# A Fully Distributed Location Management Scheme for Large PCS

KARUNAHARAN RATNAM
Dept. of Elec. and Comp. Eng.
Northeastern University
Boston, MA 02115
karu@ece.neu.edu

IBRAHIM MATTA
Dept. of Computer Science
Boston University
Boston, MA 02215
matta@cs.bu.edu

SAMPATH RANGARAJAN
Bell Laboratories
700 Mountain Avenue
Murray Hill, NJ 07974
sampath@research.bell-labs.com

*Abstract*— **In [1], [2], we presented the design, specification and proof of correctness of a fully distributed location management scheme for PCS networks and argued that fully replicating location information is both appropriate and efficient for small PCS networks. In this paper, we analyze the performance of this scheme. Then, we extend the scheme in a hierarchical environment so as to scale to** *large* **PCS networks. Through extensive numerical results, we show the superiority of our scheme compared to the current IS-41 standard.**

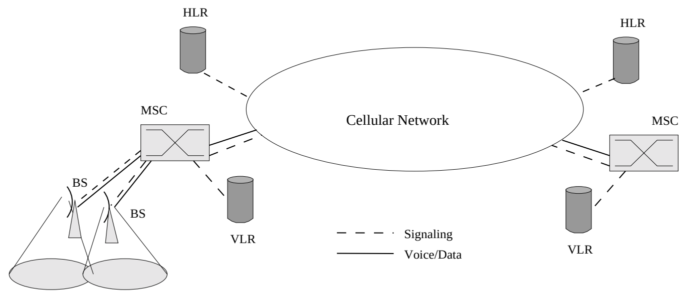


Fig. 1. Network reference model

## I. INTRODUCTION

Recent advances in communication technology have created the opportunity for mobile terminals to receive many services that were, until not long ago, only available to tethered terminals. The first system to support large-scale mobility was the *Advanced Mobile Phone System* (AMPS), a 900 MHz analog system. A new digital system, *Personal Communication Services* (PCS) provides voice as well as limited data services to wireless users. PCS works in the 1900 MHz spectrum. There are competitive standards for analog, digital, and PCS systems throughout the world. The literature covering these topics are abound [3], [4], [5].

One of the challenging tasks in a PCS environment is to efficiently maintain the location of the PCS subscribers who move around freely with their wireless unit (hereafter called mobile host or *mobile* for short). In North America, Telecommunications Industry Association's interim standard *IS-41* [6], [7] is used for managing location information of the subscribers and enabling them to send and receive calls and other services such as messaging and data service.

The network reference model of a PCS network is shown in Figure 1. It consists of the following components [8]:

- *Home Location Register (HLR):* Maintains the profiles of all the customers that are registered with the home network. When a mobile subscriber roams to another area, it has to register with the Visitor Location Register (VLR) of that area. The HLR maintains a pointer to the VLR which currently serves the mobile.
- *Visitor Location Register (VLR):* Supports registration, authentication, and call routing to/from a mobile while it is away from its home area.
- *Mobile Switching Center (MSC):* Responsible for switching the voice/data connection to the mobile host.
- *Base Station (BS):* The base station is the gateway between the wireless network and wired network. It provides the wireless connection to the mobile subscribers within its coverage area (cell). A set of base stations are connected to the MSC through a Base Station Controller (not shown).

Every subscriber is registered with a home network, the HLR of which maintains the subscriber's current physical location. In IS-41, this physical location is the ID of the MSC currently serving the subscriber. If the subscriber has roamed to another region then he/she has to register with the 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 some other VLR before, HLR will send a registration cancellation message to it.

### *Shortcomings of the Current IS-41 Standard*

In IS-41 [6], 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 mobile host is currently being served by the originating MSC (i.e. the mobile host is not roaming), then this MSC queries the HLR to obtain the registration status

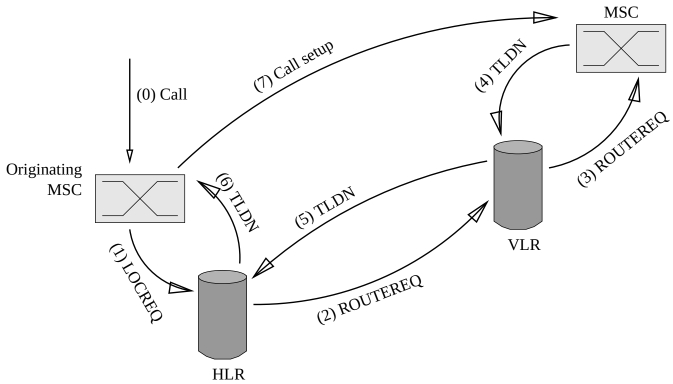


Fig. 2. Call delivery in IS-41 to an idle mobile in visited system

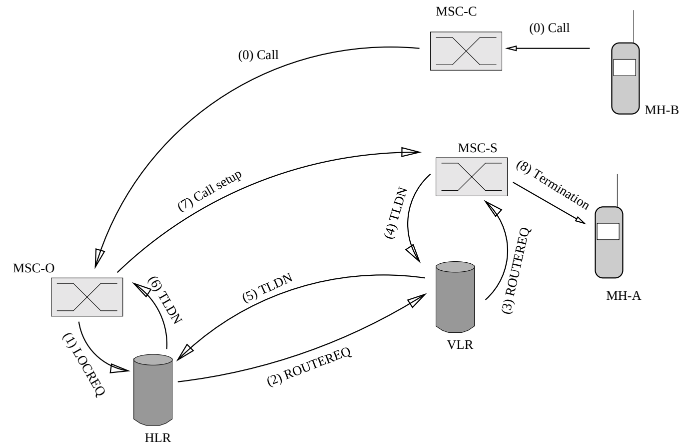


Fig. 3. Tromboning problem

and feature information of the mobile host. After receiving the response from the HLR, the originating MSC pages the mobile host. When the mobile host responds (i.e. subscriber accepts the call by pressing the proper button), the originating MSC sets up the circuit to terminate the call to the mobile host.

Figure 2 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 find out 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 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 the call routed using the TLDN, it pages the mobile host. If the mobile responds, then the call is terminated at the mobile.

Thus, HLR is a critical entity in the IS-41 location management system. There are many disadvantages to having a centralized location management scheme such as the scheme used in IS-41. One disadvantage is that since every location request as well as location registration are serviced through a HLR, in addition to the HLR being overloaded with database lookup operations [9], the 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. The other disadvantage is that any HLR system failure causes all mobiles registered with the HLR to be unreachable even though mobiles may be roaming and away from the HLR region. Thus, HLR is the single point of failure in the network.

There is also another disadvantage which is generally referred to as *tromboning problem*. Consider the situation depicted in Figure 3. The subscriber MH-A's home MSC is MSC-O, and MH-A is currently roaming and being served by MSC-S. Another mobile MH-B, which is currently being served by MSC-C, makes a call to MH-A. MSC-C and MSC-S are geographically closer to each other, and connected by the local exchange carrier. But, MSC-O (the home MSC of MH-A) is geographically far away from both MSC-C and MSC-S and connected to them by a long distance carrier. Routing the call from MH-B to MH-A involves two long distance legs, one between MSC-C and MSC-O, and the other between MSC-O and MSC-S. The latter leg is used twice, first to obtain the TLDN, and then to provide the voice/data connection.

Many location management schemes and improvements to IS-41 have been proposed in recent years [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]. In [1], [2] we presented a novel approach for efficient location management by fully distributing the location information across Location Registers (LR). These LRs replace the centralized VLRs and HLRs which are found in current PCS networks. Since there are no HLRs or VLRs in this system, each LR maintains the location information of not only the mobiles that are local to it, but also of other mobiles in the network [1], [2]. That is, the location information of all mobile hosts are fully replicated in all the LRs. The LRs are distributed throughout the network. An LR serves one or more MSCs just like the VLR in the PCS architecture (cf. Figure 1). An LR could co-exist with an MSC, and serve only that MSC. (This allows the LR and the MSC to exchange signals internally and avoids the need for a standards based signaling between them.)

LRs function as both the location registry for the local mobile hosts as well as the lookup directory for the location of other mobile hosts. The type of location information maintained for a mobile host depends on whether the mobile is local to the LR or not. For local mobile hosts, LR maintains the *id* of the MSC that is currently serving the mobile. For mobile hosts that are not local, LR maintains the *id* of the LR where the mobile host 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 directly contact the *serving* LR, thus avoiding the tromboning problem present in the current IS-41 standard. In this paper, we analyze this fully distributed location management scheme. In order to scale to *large* PCS networks, we extend our scheme by organizing the LRs hierarchically so as to reduce the cost of updating location information.

The paper is organized as follows. Section II briefly describes the different facets of our location management scheme for flat (non-hierarchical) networks [1], [2]. In Section III, we analyze this scheme and compare it to the IS-41 scheme. Numerical results are presented in Section IV. Section V extends our scheme to hierarchical networks. Section VI analyzes this hierarchical extension and numerical results are then presented in Section VII. Section VIII concludes the paper.

## II. Fully Distributed (FD) Location Management in Flat Network

In this section, we briefly describe our recently proposed location management scheme. Details of the scheme including correctness arguments can be found in [1], [2].

### *A. Registration*

In our location management scheme, the base stations in the network periodically broadcast a "beacon" message to the mobile hosts (MH) in its coverage area (a.k.a. cell). The beacon message contains the id of the LR serving this area. If the LR id in the beacon message is different from that of the MH's current LR, the MH sends a "registration" request to the new LR. Along with this registration message, information about the identity of the MH and a location counter ($LC$) value (a sequence number which is explained in Section II-B) are also sent. A similar procedure is followed when a MH switches itself off and then wakes up again.

Upon receiving a registration request from an MH, the base station informs its MSC about this request. The MSC, in turn, forwards the request to its LR. The LR queries its database and retrieves the LC value stored for this MH. The LR increments the larger of this LC value and the LC value in the registration message, and sends an acknowledgment to the MH with the new LC value. From then on, whenever a call is sent from/to this MH, the call is supported by this LR.

### *B. Location Information Dissemination*

As indicated in the previous subsection, each MH has a location counter ($LC$) associated with it. The location counter acts as a logical time stamp (or a nonce). Whenever a MH requests registration, the LR increments the corresponding LC value appropriately as described in the last subsection and sends it back to the MH. The LR then updates its own database, i.e. location directory (LD), and disseminates information about the new location of the MH together with the new $LC$ value to the neighboring LRs in the network. The LRs that receive this location information determine if this information is new or old, depending on whether the LC value they received for the MH is larger or smaller than the LC value they have locally stored for this MH. If the information is new, a LR propagates this location information to all its neighbors, and also updates its local LD. If the information is old, it (the LC value for this MH and its location) is updated and sent back to (only) the sender. Thus, the location counter serves to distinguish between new and old information. By propagating location information in this fashion, the location information of all MHs is fully replicated at all LRs in the network.

It is important to ensure that the location counter values contained locally at an LR and those that are carried in the disseminated location information messages, always monotonically increase. This property is required to enable more recent information to be associated with a larger LC value than the value associated with older information. Informally, we would like to guarantee that newer information does not get overwritten by older information. Our protocol is tailored to recover from situations where this notified location counter value is incorrect due to corruption or failure. Description of this capability can be found in [1], [2].

It is to be noted that a MH may cross several base station cells before crossing a LR service area as there could be many base stations associated with one LR. Only when a MH crosses over to a cell served by a different LR, the location information dissemination is triggered for that MH.

### *C. Call Setup*

Our fully distributed location management scheme ensures that the location information of each mobile host is replicated in all location registers. The MH need not be assigned a particular location register to serve as its *home* location register. Hence, when a call originates for a mobile from one LR area, this originating LR can directly contact

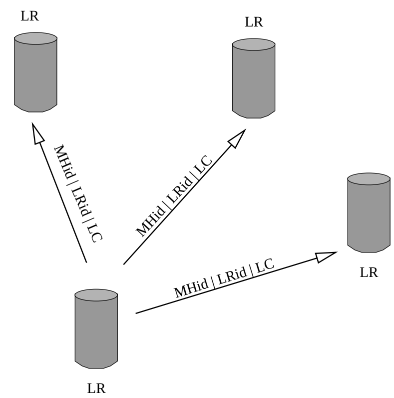


Fig. 4. Location information dissemination

the serving LR to terminate the call. Note that, IS-41 mandates contacting the HLR for every call setup, leading to inefficiency, such as the *tromboning* problem. With fully distributed location management, the serving LR contacts the serving MSC to assign a switching number (TLDN) to the call. However, due to the non-zero delay involved in completing the dissemination of new location information, when an originating LR receives a call request to a non-local MH, there is a non-zero probability that the LR has old location information for the called MH. Because of this, location request for a MH could be received at an LR that is no longer serving this MH. In this case, the location request is forwarded to the LR that is currently serving the MH as per the location information available at the LR that received the location request. This way, through a chain of forwarding steps, the location request eventually reaches the LR that is currently serving the MH. It is to be noted here that since many BSs are served by an LR, the chances of a mobile host crossing over to another LR region while its earlier location update is still propagating over the network, is quite small.

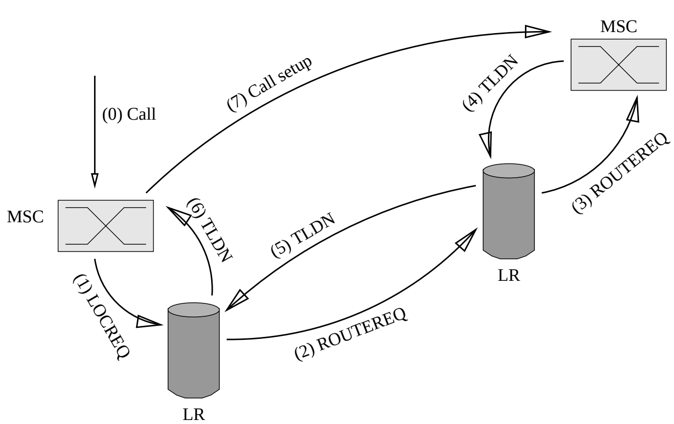


Fig. 5. Call delivery in fully distributed location management

## III. Performance Analysis for Flat Network

In this section, we analyze our recently proposed fully distributed (FD) location management scheme [1], [2] and compare it with that of the IS-41 scheme. For simplicity, it is assumed that there is only one MSC per service area, and the LR/VLR is co-located with the MSC. Thus, we use LR to indicate an MSC/LR combination, and VLR to indicate MSC/VLR combination. In both schemes (fully replicated and IS-41), the total cost consists of *UPDATE cost* and *FIND cost*. The *UPDATE cost* covers all the costs involved in mobile host registration and location update. In the case of fully distributed location management, *UPDATE cost* also includes the cost involved in the dissemination of location information. The *FIND cost* covers all the costs involved in terminating a call to mobile host. In the case of IS-41, *FIND cost* consists of all the costs involved in the call termination as depicted in Figure 2. However, since we have assumed that VLR is co-located with the MSC, *FIND cost* basically consists of the cost of signaling between originating area VLR and HLR, and of signaling between HLR and serving VLR. In order to compare the cost efficiency of our FD scheme and the IS-41 scheme, we use the expected total cost incurred for a mobile host 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 mobile host when it moved into the LR (or VLR) service area, and the *FIND cost* incurred for *every* call terminated to the mobile host while it is in this service area and before it moves to another service area.

In IS-41, UPDATE involves the new VLR registering the MH with its HLR, and the HLR sending registration cancellation to the old VLR. Hence the *UPDATE cost* is given by:

$$UPDATE_{IS41} = Cost(VLR_{new} \leftrightarrow HLR) + Cost(HLR \leftrightarrow VLR_{old}) \quad (1)$$

Assuming the time to register with the HLR is very short (i.e. the probability that a location request to the HLR falls during the registration time is negligible), the FIND cost of a roaming mobile is given by (cf. Figure 3):

$$FIND_{IS41}^{roam} = Cost(VLR_{caller} \leftrightarrow VLR_{orig}) + Cost(VLR_{orig} \leftrightarrow HLR) + Cost(HLR \leftrightarrow VLR_{callee}) \quad (2)$$

and for a non-roaming mobile host, the FIND cost is given by:

$$FIND_{IS41}^{local} = Cost(VLR_{caller} \leftrightarrow VLR_{orig}) + Cost(VLR_{orig} \leftrightarrow HLR) \quad (3)$$

Here, $VLR_{caller}$ is the MSC/VLR where the call is generated, $VLR_{orig}$ is the *home* MSC/VLR of the mobile host, and $VLR_{callee}$ is the MSC/VLR that is currently serving the roaming mobile host.

In our fully distributed (FD) scheme, new location information needs to be disseminated to all LRs in the network. For fault tolerance, we use *flooding* to implement full dissemination. For simplicity, assume that for any mobile host there is at most one location update propagating in the network at any point in time. Also assume normal operation of update (i.e. no location counter corruption). Then, for a given topology, if $C_l$ is the average cost of a link between two adjacent (neighbor) MSCs/LRs, then the UPDATE cost is independent of the location of the LR that generates the update. Specifically, let $Graph(V, E)$ be the topology, where $V$ is the set of all nodes (LRs) and $E$ is the set of all links. Let $adj_v$ be the adjacency list of node $v$. Since each node (MSC/LR) propagates an incoming location update information to all its adjacent nodes except the node from which it received the update information, there will be $(|adj_v| - 1)$ updates sent by each MSC/LR $v$. An exception is the originating MSC/LR which floods the update to all its neighbors. Then, the total update cost per move in the FD scheme is given by:

$$UPDATE_{FD} \;=\; C_l \left(1 + \sum_{v \in V} (|adj_v| - 1)\right) \tag{4}$$

Until the update about the mobile host is completed, some of the calls to the mobile may arrive to an old (incorrect) LR that is no longer serving the mobile host. Since the old LR is likely to be immediately updated after the move because of its proximity to the new LR, we assume that there will be at most one call forwarding involved from the old LR to the new LR. Then the FIND cost in the FD scheme is given by:

$$\begin{aligned} &FIND_{FD} = Cost\,(LR_{caller} \leftrightarrow LR_{callee}) + \\ &P\,(\text{call arrives to } LR_{old}) \times Cost\,(LR_{old} \leftrightarrow LR_{callee}) \end{aligned} \tag{5}$$

Now we need to find the probability that the call arrives to an old (incorrect) LR. We define the following (cf. Figure 6):

- $f_c(t)$: p.d.f. of the call arrival process to the mobile
- $\lambda$: average number of call arrivals per second
- $t_r$: amount of time the mobile spends in a service area
- $f_r(t)$: p.d.f. of the random variable $t_r$. It is assumed to be exponentially distributed with mean residence time $1/\mu$, i.e. $f_r(t) = \mu e^{-\mu t}$
- $t_u$: time taken for the location information to reach the LRs.
- $f_u(t)$: general distribution describing $t_u$. If the total number of LRs is $M$, after the mobile moves, let the time taken for the update to reach LR $i$ be $t_i$, then $(t_1, t_2, ....t_M)$ forms a histogram which describes $t_u$.

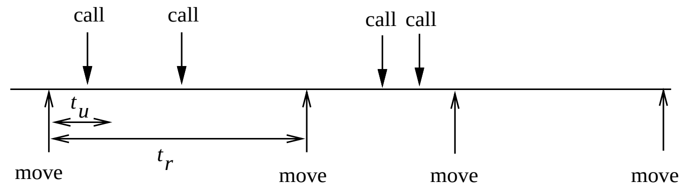


Fig. 6. Diagram depicting the parameters

$$\begin{aligned} &P\,(\text{call arrives to } LR_{old}) = \\ &\frac{\text{Expected num. of calls arriving during } t_u}{\text{Expected num. of calls arriving during } t_r} \end{aligned} \tag{6}$$

$$\begin{aligned} &\text{Expected num. of calls arriving during } t_u = \\ &\int_0^\infty \left[\int_0^{t_r} \lambda\, t\, f_u(t)\, dt\right] f_r(t)\, dt \end{aligned} \tag{7}$$

$$\begin{aligned} &\text{Expected num. of calls arriving during } t_r = \\ &\int_0^\infty \lambda\, t\, f_r(t)\, dt = \frac{\lambda}{\mu} \end{aligned} \tag{8}$$

The solution to equation (7) depends on the distribution $f_u(t)$, and it can generally be solved by numerical techniques. Here, we solve it for two simple cases: $t_u$ is exponentially distributed, and $t_u$ is uniformly distributed.

- **$t_u$ is exponentially distributed with mean $1/\alpha$:**

Expected num. of calls arriving during $t_u$ =

$$\frac{\lambda}{\alpha} - \lambda\mu \left(\frac{1}{\alpha(\alpha+\mu)} + \frac{1}{(\alpha+\mu)^2}\right) \tag{9}$$

$P\,(\text{call arrives to } LR_{old})$ =

$$\frac{\mu}{\alpha} - \mu^2 \left(\frac{1}{\alpha(\alpha+\mu)} + \frac{1}{(\alpha+\mu)^2}\right) \tag{10}$$

- **$t_u$ is uniformly distributed in the range (a,b):**

$$\int_0^{t_r} \lambda\, t\, f_u(t)\, dt = \begin{cases} 0 & t_r \le a \\ \frac{1}{2}\frac{\lambda\left(t_r^2 - a^2\right)}{b-a} & a < t_r \le b \\ \frac{1}{2}\lambda(b+a) & t_r > b \end{cases}$$

$$\begin{aligned} &\text{Expected num. of calls during } t_u = \\ &\int_0^\infty \left[\int_0^{t_r} \lambda\, t\, f_u(t)\, dt\right] f_r(t)\, dt \\ &= \int_a^b \frac{1}{2}\frac{\lambda\,(t^2 - a^2)}{b-a}\mu e^{-\mu t} dt + \int_b^\infty \frac{1}{2}\lambda(b+a)\mu e^{-\mu t} dt \\ &= \frac{\lambda}{\mu\,(b-a)} \left(\frac{1}{\mu} + a\right) e^{-\mu\, a} - \\ &\qquad \frac{\lambda}{\mu\ (b-a)} \left(\frac{1}{\mu} + b\right) e^{-\mu\, b} \end{aligned} \tag{11}$$

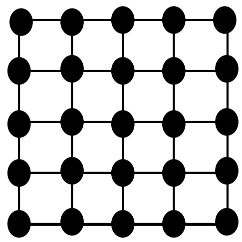

Fig. 7. A $5 \times 5$ network topology ($M = 25$ service areas)

$$P\,(\text{call arrives to } LR_{old}) = \frac{1}{b-a}\left(\frac{1}{\mu}+a\right)e^{-\mu a} - \frac{1}{b-a}\left(\frac{1}{\mu}+b\right)e^{-\mu b} \quad (12)$$

Table I shows the cost incurred due to incorrect location information as the update is propagating over the network to all LRs, for a 400-LR network and $\lambda$ of 10 calls per hour. Given $1/\alpha$ is the average update duration (assuming exponentially distributed duration), this cost is given by:

$$(\lambda/\alpha)\ P\,(\text{call arrives to } LR_{old}) \times Cost\,(LR_{old} \leftrightarrow LR_{callee}) \quad (13)$$

Assuming $Cost\,(LR_{old} \leftrightarrow LR_{callee})$ equals 1 msec, the table shows that the cost due to outdated location information is negligible. We henceforth estimate the FIND cost in the FD scheme as:

$$FIND_{FD} = Cost\,(LR_{caller} \leftrightarrow LR_{callee}) \quad (14)$$

## IV. Numerical Results for Flat Network

The above analysis provides a mean to compare the cost of using the two alternative location management schemes: IS-41 and our fully distributed location management scheme. In this section, we numerically compare the cost by making reasonable assumptions on network deployment and parameters. We assume a network topology as shown in Figure 7. There are $N \times N$ network nodes, each connected to four of its neighbors, except the boundary nodes which are connected to either two or three neighbors only. For this network topology, the average distance between any two nodes is given by $1.333(N/2)$. As mentioned earlier, it is assumed that VLR (or LR) are co-located with the MSC. We further assume here that HLR is also co-located with the MSC, thus each node in Figure 7 represents a VLR/LR, HLR and MSC. Hence we assume that the link cost between VLR (LR), HLR, and MSC of the same service area is negligible. Table II shows our cost assumptions and parameters.

As mentioned earlier, the comparison merit is the expected total cost incurred for a mobile host while it is in a single LR (or VLR) service area. The cost we compute here assumes that the mobile host is away from its home service area (i.e. roaming), and is given by:

$$\text{TotalCost}_{IS41} = \text{UPDATE}_{IS41} + \text{Expected num. of calls per move} \times \text{FIND}^{roam}_{IS41} \quad (15)$$

$$\text{TotalCost}_{FD} = \text{UPDATE}_{FD} + \text{Expected num. of calls per move} \times \text{FIND}_{FD} \quad (16)$$

where $\lambda/\mu$ is the expected number of calls per move, and $\text{UPDATE}_{IS41}, \text{FIND}^{roam}_{IS41}, \text{UPDATE}_{FD}$ and $\text{FIND}_{FD}$ are given by equations (1), (2), (4) and (14), respectively.

The expected number of calls per move is often referred to as the *call-to-mobility ratio* [14]. Figures 8 and 9 show the total cost for IS-41 and fully distributed schemes for two different network sizes, $5 \times 5$ and $10 \times 10$. $C_l$ is taken to be 1. As expected, when the call-to-mobility ratio increases our fully distributed scheme offers better cost performance. However, the network size is also another important factor. For larger networks, the fully distributed scheme introduces heavy update cost, which increases the total cost. We next extend our FD scheme so as to scale to larger networks.

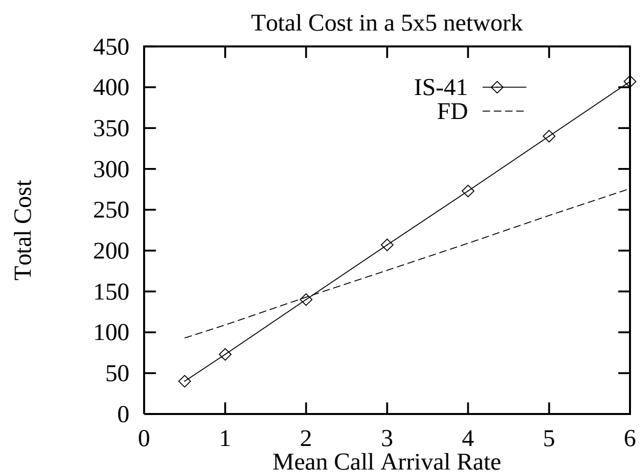


Fig. 8. Total cost versus call-to-mobility ratio for $N = 5$

## V. Hierarchical Location Management

Our fully 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, location information dissemination not only consumes a significant portion of the network bandwidth but also consumes significant portion of LR resources to process large number of update messages. In addition, the gain of employing full dissemination diminishes with the size of the network as seen by the results presented in the previous section. That is, for a large

TABLE I
COST DUE TO OUTDATED LOCATION INFORMATION

| **1 / $\alpha$** | **$P$(call arrives to incorrect LR)** | **Average Cost** |
|---|---|---|
| 1 sec | $2.77 \times 10^{-5}$ | $7.69 \times 10^{-11}$ |
| 10 sec | $2.77 \times 10^{-4}$ | $7.69 \times 10^{-9}$ |
| 60 sec | $1.66 \times 10^{-3}$ | $2.76 \times 10^{-7}$ |

TABLE II
COST ASSUMPTIONS AND PARAMETERS FOR FLAT NETWORK

| **Link** | **Average cost** | **Justification** |
|---|---|---|
| Single hop | $C_l$ | Cost involved over a single hop |
| $LR_{old} \leftrightarrow LR_{callee}$ | $C_l$ | A mobile's move in general involves directly connected LRs |
| $VLR_{callee} \leftrightarrow HLR$<br>$VLR_{caller} \leftrightarrow HLR$ | $1.33(N/2)C_l$ | Average cost to an HLR |
| $LR_{caller} \leftrightarrow LR_{callee}$ | $1.33(N/2)C_l$ | Average cost between any two nodes |
| Mean residence time ($\frac{1}{\mu}$) | 10 hours | |
| Mean call arrival rate ($\lambda$) | $0.5 - 6$ calls per hour | |

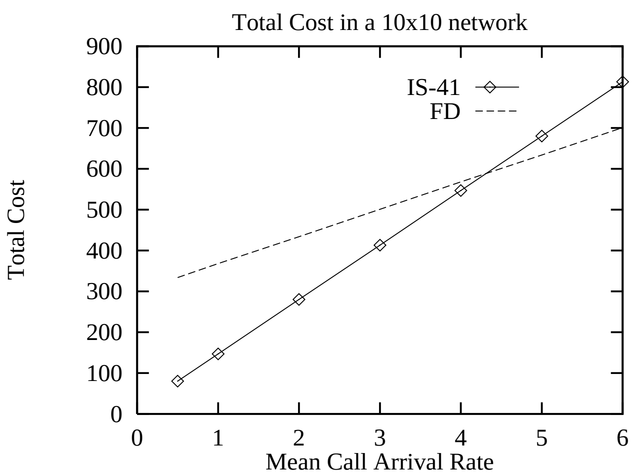


Fig. 9. Total cost versus call-to-mobility ratio for $N = 10$

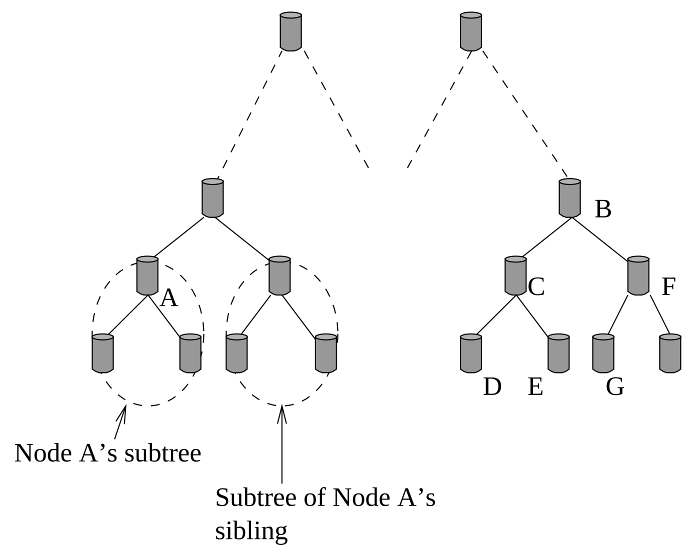


Fig. 10. Conceptual diagram showing the hierarchical arrangement

network, it is impractical to have a location management scheme based on full location information dissemination. Full location information dissemination can be avoided by logically arranging LRs in a hierarchical fashion—a tree structure as in [23] or a cluster-supercluster arrangement as in [24]. The idea here is to divide the LRs into hierarchy of clusters, and confine location information dissemination to within the clusters as much as possible. This section analyzes the performance of our fully distributed location management in a hierarchical environment and assesses its applicability and benefits.

### A. Proposed Hierarchical Location Management

Figure 10 shows the conceptual arrangement of the LRs in a hierarchical network under our proposed scheme. The proposed approach uses a distributed location management. The mobile hosts are not associated with a home location register like in IS-41. Each LR maintains the location information of all the mobiles that are currently being served in the subtree rooted from the LR. It *also* maintains the location of the mobiles that belong to the subtree rooted from its sibling LRs. Note here that the subtree rooted from a leaf node contains only that leaf node. If a mobile host is being served by one of the descendants of an LR, then the LR maintains the ID of its immediate child LR, whose subtree contains the mobile host, to track the mobile host. Referring to Figure 10, if a mobile host is in the service area of LR **D**, then location information in LR **C** for the mobile host would point to LR **D**, but the location information in LR **B** for the same mobile host would point to LR **C**. For the mobile hosts that reside in the subtree of a sibling, the LR maintains its sibling's ID to track the mobile host. That is, location information in LR **F** for that mobile host served by LR **D** would be LR **C**. This way the location information of a mobile host is only maintained by the following LRs:

- serving LR of the mobile host,
- sibling LRs of the serving LR,
- ancestor LRs of the serving LR, and
- sibling LRs of the ancestors.

That is, location information of the mobile host being served by **D** are maintained only in the LRs **D**, **E**, **C**, **F**, **B**, and so on. LRs **A** and **G** do not maintain the location information for that mobile host.

Tracking the LR serving a mobile host involves traversing the LR tree hop-by-hop until the serving LR is reached. If the location entry for a mobile host does not exist in an LR, then the tracking request is forwarded to the LR's parent LR. In this way the tracking request traverses the tree upwards until the LR which has the location information for the mobile host is reached. That LR forwards the tracking request to the LR pointed to by the location information. Here, location tracking traverses laterally. From there, it traverses downwards until the LR currently serving the mobile host is reached. For example, if **G** were to track the LR of a mobile host 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 back to **G**.

### *B. Registration and Location Information Dissemination*

Section II presented an efficient fault-tolerant fully distributed location management scheme. This section deals with its hierarchical design for large networks. Again, as in Section II, mobile hosts identify their current LR by the periodic beacon message broadcasted by the base stations. If the mobile host 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 mobile host and the location counter value. This registration message is propagated to the serving LR of the area. Upon receiving the registration message, in addition to sending registration confirmation back to the mobile host, 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.

### *C. Location Update Algorithm for Hierarchical Network*

In this subsection, we first present the notation used in explaining the steps involved in the processing of the location information message and the algorithm for processing the location information.

- $MHid$: id of the mobile host under consideration.
- $LD_i[MHid]$: Location directory entry at $LR_i$ for the mobile host MHid. It contains the id of the LR that serves the mobile host or an ancestor of the LR that serves the mobile host. $LD_i[MHid].LRid$ identifies that LR. If there is no location directory entry for the mobile host, then $LD_i[MHid]$ would be NULL.
- $UPDATE$: Location update message flowing in the network. It contains $UPDATE.MHid$ which indicates the mobile host id, and $UPDATE.LRid$ which indicates the id of the LR which generated the update message. It also contains $UPDATE.DList$ which is the dissemination list associated with the LR which generated the update. The update should be disseminated to LRs in this list.
- $RemoveMHfromList$: It tells an LR to remove the LD entry of a mobile host from the database.
- $Child(LRid)$: The set containing the list of all the child LR nodes of the node LRid.
- $Parent(LRid)$: Identifies the parent node of LRid.
- $DissemList(LRid)$: The set containing the list of all the sibling nodes and the parent node of LRid to which the message should be disseminated.

Mobile host location updates are confined to the local nodes as much as possible. The pseudo-code in Figure 11 describes the location update algorithm executed at node $LR_i$ upon the reception of an UPDATE message.

## VI. Performance Analysis for Hierarchical Network

In this section, we try to answer the question of when our hierarchical location management system is cost efficient compared to IS-41 and the flat fully distributed location management proposed in Section II. Here we analyze a two-level hierarchy as shown in Figure 12. Note here that this analysis can be extended in a straightforward way to higher levels of hierarchy as well.

Now, if a mobile host moves across level-1 LRs belonging to the same level-2 LR, henceforth called *level-1 move*, then the cost of updating the move is the cost of distributing the location update to all the LRs in that cluster only.

if $LD_i[MHid] = NULL$
  // MHid has moved in from another subtree, or
  // it is a new subscriber
  if $UPDATE.LRid \in Child(LR_i)$
    // MHid now belongs to the local subtree
    Generate UPDATE msg with $UPDATE.LRid = LR_i$
    Send UPDATE msg to DissemList($LR_i$)
  else
    // MH belongs to a sibling's subtree or $LR_i$ is a leaf node
    $LD_i[MHid].LRid = UPDATE.LRid$
    Forward UPDATE msg to next LR in $UPDATE.DList$
  end if
else
  // Last LR of the MH belongs to the local subtree or
  // the subtree of a sibling
  if $UPDATE.LRid \in Child(LR_i)$
    // MH is now in the local subtree
    if $LD_i[MHid].LRid \in Child(LR_i)$
      // $LR_i$ is a parent node, and MH moved into one
      // child LR from another child LR of $LR_i$
      $LD_i[MHid].LRid = UPDATE.LRid$
      Forward UPDATE msg to next LR in $UPDATE.DList$
    else
      // MH moved in to the local subtree from
      // a subtree of a sibling
      Generate UPDATE msg with $UPDATE.LRid = LR_i$
      Send UPDATE msg to DissemList($LR_i$)
    end if
  else
    // MH moved into the subtree of a sibling
    Forward UPDATE msg to next LR in $UPDATE.DList$
    if $LD_i[MHid].LRid \in Child(LR_i)$
      // MH moved out from local subtree
      Send RemoveMHfromList to all LRs $\in Child(LR_i)$
    end if
    $LD_i[MHid].LRid = UPDATE.LRid$
  end if
end if

Fig. 11. Location update algorithm for hierarchical network

We assume here that location information is carried reliably. Then, instead of disseminating location updates to other LRs using flooding as in Section II, 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 mobile host. Then the cost is given by:

$$\text{UPDATE}_{H-level1} = C_{level1} \times (M_{level1} - 1) \quad (17)$$

Here, $C_{level1}$ is the average cost of the link connecting two adjacent level-1 LRs, and $M_{level1}$ is the average number of LRs in a level-1 cluster.

If a mobile host moves across level-2 LRs, henceforth called *level-2 move*, then 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 the RemoveList message to all the LRs in the old cluster.

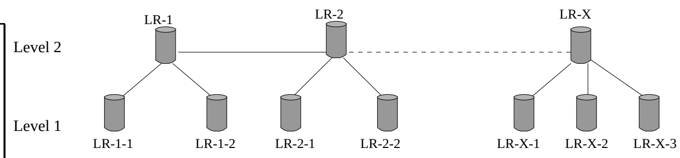


Fig. 12. Conceptual diagram showing a two-level hierarchical arrangement used in the analysis

$$\text{UPDATE}_{H-level2} = 2 \times C_{level1} \times (M_{level1} - 1) + C_{level2} \times (M_{level2} - 1) \quad (18)$$

Assuming $P_{local-move}$ is the probability that a mobile host move is across the LRs in level-1, the update cost in the hierarchical system is given by:

$$\text{UPDATE}_H = P_{local-move} \times \text{UPDATE}_{H-level1} + (1 - P_{local-move}) \times \text{UPDATE}_{H-level2} \quad (19)$$

The find cost (location tracking cost) of a mobile depends on whether the call is from a mobile host in the local cluster or not. The find cost for a call from a local cluster is given by:

$$\text{FIND}_{local-call} = \text{Cost}\,(LR_{caller} \leftrightarrow LR_{callee}) = \text{Cost}\,(LR_{local} \leftrightarrow LR_{local}) \quad (20)$$

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

$$\text{FIND}_{remote-call} = \text{Cost}\,(LR_{caller} \leftrightarrow LR_{caller-level2}) + \text{Cost}\,(LR_{caller-level2} \leftrightarrow LR_{callee-level2}) + \text{Cost}\,(LR_{callee-level2} \leftrightarrow LR_{callee}) \quad (21)$$

Let $P_{local-call}$ be the probability that the call that arrived is from a mobile in the local cluster. Then the find cost in the hierarchical network is given by:

$$\text{FIND}_H = P_{local-call} \times \text{FIND}_{local-call} + (1 - P_{local-call}) \times \text{FIND}_{remote-call} \quad (22)$$

Following the same method of analysis as in Section III, given $\lambda$ is the call arrival rate to a mobile and $1/\mu$ is the mean of the (exponentially distributed) residence time of the mobile in a service area, the total cost of the location management in the hierarchical network is given by:

$$\begin{aligned} \text{TotalCost}_H &= \text{UPDATE}_H + \\ &\quad \text{Expected num. calls per move} \times \text{FIND}_H \\ &= \text{UPDATE}_H + \frac{\lambda}{\mu} \times \text{FIND}_H \qquad (23) \end{aligned}$$

## VII. Numerical Results for Hierarchical Network

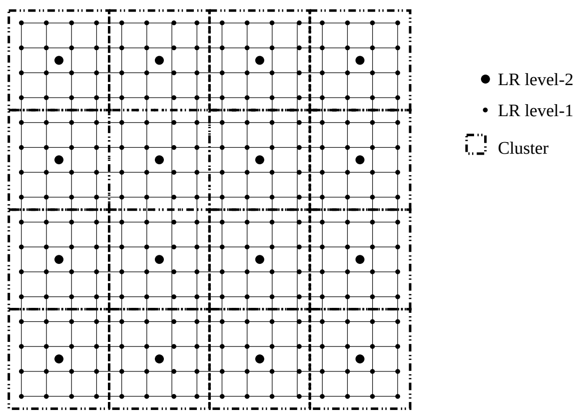


Fig. 13. Mesh deployment of Location Registers

We consider a mesh topology as shown in Figure 13. 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 the cost of the link connecting two adjacent LRs is proportional to the distance between the LRs, parameters $C_{level1}$ and $C_{level2}$ are related by $C_{level2} = \sqrt{N_{LR}/N_c}\ C_{level1}$. The cost between any of the 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 III summarizes values of the parameters involved in the equation for total cost. In the following numerical results, $C_{level1}$ is taken to be 1, $P_{local-move} = 90\%$ and $P_{local-call} = 1/N_c$.

Figures 14 and 15 show the total cost versus call arrival rate for IS-41, our flat FD and hierarchical FD schemes. The (two-level) hierarchical FD scheme performs the best. Observe that in the 20 × 20 network, our flat FD scheme outperforms the IS-41 scheme at lower call arrival rates (or call-to-mobility ratios) than in the smaller 10 × 10 network of Figure 9. This is because here our flat FD scheme implements full dissemination more efficiently over a spanning tree rather than by flooding. Also observe that at very high call arrival rates, flat FD starts to perform as well as hierarchical FD. This is because the FIND cost incurred due to traversing the LR tree in hierarchical FD becomes significant.

Figure 16 shows the total cost versus the number of clusters in the two-level hierarchical FD scheme for varying call arrival rates. As the number of clusters increases, the cost decreases. When the number of clusters become very high, in other words, the location update overhead approaches that of the flat-FD scheme, the cost increases.

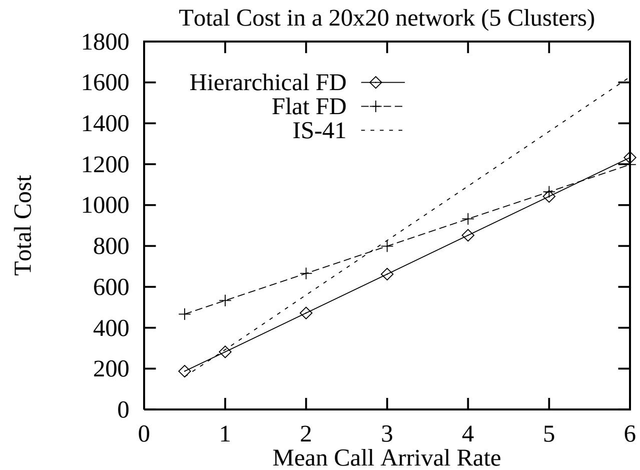


Fig. 14. Total cost in a 20 × 20 network

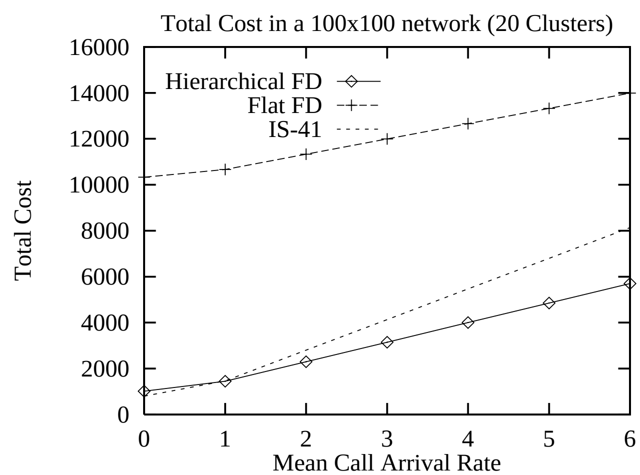


Fig. 15. Total cost in a 100 × 100 network

## VIII. Conclusions

As shown by analytical and numerical performance analysis, our fully distributed (FD) location management scheme is more suitable than IS-41 management. The fully distributed location management not only reduces the overall system cost, but also reduces the call establishment latency. The application environments for such a location management scheme includes military networks (e.g. a packet radio network), distribution networks (e.g. UPS), etc. For example, in a military network, fully distributing

TABLE III

COST ASSUMPTIONS AND PARAMETERS FOR HIERARCHICAL NETWORK

| Parameter | Value | Comment |
|---|---|---|
| $N_{LR}$ | $N_{LR}$ | Total number of LRs |
| $N_c$ | $N_c$ | 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 |
| $Cost\,(LR_{local} \leftrightarrow LR_{local})$ | $1.33(\sqrt{N_{LR}/N_c}/2)C_{level1}$ | Average cost between any two level-1 LRs |
| $Cost\,(LR_{caller} \leftrightarrow LR_{caller-level2})$ $Cost\,(LR_{callee} \leftrightarrow LR_{callee-level2})$ | $1/2\sqrt{N_{LR}/N_c}C_{level1}$ | Average distance between the level-1 LR and its parent LR |
| $Cost\,(LR_{caller-level2} \leftrightarrow LR_{callee-level2})$ | $1.33(N_c/2)C_{level2}$ | Average cost between two level-2 LRs |

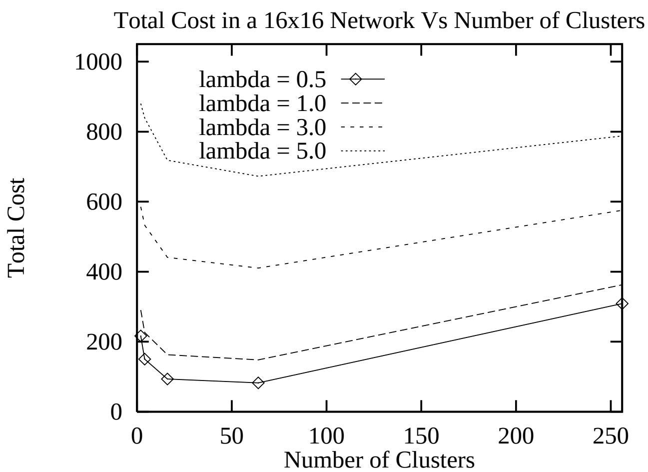


Fig. 16. Total cost versus number of clusters

the location management information helps find mobiles quickly and avoids the involvement of their home system. The hierarchical implementation of our FD scheme allows for scaling to large PCS networks.

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