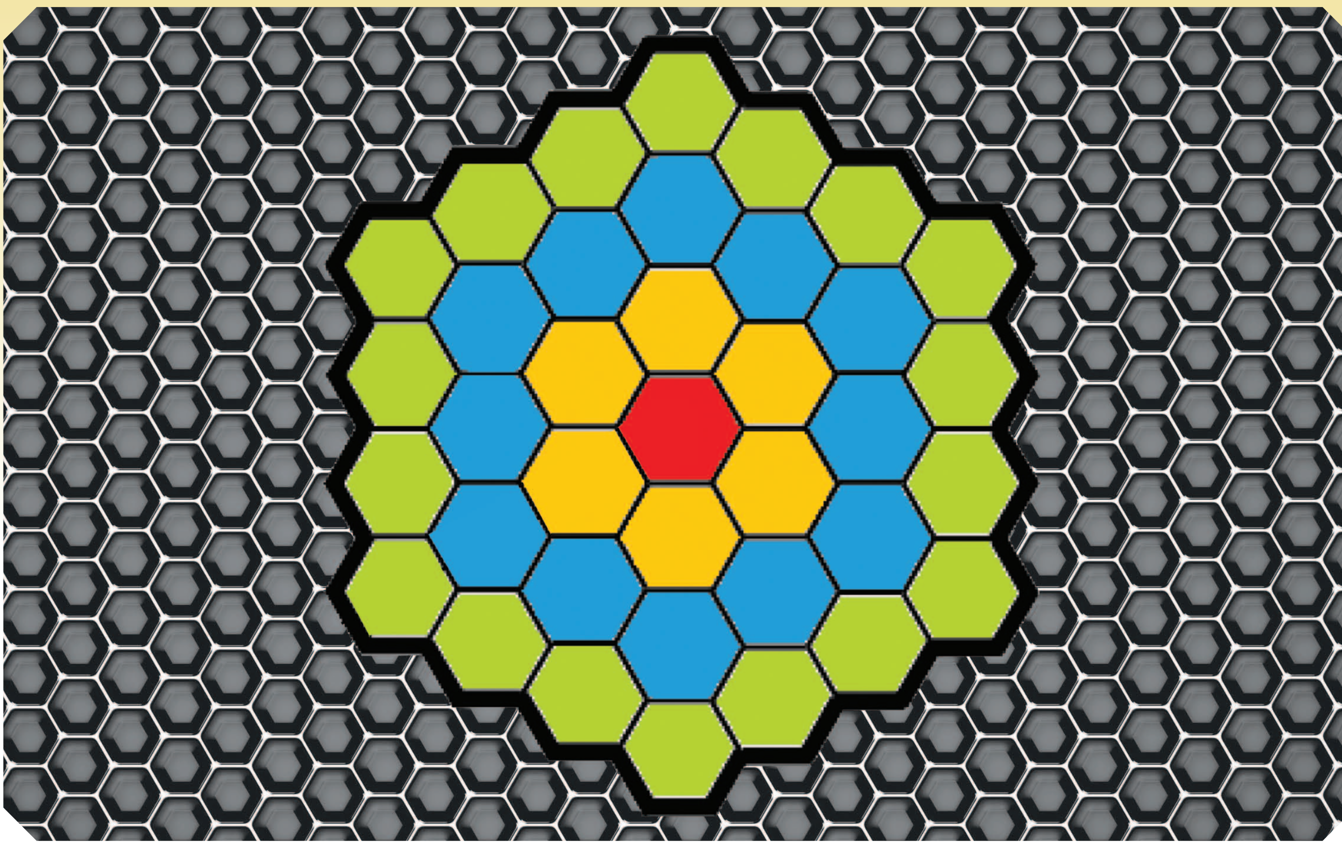
Location management in cellular mobile networks



ANIRUDDHA CHANDRA AND POULAMI DAS

Cell phones are meant for people and not for places. The freedom of movement offered by wireless technology was likely the sole reason behind the cell phone's increasing popularity in the early 1990s. Nevertheless, every new technology brings new challenges along with new opportunities, and wireless is no exception.

In super-centenarian wireline public switched telephone networks (PSTN), delivering calls to a terminal had always been pretty straightforward, as the dialed device number itself indicates the location of the device. For example, if you dial our office number 91 343 275 4380, the first two digits (91) denote the country in which we are residing, the next three digits (343) dictate our telecom circle, and the third segment (275) is our campus exchange code. Once the call reaches our exchange, it is routed through a slot number given by the last four digits (4380).

In contrast, our mobile numbers do not provide any such information regarding our whereabouts. We are free to move throughout the country and are still able to make/receive calls, provided that the mobile phone is within the network coverage area. This implies that network access point for any mobile terminal (MT) is not fixed, and to deliver services, there is a constant need to find out the location of terminals. The associated mobile network functionalities

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are collectively referred to as location management (LM).

LM in 2G cellular mobile networks is comprised of two network functions: location update (LU) and paging. By LU, an MT in its idle state informs the network about its current location. In the event of an incoming call to the MT, the complementary phase, i.e., the process of searching an MT from the last reported location, is performed. This is commonly referred to as paging. Paging involves polling the cells with a query message (a radio beacon) until there is a reply from the target MT.

While LU utilizes the uplink bandwidth (BW) and MT power, paging mainly utilizes the downlink resource. The BW, both wireless and wireline, and the computational requirements for LU are much more severe compared to paging. Moreover, the cost factors for LU and paging are often mutually conflicting. The larger the LU frequency, the more accurate the location information and the less paging traffic. Conversely, too few updates increase the paging traffic considerably. A network engineer is expected to trade off the cost overheads involved in the two processes as efficiently as possible. Application requirements and individual MT characteristics determine the exact degree of trade off.

In the late 1990s, the digital compatibility of cell phones opened up a plethora of new Internet-based applications—social networking, live multimedia streaming, and so on—resulting in a meteoric growth in the number of cell phone users over the last two decades. The possibility of global roaming in 3G and the introduction of new networking strategies in 4G—cognitive radio, relaying, etc.—led to the development of several LM techniques. An exhaustive survey of all the currently employed LM techniques is beyond the scope of this article. Instead, our goal is to introduce the basic concepts and motivate young readers to probe further.

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Understanding the terms

Architecture

As illustrated in Fig. 1, the service area in 2G (and beyond) cellular networks is partitioned into location areas (LAs), and each LA contains a number of cells. An MT is able to roam freely within the LA without updating its location information and would only need to perform an LU when it enters a new LA. When an incoming call arrives, the network locates the MT by paging all cells within the LA. A cell, usually represented with a hexagon, is served by a base station (BS) that transmits paging messages to all MTs within the cell over a common broadcast channel. All BSs of an LA are directly connected to the mobile switching center (MSC) via the backbone network. MSCs are telephone exchanges that act as interfaces between the MT and the PSTN/Internet. Moreover, the LM system resides in the MSCs. While the MT-BS links are wireless, BS-MSC links are usually fixed and wired.

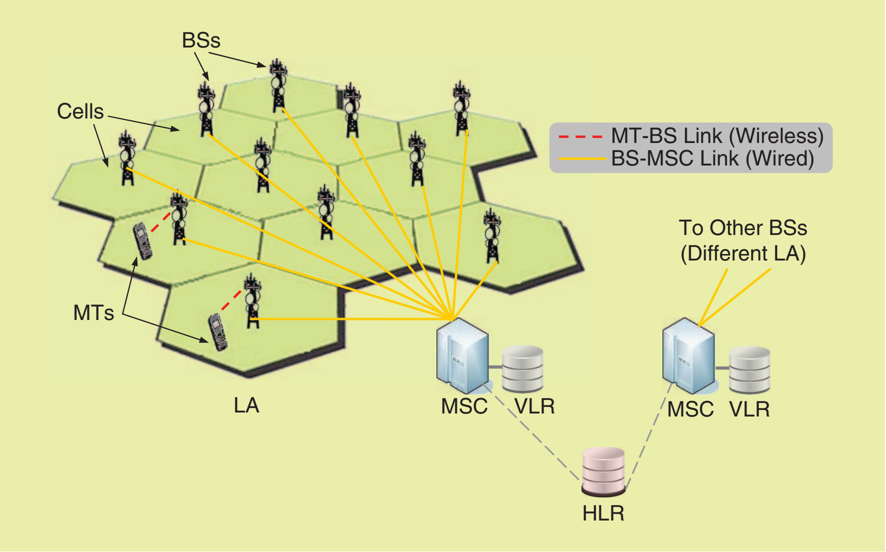

Fig. 1 The LM architecture of existing 2G cellular mobile networks.

Databases

The 2G cellular networks maintain two-tier mobility databases to track MTs, home location registers (HLRs) and visitor location registers (VLRs). The VLR is stored at MSC and it records, on a temporary basis, profile and location information of each MT currently active in the LA serviced by the MSC. On the other hand, there is an HLR for each network that maintains permanent subscription information of the MTs and contains pointers to the VLRs where MTs are currently residing.

LU involves updating location data in both HLR and VLR databases. When an MT moves to a new LA, it registers at the new VLR after being authenticated by the HLR. This is followed by a deregistration operation to remove the obsolete record in the old VLR.

In its basic form, paging area (PA), i.e., the cells that need to be searched in the event of an incoming call, is equal to that of an LA. However, modifications in the HLR/VLR architecture allow multiple PAs within a fixed LA. Furthermore, for dynamic LM schemes, both the size of LAs and PAs may vary.

Performance metrics

At the end of the day, a mobile user evaluates the overall quality of experience (QoE) of his/her cellular mobile network. QoE is a measure of the customer satisfaction level of the delivered service. It includes quality of service (QoS), measured through metrics like bandwidth allocation, bit rate, and throughput, from the service provider's end. However, ensuring excellent QoS does not guarantee great QoE. For instance, a poor QoE results when a video-conference customer experience variable delays, a voice over IP user hears an echo, or a video stream inexplicably stalls.

LM system design contributes heavily toward QoE, and thus it is important to identify the factors that affect the performance of an LM system. The task is difficult, as QoE is rather qualitative, and there exists several design parameters that affect QoE. In this article, however, we will restrict our discussion to the two most important performance metrics, namely, call to mobility ratio (CMR) and paging delay.

CMR is computed by dividing the average number of incoming calls by the average number of cell crossings the user makes in a given period of time. Users with smaller CMR values require more frequent location updates than users having higher CMRs.

Paging delay refers to the time required by the network to find the called MT through polling each cell until a reply message is received by the serving BS. An LM scheme that introduces more paging delay is less preferable but, quite interestingly, is not necessarily less efficient. For example, consider an LA that is divided into several PAs. Searching the PAs one by one requires many polling cycles, but once the MT is found, paging is immediately terminated and the rest of the cells in the LA are not paged. If the PA is same as LA, all the cells in the LA are searched in a single polling cycle. The extra cells that need to be paged generate unnecessary paging traffic and reduces efficiency of the LM system.

Finally, we would also like to include two important issues in LM system design: scalability and fault tolerance. While scalability is described as an LM system's capability to function in a similar fashion (without performance degradation) with an increasing number of mobile nodes, fault tolerance denotes the level of system survival during paging and update errors.

For a given network, the best design will include a scheme, or a set of schemes, which provides the best compromise between performance and implementation constraints and is often suboptimum for a different network.

Location update schemes

LU schemes are broadly classified into two categories: static and dynamic. In static LU schemes, HLR/VLR location updates are performed when an MT enters an LA. Quite naturally, for static schemes, the PA and LA are of the same size. Also, computational requirements are low owing to a lack of personalized user tracking. Dynamic schemes take into consideration the movement and call arrival characteristics of individual users and exhibit better performance over their static counterparts. The cost for this improved performance is the higher computational overhead involved. Figure 2 presents all popular subclasses of these two LU mechanisms.

Static schemes

Among the static LU schemes based on user mobility, there are primarily three variants, LU on cell crossing, LU on LA crossing, and LU at reporting cells. In the LU on cell crossing scheme, the location information is updated during a handover, i.e., each time an MT enters into a new cell. The exact location of an MT is always known and hence no paging is needed. In LU on LA crossing, the MT updates its location on entering a new LA, instead of a new cell, and thus necessitates paging all cells within the LA. A common problem in both these schemes is the so-called ping-pong effect, as illustrated in Fig. 3, that comes into picture when an MT repetitively moves between two adjacent cells/LAs. The problem is somehow overcome in the reporting-cell-based technique, where updates take place only when an MT enters into some specific cells, selected as reporting centers. The paging area consists of cells neighboring the latest reporting cell. Usually two immediate neighbors are never selected for reporting, and thus the ping-pong effect is largely reduced.

Another popular LU strategy that falls under the static category is the periodic update method, where an MT updates its location after fixed time intervals irrespective of its movement. This helps in regularizing the frequency of update requests and is particularly useful when a fixed LU cost is desirable.

Although static schemes are still widely employed due to their ease of implementation, they have many disadvantages that weaken their candidature for future generation cellular networks. For example, LU on cell crossing leads to an overwhelming increase in LU traffic causing unnecessary network overload.

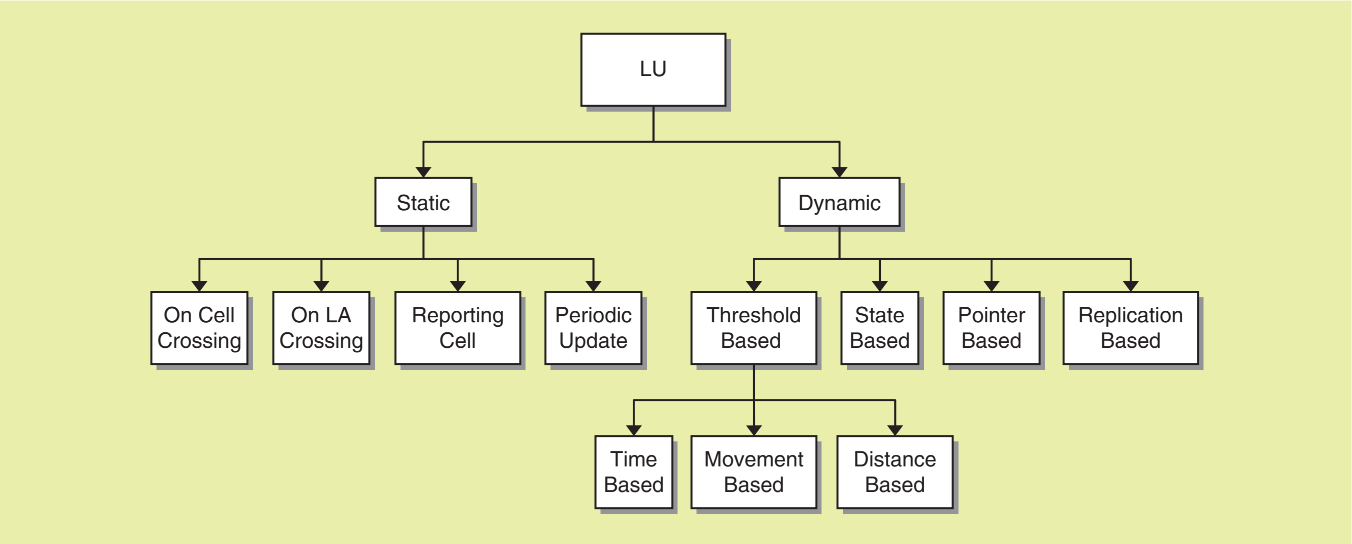

Fig. 2 The LU method classification.

The effect is more pronounced in low CMR regimes, i.e., when the user mobility is very high or the call arrival rate is very low. LU on LA crossing, on the other hand, requires excessive paging. As discussed earlier, both schemes also suffer from redundant updates when the user moves back and forth between two cells/LAs.

Reporting cells can provide a better trade-off between paging and update operations, but selecting the reporting centers itself is a complex task. Further, locating highly mobile users is difficult. The high degree of mobility also poses a great challenge to periodic update-based LM systems as there is no guarantee that the network is aware of the exact LA of an MT's residence and as paging across multiple LAs is often required. Conversely, users with extremely low mobility generate too many redundant updates. A matter of concern is that all these disadvantages become manifold when the network size grows. Considering the scalability of next-generation cellular networks, it appears that the scope of the static schemes is not very significant. Albeit, their understanding was crucial for studying the more complex LM mechanisms that are described in the next section.

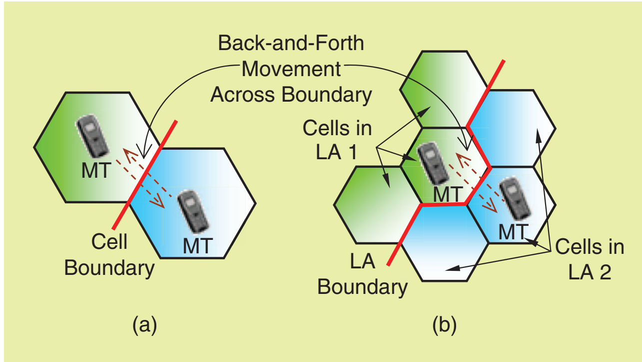

Fig. 3 The ping-pong effect in (a) an LU on cell crossing and (b) an LU on LA crossing.

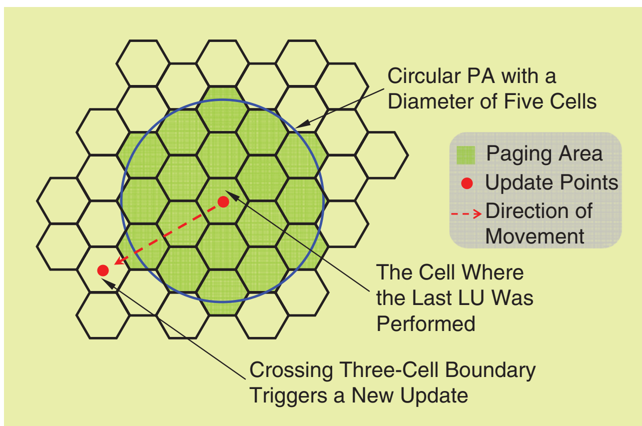

Fig. 4 The PA for movement-based LU with $n = 3$.

Threshold-based dynamic schemes

Mobility of the user and call arrival patterns greatly influence the performance of any LU strategy. A natural approach for dynamic LU schemes is to extend the static schemes to integrate call and mobility patterns of mobile users.

The most obvious extension is to define dynamic LAs for individual MTs. The size of a dynamic LA depends on the call arrival rate and mobility of the user. Further, updates may be skipped at some of the LAs where the MT stays for a very small amount of time and doesn't receive any calls. Another approach is to select user-specific dynamic reporting cells based on the most recent update and the direction of motion.

The most widely discussed dynamic schemes are, however, threshold based, in which an LU is performed whenever the value of a specified parameter exceeds a predetermined threshold. This threshold value is optimized on a user basis. Such schemes may be time based, movement based, or distance based.

Time-based LU is basically a periodic update strategy, discussed earlier, with a slight modification. The update interval is optimized for each MT based on its CMR. Further, the time threshold need not be fixed for a user. An adaptive threshold, which responds to the ever-changing user mobility and call arrival characteristics, may also be used. Time-based strategy is simple to implement with a network-controlled hardware/software-based time counter embedded in the MT.

The movement based scheme requires an MT to update its location whenever it crosses a specified number (say n) of boundary crossings. This number is assigned separately for each user. As seen from Fig. 4, the PA is therefore a circular area with a diameter $2n-1$ cells with a center cell where the last LU was performed. Boundary crossings are easily identified during a handover and may be stored in a counter.

To enforce the scheme in current cellular networks, the application layer of the protocol stack in mobile handsets needs some modification so as to enable it to count the number of cell boundaries crossed since the last VLR update. With smartphones becoming increasingly popular, this modification is not very difficult to implement and can be easily achieved by an online update by the network. For non-smartphones, the scheme can be pre-embedded during the manufacturing process.

In the distance-based scheme, the MT performs an LU after traversing a certain distance from the cell where it last updated its location. This distance threshold is specific for every user. Now, calculating Euclidean distance (the linear distance between the two points, one where the last update took place and the other where the MT currently is, measured on the user mobility plane) requires knowledge about the topology of the entire network and is a difficult task with irregular shaped cells. A predictive version of the distance-based scheme seems more practical, where the future location of an MT is predicted instead of actually locating the same. The prediction of the distance traversed can be calculated from the information of the past locations and the velocity of the corresponding MT.

A quick inspection of these three threshold-based schemes reveals that the time-based update strategy is the easiest to implement and may be realized with minimum computational overhead for nodes with moderate mobility. On the other extreme, distance-based strategies provide the best results but require excessive computation. Movement-based strategies lie somewhere in the middle and provide a good balance between the performance and implementation complexity.

Other dynamic schemes

Much like the threshold-based schemes, an MT performs a state-based LU depending on the state threshold. The state threshold however, is not governed by a single parameter like time, movement, or distance. Rather, the state information includes current location, time elapsed since last update, number of cell crossings since the last update, and the distance between the two last reported cells.

An important part of the update process is to contact the HLR so that the originating calls may be forwarded to the new VLR. Contacting the HLR each time an update takes place is a costly affair. To minimize the overall LM cost, some dynamic schemes make use of pointer forwarding or replication to reduce VLR-HLR communication. Other similar schemes like local anchoring and location caching do exist but are not included here for the sake of brevity. Some other schemes based on distributed database architectures (e.g., distributed registration and partitioning) are also excluded as our sole focus is on LM schemes that are based on two-tier HLR-VLR database architecture.

The pointer forwarding strategy works in the following way. When an MT enters a new LA belonging to a new VLR, instead of informing the HLR, a forwarding pointer from the old VLR to the new VLR is set. When a call for the MT is initiated, the network contacts the first VLR and follows the pointer chain to reach the current VLR. A threshold value for the length of the pointer chain is used to avoid lengthy delay. Once this threshold value has been reached, additional forwarding is not allowed and an update in the HLR record takes place.

The need for VLR-HLR communication can be reduced even further if the local database contains the profile information of the MT. In replication-based dynamic LU schemes, user profiles are replicated at selected local databases. Thus, for a roaming MT, networks need not query the HLR each time a call is made to the MT. This significantly reduces the signaling and database access overhead. Replication-based schemes work well for users with low mobility. For MTs with low CMR values, however, the entire profile needs to be replicated frequently, causing the waste of network BW. In addition, maintaining such large local databases is cumbersome.

In general, dynamic LU schemes offer both flexibility and adaptability and optimize the total signaling cost by adjusting LU frequency in accordance with call and mobility pattern of individual users. Although resorting to a dynamic scheme involves a compromise with the computational overhead, it is well compensated with the improved network performance.

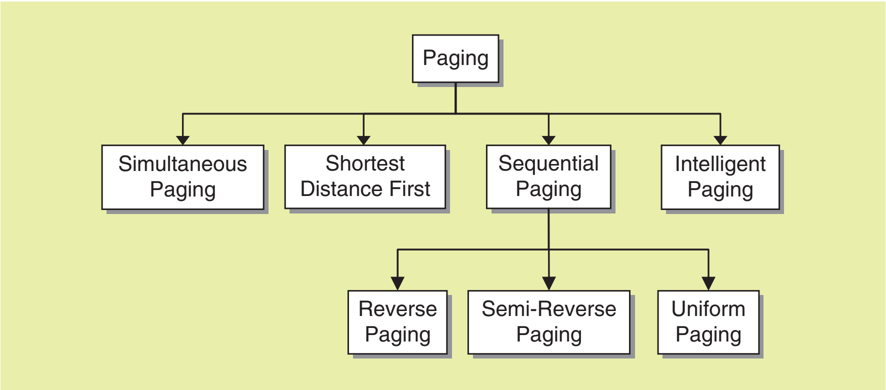

Fig. 5 A paging method classification.

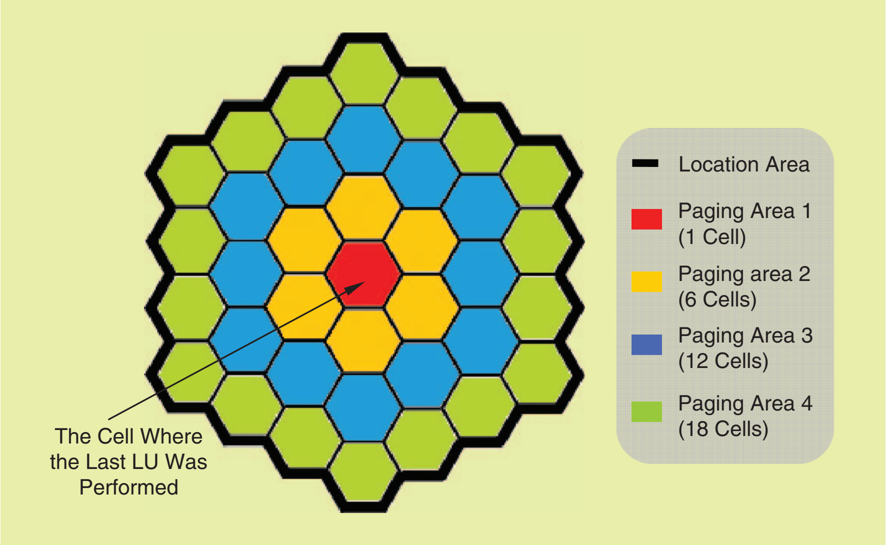

Fig. 6 The shortest distance for first paging for four paging areas within a location area.

Paging schemes

The LU processes discussed so far enable a cellular network to restrict its MT searching operation at the LA granularity. Terminal paging is the next logical step in any LM process. Paging refers to the examination of all possible cells within the LA to find the cell in which the MT is actually located.

Paging is performed on the arrival of an incoming call and involves sending a query message over the downlink signaling channel to all cells in the LA. All MTs monitor the common control channel periodically to check whether it has been paged or not. When an MT finds a paging signal for itself, it responds by sending an acknowledgement message over the uplink signaling channel.

The total area to be paged (i.e., the PA), in its basic form, equals the LA and depends on the accuracy and frequency of LU. A simple trade-off exists here—the better the location prediction through LU, the lesser is the size of PA. A smaller PA results in a reduced paging cost as the paging cost is proportional to the number of paged cells. To reduce the paging cost further, instead of paging all the cells within the LA at one go, the LA can be partitioned into several PAs that will be polled sequentially. There is a timeout period for each polling cycle. If the target MT replies before the timeout, the paging process is terminated. Otherwise, another PA is chosen in the next polling cycle.

Two questions arise: how to construct the PAs within a LA, and what should be the order of polling? The answers to these questions have resulted in the proposal of several paging schemes, as shown in Fig. 5. There is no doubt that for a network with small PAs we end up with polling lesser cells to find an MT. This translates into lower paging traffic, and the unnecessary waste of scarce radio BW is avoided. However, one should keep in mind that the prime concern for selecting a paging strategy is the paging delay, often limited by the QoE requirement of the network. The paging delay threshold denotes the maximum allowable time delay before which the target cell has to be tracked. In the recent literature, it has been often stated that one to three polling cycles are acceptable for practical implementations.

Simultaneous paging

In simultaneous paging (also known as blanket polling), all of the cells in the user's LA are paged simultaneously to determine the exact location of the MT. Such a parallel paging approach ensures a minimum delay in locating an MT but incurs a high degree of paging traffic. When the number of users is very large, a simultaneous paging approach renders the LM system unmanageable. This very fact inspired the development of other sophisticated paging schemes, some of which are discussed next.

Shortest distance first

In a shortest distance first (SDF) scheme, paging is initiated from the last updated cell and thereafter moving onward in a shortest distance first order. Fig. 6 shows one such example, where concentric rings are paged successively. When there is no paging delay constraint, these PAs may be polled one by one to ensure minimum paging overhead. With delay constraints, the number of maximum polling cycles is fixed, and the PAs need to be grouped to form a bigger PA. For the LA in Fig. 6, if the maximum paging delay is equal to two cycles, PA 1 and PA 2 may form the first group and polled in one cycle whereas PA 3 and PA 4 are polled in the next cycle.

Sequential paging

In a sequential paging scheme, the current location of the MT is predicted based on its location probability distribution and signals are sent only to selective locations. When delay is unconstrained, the polling cost is minimized by sequentially searching the LAs in decreasing order of probability of containing the MT.

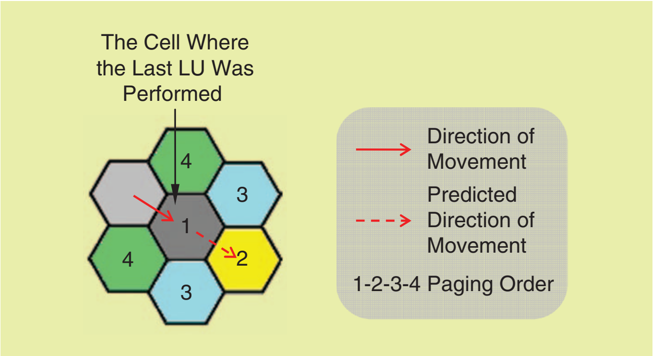

Fig. 7 The order of paging that will give the least traffic.

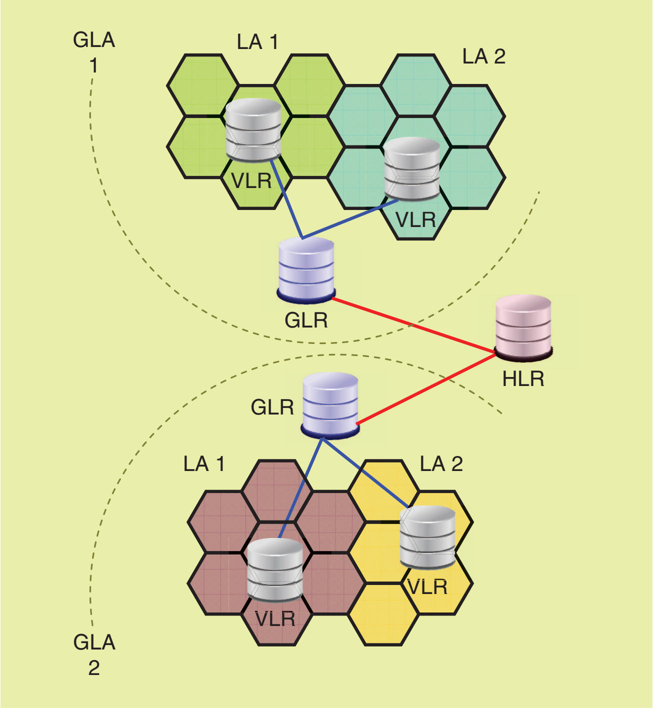

Fig. 8 The LM architecture of 3G cellular mobile networks.

Again, just like the SDF case, when there is a maximum paging delay constraint, a group of cells can be polled together in each polling cycle.

The order in which different PAs will be polled is calculated considering the call arrival characteristics and mobility pattern of the MTs. An example of such partitioning is shown in Fig. 7, where the first PA contains the last reported cell, the second PA is comprised of another single cell in the direction of movement, and the subsequent PAs contain cells where the MT is less (and lesser) likely to move.

There exist three major variations of the sequential paging scheme: reverse, semireverse, and uniform paging. In reverse paging, the total procedure is comprised of n polling cycles. In the first $n-1$ cycles, one cell is paged at a time in nonincreasing order of the MT's cell residing probability. In the last stage, i.e., in the nth polling cycle, the remaining cells are paged all at once. This method performs well in those cases when the MT is likely to be found within a few cells. In semireverse paging, cells are listed in order of decreasing probabilities of containing the MT. This is followed by the repeated grouping of two cells with the lowest probability into a PA. The process is continued until the number of PAs become equal to the number of allowable polling cycles. In uniform paging, the LA is partitioned into PAs in such a way that each PA contains approximately the same number of cells.

Intelligent paging

The idea of selective paging can be carried forward with more intelligent paging strategies. By intelligent paging, we refer to a group of schemes (e.g., rule based, bio-inspired, etc.), where the sequential paging scheme is further modified by computing the paging order of the different PAs based on pre-established probability metrics. The primary goal is to poll the correct PA in the first pass with a high degree of success. As expected, intelligent strategies entails even more computational overhead.

LM in next-generation networks

So far we have discussed several LU and paging techniques that were primarily devised for 2G cellular networks. Networks are evolving continuously but in a gradual manner. A big challenge for network engineers is to embrace new technologies and, at the same time, retain backward compatibility. Thus, the future LM systems are often modified versions of the older schemes.

LM in 3G networks

As far as location management issues are concerned, the biggest challenge in 3G networks, such as in the universal mobile telecommunications system (UMTS) or the standard international mobile telecommunication (IMT-2000), is to support global roaming. The traditional two-tier VLR-HLR database hierarchy, which was used in 2G, would result in frequent and costly HLR updates. A better approach is to introduce a three-tier architecture instead, namely VLR-GLR-HLR. Gateway location register (GLR) is an additional node between the VLR and the HLR in the roaming network and is used for keeping record of roaming subscriber's profile and location information.

When the first LU takes place during roaming, the roaming user's profile information is downloaded from the HLR to the GLR. For the subsequent LUs, the GLR continues to act as a local HLR until the user leaves the roaming network. This causes a huge reduction in internetwork signaling.

Figure 8 illustrates the LM architecture for 3G systems. The network coverage area is divided into gateway location areas (GLAs). Each GLA may encompass a small country or a big state and is composed of several LAs. Within a GLA, when a roaming MT transitions between two LAs, both the GLR and VLR are updated without contacting the HLR. The HLR is updated only when a MT crosses boundary of a GLA and move to a new roaming network.

LM in 4G networks

In the popular 4G networking standard, long-term evolution (LTE), there is a separate entity called the mobility management entity (MME) to control the mobility management functions. In general, the LM in 4G outperforms 3G mobility management as the paging traffic is greatly reduced. In the language of LTE, BSs are referred to as evolved Node Bs (eNBs) and its radio coverage is known as a cell. Cells are grouped into tracking areas (TAs) and each TA has its separate identity (TAI). Further, the TAs are cataloged in tracking area lists (TALs). If a user equipment (UE), which is an enhanced MT, moves out of the current TAL, it reports its new location to the MME. When the LTE network attempts to connect to the UE, the MME asks the cells in the TAL to page the UE. LTE partially implements the distance-based update scheme with SDF paging. Apart from periodic updates, a tracking area update (TAU) procedure is also invoked dynamically depending on the UE mobility or for MME load balancing.

It is expected that LTE will be a support for shared networks during mobility and initial access. In addition, it will also support various cell sizes and planned as well as ad-hoc deployments. In such a heterogeneous and overlapping network scenario, an MT is reachable via multiple access points. To manage different signaling formats, authentication procedures, and registration messages from different networks, a multitier HLR (MHLR) is proposed, where a tier manager is connected to all the HLRs.

Studies reveal that the performance of different LU and paging schemes is largely affected by the user mobility pattern and call arrival characteristics.

4G networks would also enable novel networking concepts like femto cells, cognitive radio (CR), and relaying. While relaying won't pose much of a challenge toward mobility management, femto cells and CR networks complicate the issues. Femto cells are meant for indoor communication between closed subscriber groups (CSGs). The paging mechanisms discussed earlier are mainly suitable for macro cells, and an optimum paging scheme for femto cells is still an open technical issue. In CR networks, unlicensed secondary users (SUs) share the spectrum without interfering with the transmission of other licensed primary users (PUs). Due to PU activity, an SU may have to move to another spectrum band. Apart from the normal user mobility, this spectrum mobility makes the mobility management much more challenging.

Recent trends in location update and paging

One of the important emerging LM schemes is the profile-based LM. From our regular observation we find that most users often follow a routine every day. Future networks may exploit this feature by maintaining user mobility patterns (UMPs), i.e., the routes traversed by the user as well as the time of entry to an LA and the residence time there. When the user follows his/her routine well, no LU is required, whereas in case of any deviation, the MT itself reports to the new VLR. The user's actual path information may be used to update the UMP periodically. To route an incoming call, only those LAs are paged where the MT is likely to be, which is predicted from the UMP.

There are some recent advancements in the paging domain too. Pipeline paging is such a scheme where the LA is divided into n PAs, with n being the maximum allowable polling cycles. Using subpaging channels, multiple MTs are searched in the same PA in a pipeline manner. If there are L paging channels available, $n \times L$ paging requests may be served by queueing paging requests in a first in first out order. In the next paging cycle, those requests for which the MTs had been found are removed from the queue and new requests (if available) are added to the queue. This scheme outperforms blanket paging and sequential paging schemes and can serve a large number of paging requests simultaneously.

Future 4G (3G and beyond) networks promise the integration of the Internet with the cellular network in a seamless manner. The network would be Internet protocol (IP) based, and it is envisioned that the respective LM systems would use mobile IP. One possible LM structure in 4G is that when an MT visits a foreign network, instead of sending the traffic to the original IP address assigned by the home agent (HA) at the MT's home network, the HA would forward traffic to a temporary IP allocated by a foreign agent through dynamic host configuration protocol.

Conclusion

Increasing traffic generated from users and different QoE requirements has increased the importance of LM recently. This increasing importance has given way to the development of newer and intelligent schemes as well as the modification of the existing ones. In this article, we have discussed various methods proposed for the two important LM functions, LU and paging. The features, relative performances, and inherent disadvantages associated with each of them have been thoroughly dealt with. Studies reveal that the performance of different LU and paging schemes is largely affected by the user mobility pattern and call arrival characteristics. Further, the newly devised schemes are often associated with tremendous implementation complexity as well as large computational overhead, and require smarter MTs/ networks. For a given network, the best design will include a scheme, or a set of schemes, that provides the best compromise between performance and implementation constraints and is often sub-optimum for a different network.

Read more about it

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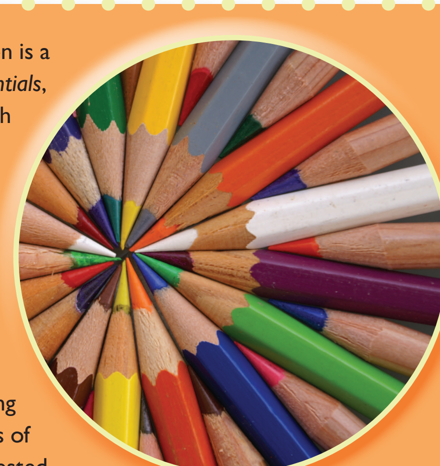

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