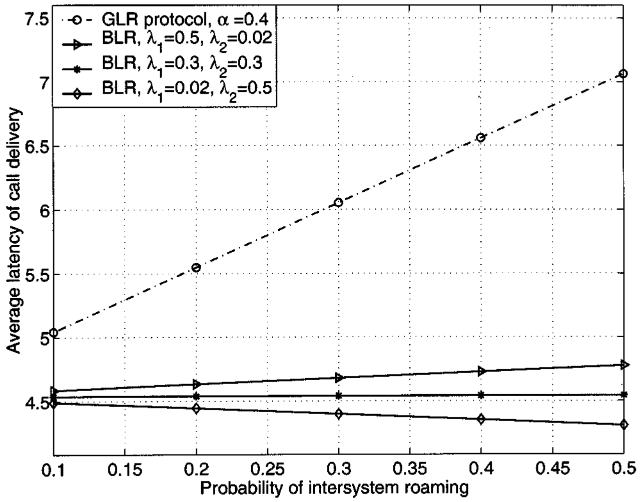
Fig. 8. Average latency of location registration.

of the BLR, causing higher registration cost. If the intersystem 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 protocol with which the cost increases as the roaming probability increases.

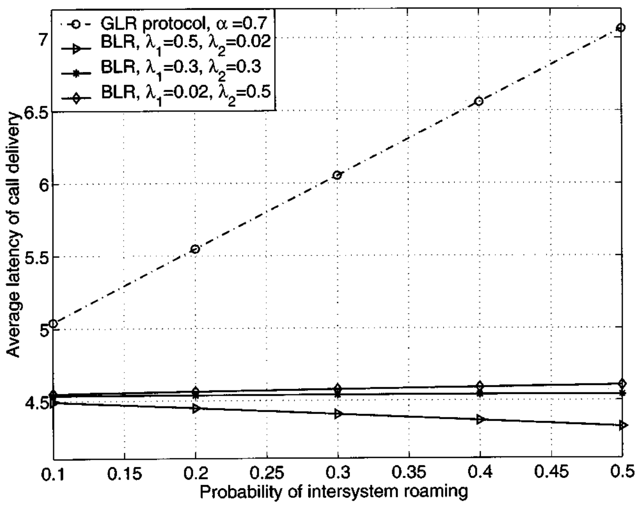
Fig. 7(b) reveals the comparison of total cost when $\alpha = 0.7$, which means the transmission cost is the major part of the total cost. If most of the incoming calls are initiated by the users in the MT's home network X, the total cost resulting from the BLR protocol does not change too much as the roaming probability increases. It is even slightly higher than that of the GLR protocol when the roaming probability is small. Actually, in this case, the registration cost increases with the increasing roaming probability, but the cost of call delivery decreases. The effect is that the total cost decreases with the increasing roaming probability very slowly. When the incoming call is not dominated by those users in the home network X, the total cost of BLR protocol is less than that of the GLR protocol. Therefore, BLR protocol reduces the total signaling cost so that it is more suitable for an intersystem roaming environment.

B. Latency

The latency of location registration is shown in Fig. 8 in which we observe that the BLR protocol causes less delays than the GLR protocol does. Similar to the case of total signaling cost, the latency of location registration of the BLR protocol decreases with the increasing intersystem roaming probability. In the same way as for the registration cost, it is associated with BLR and VLR. When intersystem roaming probability is small, the registration delay is mainly determined by accessing the HLR while it is dominated by accessing the BLR when intersystem roaming probability is high. Considering that the retrieving delay of HLR is higher than that of the BLR, the delays are decreased with the increasing intersystem roaming probabilities. Fig. 9 demonstrates the latency of call delivery as a function of intersystem roaming probability using (8) and (10) for $\alpha = 0.4$ and $\alpha = 0.7$ where the changes in the latency of call delivery are very small.

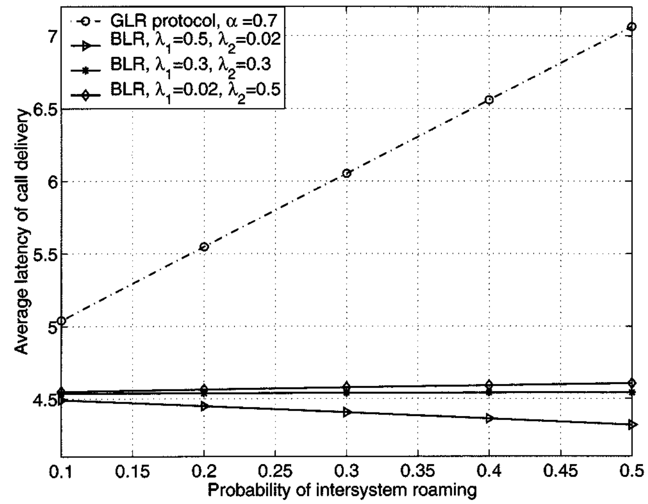


(a)

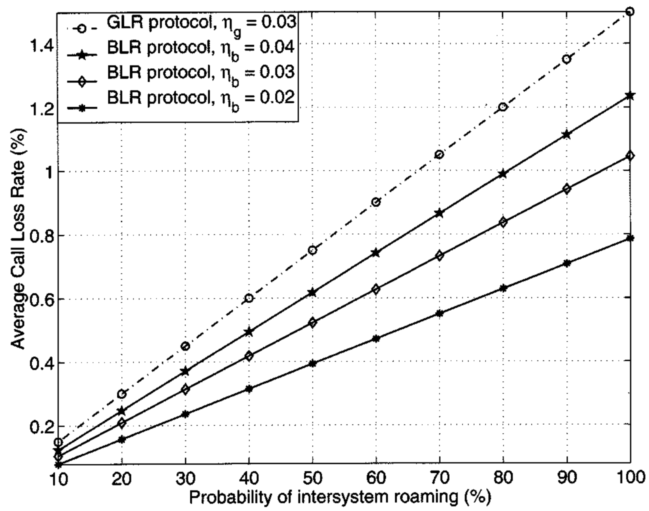


(b)

Fig. 9. Average latency of call delivery.



(a)



(b)

Fig. 10. Comparison of call losses versus intersystem roaming probability.

C. Comparison of Call Loss Rates

The main difference between the BLR protocol and the GLR protocol is that the former allows the MTs to perform location registration/update before they arrive at the new system. As a result, the call losses of ongoing calls may be reduced. To study this effect, we show the comparison of call losses with different Δt as a function of intersystem roaming probabilities in Fig. 10, which are obtained from (13) and (14). We assume that the incoming or outgoing calls would be lost if an MT cannot finish its intersystem location registration. Thus, if the GLR protocol is used, the incoming or outgoing calls may be lost due to the latency of registration process. However, when the BLR protocol is used, the MTs may initiate location registration before they arrive at the new network. Thus, the call loss rates can be reduced. In Fig. 10(a), the call losses of the BLR protocol are smaller than that of the GLR protocol for the same arrival rate. If Δt increases as shown in Fig. 10(b), the effect of the BLR protocol is even more visible. For the same arrival rate, the improvement is up to 40%. Therefore, we can conclude that the BLR protocol outperforms the GLR protocol with respect of call losses of ongoing services during intersystem roaming.

VI. CONCLUSION

In this paper, we introduced a new signaling protocol for mobility management, which is based on the new concept of BLR. We proposed the detailed procedure of location registration and call delivery for the BLR protocol. This protocol is specifically developed to maintain ongoing calls which are not well supported in the current GLR protocol. To summarize the comparison of BLR and GLR protocol, we measured the signaling cost that is defined in terms of number of messages that are exchanged to complete the operation of location registration and call delivery, and the database access costs at HLR, VLR, GLR, and BLR. Moreover, we evaluated the latency of location registration and call delivery, which is composed of waiting time and processing time at a specific database. Furthermore, we analyzed call losses of ongoing services due to the intersystem roaming. The numerical results demonstrated that the BLR protocol is able to reduce the signaling costs and the latency of location registration and call delivery, as well as the call loss rates for the MT's moving across different networks.

REFERENCES

[1] ETSI TS 129 120 V3.0.0, "Universal mobile telecommunications systems (UMTS); mobile application part (MAP) specification for gateway location register (GLR); stage 3,", 3GPP/ETSI 2000, 2000–2003.

[2] I. F. Akyildiz, J. McNair, J. S. M. Ho, H. Uzunalioğlu, and W. Wang, "Mobility management in next-generation wireless systems," *Proc. IEEE*, vol. 87, pp. 1347–1384, Aug. 1999.

[3] I. F. Akyildiz and W. Wang, "A dynamic inter-system location management scheme for next generation multi-tier PCS systems," *IEEE J. Selected Areas Commun.*, to be published.

[4] A. Bertrand, "Jambala mobility gateway—Convergence and inter-system roaming," *Ericsson Rev.*, no. 2, pp. 89–93, 1999.

[5] S. Dixit and Z. Antoniou, "Resource management and quality of service in third-generation wireless networks," *IEEE Commun. Mag.*, vol. 39, pp. 125–133, Feb. 2001.

[6] V. Garg and J. E. Wilkes, "Interworking and interoperability issues for North American PCS," *IEEE Commun. Mag.*, vol. 34, pp. 94–99, Mar. 1996.

[7] J. S. Ho and I. F. Akyildiz, "Dynamic hierarchical database architecture for location management in PCS networks," *IEEE/ACM Trans. Networking*, vol. 5, pp. 646–660, Oct. 1997.

[8] L. Kleinrock, *Queueing Systems Volume 1: Theory*: Wiley, 1975.

[9] K. K. Leung and Y. Levy, "Global mobility management by replicated databases in personal communication networks," *IEEE J. Select. Areas Commun.*, vol. 15, pp. 1582–1595, Oct. 1997.

[10] A. R. Modarressi and S. Mohan, "Control and management in next-generation networks: Challenges and opportunities," *IEEE Commun. Mag.*, vol. 38, pp. 94–102, Oct. 2000.

[11] T. Nillson, "Toward third-generation mobile multimedia communication," *Ericsson Rev.*, no. 3, pp. 122–131, 1999.

[12] S. G. Niri and R. Tafazoli, "Cordless—Cellular network integration for the 3rd generation personal communication systems," in *IEEE VTC'98*, Ottawa, Canada, May 1998, pp. 402–408.

[13] S. Suzuki, T. Shibata, and M. Yoshimi, "PHS roaming signaling protocol architecture toward global mobility network," *IEEE J. Select. Areas Commun.*, vol. 15, pp. 1597–1607, Oct. 1997.

[14] W. Wang and I. F. Akyildiz, "Intersystem location update and paging schemes for multitier wireless networks," in *ACM/IEEE MobiCom 2000*, Aug. 2000, pp. 99–109.

[15] ——, "A cost-efficient mobility application part (MAP) protocol for IMT-2000 systems," in *ACM/IEEE MobiCom'01*, July 2001, pp. 345–356.

[16] S. M. Walters, "Interworking in the next millennium," *IEICE Trans. Commun.*, vol. E80-B, pp. 1383–1385, Oct. 1997.

[17] A. Yamaguchi, S. Ota, Y. Ito, M. Ohashi, and F. Watanabe, "Inter-system mobility and service management in GSM/PDC roaming," in *IEEE GLOBECOM'97*, Nov. 1997, pp. 694–698.

[18] M. Zeng, A. Annamalai, and V. K. Bhargava, "Recent advances in cellular wireless communications," *IEEE Commun. Mag.*, vol. 37, pp. 128–138, Sept. 1999.

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