Performance Analysis of the Distributed Location Management Scheme in Large Mobile Networks

Dong Chun Lee*, Hong-Jin Kim, Jong Chan Lee***, and Yi Bing Lin******

Abstract: In this paper we propose a distributed location management scheme to reduce the bottleneck problem of HLR in Large Mobile Networks (LMN). Using analytical modeling and numerical simulation, we show that replicating location information is both appropriate and efficient for small mobile networks. Then, we extend the scheme in a hierarchical environment to reduce the overhead traffic and scale to LMN. In numerical results, we show the superiority of our scheme compared to the current IS-95 standard scheme in IMT-2000 networks.

Keywords: Distributed Location Management, LMN, Performance Analysis, IMT-2000

1. Introduction

One of the challenging tasks in an LMN is to efficiently maintain the location of LMN subscribers who move freely with their wireless units, called Mobile Hosts (MH) in North America; the Telecommunications Industry Association Interim Standard IS-95 [1, 2] is used for managing the location information of subscribers and enabling them to send and receive calls and other services such as message service and data service.

In mobile networks [3], each subscriber is registered with a home network, the Home Location Register (HLR) of which maintains the subscriber's current physical location. As for the IS-95 scheme in IMT-2000 networks, this physical location is the ID of the Mobile Switching Center (MSC) currently serving the subscriber. If the subscriber has roamed to another region, he/she must register with the Visitor Location Register (VLR) that covers the new region. During registration, the VLR will contact the subscriber's HLR, and the HLR will update its database to reflect the new location of the subscriber. If the mobile has registered with a different VLR before, the HLR will send it a message canceling registration. Thus, the HLR is a critical entity in the IS-95 location management system. There are many disadvantages to having a centralized location management (e.g., bottleneck problem) such as the scheme used in IS-95 scheme.

A number of works have been reported to reduce the bottleneck problem of the HLR. A Caching Strategy is introduced in [25], which reduces the cost for call delivery by reusing cached information about a called user's location from a previous call. In [23, 24], a Location Forwarding Strategy is proposed to reduce the signaling costs for location registration. A local anchoring scheme is introduced in [14, 17]. Under these schemes, signaling traffic due to location registration is reduced by eliminating the need to report location changes to the HLR. Location update and Paging subject to delay constraints are considered in [20]. When an incoming call arrives, the residing area of the terminal is partitioned into a number of sub-areas, then these sub-areas are polled sequentially. While increasing the delay time needed to connect a call, the cost of the location update is reduced. Hierarchical database system architecture is introduced in [16]. A queuing model of a three-level hierarchical database system is illustrated in [22]. These schemes can reduce both signaling traffic due to location registration and call delivery using the properties of call locality and local mobility. A user profile replication scheme is proposed in [18]. Based on this scheme, user profiles are replicated at selected local databases. If a replication of the called terminal's user profile is available locally, no HLR query is necessary. When the terminal moves to another location, the network updates all replications of the terminal's user profile. In this paper, we propose this distributed location management scheme. In order scale to LMN, we extend our scheme by organizing the Location Registers (LRs) hierarchically so as to reduce the cost of updating location information.

The paper is organized as follows. Section 2 and Section 3 analyze our location management scheme for non-hierarchical network and compare it to the IS-95 scheme. Performance analysis in a non-hierarchical network is presented in Section 4. Section 5 extends our scheme to hierarchical networks. Section 6 analyzes this hierarchical extension and the numerical results are then presented in Section 7. Section 8 concludes the paper.

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2. IS-95 Standard Mobility Management

As for IS-95 scheme in IMT-2000 networks [1], an incoming call is routed to the called subscriber as follows. The dialed call is received by the MSC in the home system. This MSC is called the originating MSC. If the MH is currently being served by the originating MSC (i.e. the MH is not roaming), this MSC queries the HLR to obtain the registration status and feature information of the MH. After receiving a response from the HLR, the originating MSC pages the mobile host. When the MH responds (i.e. the subscriber accepts the call by pressing the proper button), the originating MSC sets up the circuit to terminate the call to the MH.

Fig. 1 shows how a call is delivered to a roaming mobile host. As before, when a call to a mobile is dialed, the call is first routed to the originating MSC. The originating MSC then sends a location request message to the HLR to discover the current location of the mobile. The HLR, in turn, sends a route request message to the VLR that is currently serving the mobile. The VLR then sends a route request message to the MSC that is currently serving the mobile. The VLR then sends a route request message to the MSC that is currently serving the mobile. The serving MSC creates a Temporary Location Directory Number (TLDN) and returns it to the VLR. The TLDN is then passed back to the originating MSC through the HLR. The originating MSC then routes the call using this TLDN. When the serving MSC receives a call routed using the TLDN, it pages the MH. If the mobile responds, the call is terminated at the mobile.

Thus, the HLR is a critical entity in the IS-95 location management system. There are many disadvantages to having a centralized location management scheme such as the scheme used in the IS-95 scheme. One disadvantage is that every location request as well as location registration is serviced through an HLR; in addition to the HLR being overloaded with database lookup operations [4], traffic on the links leading to the HLR is heavy. This, in turn, increases the time required to establish a connection to a mobile host. Another disadvantage is that any HLR system failure causes all mobiles registered with the HLR to be unreachable even though the mobiles may be roaming and away from the HLR region. Thus, the HLR is a single point of failure in the network.

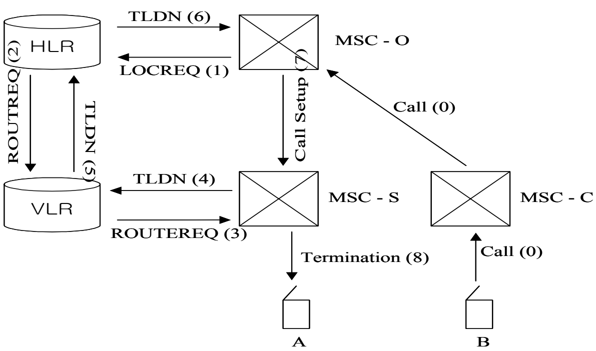

Fig. 1. Call Delivery in IS-95 standard

There is also another disadvantage which is generally referred to as a *tromboning problem*. Consider the situation depicted in Fig. 1. Subscriber A's home MSC is MSC-O, and A, currently roaming and being served by MSC-S, makes a call to the local exchange carrier. But MSC-O (A's home MSC) is geographically far from both the MSC-C and MSC-S and connected to them by a long distance carrier. Routing the call from B to A involves two long distance legs, one between the MSC-C and MSC-O, and the other between the MSC-O and MSC-S. The latter leg is used twice, first to obtain the TLDN, then to provide the voice/data connection.

3. Distributed Location Management

We present a novel approach for efficient location management by distributing the location information across Location Registers (LRs). These LRs replace the centralized VLRs and HLRs which are found in current mobile networks. Thus, a unique feature of our proposed scheme is availability (fault-tolerance) by not having the concept of "home." Since there are no HLRs or VLRs in this system, each LR maintains the location information not only of the mobiles that are local to it, but also of other mobiles in the network. That is, the location information of all MHs is fully replicated in all the LRs. The LRs are distributed throughout the network. An LR may serve one or more MSCs just like the VLR in the mobile network architecture. An LR/VLR may also co-exist with an MSC, and serves only that MSC. The LRs function as both the location registry for the local MHs as well as the lookup directory for the location of other MHs. The type of location information maintained for an MH depends on whether the mobile is local to the LR or not. For local MHs and MHs that are not local, LR maintains the id of the LR where the MH currently resides. When a mobile registers with an LR, the new location information is disseminated to all other LRs in the network. This dissemination is carried out in parallel through the whole network so that the new location is very quickly updated at all LRs. When a call request arrives at the local LR, this LR can contact the serving LR (cf. Fig. 2) directly, thus avoiding the *tromboning problem* present in the current IS-95 standard. We analyze this distributed location management scheme.

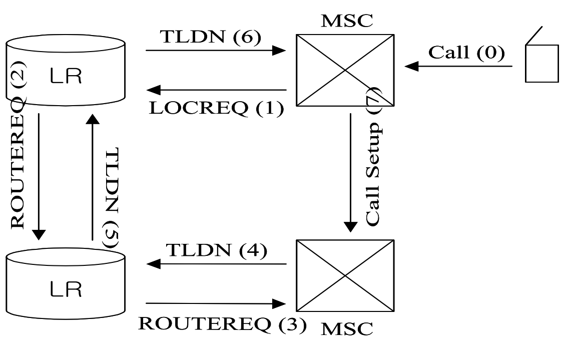

Fig. 2. Call Delivery in our distributed location management

In order to scale to the LMN, we extend our scheme by organizing the LRs hierarchically to reduce the cost of updating location information.

4. Performance for a Non-Hierarchical Distributed Network

We analyze our proposed distributed location management scheme and compare it with that of the IS-95 scheme. For simplicity, it is assumed that there is only one MSC per service area, and the LR/VLR is collocated with the MSC. Thus, we use the LR to indicate an MSC/LR combination, and the VLR to indicate an MSC/VLR combination. In both schemes (fully replicated and IS-95), the total cost consists of the update cost and the location tracking cost (Find cost). The update cost covers all the costs involved in MH registration and the location update. In the case of distributed location management, the update cost also includes the cost involved in the dissemination of location information. The location tracking cost covers all the costs involved in terminating a call to the MH. In the case of the IS-95 standard, the location tracking cost consists of all the costs involved in the call termination as depicted in Figure 1. However, since we have assumed that the VLR is co-located with the MSC, the location tracking cost basically consists of the cost of signaling between the originating area VLR and HLR, and of signaling between the HLR and serving VLR. In order to compare the cost efficiency of our distributed scheme and the IS-95 scheme, we use the expected total cost incurred for an MH while it is in a single LR (or VLR) service area as the comparison metric. The total cost includes the update cost incurred for registering the MH when it moved into the LR (or VLR) service area, and the location tracking cost incurred for every call terminated to the MH while it is in this service area and before it moves to another service area.

In the IS-95 scheme, the update involves the new VLR registering the MH with its HLR, and the HLR sending a registration cancellation to the old VLR. Hence the update cost, $C_{\text{Update IS-95}}$ is given by:

$$C_{Update_{IS-95}} = Cost(VLR_{new} \leftrightarrow HLR) + Cost(HLR \leftrightarrow VLR_{old}) \quad (1)$$

Assuming the time to register with the HLR is very short (i.e. the probability that a location request to the HLR will fall during the registration time is negligible), the location tracking cost, $C_{Lacation\ tracking\ IS-95}^{roa\min g}$ of a roaming mobile is given by (cf. Fig 1):

$$C_{Location\ \text{tracking}_{IS-95}^{roam}} = Cost(VLR_{Caller} \leftrightarrow VLR_{orig}) + Cost(VLR_{orig} \leftrightarrow HLR) + Cost(HLR \leftrightarrow VLR_{callee}) \quad (2)$$

and for a non-roaming MH, the location tracking cost, $C_{Lacation\ tracking\ IS-95}^{non-roa\min g}$ is given by:

$$C_{Location\ \text{Tracking}_{IS-95}^{non-roam}} = Cost(VLR_{caller} \leftrightarrow VLR_{orig}) + Cost(VLR_{orig} \leftrightarrow HLR) \quad (3)$$

Here, VLR $_{\text{caller}}$ is the MSC/VLR where the call is generated, VLR $_{\text{orig}}$ is the home MSC/VLR of the MH, and VLR $_{\text{callee}}$ is the MSC/VLR that is currently serving the roaming MH.

5. Hierarchical Location Management

Our distributed location management scheme requires that new location information about all mobiles be disseminated to all the LRs in the network. As the size of the network grows, the dissemination of location information not only consumes a significant portion of the network bandwidth, but also consumes a significant portion of the LR resources to process a large number of update messages. In addition, the gain of employing full dissemination diminishes with the size of the network. That is, for a large network, it is impractical to have a location management scheme based on full dissemination of location information. Full dissemination of location information can be avoided by logically arranging the LRs in a hierarchical fashion - a tree structure, as in [10], or a cluster-super cluster arrangement, as in [11]. The idea here is to divide the LRs into a hierarchy of clusters, and confine the dissemination of location information within the clusters as much as possible. This section analyzes the performance of our distributed location management in a hierarchical environment and assesses its applicability and benefits. Our scheme is different from other hierarchical schemes (e.g., [6]) in that its goal is not only to reduce the overhead of location management, but also to uniquely provide high availability through the (selective) replication of location information.

Fig. 3 shows the conceptual arrangement of the LRs in a hierarchical network under our proposed scheme. The proposed approach uses distributed location management. The MHs are not associated with an HLR such as in the IS-95 standard. Each LR maintains the location information of the entire mobile that is currently being served in the sub-tree rooted from the LR. It also maintains the location of the mobiles that belong to the sub-tree rooted from its sibling LRs. Note here that a sub-tree rooted from a leaf node contains only that leaf node. If an MH is being served by one of the descendants of an LR, the LR maintains the ID of its immediate child LR, whose sub-tree contains the MH, to track the MH. Referring to Fig. 3, if an MH is in the service area of LR D, the location information in LR C for the MH would point to LR D, but the location information in LR B for the same MH would point to LR C. For MHs that reside in the sub-tree of a sibling, the LR maintains its sibling's ID to track the MH. That is, location information in LR F for the MH served by LR D would be LR C. In this manner, the location information of an MH is only maintained by the following LRs: serving LR of the

MH, sibling LRs of the serving LR, ancestor LRs of the serving LR, and sibling LRs of the ancestors. That is, the location information of the MH being served by D is maintained only in LRs D, E, C, F, B, and so on. LRs A and G do not maintain the location information for that MH.

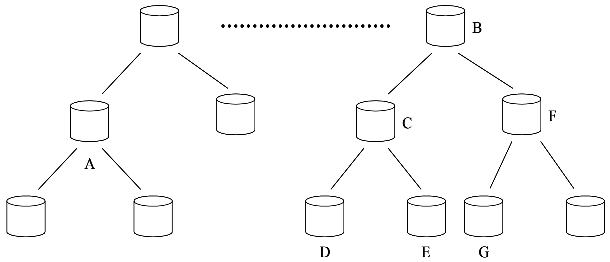

Fig. 3. Conceptual diagram in the hierarchical arrangement

Tracking the LR serving an MH involves traversing the LR tree hop-by-hop until the serving LR is reached. If the location entry for a MH does not exist in an LR, the tracking request is reached. That LR forwards the tracking request to the LR pointed out by the location information. Here, the location tracking traverses laterally. From there, it traverses downwards until the LR currently serving the MH is reached. For example, if G were to track the LR of an MH being served by D, G forwards the tracking request to F. F forwards the request to C, which forwards it to D. This information is returned to G.

For registration and location update algorithm, the MHs identify their current LR by the periodic beacon message broadcasted by the base stations. If the MH receives a beacon message with a different service area than its currently registered service area, it registers with the new LR serving the area. The registration message contains the ID of the MH. This registration message is propagated to the serving LR of the area. Upon receiving the registration message, in addition to sending the registration confirmation back to the MH, the LR also sends a location update message to other LRs in the dissemination list. The dissemination list of an LR contains all its sibling LRs and the parent LR .

6. Performance Analysis

We try to answer the question of when our hierarchical location management system is cost-efficient compared to the IS-95 standard and the non-hierarchical distributed location management evaluated in Section 4. Here, we analyze a two-level hierarchy as shown in Fig.4. Note here that this analysis can be extended in a straightforward manner to higher levels of the hierarchy as well.

Now, if an MH moves across level-1 LRs belonging to the same level-2 LR, henceforth called a level-1 move, the cost of updating the move is the cost of distributing the location update to all the LRs in that cluster only. We assume location updates to other LRs using flooding as in Section 4; they can be efficiently disseminated to all the LRs in the dissemination list over a spanning tree rooted at the new level-1 LR that is currently serving the MH. Then the update cost, $C_{\text{Update } H\text{-}level\ 1}$ is given by:

$$C_{Update\,H-level1} = C_{level1} \times (M_{level1} - 1) \quad (4)$$

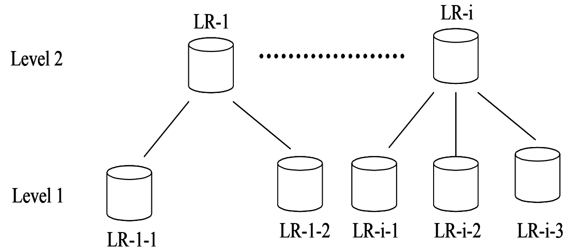

Fig. 4. Two-level hierarchical arrangement

Here, $C_{level\ 1}$ is the average cost of the link connection of two adjacent level-1 LRs, and $M_{level\ 1}$ is the average number of LRs in a level-1 cluster. If an MH moves across level-2 LRs, henceforth called a level-2 move, the cost of updating the move is the cost of distributing the location update in the new cluster plus the cost of updating all the level-2 LRs to point to the new level-2 LR plus the cost of distributing "delete" message to all the LRs in the old cluster. Then, the update cost, $C_{\text{Update } H\text{-}level\ 2}$ is given by:

$$C_{\text{Update } H\text{-}level\ 2} = 2 \times C_{level\ 1} \times (M_{level\ 1} - 1) + C_{level\ 2}(M_{level\ 2} - 1) \quad (5)$$

Assuming $P_{local\text{-}move}$ is the probability that an MH move is across the LRs in level-1, the update cost, $C_{\text{update H}}$ in the hierarchical system is by:

$$C_{\text{Update } H} = P_{local\text{-}move} \times C_{\text{Update } H\text{-}level\ 1} + (1 - P_{local\text{-}move}) \times C_{\text{Update } H\text{-}level\ 2} \quad (6)$$

The location tracking cost of an MH depends on whether the call is from an MH in the local cluster or not. The location tracking cost, $C_{\text{Location tracking } local\text{-}call}$ for a call from a local cluster is given by:

$$C_{\text{Location tracking } local\text{-}call} = \text{Cost}(LR_{caller} \leftrightarrow LR_{callee}) = \text{Cost}(LR_{local} \leftrightarrow LR_{local}) \quad (7)$$

If the call is from a mobile in another cluster (henceforth called a remote-call), the calling party LR (a.k.a. LR_{caller}) needs to contact its parent LR (a.k.a $LR_{caller\text{-}level2}$) to track the callee. $LR_{caller\text{-}level2}$ will contact the callee level-2 LR (a.k.a. $LR_{callee\text{-}level2}$), which in turn will contact the currently serving LR of the callee (a.k.a. LR_{callee}). Hence the location tracking cost, $C_{\text{Location tracking } remote\text{-}call}$ tracking of a remote-call is given by:

$$C_{\text{Location tracking } remote\text{-}call} = \text{Cost}(LR_{caller} \leftrightarrow LR_{caller\text{-}level2}) + \text{Cost}(LR_{caller\text{-}level2} \leftrightarrow LR_{callee\text{-}level2}) + \text{Cost}(LR_{callee\text{-}level2} \leftrightarrow LR_{callee}) \quad (8)$$

Let $P_{local\text{-}call}$ be the probability that the call that has arrived is from an MH in the local cluster. Then the location tracking cost, $C_{\text{Location tracking H}}$ in the hierarchical network is given by:

$$C_{\text{Location tracking } H} = P_{local\text{-}call} \times C_{\text{Location tracking } local\text{-}call}$$
$$(1 - P_{local\text{-}call}) \times C_{\text{Location tracking } remote\text{-}call} \quad (9)$$

Following the same method of analysis as in Section 4, given λ is the call arrival rate at a mobile and $1/\mu$ is the mean of the (exponentially distributed) residence time of the mobile in a service area, the total cost $C_{\text{total H}}$ of the location management in the hierarchical network is given by:

$$Cost_{\text{total } H} = C_{\text{Update } H} + \text{Expected no. of Calls per move} \times C_{\text{Location tracking } H}$$
$$= C_{\text{Update } H} \times \frac{\lambda}{\mu} \times C_{\text{Location tracking } H} \quad (10)$$

Table 1. Cost Assumptions and parameters for the hierarchical network

Parameter	Value	Comment
N_{LR}	N_{LR}	Total number of LRs
Nc	Nc	Number of clusters
C_{level1}	C_{level1}	Cost of the link connecting Adjacent level-1 LRs
C_{level2}	$\sqrt{\frac{N_{LR}}{N_c}C_{level1}}$	Cost of the link connecting Adjacent level-2 LRs
Cost (LR $_{local}$ ↔ LR $_{local}$)	1.33 $(\sqrt{N_{LR}/N_C/2})C_{level1}$	Average cost between any two level-1 LRs
Cost (LR $_{caller}$ ↔ $LR_{caller\text{-}level1}$) Cost (LR $_{callee}$ ↔ $LR_{callee\text{-}level2}$)	$1/2\sqrt{N_{LR}/N_c}C_{level1}$	Average distance between the level-1 LR and its parent LR
Cost ($LR_{caller\text{-}level2}$ ↔ $LR_{callee\text{-}level2}$)	$1.33(N_c/2)\ C_{level2}$	Average cost between two level-2 LRs

7. Numerical Results

We consider a mesh topology. If the total number of LRs in the network is N_{LR}, and the number of clusters is N_c, then the average number of LRs in a cluster is N_{LR}/N_c. The level-2 LR is placed along with the level-1 LR at the center of the cluster. If there is no single center LR, then the level-2 LR co-locates with one of the four center LRs. Assuming that the cost of the link connecting two adjacent LRs is proportional to the distance between the LRs, the parameters C_{level1} and C_{level2} are related by C_{level2} = $\sqrt{N_{LR}/N_C}$ C_{level1}. The cost between any level-1 LR and its level-2 LR is given by 1/2 $\sqrt{N_{LR}/N_C}$ C_{level1} for large values of $\sqrt{N_{LR}/N_c}$ (greater than 4). Table 1 summarizes the values of the parameters involved in the equation for total cost. In the following numerical results, C_{level1} is taken to be 1, $P_{local\text{-}move}$ = 90% and $P_{local\text{-}call} = 1/N_c$.

Fig.5 shows the total cost versus call arrival rate for the IS-95 scheme, our non-hierarchical distributed and hierarchical distributed schemes. Both distributed schemes implement full dissemination over a spanning tree rather than by flooding. The two-level hierarchical distributed scheme performs the best.

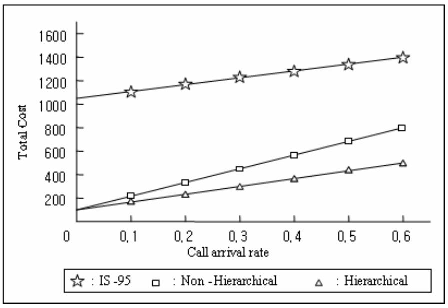

Fig. 5. Total cost in a non-hierarchical network

Fig. 6 illustrates how hierarchical distributed scales compare to the non-hierarchical distributed scheme and the IS-41 scheme as the network size increases for λ = 3 and μ = 0.1. The network size varies from 50×50 to 200×200, where the number of clusters N_c equals 10, 20, 30, and 40, respectively. The results suggest that our hierarchical distributed scales are much better than the IS-95 scheme.

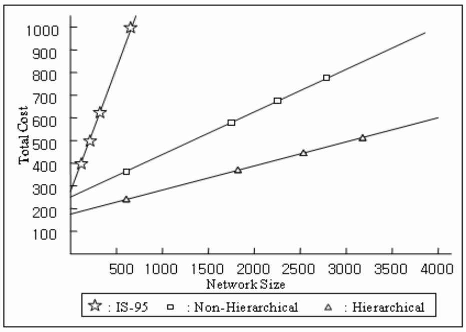

Fig. 6. Total cost in hierarchical networks

8. Conclusions

As shown by analytical and numerical performance analysis, our proposed location management scheme is more suitable than the IS-95 standard management in the IMT-2000 networks. The distributed location management not only reduces the overall system cost, but also reduces the call establishment latency and increases the availability of the system. The hierarchical implementation of our proposed scheme allows scaling to the LMN, while still providing high availability.

Our proposed scheme is general and can make use of other scalability and fast location lookup techniques [13], besides hierarchically organizing the location registers, For example, location information can be disseminated only to the most frequent callers, who can cache it in memory to speed up their location lookups. In our future work, we will investigate such extensions and study the tradeoffs between availability and cost/overhead.

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