A SURVEY OF MOBILITY MANAGEMENT IN NEXT-GENERATION ALL-IP-BASED WIRELESS SYSTEMS

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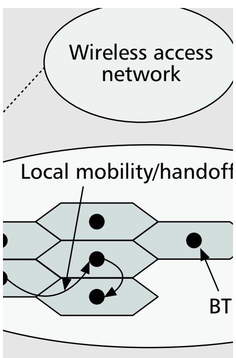

One of the research challenges for next-generation all-IP-based wireless systems is the design of intelligent mobility management techniques that take advantage of IP-based technologies to achieve global roaming among various access technologies.

ABSTRACT

Next-generation wireless systems are envisioned to have an IP-based infrastructure with the support of heterogeneous access technologies. One of the research challenges for next-generation all-IP-based wireless systems is the design of intelligent mobility management techniques that take advantage of IP-based technologies to achieve global roaming among various access technologies. Next-generation wireless systems call for the integration and interoperation of mobility management techniques in heterogeneous networks. In this article the current state of the art for mobility management in next-generation all-IP-based wireless systems is presented. The previously proposed solutions based on different layers are reviewed, and their qualitative comparisons are given. A new wireless network architecture for mobility management is introduced, and related open research issues are discussed in detail.

INTRODUCTION

Currently, various wireless technologies and networks exist that capture different needs and requirements of mobile users. For high-data-rate local-area access, wireless LANs (WLANs) are satisfactory solutions. For wide-area communications, traditional and next-generation (NG) cellular networks may provide voice and data services. For worldwide coverage, satellite networks have been used extensively in military and commercial applications. Since different wireless networks are complementary to each other, their integration will empower mobile users to be connected to the system using the best available access network that suits their needs. The integration of different networks generates several research challenges because of the following heterogeneities:

- **Access technologies**: NG wireless systems will include many heterogeneous networks using different radio technologies. These networks may have overlapping coverage areas and different cell sizes, ranging from a few square meters to hundreds of square kilometers.
- **Network architectures and protocols**: NG wireless systems will have different network architectures and protocols for transport, routing, mobility management, and so on.
- **Service demands**: Mobile users demand different services ranging from low-data-rate non-real-time applications to high-speed real-time multimedia applications offered by various access networks.

The above intrinsic technology heterogeneities ask for a common infrastructure to interconnect multiple access networks. IP is recognized to become the core part of NG integrated wireless systems to support ubiquitous communications [1]. For interoperation of different communication protocols, an adaptive protocol suite is required that will adapt itself to the characteristics of the underlying networks and provide optimal performance across a variety of wireless environments [2]. Furthermore, adaptive terminals in conjunction with "smart" base stations will support multiple air interfaces and allow users to seamlessly switch among different access technologies.

One important component of the adaptive protocol suite is the integration of mobility management schemes. In this article we address the design of intelligent mobility management techniques that take advantage of IP-based technologies to achieve global roaming among heterogeneous networks [1]. To make this roaming seamless, the integration and interoperation of heterogeneous mobility management techniques with efficient support for both intra- and interdomain roaming are required. Some proposed mobility management techniques try to support mobility associated with intradomain roaming [3–5]. However, these solutions have high signaling load and long handoff delay for interdomain roaming. Therefore, we advocate new mobility management architectures for a heterogeneous environment that reduce both intra- and interdomain signaling load and handoff delay.

The rest of this article is organized as follows. In the next section we describe the challenges for mobility management in NG all-IP-based wireless systems. We review the network layer mobility management solutions, and then investigate the link layer solutions. We present mobility management solutions based on both the network and link layers. Finally, we introduce a new

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architecture for mobility management, followed by the conclusions in the last section.

Mobility Management

Mobility management contains two components: location management and handoff management [6]. In NG wireless systems, there are two types of roaming for mobile terminals (MTs): *intrasystem* (intradomain) and *intersystem* (interdomain) roaming. Intrasystem roaming refers to moving between different cells of the same system. Intrasystem mobility management techniques are based on similar network interfaces and protocols. Intersystem roaming refers to moving between different backbones, protocols, technologies, or service providers. Based on intra- or intersystem roaming, the corresponding location management and handoff management can be further classified into intra- and intersystem location management and handoff management.

Location Management

Location management enables the system to track the locations of MTs between consecutive communications. It includes two major tasks. The first is *location registration* or *location update*, where the MT periodically informs the system to update relevant location databases with its up-to-date location information. The second is *call delivery*, where the system determines the current location of the MT based on the information available at the system databases when a communication for the MT is initiated. Two major steps are involved in call delivery: determining the serving database of the called MT and locating the visiting cell/subnet of the called MT. The latter is also called *paging*, where polling messages are sent to all the cells/subnets within the residing registration area of the called MT. For intersystem roaming, the design of location management techniques has the following challenges:

- Reduction of signaling overheads and latency of service delivery
- Quality of service (QoS) guarantees in different systems
- When the service areas of heterogeneous wireless networks are fully overlapped:
  - –Through which networks an MT should perform location registrations
  - –In which networks and how the up-to-date user location information should be stored
  - –How the exact location of an MT would be determined within a specific time constraint

Handoff Management

Handoff management is the process by which an MT keeps its connection active when it moves from one access point to another. The handoff process can be intra- or intersystem. Intrasystem handoff is the handoff in homogeneous networks. The need for intrasystem handoff (or horizontal handoff) arises when the signal strength of the serving base station (BS) deteriorates below a certain threshold value. The need for intersystem handoff (or vertical handoff) between heterogeneous networks may arise in the following scenarios [7]:

- When a user is moving out of the serving network and will enter another overlaying network shortly
- When a user is connected to a particular network, but chooses to be handed off to the underlying or overlaid network for its future service needs
- When distributing the overall network load among different systems is needed (this may optimize the performance of each individual network)

The design of handoff management techniques in NG all-IP-based wireless systems has the following challenges:

- Reduction of both signaling and power overheads
- QoS guarantees during the handoff process:
  - –Extreme low intra- and intersystem handoff latency, which includes signaling message processing time, resources and routes setup delay, format transformation time, and so on
  - –Limited disruption to user traffic
  - –Near-zero handoff failure and packet loss rate
- Efficient use of network resources
- Enhanced scalability, reliability, and robustness

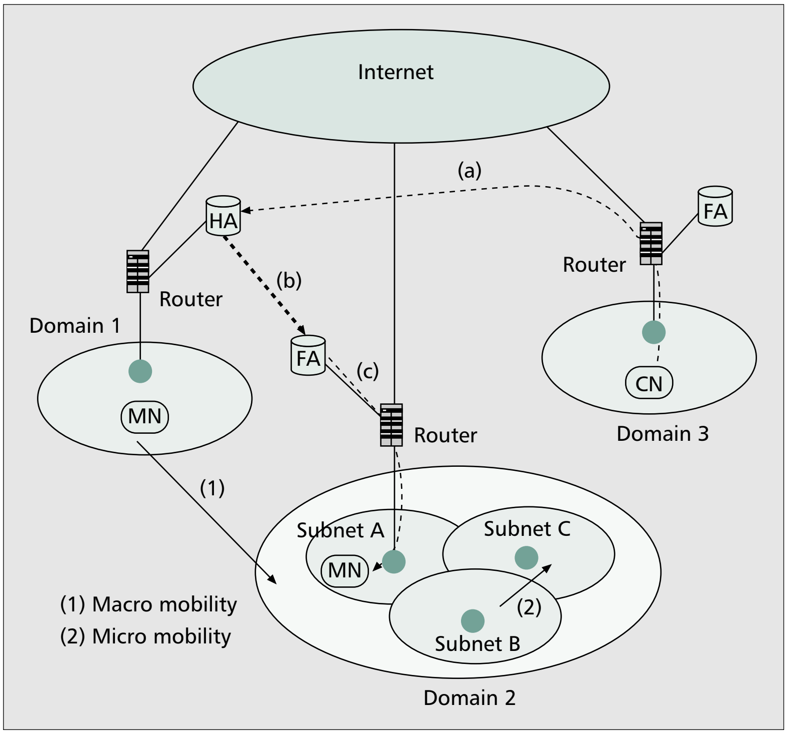
Mobility Management Based on Different Layers

Mobility management in homogeneous networks has been comprehensively surveyed in [6]. In this article we focus on mobility management techniques in heterogeneous wireless networks. Several protocols are proposed for NG all-IP-based wireless systems. These solutions try to support mobility from different layers of the TCP/IP protocol stack reference model. We classify these mobility management solutions into the following categories:

- Network layer solutions (layer 3 solutions)
- Link layer solutions (layer 2 solutions)
- Cross-layer solutions (layer 3 + layer 2 solutions)

Network layer solutions provide mobility-related features at the IP layer. They do not rely on or make any assumption about the underlying wireless access technologies [4]. Signaling messages for mobility purposes are carried by IP traffic. Link layer solutions provide mobility-related features in the underlying radio systems. They ensure uninterrupted communications when MTs change positions within the scope of an access router. Additional gateways are usually proposed to handle the interworking and interoperating issues when roaming among heterogeneous access networks. Signaling messages are transmitted through wireless links. Link layer solutions are tightly coupled with specific wireless technologies. Mobility supported from the link layer is also called *access mobility* or *link-layer mobility* [1]. Cross-layer solutions are mainly proposed for handoff management. They aim to achieve layer 3 handoff with help from layer 2. By obtaining signal strength reports and movement detection information from the link layer in advance, the system can make better preparation for the network layer handoff so that the packet loss is eliminated and the handoff latency is reduced.

Location management enables the system to track the locations of MTs between consecutive communications. It includes two major tasks: location registration or location update, and call delivery.



■ **Figure 1.** *Mobile IP architecture.*

Network Layer (Layer 3) Solutions

Network layer mobility management solutions can be broadly classified into two categories: *macro-mobility* and *micro-mobility* management solutions, which are explained below:

- The movement of mobile users between two network domains is referred to as macro-mobility; for example, the movement from domain 1 to domain 2 shown in Fig. 1. One domain is an administrative body, which may include different access networks, such as WLAN, second-generation (2G), and third-generation (3G) networks of one service provider.
- The movement of mobile users between two subnets within one domain is referred to as micro-mobility; for example, the movement from subnet B to subnet C shown in Fig. 2.

Macro-Mobility Solutions

In the Internet, a node is identified by an IP address that uniquely identifies its point of attachment to the Internet, and packets are routed to the node based on this address. Therefore, a node must be located on the network indicated by its IP address in order to receive datagrams. This prohibits the node from moving and remaining able to receive packets using the base IP protocol. Mobile IP [8] is proposed to solve the problem of node mobility by redirecting packets for the mobile node to its current location.

Overview — Mobile IP is a mobility-enabling protocol for the global Internet. It introduces three new functional entities: home agent (HA), foreign agent (FA), and mobile node (MN).[1] Mobile IP supports mobility management using the following procedures:

Agent discovery: An MN is able to detect whether it has moved into a new subnet by periodically receiving unsolicited *Agent Advertisement* messages broadcasted from each FA. An MN can also send *Agent Solicitation* messages to learn about the presence of any prospective mobility agent.

Registration: When an MN discovers it is in a foreign network, it obtains a new care-of address (CoA). This CoA can be obtained by soliciting or listening for FA advertisements (an FA CoA), or contacting Dynamic Host Configuration Protocol (DHCP) or Point-to-Point Porotocol (PPP) (a collocated CoA) [8]. The MN registers the new CoA with its HA. Then the HA updates the mobility binding by associating the CoA of the MN with its permanent IP address.

Routing and tunneling: Packets sent by a correspondent node (CN) to an MN are intercepted by the HA. The HA encapsulates the packets and tunnels them to the MN's CoA. With an FA CoA, the encapsulated packets reach the FA serving the MN, which decapsulates the packets and forwards them to the MN, as shown in steps a, b, and c in Fig. 1. With a collocated CoA, the encapsulated packets reach the MN, which then decapsulates them. In Fig. 1 the tunneling (step b) ends at the MN instead of at the FA.

Handoff Management in Mobile IP — When an MN moves from one subnet to another, the handoff procedure is carried out by the following steps:

- The MN obtains a new CoA when it enters a new subnet.
- The MN registers the new CoA with its HA. The HA sets up a new tunnel up to the end point of the new CoA and removes the tunnel to the old CoA.
- Once the new tunnel is set up, the HA tunnels packets destined to the MN using the MN's new CoA.

Paging Extension for Mobile IP — In order to save battery power consumption at MNs, IP paging is proposed as an extension for Mobile IP [9]. Under Mobile IP paging, an MN is allowed to enter a power saving idle mode when it is inactive for a period of time. During idle mode, the system knows the location of the MN with coarse accuracy defined by a paging area composed of several subnets [9]. The MN may also deactivate some of its components for energy-saving purposes. An MN in idle mode does not need to register its location when moving within a paging area. It performs location update only when it changes paging areas. When packets are destined to an MN in idle mode, they are terminated at a paging initiator. The paging initiator buffers the packets and locates the MN by sending out IP paging messages within the paging area. After knowing the subnet where the MN resides, the paging initiator forwards the data packets to the serving FA of the subnet and further to the MN. When an MN is in active mode, it operates in the same manner as in Mobile IP, and the system keeps the exact updated location information of the MN.

Analysis of Mobile IP — Mobile IP has the following shortcomings:

[1] *In this article, we use mobile node (MN), mobile host (MH), and mobile terminal (MT) terms interchangeably.*

- Packets sent from a CN to an MN are first intercepted by the HA and then tunneled to the MN. However, packets from the MN are sent directly to the CN. This triangular routing problem results in communication routes significantly longer than the optimal routes and introduces extra delay for packet delivery.
- When an MN moves from one subnet to another, the new FA cannot inform the old FA about the movement of the MN. Hence, packets already tunneled to the old CoA and in flight are lost.
- Mobile IP is not a satisfactory solution for highly mobile users. Mobile IP requires an MN to send a location update to its HA whenever it moves from one subnet to another. This location registration is required even though the MN does not communicate with others while moving. The signaling cost associated with location updates may become very significant as the number of MNs increases. Moreover, if the distance between the visited network and the home network is large, the signaling delay is long.

Mobile IP supports mobility across both homogeneous and heterogeneous systems. It is well suited for macro mobility management, but less suited for micro mobility management.

Enhancement to Mobile IP — The problem of triangular routing can be solved by route optimization [10]. The basic idea behind route optimization is to use a direct route between MNs and their CNs to bypass the HA. CNs maintain a binding cache of the CoAs of MNs. When a CN sends packets to an MN, it first checks if it has a binding cache entry for the MN. If yes, the CN tunnels the packets directly to the CoA of the MN. If no binding cache entry is available, the CN sends the packets following the basic Mobile IP procedure, that is, via the HA of the MN. The CN learns about the most recent CoA of an MN in either of the following two ways:
- When the HA intercepts and tunnels packets destined to an MN, it sends a *Binding Update* message to the source of the packets about the current CoA of the MN.
- When tunneled packets reach an FA which no longer has the destination MN in its visitor list, the FA sends a *Binding Warning* message to the HA asking the HA to send a *Binding Update* message to the source node.

Route optimization also takes care of the packets already tunneled to the old CoA and in flight. When an MN registers with a new FA, it requests the new FA to notify the previous FA about the movement. This ensures that packets in flight to the old CoA are successfully forwarded. It also ensures that packets from the CN with out-of-date binding cache entries for the MN are successfully delivered to the MN's new CoA. Moreover, route optimization also ensures that any resources consumed by the MN at the old FA are released immediately, rather than waiting for the registration time to expire [10].

Micro-Mobility Solutions

MNs usually move frequently between subnets of one domain. To reduce signaling load and delay to the home network during movements within one domain, many micro-mobility solutions have been proposed. They can be broadly classified into two groups: *tunnel-based* and *routing-based* micro-mobility schemes [11]:
- Tunnel-based schemes use local or hierarchical registration and encapsulation concepts to limit the scope of mobility-related signaling messages, thus reducing the global signaling load and handoff latency. Mobile IP regional registration (MIP-RR) [12], hierarchical Mobile IP (HMIP) [13], and intradomain mobility management protocol (IDMP) [4] are tunnel-based micro-mobility protocols.
- Routing-based schemes maintain host-specific routes in the routers to forward packets. The host-specific routes are updated based on host mobility. Cellular IP (CIP) [3] and handoff-aware wireless access Internet infrastructure (HAWAII) [5] are routing-based micro-mobility protocols.

Mobile IP Regional Registration/Hierarchical Mobile IP — MIP-RR [12] aims to reduce the number of signaling messages to the home network and also reduce the signaling delay by performing registrations locally in a regional network. When an MN first arrives at a regional network, it performs a home registration with its HA. During the home registration, the HA registers the CoA of the MN, which is actually a publicly routable address of another mobility agent called a *gateway foreign agent* (GFA). When an MN changes FAs within the same regional network, it performs only a regional registration to the GFA to update its CoA. When it moves from one regional network to another, it performs a home registration with its HA. The packets for the MN are first intercepted by its HA, which tunnels those to the registered GFA. The GFA checks its visitor list and forwards the packets to the corresponding FA of the MN. The FA further relays the packets to the MN.

The GFA introduces a layer of hierarchy

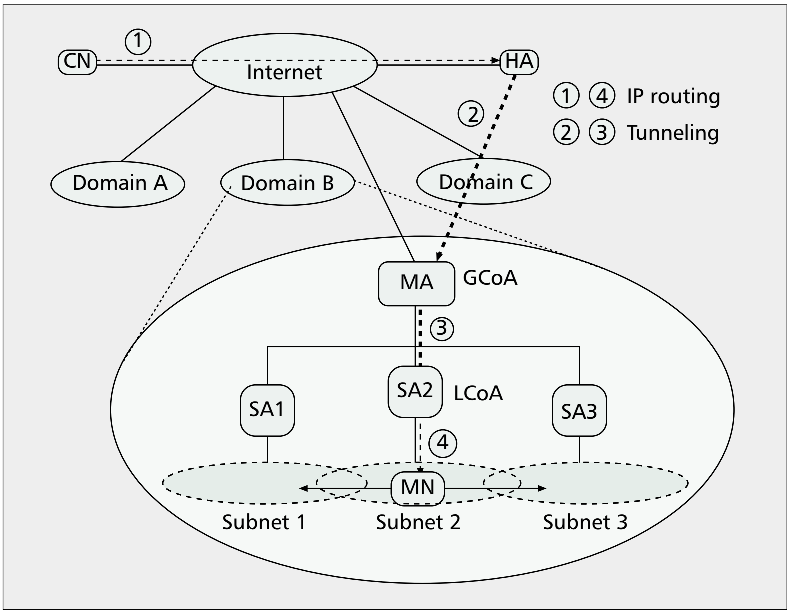


Figure 2. *The architecture of IDMP.*

Cellular IP (CIP) is proposed to provide local mobility and handoff support for frequently moving hosts. It supports fast handoff and paging in CIP access networks. For mobility between different CIP networks, it can interwork with Mobile IP to provide wide-area mobility support.

between the HA and the FA of the MN. The use of the GFA avoids any signaling traffic to the HA as long as the MN is within a regional network. The structure can be extended to include multiple hierarchy levels of FAs beneath the GFA level. Such multiple hierarchy levels are discussed in HMIP [13].

IDMP — IDMP [4] is a two-level hierarchical approach to provide mobility support for MNs in IP-based mobile networks. The first hierarchy consists of different mobility domains. The second hierarchy consists of IP subnets within one domain. This hierarchical approach localizes the scope of intradomain location update messages and thereby reduces both the global signaling load and update latency.

The two-level hierarchical architecture defined by IDMP is shown in Fig. 2. IDMP defines two new network entities, a mobility agent (MA), which is responsible for the mobility management within a domain, and a subnet agent (SA), which handles the mobility of MNs within a subnet. IDMP proposes two CoAs for each MN:

- *Global CoA (GCoA)*: This address specifies to which domain the MN is currently attached. An MN's GCoA remains unchanged as long as it stays within a domain.
- *Local CoA (LCoA)*: This address provides the subnet level location resolution for an MN. When an MN changes its subnet inside a domain, its LCoA also changes.

For packet transmission under IDMP, we assume the use of MIP as the macro-mobility management mechanism. Note that any other global mobility management mechanism can be used without any modification to the IDMP. Packets destined to an MN are first sent to its HA (*step 1* in Fig. 2). Then the HA tunnels the packets to the MA using the MN's GCoA (*step 2*). The MA first decapsulates the packets, determines the current LCoA of the target MN using its internal table, and then tunnels the packets to the LCoA. The encapsulated packets are received by the SA serving the MN (*step 3*), which decapsulates and then forwards the packets to the MN using the layer 2 mechanism (*step 4*).

When an MN moves from one subnet to another inside the same domain, it receives a new LCoA and then registers this new address with its MA. Before the registration at the MA is over, the MA forwards packets destined to the MN to its old LCoA. Hence, the MN will lose the packets sent during this transient phase of intradomain handoff. A fast handoff procedure is proposed in [4] to reduce packet loss. This procedure assumes that each MN is aware of an impending intradomain handoff with the help of layer 2 information such as signal strength or trouble in hearing the beacon signals from the current SA. Once the MN learns about its possible handoff, it initiates a request to the MA to multicast packets to the neighboring SAs. The MA forwards all the packets for this MN to all the neighboring SAs until the MN successfully registers its new LCoA with the MA. In this way, packet loss may be eliminated during the handoff process.

Cellular IP — CIP [3] is proposed to provide local mobility and handoff support for frequently moving hosts. It supports fast handoff and paging in CIP access networks. For mobility between different CIP networks, it can interwork with MIP to provide wide-area mobility support. The architecture of CIP is shown in Fig. 3. It shows different wireless access networks connected to the Internet through a gateway (GW), which handles the mobility within one domain. Packets destined to a mobile host (MH) reach the GW first. Then the GW forwards the packets to the MH using the host-specific routing path.

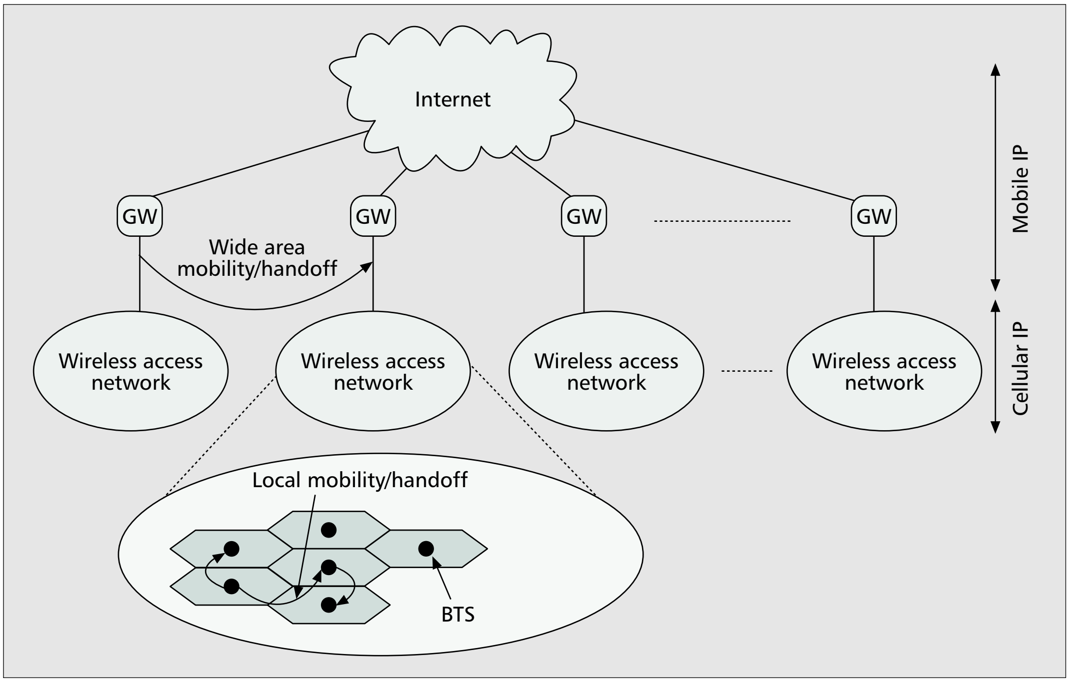
The design of CIP is based on four fundamental principles:

- Distributed caches are used to store location information of MHs.
- Location information of an active MH is updated by regular IP datagrams originated by itself. For an idle MH, this is achieved by the use of dummy packets that are sent by the idle host at regular intervals.
- Location information is stored as soft states.
- Location management for idle MHs is separated from location management of MHs that are actively transmitting/receiving data.

CIP uses *distributed paging cache* and *distributed routing cache* for location management and routing, respectively. Distributed paging cache coarsely maintains the position of the idle MHs for efficient paging, whereas the routing cache maintains the position of an active MH up to subnet level accuracy. When an MH performs handoff, the routing states in the routing cache are dynamically updated.

The handoff process of CIP is automatic and transparent to the upper layers. When the strength of the beacon signal from the serving BS is lower than that of a neighboring BS, the MH initiates a handoff. The first packet that travels to the GW through the new BS configures a new path through the new BS. This results in two parallel paths from the GW to the MH: one through the old BS and one through the new BS. If the MH is capable of listening to both BSs at the same time, the handoff is soft; otherwise, the handoff is hard. The path through the old BS will be active for a duration equal to the timeout of route caches. After timeout, the entries corresponding to the MH in the nodes that belong only to the old path are deleted. Thereafter, only the new path exists between the GW and the MH.

HAWAII — HAWAII [5] is a domain-based approach to mobility support. The network architecture of HAWAII is shown in Fig. 4. All issues related to mobility management within one domain are handled by a gateway called a *domain root router*. When an MH is in its home domain, packets destined to the MH are routed using typical IP routing. When the MH is in a foreign domain, packets for the MH are intercepted by its HA first. The HA tunnels the packets to the domain root router serving the MH. The domain root router routes the packets to the MH using the host-based routing entries. When the MH moves between different subnets of the same domain, only the route from the domain root router to the BS serving the MH is



■ **Figure 4.** *Cellular IP architecture.*

For mobility between different administrative domains, except in IDMP, MIP is widely used. IDMP gives freedom to use any other interdomain protocol. However, the fundamental operating principle of IDMP has much similarity with that of MIP-RR with two-level hierarchy.

modified, and the remaining path remains the same. Thus, during an intradomain handoff, the global signaling message load and handoff latency are reduced.

To establish and maintain a dynamic path to the MH, HAWAII uses three types of messages: *powerup*, *path refresh*, and *path update*. The *path setup* messages after powerup establish the host-specific path from the domain root router to the MH by creating host-specific forwarding entries in the routers along the path. When the MH is in its home domain, once the host-specific forwarding entries are created in the routers along the path from the domain root router to the MH, the powerup procedure is complete. When the MH is in a foreign domain, it registers its CoA with its HA upon receipt of the acknowledgment from the domain root router in reply to the path setup message. Once the host-specific forwarding entries are created for an MH, they remain active for a time period. The MH periodically sends path refresh messages to its current BS before timeout occurs. In response to the path refresh messages, the BS sends *aggregate hop-by-hop* refresh messages to the next-hop router toward the domain root router. The path update messages are used to maintain end-to-end connectivity when an MH moves from one BS to another within the same domain.

HAWAII also supports IP paging. It uses IP multicasting to page idle MHs when packets destined to an MH arrive at the domain root router and no recent routing information is available.

A Summary of Network Layer Solutions

For mobility between different administrative domains, except in IDMP, MIP is widely used. IDMP gives freedom to use any other interdomain protocol. However, the fundamental operating principle of IDMP has much similarity with that of MIP-RR with two-level hierarchy.

Comparisons of network layer micro-mobility solutions are conducted in [1, 5, 11] based on different criteria. As stated in [11], despite the different design approaches of the proposed micro-mobility protocols, the operational principles that govern them are largely similar. Domain root routers are designed in each protocol. All the solutions try to localize most of the signaling traffic into one domain to reduce global signaling. Routing-based schemes take advantage of robust IP forwarding. Mobile-specific address lookup tables are maintained by all the mobility agents within the domain. Under the tunnel-based schemes, registration and encapsulation are performed in a local or hierarchical fashion. Generally speaking, routing-based schemes avoid tunneling overhead, but suffer from the high cost of propagating host-specific routes in all routers within the domain. The root node of routing-based schemes constitutes a single point of failure [1]. Tunnel-based schemes enhance scalability by introducing hierarchies, but lead to additional costs and delays. Their reliability depends on the mobility agents at each hierarchy. A comparison of micro-mobility protocols is shown in Table 1. It is demonstrated in [11] that the basic handoff performance of the existing micro-mobility protocols depends only on the position of the crossover mobility agents. The choice of a micro-mobility protocol should be dictated more by deployment considerations.

Link Layer (Layer 2) Solutions

Link layer mobility management solutions focus on the issues related to intersystem roaming between heterogeneous access networks with different radio technologies and different network management techniques. There are two issues critical for intersystem roaming: the air interface protocol and the mobile application part (MAP).

Link layer mobility management solutions focus on the issues related to intersystem roaming between heterogeneous access networks with different radio technologies and different network management techniques.

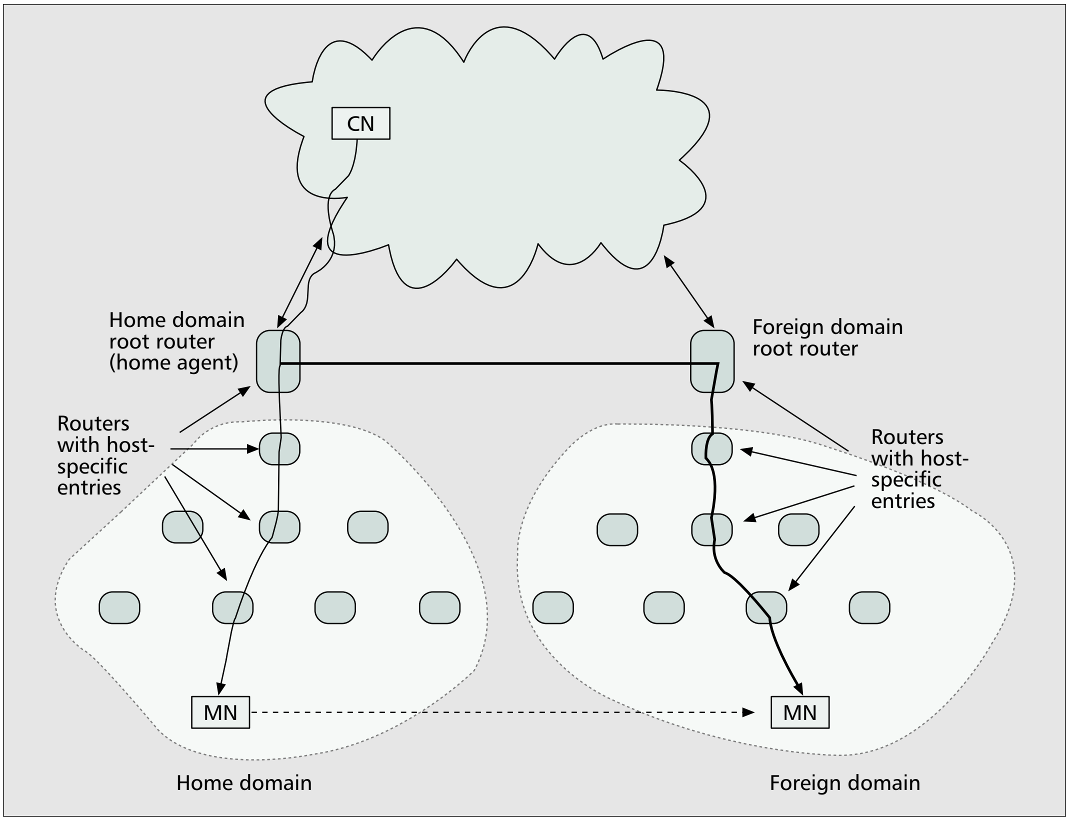


Figure 4. *The network architecture of HAWAII.*

When an MT roams from one wireless access network to another that supports the same air interface and MAP, services are provided seamlessly. However, when the MAPs in the two systems are different, additional entities and signaling traffic are required for interworking and interoperation between dissimilar systems. Since each individual system has its own mobility management procedures, the new interworking entities should not replace existing systems, although they may affect some of the functions or signaling in the present systems.

Location Management Research

For NG heterogeneous wireless networks, the interworking/interoperating (I&I) function is suggested to accommodate roaming between dissimilar networks [14]. For existing practical systems, several solutions are proposed for some specific pairs of interworking systems. Under the proposed solutions, the I&I function is implemented in either some additional interworking unit with the help of dual-mode handsets [15], or a dual-mode home location register (HLR) [16] to take care of the transformation of signaling formats, authentication, and retrieval of user profiles.

Recent research efforts attempt to design general location management mechanisms for the integration and interworking of heterogeneous networks. The research activities can be grouped into two categories: location management for adjacent dissimilar systems with partially overlapping coverage at the boundaries [17–19] and location management in multitier systems where service areas of heterogeneous networks are fully overlapped [20]. All these solutions propose additional entities that take care of interworking issues between different wireless access networks.

Location Management for Adjacent Networks — Location management schemes proposed in [17–19] are considered for any two adjacent networks with partially overlapping areas. They are also applicable to multiple networks by using them on each pair of adjacent networks.

Gateway Location Register Protocol — In order to support intersystem roaming, the mobility gateway location register (GLR) is developed in [19]. The GLR is a gateway for two interworking networks. It converts signaling and data formats from one network to another. According to Universal Mobile Telecommunications Systems (UMTS) standards, the visitor location register (VLR) sees the GLR as an HLR, and the HLR sees the GLR as a VLR. When an MT roams from a Global System for Mobile Communications (GSM) to an IS-41 network, user profiles including the service and location information of the MT are acquired through accessing the GSM HLR. From the point of view of the VLR in an IS-41 network, the GLR looks like an HLR that provides up-to-date location information. When a location update initiated by a GLR has been successfully completed, the HLR sees the GLR as a VLR.

The GLR protocol is capable of identifying an MT and allows it to initiate a call in the new visiting network. However, the GLR protocol is not designed for ongoing call connection during

	Routing-based schemes		Tunnel-based scheme	
	Cellular IP	HAWAII	Regional registration/hierarchical Mobile IP	IDMP
Domain root router	GW	*Domain root router*	The highest level of GFA in the hierarchy	MA
Additional cost	Propagating route information in routers		Tunneling overhead at each hierarchy	
Gradual deployment	Difficult		Easy	
Reliability	Rely on root (gateway) router		Rely on mobility agents at each hierarchy	

Table 1. *Comparison of micro-mobility protocols.*

intersystem roaming [18]. Moreover, under the GLR protocol, incoming calls are always delivered to the home network of an MT first, regardless of whether the MT has moved to a new network. This causes the triangular routing problem.

Boundary Location Register Protocol — A dynamic intersystem location update policy is developed in [17]. This location-tracking mechanism consists of intersystem location updates and paging. Intersystem location update is implemented by using the concept of a boundary location area (BLA) existing at the boundary between two systems, X and Y, as illustrated in Fig. 5. The BLA is controlled by a boundary interworking unit (BIU) that is connected to mobile switching centers (MSCs) in both systems. The BIU is responsible for querying the user's service information and transforming message formats. It also takes care of some other issues, such as compatibility of air interfaces and authentication of mobile users. The BLA of an MT is defined as a region in which the MTs can send a location registration request to the new system toward which the MT is moving. A distance-based location update mechanism is designed such that the MT reports its location when its distance from the boundary is less than an *update distance*. This update distance takes the bandwidth requirement of multimedia service and the movement velocity of an MT into account. This intersystem location update scheme is dynamic in the sense that the update distance is variable over time depending on the network load and each user's mobility characteristics.

Intersystem paging is based on the concept of a boundary location register (BLR), which is a location information cache to maintain the roaming information of MTs crossing the boundary of systems. During the intersystem paging process, only one system (X or Y) is searched.

The associated MAP protocol based on BLA/BLR is described in [18]. This protocol is designed for MTs with ongoing connections during intersystem roaming. Instead of performing location registration after an MT arrives at the new system, the BLR protocol enables an MT to update its location and user information actively before it arrives at a new system. Since the BLR provides the up-to-date location information of MTs, the incoming calls of the intersystem roaming MTs are delivered to them directly, rather than to the home network. The BLR also helps to reduce the zigzag effect caused by intersystem roaming.

Location Management for Overlay Networks — When the service areas of heterogeneous wireless networks are fully overlapped, an MT is reachable via multiple networks. Multitier wireless systems are recognized as an efficient way to improve the capacity and quality of mobile services. The objective is to integrate the higher- and lower-tier systems into a single system to provide the advantages of all tiers in an integrated manner.

Since heterogeneous networks use different signaling formats, authentication procedures, and registration operations, it is difficult to merge heterogeneous HLRs of different networks into a single HLR. The multitier HLR (MHLR) approach is introduced in [20]. Inside the MHLR, a tier manager connects all heterogeneous HLRs. Based on this MHLR approach, two location registration strategies are proposed, single registration (SR) and multiple registration (MR).

Under the SR method, an MT is allowed to register with the MHLR on only one tier, the lowest, at any given time. The MT always receives services from the lowest tier because of low cost and high bandwidth. Under the MR method, an MT is allowed to register with the MHLR on multiple tiers concurrently at any given time. The individual tiers perform their own roaming management as if they are not integrated. The tier manager of the MHLR keeps track of the currently visited high-tier and low-tier VLRs of an MT. It is explained in [20] that the MR scheme generates less registration traffic than the SR scheme because of fewer tier switchings. However, since the MHLR does not know the current tier where an MT resides, MR suffers from a high penalty during the call delivery procedure when the MHLR selects the wrong tier to deliver a call for the first trial.

Handoff Management Research

Intersystem roaming requires the support of handoff between different types of networks. To implement intersystem handoff, several interoperability issues must be solved [16, 20]:

- MTs must become operable in the new network through a format transformation.
- A technique is needed to measure and compare signals from different air interfaces and power levels.
- Transmission and signaling facilities must exist between the BSs and switches of each system to manage network transfer.
- QoS guarantees must be available for MTs on the rerouted handoff connections in each network.

The intersystem rerouting procedure is executed at the same time as the format transformation. Intersystem boundary cells are used to increase the opportunity for format transformation and provide advanced warning of an intersystem handoff.

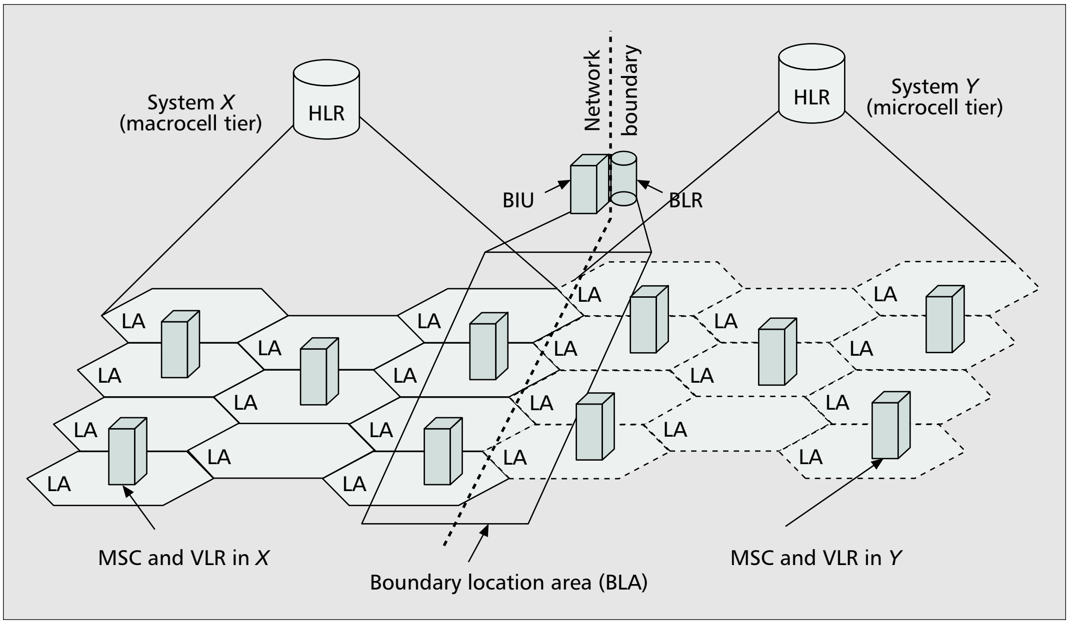


Figure 5. *The boundary location area (BLA) and boundary location register (BLR).*

During intersystem handoff, each network service provider must monitor usage to bill users for the bandwidth being used in its network. Encapsulated packets must be translated to the data link format of each network. Addresses must also be translated for heterogeneous connections through multiple networks. Finally, QoS maintenance must be renegotiated when the MT passes into the new network. To enable this increased level of interoperability, new intersystem network gateways are necessary that enable legacy services within the individual networks and provide a common rerouting protocol for connections that cross between networks.

Proposals for intersystem handoff have been explored. Some techniques [21, 22] addressed handoff between different tiers or different technologies used within an existing architecture, such as the IMT-2000 or UMTS system. Other proposals developed new architectures to support intersystem roaming between different networks [23, 24].

Handoff Management in UMTS/IMT-2000 — In [21] a signaling protocol for intersegment handoff in an integrated space/terrestrial UMTS environment is presented. Backward mobile-assisted handoff with signaling diversity is used for the intersegment handoff scheme. In [22] an advanced procurement handoff signaling technique is introduced. Advanced preparation for format transformations is supported, as well as advanced handoff routing between different tiers, technologies, or networks. The intersystem rerouting procedure is executed at the same time as format transformation. Intersystem boundary cells are used to increase the opportunity for format transformation and provide advanced warning of an intersystem handoff.

Handoff Management in an Integrated Heterogeneous System — In [23] a framework for programmability of wireless access networks is developed that allows system designers to architect and program their own handoff and medium access control architectures. Two handoff services are designed and programmed using the programmable handoff architecture.

Vertical handoff in wireless overlay networks is designed in [24] where heterogeneous networks in a hierarchical structure has fully overlapping service areas. Vertical handoff is defined as handoff between BSs using different wireless network technologies. Rather than depending on network-specific channel measurements to predict disconnections, the proposed scheme depends on higher-order information such as the presence or absence of beacon and data packets.

Some recent research activities focus on intersystem handoff management in the integrated 3G/WLAN environment [7, 25]. The integrated WLAN and 3G possesses the strength of both 3G and WLAN. At the same time, the integration eliminates the weaknesses of either system.

A Summary of Link Layer Solutions

Link layer mobility support for intersystem roaming requires additional interworking entities to help information exchange between different systems. Under all the proposed solutions, new interworking entities are designed, such as the dual-mode HLR for interworking between IS-41 and PCS1900, the GLR/BLR for intersystem location management, the MHLR for a multitier PCS system, and the gateways in the integrated 3G/WLAN system. All the proposed new interworking entities are connected to the mobility management entities in individual systems and provide the following functions:

- *Format transformation and address translation*: Signaling messages, data packets, and addresses must be translated for communication between heterogeneous networks.
- *User profile retrieval*: A user profile is retrieved from an MT's home network for its communication in the new visiting network.

- *Signaling message transmission and connection setup*: The interworking unit acts as a gateway for message transmission and connection rerouting.
- *Mobility information related to intersystem roaming recording*: The mobility pattern of intersystem roaming needs to be recorded for future mobility management.
- *QoS negotiation*: QoS maintenance must be renegotiated when an MT moves into a new network.
- *Authentication between systems*: Authentication is necessary for security reasons.

The differences in the proposed solutions address the following problems in different ways:
- Where are the interworking entities located in the integrated system?
- How tightly are the interworking entities coupled with individual systems?
- When should location registration and handoff be initiated?
- How are location management and handoff management performed?

Cross-Layer (Layer 3 + Layer 2) Solutions

As described previously, cross-layer solutions are mainly proposed for handoff management techniques. MIP handoff latency is composed of latencies for movement detection and registration [26]. The proposed micro-mobility solutions particularly achieve reduction in registration signaling delay, but fail to address the problem of movement detection delay. Cross-layer mobility management protocols reduce movement detection delay using link layer information, such as signal strength. Some algorithms use signal strength measurements directly to reduce handoff latency [26], while others use signal strength measurement for tracking the MNs and then use this tracking information to support low-latency MIP handoff [27].

A low-latency handoff method for a WLAN environment is introduced in [26], where access points and a dedicated medium access control (MAC) bridge are jointly used to alleviate packet loss without altering the MIP specifications. A seamless handoff architecture for MIP, S-MIP, is proposed in [27] and provides a unique way of combining a location tracking scheme and the hierarchical MIP handoff scheme. In this article we only introduce this scheme in detail. Note that the working principles of other cross-layer protocols are similar.

S-MIP

The architecture of the S-MIP scheme is shown in Fig. 6. This architecture extends MIP architecture by adding a new entity called a *decision engine* (DE). The DE has the same scope as the mobile anchor point (MAP) defined in HMIP [13]. The DE makes handoff decisions for intradomain roaming. It maintains the global view of the connection states and movement patterns of the MNs in its network domain. For movement patterns of the mobile devices, the DE uses the signal strength obtained from the link layer and IDs of access routers (ARs).

For interdomain handoff, S-MIP uses the HMIP handoff algorithm. It also uses movement tracking of MNs to enhance performance. Movement tracking is implemented as a two-phase process. First, the location of an MN is tracked, and the location information is used to detect the movement pattern. Then the movement pattern is used to determine the next ARs upon handoff, which is used to prepare the MN for handoff before actual handoff initiation. Thus, the movement detection latency associated with MIP handoff is reduced.

S-MIP defines three types of movement patterns: *linear*, *stationary*, and *stochastic*. When the MN moves linearly, the DE determines to which AR the MN is going to be handed off and instructs other ARs to discontinue further participation in the handoff process. When the MN is in stationary mode, the DE instructs both ARs in the boundary region of two network coverage areas to maintain bindings with the MN. Under this scenario, the MN uses more than one CoA. When the mobility pattern of an MN is stochastic, the neighboring ARs are asked to be in anticipation mode. When an AR is in anticipation mode, it maintains the MN's bindings. In this way, the ping-pong effect is avoided.

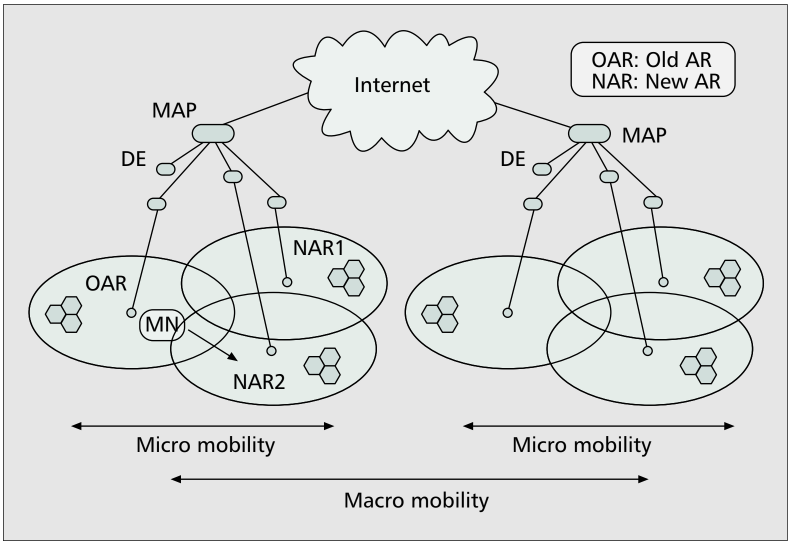
The Proposed Mobility Management Architecture

The standard network layer solution, MIP [8], is simple to implement, but has several shortcomings, such as triangular routing, high global signaling load, and high handoff latency. MIP route optimization [10] eliminates the triangular routing problem. HMIP [13] and other micro-mobility protocols [3–5] address the problem of high global signaling load and high handoff latency by introducing another layer of hierarchy to the basic MIP architecture to localize the signaling messages to one domain. The S-MIP architecture [27] further reduces intradomain handoff latency by using the movement pattern information of the MNs along with the hierarchical architecture and fast-handoff mechanism.

Current proposed micro-mobility solutions described previously do not have advantages for interdomain mobility. Most of the micro-mobility solutions assume one domain to be one wireless access network or under one administrative domain. Although IDMP [4] defines a domain based on geographic proximity where one domain consists of networks with different access technologies in a particular geographic region, there is no procedure on how to carry out intersystem authentication, format transformation, and so on. In a heterogeneous environment where users have freedom to move between different domains based on various factors, such as service requirements, connection quality, and network load, the global signaling load and corresponding handoff delay will increase significantly, adversely affecting the network performance. In addition, the long interdomain handoff delay also results in undesirable disruption to ongoing communications.

IDMP's fast handoff procedure assumes that a layer 2 trigger is available to indicate the immi-

The standard network layer solution, Mobile IP, is simple to implement, but has several shortcomings, such as triangular routing, high global signaling load, and high handoff latency. Mobile IP route optimization eliminates the triangular routing problem.



■ **Figure 6.** *The architecture of the S-MIP scheme.*

nent change in connectivity and hence the need for intradomain handoff. Other micro-mobility protocols implicitly assume that link layer information such as received signal strength is used to detect the possibility of intradomain handoff. The S-MIP approach [27] proves that along with the hierarchical architecture and procedures for fast handoff, the link layer information used to determine the mobility pattern of the MHs greatly improves intradomain handoff performance. This approach and the promising results show that cooperation between the network and link layers is able to improve the performance of mobility management in future heterogeneous communication networks. However, S-MIP protocol is still limited to classifying the mobility pattern into linear, stationary, and stochastic. Moreover, this protocol uses the fact that the coverage of different ARs overlaps. Hence, the protocol cannot be extended to support mobility between different domains, because the coverage area of one domain might be completely covered by another domain in the hierarchical heterogeneous environment; for example, a WLAN domain is mostly covered completely by the overlaying 2G/3G network.

The above factors motivate us to design a mobility management architecture with the following requirements:

- Reduced intradomain and interdomain signaling load and handoff delay.
- Scalable, that is, integration of any number of heterogeneous wireless systems belonging to different service providers or administrators.
- Both the interdomain and intradomain mobility management solutions must work for partially as well as fully overlapping systems.

The New Architecture

Our proposed architecture for NG all-IP-based wireless systems is shown in Fig. 7. In this architecture, different wireless networks are integrated through a novel third party, the network interworking agent (NIA). Figure 7 shows an NIA that integrates one WLAN, one cellular network, and one satellite network. Note that the NIA can integrate several wireless networks belonging to different service providers. It handles authentication, billing, and mobility management issues during intersystem (interdomain) roaming. Details about the building blocks and functionality of the NIA are described in [7].

In our architecture, an MH's movement can be categorized into two different types: movement between different subnets of one domain (*intradomain* mobility) and movement between different access networks belonging to different domains (*interdomain* mobility). For intradomain mobility, existing micro-mobility management protocols discussed earlier can be used, whereas for interdomain mobility we propose a novel cross-layer mobility management protocol. The basic idea of our algorithm is early detection of the possibility of interdomain handoff and then to carry out authentication, authorization, and mobile IP registration of the MH in the next domain before the actual handoff. Because the current and new domains may or may not have a service level agreement (SLA) between them, these operations are carried out through the NIA, which has separate SLAs with both domains. The early detection of a possible interdomain handoff is carried out using the link layer information, details of which are described in [7]. In our new mobility management architecture, interdomain handoff delay is comparable to that of intradomain handoff delay, unlike the existing mobility management schemes where interdomain handoff delay is significantly higher than intradomain handoff delay.

Note that the NIA is used only during interdomain roaming. Once the MH moves into a new domain, the NIA is no longer involved. Hence, the load on NIA is minimal. If the number of heterogeneous networks increases or the number of mobile users with intersystem roaming requests increases, the NIA can be built in a hierarchical structure to make it more scalable. We are currently investigating how to determine the optimal number of NIAs required for a particular heterogeneous network configuration.

Open Research Issues

Future wireless systems will be based on IP infrastructure and heterogeneous wireless access technologies. However, they will still suffer from the diverse standards that limit roaming of mobile users between different networks. Mobility management will continuously play an important role in providing seamless services. There are many challenging research issues related to mobility management for NG all-IP-based wireless systems.

QoS Issues — NG all-IP-based wireless systems will provide guaranteed QoS to mobile terminals carrying multimedia applications, including best effort and real-time traffic. These applications have varying requirements which challenge the best effort service model of the original framework for IP. Bandwidth, throughput, timeliness, reliability, perceived quality, and costs are the foundations of QoS. There have been some pro-

The proposed cross-layer solutions show that cooperation between the network and link layers is able to improve the performance of mobility management in IP-based heterogeneous communication environment.

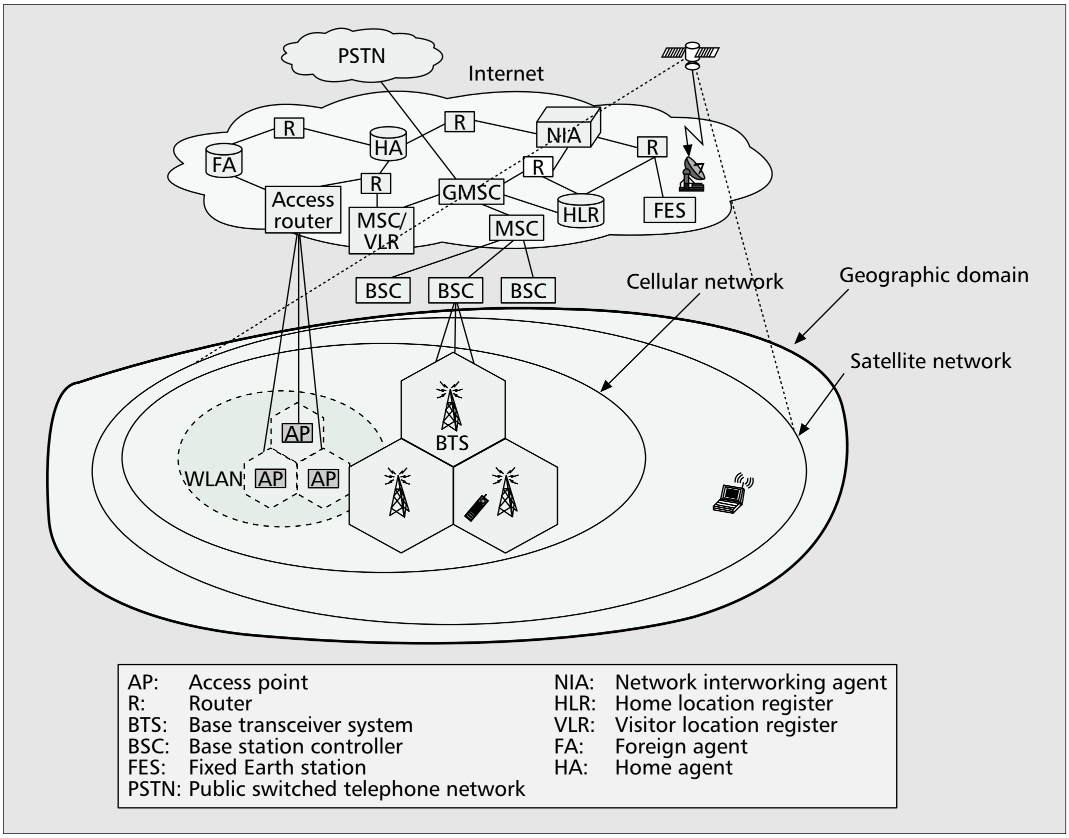


Figure 7. *The proposed mobility management architecture for NG all-IP-based wireless systems.*

posed QoS architectures for wired networks. However, QoS provisioning in a heterogeneous mobile computing environment introduces new problems to mobility management, such as location management for efficient access and timely service delivery, QoS negotiation during intersystem handoff, and others. In addition, there has been very little work on a suitable QoS model for combined macro- and micro-mobility [11].

Location and Handoff Management in Wireless Overlay Networks — Future wireless systems have a hierarchical architecture where different access networks have dramatically different coverage areas. Mobility management in wireless overlay networks that have fully overlapping coverage should be paid more attention. Mobility management techniques should allow mobile users to roam among multiple wireless networks in a manner that is completely transparent to applications and disrupts connectivity as little as possible. Moreover, in wireless overlay networks the choice of the "best" network for location and handoff management places a new challenge because different overlay levels may have widely varying characteristics [24].

Cross-Layer Optimization — The proposed cross-layer solutions show that cooperation between the network and link layers is able to improve the performance of mobility management in IP-based heterogeneous communication environment. Information from the link layer, such as signal strength and velocity of mobile terminals, may help the decision making of mobility management techniques at the network layer. Therefore, cross-layer optimization for mobility management is worthy of further investigation. How to cooperate, how tight the cooperation is, and how much information is exchanged between the two layers are possible research issues.

Conclusion

In this article we give a comprehensive survey of mobility management techniques in NG all-IP-based wireless systems. Since global roaming in heterogeneous wireless environments wil become an essential trend in the near future, we focus on mobility management techniques in heterogeneous wireless networks. We describe current proposed protocols for mobility management in NG all-IP-based wireless systems. These protocols try to provide mobility management from different layers. We compare the existing solutions and point out the motivations for the design of a more efficient mobility management architecture. We also developed a discussion for open research issues in this field.

References

[1] F. M. Chiussi, D. A. Khotimsky, and S. Krishnan, "Mobility Management in Third-Generation All-IP Networks," *IEEE Commun. Mag.*, Sept. 2002, pp. 124–35.
[2] I. F. Akyildiz *et al.*, "AdaptNet: An Adaptive Protocol Suite for the Next-Generation Wireless Internet," *IEEE Commun. Mag.*, vol. 42, no. 3, Mar. 2004, pp. 128–36.
[3] A. T. Campbell *et al.*,"Design, Implementation, and Evaluation of Cellular IP," *IEEE Pers. Commun.*, Aug. 2000, pp. 42–49.

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[4] A. Misra *et al.*, "IDMP-Based Fast Handoffs and Paging in IP-Based 4G Mobile Networks," *IEEE Commun. Mag.*, Mar. 2002, pp. 138–45.

[5] R. Ramjee *et al.*, "HAWAII: A Domain-Based Approach for Supporting Mobility in Wide-Area Wireless Networks," *IEEE/ACM Trans. Net.*, vol. 10, no. 3, June 2002, pp. 396–410.

[6] I. F. Akyildiz *et al.*, "Mobility Management for Next Generation Wireless Systems," *Proc. IEEE*, vol. 87, no. 8, Aug. 1999, pp. 1347–84.

[7] S. Mohanty and I. F. Akyildiz, "An Architecture and Associated Protocols for Inter-System Handover between 3G and WLAN," submitted for publication, 2003.

[8] C. E. Perkins, "IP Mobility Support for IPv4," RFC 3220, Jan. 2002.

[9] H. Haverinen and J. Malinen, "Mobile IP Regional Paging," Internet draft, IETF, draft-haverinen-mobileip-reg-paging-00.txt, June 2000, work in progress.

[10] C. E. Perkins and D. B. Johnson, "Route Optimization in Mobile IP," Internet draft, IETF, draft-ietf-mobileip-optim-11.txt, Sep. 2001.

[11] A. T. Campbell *et al.*, "Comparison of IP Micromobility Protocols," *IEEE Wireless Commun.*, Feb. 2002, pp. 72–82.

[12] E. Gustafsson, A. Jonsson, and C. E. Perkins, "Mobile IPv4 Regional Registration," Internet draft, IETF, draft-ietf-mobileip-reg-tunnel-09.txt, June 2004, work in progress.

[13] H. Soliman *et al.*, "Hierarchical Mobile IPv6 Mobility Management (HMIPv6)," Internet draft, IETF, draft-ietf-mipshop-hmipv6-02.txt, June 2004, work in progress.

[14] R. Pandya *et al.*, "IMT-2000 Standards: Network aspects," *IEEE Pers. Commun.*, vol. 4, no. 4, Aug. 1997, pp. 20–29.

[15] J. Phillips and G. M. Namee, *Personal Wireless Communication with DECT and PWT*, Artech House, 1998.

[16] V. Garg and J. E. Wilkes, "Interworking and Interoperability Issues for North American PCS," *IEEE Commun. Mag.*, vol. 34, no. 3, Mar. 1996, pp. 94–99.

[17] I. F. Akyildiz and W. Wang, "A Dynamic Location Management Scheme for Next-Generation Multitier PCS Systems," *IEEE Trans. Wireless Commun.*, vol. 1, no. 1, Jan. 2002, pp. 178–89.

[18] W. Wang and I. F. Akyildiz, "A New Signaling Protocol for Intersystem Roaming in Next-Generation Wireless Systems," *IEEE JSAC*, vol. 19, no. 10, Oct. 2001, pp. 2040–52.

[19] ETSI TS 129 120 V4.0.0, "Universal Mobile Telecommunications Systems (UMTS); Mobile Application Part (MAP) Specification for Gateway Location Register (GLR); Stage 3," 3GPP/ETSI, 2002.

[20] Y-B Lin and I. Chlamtac, "Heterogeneous Personal Communications Services: Integration of PCS Systems," *IEEE Commun. Mag.*, Sep. 1996, pp. 106-13.

[21] N. Efthymiou, Y. F. Hu, and R. Sheriff, "Performance of Intersegment Handover Protocols in an Integrated Space/Terrestrial-UMTS Environment," *IEEE Trans. Vehic. Tech.*, vol. 47, no. 4, Nov. 1998, pp. 1179–99.

[22] J. McNair, I. F. Akyildiz, and M. D. Bender, "An Inter-System Handoff Technique for the IMT-2000 System," *Proc. IEEE INFOCOM 2000*, vol. 1, 2000, pp. 208–16.

[23] M. E. Kounavis *et al.*, "Design, Implementation and Evaluation of Programmable Handoff in Mobile Networks," *ACM Mobile Nets. and Apps.*, vol. 6, 2001, pp. 443–61.

[24] M. Stemm and R. H. Katz, "Vertical Handoffs in Wireless Overlay Networks," *ACM Mobile Nets. and Apps.*, vol. 3, 1998, pp. 335–50.

[25] M. Buddhikot *et al.*,"Integration of 802.11 and Third-Generation Wireless Data Networks," *Proc. IEEE INFOCOM 2003*, vol. 1, 2003, pp. 503–12.

[26] H. Yokota *et al.*, "Link Layer Assisted Mobile IP Fast Handoff Method over Wireless LAN Networks," *Proc. ACM MOBICOM 2002*, 2002.

[27] R. Hsieh, Z. G. Zhou, and A. Seneviratne, "S-MIP: A seamless handoff architecture for Mobile IP," *Proc. IEEE INFOCOM 2003*, vol. 3, 2003, pp. 1774–84.

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