Mobility Management in Current and Future Communications Networks

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Abstract

This article describes current and proposed protocols for mobility management for PLMN-based networks, Mobile IP, wireless ATM, and satellite networks. The integration of these networks is discussed in the context of the next evolutionary step of wireless communications networks. First, a review is provided of location management algorithms for PCS implemented over a PLMN network. The latest protocol changes for location registration and handoff are investigated for Mobile IP, followed by a discussion of proposed protocols for wireless ATM and satellite networks. Finally, an outline of open problems to be addressed by the next generation of wireless network service is discussed.

The commercial proliferation of cellular voice and limited data service has created a great demand for global mobile communications and computing. Current voice, fax, e-mail, and paging services will give way to data transfer, videoconferencing, image transfer, and video delivery, while regional and national network coverage becomes worldwide coverage. While third-generation systems, such as International Mobile Telecommunication System 2000 (IMT-2000) and the Universal Mobile Telecommunications System (UMTS), seek to unify existing cellular, cordless, and paging networks for universal use [1], the next generation will have the additional goal of offering heterogeneous services to users that may roam across various geographical and network boundaries. To support roaming terminals, the future network will require the integration and interoperation of mobility management processes under a worldwide wireless communications infrastructure.

This article discusses the challenging mobility management issues for the next generation of wireless communications networks by investigating current protocols from various mobile networks and then describing the open problems regarding the interoperation and integration of mobility management for global heterogeneous network coverage. We include the following mobile networks in our discussion: public land mobile networks (PLMNs), Mobile Internet Protocol (Mobile IP) networks, wireless asynchronous transfer mode (WATM) networks, and low Earth orbit (LEO) satellite networks.

The next section defines the driving concepts behind mobility management. The section after that presents the future wireless network architecture. We then review the location management process for PLMN networks, and investigate mobility protocols for Mobile IP. We examine a selection of location advertisement and handoff protocols for WATM, and present the mobility management issues for satellite networks. Finally, the article concludes with a discussion of the open problems faced by the next generation of wireless networks.

Mobility Management

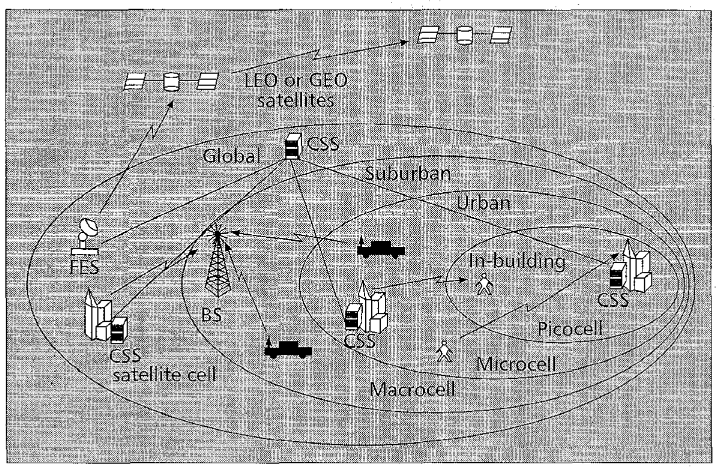
Mobility management enables telecommunications networks to:
- Locate roaming mobile terminals (MTs) for call delivery
- Maintain connections with MTs that change their point of attachment

The wireless network consists of many small service regions called *cells*. Each cell is served by a *base station* (BS) that assigns radio frequencies, or channels, to each MT within the cell. *Location management* tracks and locates the MT for the delivery of incoming calls, while *handoff* (or *handover*) management allows a call in progress to continue as the MT changes channels or moves between cells. In location management, the MT periodically performs *location registration* (i.e., *location update*), to explicitly notify the network of its new access point and store changes to its user location profile. Then, when incoming calls arrive, the network performs *call delivery* by querying the user profile to deliver the calls to the current cell location of the MT. Location management protocols deal with querying and storing information in location databases and sending paging signals to locate the user within the network. As a result, many of the issues are not protocol-dependent and can be applied to any of the mobile networks.

In handoff management, ongoing calls are modified under two conditions: signal strength deterioration and user mobility. Deterioration of the radio channel results in *intra-cell* handoff, where the calls are transferred to new radio channels of appropriate strength within the same cell, or *inter-cell* handoff, where the MT's connections are transferred to an adjacent cell. User mobility always results in inter-cell handoff. In each case, the MT's connections may be passed to the new BS without interrupting communications with the old BS. This is called *soft handoff.* On the other hand, if the connections are interrupted at the old base station and then established at the new BS, the process is called *hard handoff* [1].

Once the above conditions are identified by the user terminal or a network agent, handoff is initiated. Then, the network or the MT controls the handoff process. Under network-controlled handoff (NCHO) or mobile-assisted handoff (MAHO), the network generates a new connection, finding new resources for the handoff and performing any additional routing operations. For mobile-controlled handoff (MCHO), the MT finds the new resources and the network approves. Finally, the network must control the flow of data so that the sequencing, delay, and error constraints are maintained according to agreed-upon service guarantees. Handoff protocols rely on routing, resource management, and data delivery systems. Thus, unlike location management, the algorithms are network-protocol-dependent, causing an increased level of complexity with regard to interoperation.

Another dependency that must be reduced in order to support interoperability is region- or network-specific wireless network interfaces and infrastructures. Future wireless networks require the development of a standardized network architecture, employing increasingly common access to regional, national, and global services. In the following section, we discuss the basic building blocks of future wireless network architectures.



■ Figure 1. *Next-generation heterogeneous network services.*

Future Wireless Network Architecture

The International Telecommunication Union (ITU) has specified architecture and system standards for IMT-2000 that provide a structural basis for the properties of a global network. These specifications include a hierarchical cell structure, global roaming, and an expanding radio spectrum [2].

Hierarchical Cell Structure

The hierarchical cell structure (HCS) will cover all of the proposed operating environments of the mobile user. It will support radio environments that range from high-capacity picocells, to urban terrestrial micro- and macrocells, to large satellite cells, as shown in Fig. 1. Due to the potential of satellite links performing as traffic congestion relief and global extensions to terrestrial networks, network capacity will potentially increase — supporting more subscribers and greater traffic volumes without requiring additional radio spectrum for the terrestrial networks [3].

As mentioned earlier, the MT will send data on radio channels to communicate with base stations (BSs), also referred to as base transceiver stations (BTSs), which have access to the terrestrial (PSTN, ATM, Internet) network. In the satellite network, an MT will communicate with fixed Earth stations (FESs), which govern wireless traffic for satellite terminals, or with the satellite itself [4].

The MT will be able to roam freely within an area consisting of multiple cells called the *location area* (LA). Each cell will have one dedicated BS and a corresponding broadcast channel. Channel use is managed by the BS, which converts the network signaling traffic and data traffic to the radio interface for communication with the MT. The BS will also measure the link quality to perform handoffs to other cells.

Finally, a cell site switch (CSS) will govern one or more BSs. This switch will provide access to the serving backbone network (PSTN, Internet, ATM, or satellite). The CSS will also manage connection resources and provide mobility management control functions, such as location update and handoff to manage global roaming.

Global Roaming

The next-generation wireless networks will begin to implement terminal mobility, personal mobility, and service provider portability. Terminal mobility refers to the ability of the network to route calls to the MT regardless of its point of attachment to the network, while personal mobility is the ability of the user to access their personal services independent of the their attachment point or terminal. Service provider portability allows the user and/or the MT to transcend mobile networks, as illustrated in Fig. 2. The MTs can access direct connections to their service provider or network when available. Otherwise, an IMT subsystem network can provide access to limited versions of the user's home services. Thus, future networks will require such functions as user and terminal authentication and personalized service profiles. ITU specifications currently outline the use of a Universal Personal Telecommunications (UPT) number that will distinguish a user from the terminal itself [5]. Although interworking has been investigated for Mobile IP over ATM [6], the scope of the future requires transmitting data from any mobile network (e.g., WATM) across any of the other types of mobile networks (e.g., satellite, PLMN, Mobile IP).

This level of global mobile freedom will also require the coordination of a wide range of service providers, compatibility of mobile networks, and network operator agreements. Whereas such agreements are currently governed by commercial contracts, next-generation wireless networks will facilitate this process by developing global roaming agreements between different countries, regions, and service providers, and by increasing available radio spectrum based on these international agreements.

Radio Spectrum

The international frequency allocation for wireless networks as of the 1995 ITU World Radio Conference is shown in Fig. 3. A 170 MHz section of bandwidth is reserved for terrestrial use, while 60 MHz is reserved for satellite. The total spectrum was 1885 to 2025 MHz and 2110 to 2200 MHz. Internationally, the satellite band was 1980 to 2010 MHz. However, the satellite frequency allocations for Region 2 (the Americas and the Caribbean) are 1990 to 2025 MHz and 2160 to 2200 MHz. (The frequency gaps between 2025 to 2170 MHz and beyond 2200 MHz are reserved for other services such as remote sensing, cable TV relay service, electronic news gathering, and space research and operation.) Because of the differences for Region 2, it will be difficult for U.S. service providers to support mobile terminals from other regions that use the mobile satellite service. These assignments will remain in effect until the next scheduled conference in 1999. Startup of IMT-2000 bands is proposed for Japan by the year 2000 and also for Europe by the year 2002.

The agreement among regions and network service providers to work toward global roaming will require further development of location management operations. In the next section, we discuss database and paging issues for location management for second-generation PLMNs. As mentioned earlier, these protocols depend heavily on storage and retrieval of information (user profiles) and less on the network protocol. Thus, the schemes described in the next section are independent of the type of backbone network used for relaying the user information. With the appropriate interworking function, various backbone networks, such as the public switched telephone network (PSTN), ISDN, IP, frame relay, X.25, and ATM networks, can be used as the PLMN backbone.

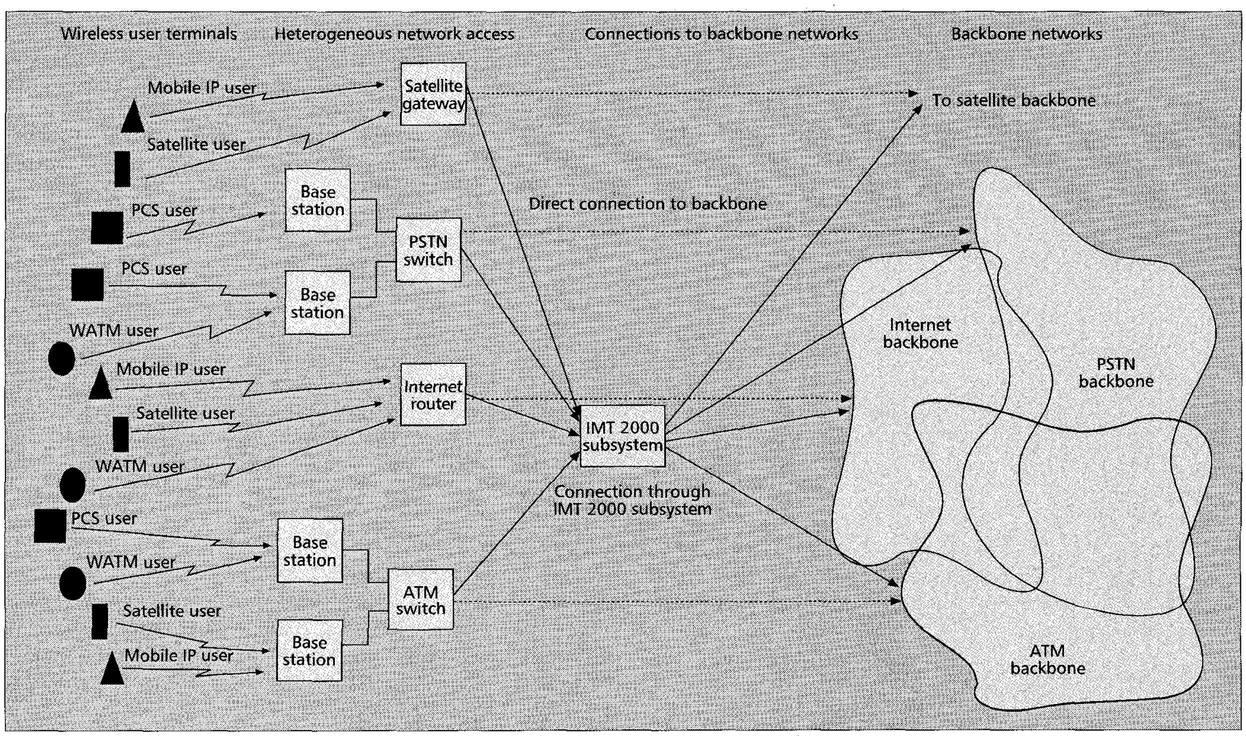
Mobility Management for PLMN

There are currently two available standards for location management in the PLMN: the Electronic and Telephone Industry Associations (EIA/TIA) Interim Standard 41 (IS-41) [7, 8] and the Global System for Mobile Communications (GSM) Mobile Application Part (MAP) [8, 9]. The IS-41 scheme is commonly used for the Advanced Mobile Phone System (AMPS) [10] and the IS-54 [11] and IS-136 networks, while GSM MAP is mostly used for GSM, Digital Cellular System-1800 (DCS-1800), and Personal Communications Service-1900 (PCS-1900) networks.

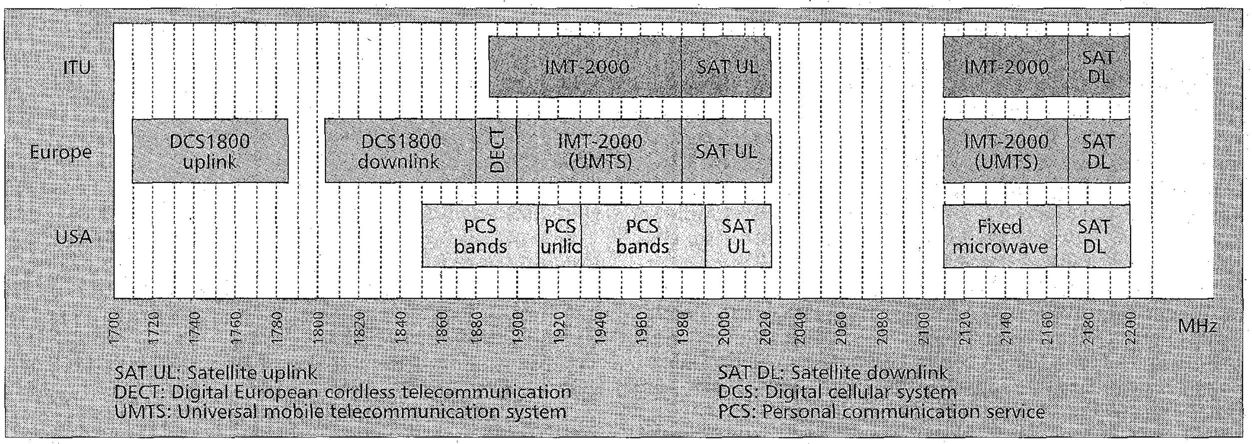
Network management functions, such as call processing and location registration, are achieved by the exchange of signaling messages through a signaling network. Signal System No. 7 (SS7) [12, 13] is the protocol used for signaling exchange, and the signaling network is referred to as the *SS7 network*. The type of CSS implemented for the PLMN is known as a *mobile switching center* (MSC).

Location Management Procedures

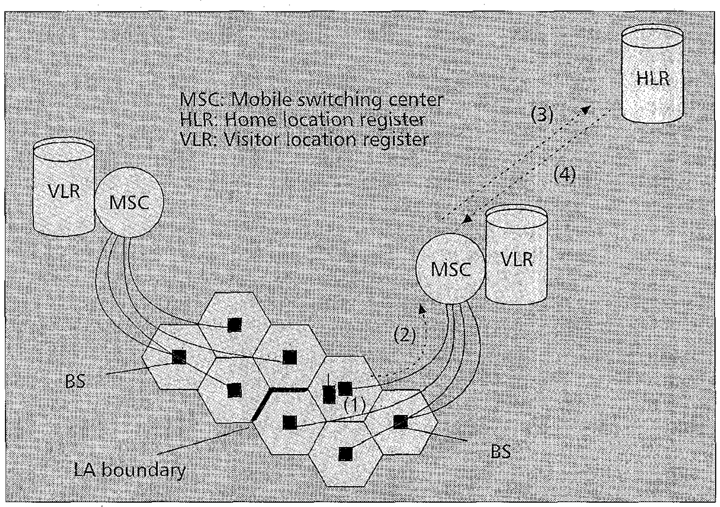
As mentioned in the first section, location management includes two major tasks: location registration and call delivery. These operations are implemented for PLMN-based networks by using a two-level hierarchy of databases, the home location register (HLR) and the visitor location register (VLR). The HLR permanently registers each user that is a subscriber to its particular network, while a VLR registers any user that has moved into its network temporarily. The location registration procedure, shown in Fig. 4, proceeds as follows:
- The MT enters a new LA and transmits a location update message to the new BS.
- The BS forwards the location update message to the MSC, which launches a registration query to its associated VLR.
- The VLR updates its record on the location of the MT. If the same VLR serves both the new LA and the old LA, *no further action is required*. If not, the address of the MT's HLR must be determined from its Mobile Identification Number (MIN). The new VLR then sends a location registration message to the HLR.
- The HLR performs the required procedures to authenticate



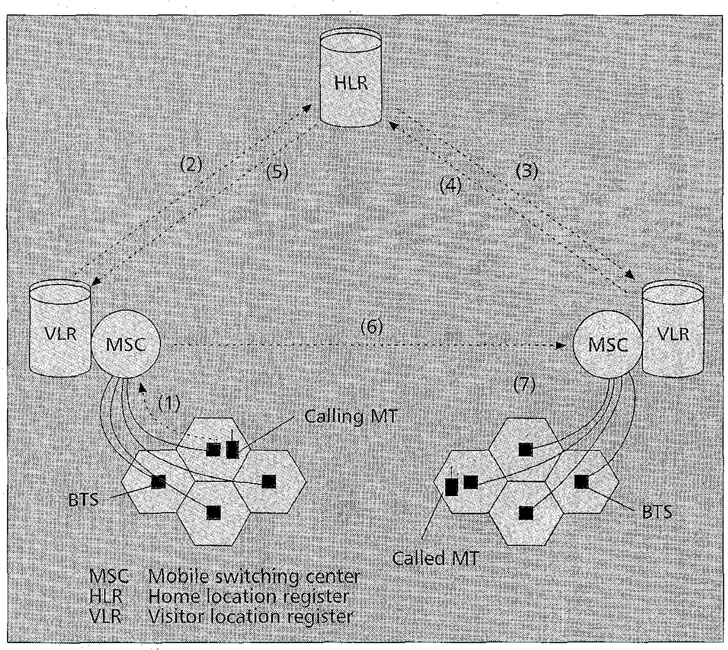
■ Figure 2. *Next-generation service provider portability.*



■ Figure 3. *Frequency allocation.*



■ Figure 4. *Location registration procedures.*



■ Figure 5. *Call delivery procedures.*

the MT and records the identity of the new serving VLR of the MT. The HLR then sends a registration acknowledgment message to the new VLR and a registration cancellation message to the old VLR. (The old VLR deletes its record of the MT.)

Once the user profile has been stored in the appropriate database, the network is ready to deliver incoming calls to the MT by retrieving the stored location records. The call delivery procedures are illustrated in Fig. 5 and listed below:

- The calling MT sends a call initiation signal to its own MSC through a nearby base station.
- The MSC determines the address of the HLR of the called MT by global title translation and sends a location request message to the HLR.
- The HLR determines the serving VLR of the called MT and sends a route request message to the VLR. This VLR then forwards the message to the MSC serving the MT.
- The MSC allocates a temporary local directory number (TLDN) to the MT and sends a reply to the HLR together with the TLDN.
- The HLR forwards this information to the MSC of the calling MT.
- The calling MSC requests a call setup to the called MSC through the SS7 network.
- The called MSC initiates a *paging* (or *alerting*) procedure within the current LA of the MT, and the MT replies in order to receive the call.

The signaling required for registration, update, and terminal paging increases the signaling load on the network through repeated queries to the VLRs, long-distance queries to the HLRs, and terminal paging throughout the LAs [14].For this reason, current research activity concerns the minimization of signaling traffic on the network [15–18]. The research areas include database architecture design, location update conditions, and terminal paging areas.

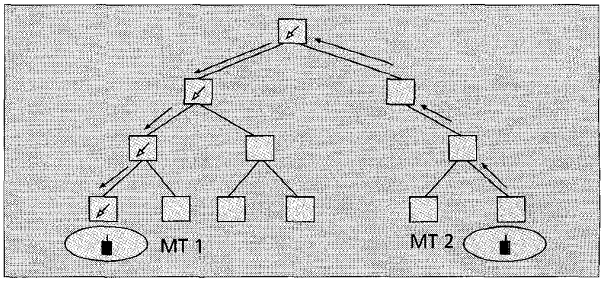
Location Management Research

Database Architectures — An important method for reducing the database querying traffic is to modify the database architecture. Modifications to the current centralized approach (storing the location information in a permanent HLR) attempt to reduce the need for long-distance queries by keeping a local reserve of pointers to the MT's current location [19, 20] or storing local copies of the MT's location information [21, 22]. Other structures abandon the centralized database and distribute the MT's location profile throughout the network, maintaining databases close to the MT's new location. For example, distributed database tree algorithms found in [23, 24] store location information or location pointers in the databases associated with the subtree location of the MT. A scheme introduced in [25] associates the MT with the leaf (lowest-level) location databases, as shown in Fig. 6. Each database node contains location profiles for the MTs that are residing in its subtree. When an MT moves to an LA that belongs to a different subtree, the corresponding databases are updated to indicate the correct location of the MT.

Location Update — Several location update techniques seek to limit update signaling for MTs repeatedly traveling across the same LA boundaries. The first technique allows the MT to perform an update only after passing a preset threshold, such as a constant time interval, after a certain number of cell crossings, or after traveling a certain distance. Other techniques tailor the updates to match the behavior patterns of the MT, determining the necessity for an update based on the gathered statistics of the MT's call arrivals [26] or mobility patterns [27, 28].

Terminal Paging Schemes — Paging schemes are similar to update schemes in that the network traffic is reduced by considering the behavior of the user before signaling the MT. Velocity paging [29] classifies the MT according to the maximum distance the MT could have traveled since the last update. Then only the cells that lie within the maximum distance are paged first. Other schemes employ user statistics. The procedure in [30] first assumes that the probability that an MT is residing in a given LA is provided. Then it is demonstrated that when delay is unconstrained, the polling cost is minimized by sequentially searching the LAs in decreasing order of probability of containing the MT.

The centralized database architecture of PLMN-based location management is conducive to interoperability with other mobile networks that use databases to store location information (e.g., ATM, satellite). However, future wireless networks will require a method for interoperating with other mobile networks such as Mobile IP, which does not incorporate



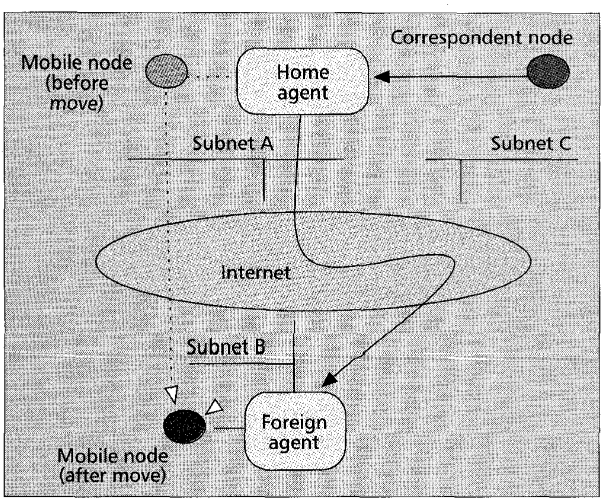
■ Figure 6. *Distributed hierarchical tree-based database architecture.*

databases and Location Areas. In the next section we investigate current research and standardization efforts supporting terminal mobility under Mobile IP.

Mobility Management for Mobile IP

Standards for terminal mobility over the Internet have been developed by the Internet Engineering Task Force (IETF) and outlined in Requests for Comments (RFCs) 2002–2006 [29]. Within the wireline Internet Protocol (IP), fixed terminals communicate differently depending on their subnetwork location. Terminals on the same subnetwork can send packets directly, while terminals belonging to different subnetworks must send their packets through IP nodes, or routers, which perform routing functions [32]. The mobility-enabling protocol for the Internet, *Mobile IP*, promises to enable terminals to move from one subnetwork to another without interrupting this process [33]. Variations in Mobile IP include versions 4 (IPv4) and 6 (IPv6). Comparatively, IPv6 can provide more addresses and mobility support than IPv4. Thus, the procedures in this section are based largely on IPv6, except where noted.

A mobile node (MN) is a host or router that changes its attachment point from one subnet to another without changing its IP address. The MN accesses the Internet via a home agent (HA) or a foreign agent, FA, in IPv4. The HA is an Internet router on the MN's home network, while the FA is a router on the visited network. The node at the other end of the connection is called the correspondent node (CN). A simple Mobile IP architecture is illustrated in Fig. 7. In this example, the CN sends packets to the MN via the MN's HA and the FA. (Note that the term mobile node is used instead of mobile terminal in order to follow Mobile IP conventions.)



■ Figure 7. *Mobile IP architecture.*

In achieving mobility between subnetworks, Mobile IPv6 allows some operations for location and handoff management:

- *Registration* — how an MN registers with its HA
- *Discovery* — how an MN finds a new Internet attachment point when it moves from one subnet to another
- *Routing and tunneling* — how an MN receives datagrams when it is away from home [31]

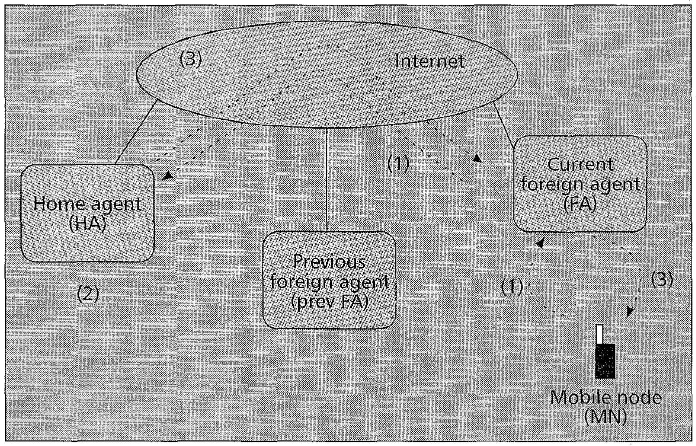
Location Registration

When visiting any network away from home, each MN must register with its HA and FA in order to track the MN's new IP address at the visited subnetwork and to complete the delivery of datagrams to that address. There are two IP addresses associated with each MN, one for locating and the other for identification. The new IP address associated with an MN while it visits a foreign link is called its care-of address (CoA), which is linked to the MN's home address by a *mobility binding*. Each binding has an associated lifetime period, which is negotiated during the MN's registration and is used to determine when the registration is deleted [31].

Depending on its method of attachment, the MN sends location registration messages directly to its HA, or through an FA which forwards the registration to the HA [34]. In either case, the MN exchanges Registration Request and Registration Reply messages based on IPv4 as described below and shown in Fig. 8:

- The MN registers with its HA using a Registration Request message (the request may be relayed to the HA by the current FA).
- The HA creates or modifies a mobility binding for that MN with a new lifetime.
- The appropriate mobile agent (HA or FA) returns a Registration Reply message. The Reply message contains the necessary codes to inform the mobile node about the status of its Request and to provide the lifetime granted by the HA [31].

In IPv6, the FAs in Fig. 8 no longer exist. The entities formerly serving as FAs are now thought of merely as Access Points (APs).



■ Figure 8. *Mobile IP location registration.*

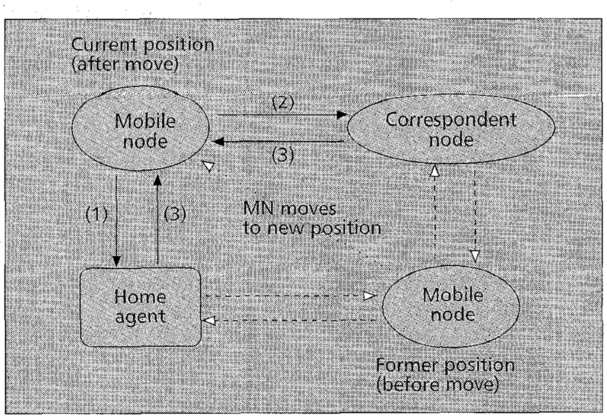
In the PLMN, the movement of the user was determined by updates performed when the user moved into a new LA. Since Mobile IP does not use LAs to periodically update the network, we discuss a new feature to determine whether the MN has moved to a new subnet after changing its network APs. Mobile agents make themselves known by sending Agent Advertisement messages. Then the MN can use two methods to determine whether it is still on its home network, or it has moved to a new network. First, the MN can record the lifetime field of the Agent Advertisement message. When the lifetime expires, the MN must perform a location update. Alternatively, the MN can compare the network prefix in the Agent Advertisement message with the network prefix of its CoA. If the prefixes are different, the MN can assume it has moved.

After discovering that MN is on a foreign network, it can obtain a new CoA for this new network from the prefix advertised by the new router, and perform the following location update procedures, as shown in Fig. 9:

- The MN registers a new CoA with its HA by sending a Binding Update.
- The MN notifies its CN of the MN's current binding information.
- If the Binding is allowed to expire, the CN and the HA send a Binding Request to the MN to get the MN's current binding information.

The MN responds to the Binding Request with its new Binding Update. After receiving the new CoA, the CN and HA send a Binding Acknowledgment to the MN.

Once the registration process is complete, packet delivery consists of reaching the MN via the new CoAs. Furthermore, a wireless network interface may actually allow an MN to be reachable on more than one link at a time. This establishment of coexisting wireless links can be very helpful for smooth handoff. The HA utilizes the registration information to establish the transmission path to the MN [35].



■ Figure 9. *Mobile IP location management operation.*

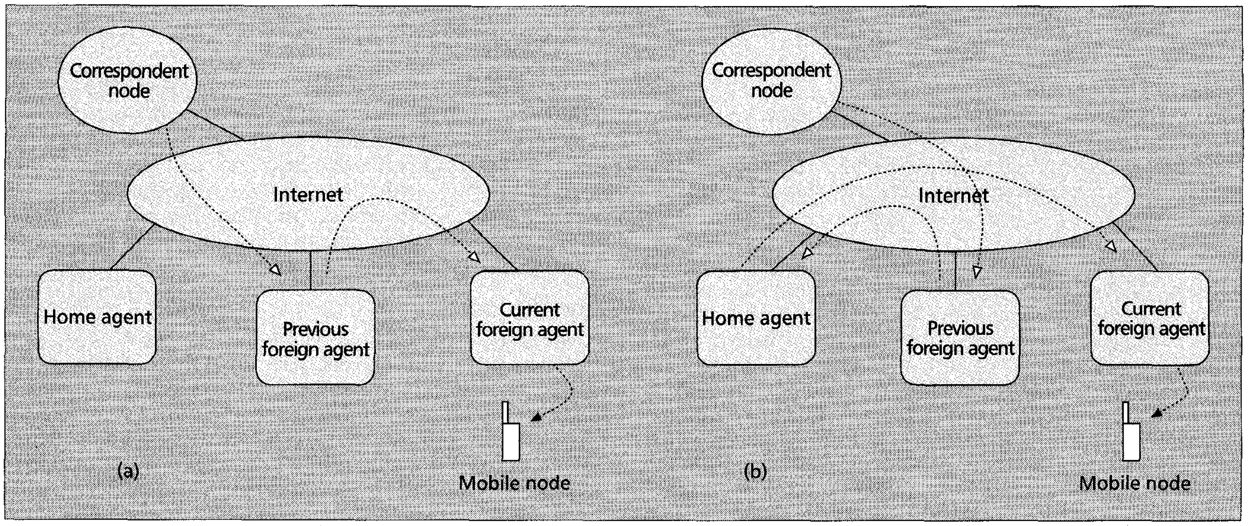
Handoff Management

Smooth Handoff — A smooth handoff for MNs that are changing their point of attachment to the Internet is crucial for maintaining service guarantees. Current routing optimization schemes in IPv4 allow the previous FA(s) to maintain a binding for their former mobile visitors, showing a current CoA for each. Then, as packets are sent to the old CoA, the previous FAs can forward the packets to the current CoA of the MN as demonstrated in Fig. 10a. As a result, an MN is able to accept packets at its old CoA while it works to update its HA and correspondent nodes with a new CoA on a new link.

If the previous FA does not have a fresh binding (i.e., the binding lifetime has expired), the previous FA forwards the packets to the HA of the MN, which sends the packets to the CoA from the MN's last location registration update, as shown in Fig. 10b. This can potentially create unnecessary traffic if the HA's binding still refers to the previous FA. Alternatively, the previous FA can invoke the use of *special tunnels* which forward the packets, but also indicate the need for special handling at the HA.

When special tunnels are used, the datagrams that are sent to the HA are encapsulated with the previous CoA address as the source IP address. Upon reception of the newly encapsulated datagrams, the HA compares the source IP address with the MN's most recent CoA. Thus, if the two addresses match, the packets will not be circled back to the FA. However, if the addresses do not match, the HA can decapsulate the packets and forward them to the MN's current CoA, as shown in Fig. 10b [31]. (Note: In IPv6, the smooth handoff procedure is based on routers — IPv6 nodes — instead of FAs).

Routing and Tunneling — Handoff techniques for Mobile IP employ the use of tunnels, such as the *special tunnels* mentioned for smooth handoff, to minimize the inefficient path use resulting from routing datagrams through the HA. *Route optimization* [36] caches the binding of an MN and then tunnels datagrams directly to the CoA indicated in that binding, bypassing the MN's HA. *Tunnel establishment* [37] transmits packets between arbitrary nodes by sending protocol data units (PDUs) to a tunnel endpoint according to a set of parameters, including the network address for the MN and the tunnel endpoint.



■ **Figure 10.** *Mobile IP smooth handoff: (a) fresh binding at previous FA; (b) no fresh binding at previous FA.*

Open Problems

Simultaneous Binding — Since an MN can maintain several CoAs at one time, the HA has to tunnel packets to several endpoints. Thus, the HA is instructed to send duplicate encapsulated datagrams to each CoA. After the MN receives the packets from the CoAs, it can invoke some process to remove the duplicates. If necessary, the duplicate packets may be preserved in order to aid signal reconstruction. Due to the slow incorporation of wireless local area networks (WLANs) technology into the marketplace, simultaneous binding has not yet been made available [31].

Regionalized Registration — Currently, three major concepts have been identified as potential methods for limiting location update and registration cost. First, there is a need to manage the local connectivity available to the MN and the buffering of datagrams to be delivered. Through this, the network can glean the benefits of smooth handoffs without implementing route optimization procedures [34]. Second, a multicast group of FAs is needed in order to allow the MN to use a multicast IP address as its CoA. Third, a hierarchy of FAs can be used in agent advertisement in order to localize the registrations to the lowest common FA of the CoA at the two points of attachment [38].

Security — As mentioned for the PLMN, the authentication of the mobile becomes more complex as the MN's address loses its tie to a permanent access point. This allows a greater opportunity for impersonating an MN in order to receive services. Thus security measures for the registration and update procedures — specifically protecting the CoAs and HAs — must be implemented in order to police terminal use [31]. Some authentication schemes for the MN, the HA, and the FA can be found in [39].

Mobile IP did not employ databases and LAs as discussed for the PLMN. However, these issues will be visited again for WATM and satellite networks. Thus, much of the research for PLMN-based networks will apply in some form to the WATM and satellite networks. Next we address the concerns for mobility management for WATM.

Mobility Management for Wireless ATM

The ATM Forum, through the WATM Working Group, has focused its efforts on developing basic mechanisms and protocol extensions for location and handoff management that address important issues such as latency, message delivery, connection routing, and quality of service (QoS). Many of the protocols are also compatible with PCS, satellite, and, to a lesser degree, Mobile IP concepts.

Location Management Research

Proposed protocols for WATM implement location management using two techniques. The first technique, *location servers*, is based on the use of databases, updates, and terminal paging, as discussed in detail for the PLMN. In this section we address the second technique, *location advertisement*, which avoids the use of databases by passing location information throughout the network on broadcast messages.

Location Advertisement Techniques — Above, advertisement was described for Mobile IP as a router notifying the MN of its new attachment point. In this section, advertisement refers to the notification of appropriate network nodes of the current location of the MT. The first method, *Mobile private network–network interface* (PNNI), uses the WATM signaling architecture in order to take advantage of an internal broadcast mechanism [40]. The status notification procedures of the PNNI network protocol are exploited in order to propagate location information about each MT in the network without the use of a database. The second method, *Integrated Location Resolution* [41], is an adaptation of an IETF Mobile IP scheme that attempts to interwork Mobile IP under WATM [5]. The scheme modifies the signaling operations of the ATM call setup process to include indications of the called terminal's current location.

In addition to the location management issues, WATM networks address the delivery of broadband traffic. Thus, it is crucial to consider handoff management under QoS guarantees for mobile connections.

Handoff Management Research

Current proposed protocols for handoff can be grouped into four categories: *full connection rerouting*, *route augmentation, partial connection rerouting*, and *multicast connection rerouting*. Full connection rerouting maintains the connection by establishing a completely new route for each handoff — as if it were a brand new call. Route augmentation simply extends the original connection via a hop to the MT's next location. Partial connection rerouting re-establishes certain segments of the original connection, while preserving the remainder. Finally, multicast connection rerouting combines the former three techniques, but includes the maintenance of potential handoff connection routes to support the original connection, reducing the time spent in finding a new route for handoff [42]. Since the first two categories of handoff connection management are self-explanatory, they will not be addressed here. Interested readers can refer to [43, 44].

Partial Connection Rerouting — Partial connection rerouting attempts to route the connection more efficiently than the full connection or route augmentation methods by preserving some portions of the original route and rerouting other portions. Examples of such algorithms can be found in [42, 45]. Each protocol bridges the handoff connection at the nearest WATM network node that is common to both the old and new switches involved in the handoff transaction. In a tree topology, *common* refers to two nodes branching from the same point. In a hierarchy, the common point is a higher node which uses separate paths to access each switch. The common node serves as a pivot for the connection path, tearing down the portion of the connection that leads to the old switch and establishing a partial connection that crosses the connection over to the new switch.

Multicast Connection Rerouting — Multicast connection rerouting reduces the time spent in selecting new routes for handoff by maintaining several prospective routes at one time. The virtual connection tree algorithm [46] arranges the ATM switching nodes in a tree with a fixed switching node at the root and the BSs at the leaves. Each mobile connection is assigned a set of virtual connection numbers (VCNs) that are used to identify a set of paths from the root to one leaf. Only one path is operational at a time. The connection extends from the MT through the BS leaf to the root of the tree and on to the fixed network, or to the root of some other connection tree. Handoff occurs when the MT begins to transmit cells with a new VCN (from its assigned set of VCNs), corresponding to one of the preassigned inactive handoff routes. When the cells arrive at the root, the root switch changes to the new VCN path. Handoff between virtual connection trees occurs as a new connection being admitted to the new tree.

ATM Forum Activity

Two protocols being considered for standardization by the ATM Forum are an extended location registers scheme and an extended mobile PNNI scheme [47]. Future work will focus on service classes for mobile connections, QoS renegotiation, signaling protocols for reconfiguring the connection path, point-to-multipoint connections, and periodic rerouting for optimality [48].

Terrestrial wireless networks such as PCS, Mobile IP, and WATM provide mobile communication services with limited geographic coverage. In recent years several LEO satellite systems have been proposed to provide global coverage to a more diverse user population. In the following section we describe the mobility management concerns for these satellite networks.

Mobility Management for Satellite Networks

LEO satellites are usually defined as those with altitudes between 500 and 2000 km above the Earth's surface. This low altitude provides small end-to-end delays and low power requirements for both the satellites and the handheld ground terminals. In addition, intersatellite links (ISLs) make it possible to route a connection through the satellite network without using any terrestrial resources. These advantages come along with a challenge; in contrast to geostationary (GEO) satellites, LEO satellites move in reference to a fixed point on the Earth. Due to this mobility, the coverage region of a LEO satellite is not stationary. Global coverage at any time is still possible if a certain number of orbits and satellites are used. The coverage area of a single satellite consists of small-sized cells, which are called *spotbeams*. Different frequencies are used in different spotbeams to achieve frequency reuse in the satellite coverage area. In the following subsections, we present the state of the art and open research areas for satellite location and handoff management.

Satellite Location Management Research

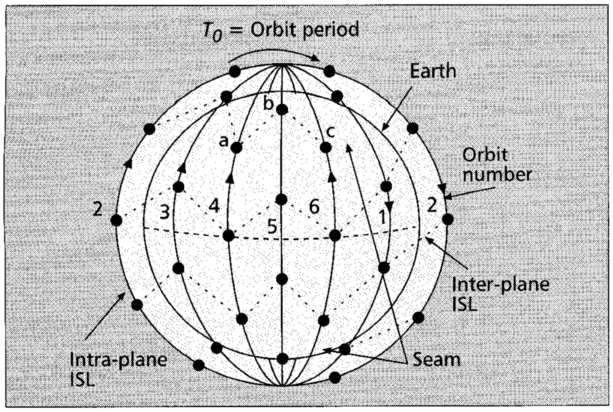
As we have discussed for PCS, Mobile IP, and WATM, location management is largely performed independent of the particular mobile network protocol. However, the geographic dependence of location management on the LA introduces new concerns. For example, LA boundaries cannot be determined by the movement of the MT, since that movement is negligible compared to the movement of the LEO satellite. Thus, current research concerns the development of new LA definitions for satellite networks as well as the signaling issues for paging and update mentioned for the PLMN. The concept of LAs for satellite networks and the levels of integration that can be achieved between terrestrial and satellite location management operations are investigated in [4, 49].

Satellite Handoff Management Research

To ensure that ongoing calls are not disrupted as a result of satellite movement, calls should be transferred or *handed off* to new spotbeams or satellites. If a handoff is between two spotbeams served by the same satellite, handoff is *intra-satellite*, while handoff between two satellites is referred to as *intersatellite handoff*. Since two satellites are involved in intersatellite handoffs, the connection route should be modified to include the new satellite in the connection route. Thus, the same connection routing issues discussed for WATM in the previous section are again encountered for satellite networks. In [50] a handoff rerouting algorithm, referred to as Footprint Handover Rerouting Protocol (FHRP), has been proposed to handle the intersatellite handoff problem in the LEO satellite networks. FHRP is a hybrid algorithm that consists of the augmentation and footprint rerouting phases. In the augmentation phase, a direct link from the new end satellite to the existing connection route is found. This way, the route can be updated with minimum signaling delay and at a low signaling cost. In case there is no such link with the required capacity, a new route is found using the optimum routing algorithm. In the footprint rerouting (FR) phase, the connection route is migrated to a route that has the same optimality feature as the original route. The goal of the rerouting is to establish an optimum route without applying the optimum routing algorithm after a number of handoffs. This property is significant because in the ideal case the routing algorithm computes a single route for each connection. In addition to handoffs resulting from the movement of satellite coverage areas, another form of handoff occurs as a result of the change in the connectivity pattern of the network. Satellites near polar regions turn off their links to other satellites in the neighbor orbits. Ongoing calls passing through these links need to be rerouted. This type of handoff is referred to as *link handoff*.

Spotbeam Handoff Algorithms — Spotbeam handoff occurs frequently due to the small size of spotbeams. As an example, a user terminal is covered with a spotbeam for an average duration of 38 s, while it stays in the footprint of a single satellite for an average duration of 10 min. Frequent spotbeam handoffs would cause blocking of the handoff call if no ground–satellite channel is available in the new spotbeam.

Handoff policies provided for satellite links include the queu-



■ **Figure 11.** *LEO satellite network with seam.*

ing of handoff requests [51] and the use of guard channels for handoff calls [52]. Handoff queuing algorithms place handoff requests in a queue when there are no channels available in the new overlapping target spotbeam. When a channel becomes available, one of the calls in the handoff queue is served. Guard channels are channels in the target spotbeam that are reserved for handoff calls. Thus, new call requests may be rejected, even when the new call arrival rate is high. There is a tradeoff between handoff call blocking and new call blocking.

Handoff rerouting has also been addressed for satellites. An analytical model has been proposed to calculate the handoff rate for single-hop satellite connections in [53]. In a more recent study [51], inter-orbit handoffs are investigated which prioritize queued handoffs according to call blocking probabilities.

Link Handoffs — The topology of LEO satellite networks changes with time due to inter-satellite links that are temporarily switched off. Each LEO satellite has up and down wireless links for communication with ground terminals and inter-satellite links for communication with neighbor satellites. There are two types of ISLs: *intra-plane* ISLs connecting satellites within the same orbit, and *inter-plane* ISLs connecting satellites in adjacent orbits. Intra-plane ISLs can be maintained permanently. On the other hand, inter-plane ISLs would be temporarily switched off due to the change in distance and viewing angle between satellites in neighbor orbits. In the analysis reported in [54] for the IRIDIUM system, it is concluded that only ISLs between latitudes of approximately 60° north or south would be maintained between counter-rotating orbits. This is labeled *seam* in the example network model depicted in Fig. 11. When the satellites go into seam, they temporarily switch off their ISLs to the neighbor orbits — resulting in a dynamic network topology. The second type of topology change in a LEO satellite network occurs due to the satellites temporarily switching off the ISLs as they cross the polar regions [55].

Any connection is subject to rerouting if it is passing through a link that will be turned off before the connection is over. This event is referred to as *link handoff*. If the number of connections that need to be rerouted due to link handoff is large, the resulting rerouting attempts cause signaling overhead in the network. The number of rerouting attempts can be reduced if the dynamic topology of the network is taken into account when connection routes are determined during call setup. The routing problem in LEO satellite networks has been addressed in [56] with an emphasis on setting up routes between pairs of satellites to minimize the rerouting attempts during link handoffs (i.e., optimization was performed for the routes between two satellites).

The optimization process results in a unique route with a minimum number of link handoffs during a system period (the time interval in which a satellite orbits the Earth) for each satellite pair. All end-user connections that are served by the same satellite pair use the same unique route. This algorithm reduces the link handoff frequency; however, it can also congest some of the links, while it underutilizes some others. An optimal route between two satellite nodes is not necessarily optimum for a connection between two ground terminals since intersatellite handoffs result in changing satellite end nodes for the connections. The optimization is needed for the route between two ground terminals.

In [56], a LEO satellite network is modeled as a finite state automaton (FSA) by dividing the period of the satellite network into equal-length intervals, or states, within which the network is considered as having a fixed topology. The algorithm determines the optimum link assignment for each satellite in a given state using simulated annealing. More connections would need to be rerouted during the state changes of the FSA model since the optimization process uses only the traffic pattern. In [57] a routing protocol referred to as the Probabilistic Routing Protocol (PRP) has been proposed to reduce the number of rerouting attempts during a link handoff. The algorithm removes all the ISLs that will experience a link handoff during the lifetime of a connection from consideration for routing during the route establishment phase of a new call. However, since the call holding time is a random variable, the connection lifetime cannot be determined exactly. Instead, the PRP finds the time duration in which the route will be used by the user terminals with a certain probability which is referred to as the *target probability*. As a result, the route does not experience any link handoff with the target probability. Additional research directions identified for the future of mobility management for satellite networks include broadband spotbeam handoff algorithms and utilizing LEO satellite network dynamics to minimize signaling traffic during the rerouting phase.

Each of the four mobile networks discussed in this article has specific mobility management issues that must be addressed for several networks. For example, the paging concerns for PCS networks are the same for WATM and satellite. Advertisement and the use of hierarchies can be explored for all networks. Smooth handoffs and connection rerouting are also required by each of the networks. Future networks must capitalize on these common issues in order to bring about interoperation that can be implemented in as simplified a method as possible. We conclude with some of the issues that are introduced by bringing heterogeneous networks and their services together under one unifying infrastructure.

Mobility Management Issues for the Next Generation of Wireless Networks

As mentioned in the introduction, the next generation of wireless communications networks promise mobility without geographical or network boundaries. Any network equipped for unified operation must be able to support such qualities as inter-carrier handoff, personal mobility, and location management for a heterogeneous network. Additional network administrative functions such as identification and authentication must also be supported in order to obtain international or regional permissions for carrying a mobile terminal into a visited country [58].

Addressing and Identification

Because of global roaming, the dynamic bindings between an MT's address and its identity will change frequently. Within the network, a mobile terminal may transition from the

PSTN to the Internet, from the Internet to ATM, from ATM to satellite, or from/to any other combination thereof [3]. Well-defined and standardized user/terminal identities are needed to manage important location and handoff operations such as determining the home network or database, updating and registration, paging and location advertisement, and exchanging location or routing information between different network types [5].

In addition to terminal mobility, the networks must be able to track the identity of the user for personal mobility. For example, a univeral personal telecommunications (UPT) number will be used to identify a user that wants to access his/her personal services at a new terminal. The IMT-2000 plans to develop personal cards, such as subscriber identification module (SIM) cards, to attach to GSM terminals in order to help identify the user and access personal services [5].

Providing access for every type of network under various mobile environments and the resulting complexity of the system leaves mobility-related procedures very vulnerable to security problems. In addition, since location information about the user will be extensively used, the providers with unlimited access to management information must come under scrutiny in order to maintain overall privacy and confidentiality. Technical strategies must be developed for achieving reliable authentication and maintaining a level of untraceability for roaming subscribers — even against the providers of the systems.

Database Issues

Consider the mobile terminal whose home network is the PSTN, but whose current visited network is WATM-based. In order to register its current location with its home network, the terminal must be registered as a visitor on the network level with the ATM network, possibly requiring database update/query, and then the ATM network must send this updated profile to the mobile's home network for further database update.

Routing Issues

In order to support point-to-point, multipoint, and point-to-multipoint communications between fixed and/or mobile terminals, connection rerouting will become a major consideration for service availability for the roaming terminal. Maintaining a connection will be more complex, since different networks provide different connection information. For example, ATM networks do not provide cell ordering numbers, but cell sequencing becomes important for wireless communications. Also, the tunneling and routing procedures of handoff for the Internet may undergo problems while the MT is traveling through a satellite-only environment.

Standardization

While there is general agreement among Japan, Europe, the United States, and other countries that global standards are in everyone's best interests, some difficulties still exist in achieving the necessary cooperation between regional and international bodies. Standardization progress between service providers, mobile networks, and regional institutions has been difficult to achieve. Specialized user needs, according to the service provider or national user base, will dictate the degree to which integration can be achieved.

As in previous generations, the next generation of wireless networks will be gradually implemented over the current infrastructures. As a result, the most likely scenarios will begin with Mobile IP interworking with ATM or WATM, and PLMN-based terrestrial networks interworking with satellite networks as traffic congestion relief. However, as research continues to explore options for integrating network services, the boundaries that prohibit global freedom for wireless communications will continue to disappear.

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