1

Introduction

Wireless connectivity to communications and information has advanced the world towards ubiquitous computing. In the space of less than thirty years, cell phones have become ubiquitous and wireless data access has become common. However, this access has brought with it a variety of technical problems. Radio physics and power constraints, the need to reuse spectrum, economic constraints on facility placement, and service balkanization due to competitive and political factors force us to implement wireless systems as cells of limited range. Furthermore, cells may use very different wireless technologies or provide fundamentally different services, such as VoIP (Voice over IP), streaming, or direct short-range communications for telematics. We then need handoff mechanisms, often in multiple protocol layers, to allow a mobile terminal to move from cell to cell and maintain service continuity.

Mobility can be described as movement of a terminal, resulting in the release of the terminal’s binding to the current cell (point of attachment to the network) and the establishment of bindings to the new cell being entered, while preserving the existing sessions associated with higher-level services. The cellular telephony community has long implemented service- and technology-specific mobility protocols that hand off voice sessions as the user moves from cell to cell. Because voice service quality is highly sensitive to service interruptions, cell-to-cell handoffs in a cellular environment have been highly optimized and are not noticed by the public. Tripathi et al. (1998) summarized some of the handoff technologies associated with cellular mobility. Pollini (1996) discussed some of the trends in handover design in cellular networks that may affect the optimization of handover performance.

For IP traffic, the IETF has defined mobility protocols for both IPv4 (Perkins, 2002b) and IPv6 (Johnson et al., 2004). However, IP traffic is dramatically more diverse than cellular voice in the range of link layer technologies used to support IP traffic, the number of economic units supplying IP services, and the authentication protocols and services running above IP. This diversity has meant that the IETF could not easily design access-specific handoff optimization techniques such as soft handoff (Chen and Mary, 2003; Wong and Lim, 1997), often seen in cellular voice, into the mobility standards. As a result, unoptimized Mobile IP handoffs can take a few seconds to perform, and degrade the quality of service in the process.

IP’s transformation from a service supporting email and file transfer to the base layer for network convergence means that the constraints on handover performance are becoming much more stringent. Handovers cannot interrupt real-time services. The mechanisms and design principles needed for
building optimized handovers in the context of mobile Internet services are poorly understood and need better analysis. To the best of our knowledge, none of the existing work has attempted to model the systems aspects of a mobility event nor was intended to systematically analyze the elementary operations involved in a mobility event. This body of work is also lacking in the ability to predict the performance of a mobility event. Some of the existing work has focused on optimizing only parts of a mobility event in an ad hoc manner, specific to a mobility protocol, without providing a comprehensive approach to solving the optimization problem in all layers or functional modules. We provide an overview of this related work for each of these mobility functions along with a detailed description of the proposed techniques in Chapter 6.

This book is intended to contribute to a general theory of optimized handover, especially with respect to the mobility of Internet-based applications. The contributions fall into four categories:

1. Identification of fundamental properties that are rebound during a mobility event. Analysis of these properties provides a systematic framework for describing mobility management and the operations that are intrinsic to handover.
2. A model of the handover process that allows one to predict performance both for an unoptimized handover and for specific optimization methodologies under conditions of resource constraints. This model also allows one to study behavioral properties of the handoff system such as data dependency and deadlocks.
3. A series of optimization methodologies, experimental evaluations of them, and optimization techniques that can be applied to the link, network, and application layers and preserve the user experience by optimizing a handover.
4. Application of the model to represent optimizations, and comparison of the results with experimental data.

1.1 Types of Mobility

There are several types of mobility, such as terminal mobility, personal mobility, session mobility, and service mobility. Schulzrinne and Wedlund (2000a) introduced several different types of mobility to support multimedia traffic for an IP-based network. We briefly review each type of mobility.

1.1.1 Terminal Mobility

Terminal mobility allows a device to move between networks while continuing to be reachable for incoming requests and maintaining existing sessions during movement. It allows an established call or session to continue when an MS (mobile station) moves from one cell to another without interruption in the call or session.

Terminal mobility may also arise from a change in the network condition, whereby a mobile may switch between two neighboring networks even without any movement. We describe here the types of terminal mobility that arise from different types of handoffs. Handoff, often also known as handover, is a process that results when a mobile disconnects from one point of attachment in a network and reconnects to another point of attachment in the same or a different network.

The handoff process can be either hard or soft. With hard handoff, the link to the prior base station is terminated before or as the user is transferred to the new cell’s base station. Thus, the mobile is linked to no more than one base station at a given time. Initiation of the handoff may begin when the
signal strength at the mobile received from the target base station is greater than that from the current base station. As the mobile moves into a new cell, its signal is abruptly handed over from its current cell (or base station) to the new one. In the old analog systems, hard handover could be heard as a click or a very short beep. In digital cellular systems, this is not noticed. However, in an IP-based handoff scenario, hard handover contributes 4–15 s of delay (Dutta et al., 2005c). With soft handoff (Wong and Lim, 1997), the MS continues to receive and accept radio signals from the base stations that are part of the previous as well as the new cell for a limited period of time. The MS signal is also received at multiple base stations. In order to ensure the layer 2 independence requirement of mobility management schemes, a maximum acceptable handoff time (MAHT) is required, which will vary based on the access type.

In an end-to-end wireless IP environment, four logical levels of handoff procedures can be defined:

- **Layer 2 handoff.** This allows an MS to move from one layer 2 point of attachment to another layer 2 point of attachment that belongs to the same subnetwork. Each layer 2 point of attachment may be equipped with same or a different type of radio access technology. One subnetwork may consist of multiple layer 2 radio access networks. The IP address of the mobile host remains the same during this handoff.

- **Subnet handoff.** This allows an MS to move from a radio access network within a subnet to an adjacent radio access network within another subnet that belongs to the same administrative domain. The IP address of the mobile may or may not change.

- **Domain handoff.** This allows an MS to move from one subnet within an administrative domain to another in a different administrative domain. Domain handoff can take place between two administrative domains that belong to the same operator or different operators.

- **Interoperator handoff.** This allows a mobile to move from one wireless service provider to another wireless service provider. Interoperator handoff involves additional steps such as authentication and authorization with the mobile’s home networks and may be subject to various roaming agreements among wireless operators. In most cases, interoperator handoff is not as frequent as subnet handoff or layer 2 handoff.

In the following section, we define several different combinations of handoffs in a heterogeneous environment.

We have analyzed, modeled, and experimented with all three of these types of handoff in heterogeneous access environments such as CDMA (code division multiple access) and IEEE 802.11. We focus on the systems optimization aspects of terminal mobility in this book. Systems optimization techniques minimize the delay and packet loss contributed by several handoff components under certain conditions of resource constraints on the mobile and the network, namely constraints on battery power, CPU cycles, and network capacity.

### 1.1.1.1 Heterogeneous Handover

An access network is defined as the backhaul network that provides the first-hop or last-hop access to a mobile in an end-to-end communication system. When a mobile moves from one access network to another access network during an active communication session and changes its point of attachment, it is subject to disruption in the continuity of service. During the handover, as the mobile changes its point of attachment in the network, the mobile terminal may end up communicating using a second interface with the new network, or change its subnet or the domain it is connected to. Heterogeneous
handover is a type of handover that requires authorization for the acquisition or modification of resources assigned to a mobile, and the authorization needs interaction with a central authority in a domain. In many cases, the authorization procedure in a heterogeneous handover follows an authentication procedure that also requires interaction with a central authority in a domain. Based on the type of handover and access technology, the following heterogeneous handover scenarios can be defined. These can be categorized primarily as (A) intersubnet and (B) intrasubnet.

An intersubnet handover can comprise the following combinations of handovers that fall into category A:

1. intertechnology, interdomain;
2. intertechnology, intradomain;
3. intratechnology, interdomain;
4. intratechnology, intradomain.

An intrasubnet handover can comprise the following types of handovers that fall into category B:

1. intratechnology, intradomain;
2. intertechnology, intradomain.

**Intrasubnet**

When a mobile moves between two radio access networks that are part of the same subnet and does not change broadcast domain, this is called an intrasubnet handover. During an intrasubnet handover, the mobile may be subject to an intertechnology handover as well if both of the access networks, with different radio access technologies (e.g., CDMA and 802.11), belong to the same subnet. However, during an intrasubnet and intertechnology handover, the effective layer 3 identifier of the terminal may change if the terminal starts to communicate using an interface that is part of a different access network, since the IP addresses associated with each interface will be different even though these addresses belong to the same subnet.

**Intersubnet**

A mobile is subject to an intersubnet handover when it moves between two radio access networks that belong to two different subnets. As a result, its layer 3 identifier (e.g., IP address) is changed, thus giving rise to a need for a mobility management protocol such as Mobile IP (Perkins, 2002b), Mobile IPv6 (Johnson et al., 2004), SIP-Mobility (Wedlund and Schulzrinne, 1999), and HIP (Moskowitz and Nikander, 2006) that can take care of the continuity of the existing application. An intersubnet handover can be viewed as orthogonal to intrasubnet handoff scenarios and may include intradomain, interdomain, intertechnology or intratechnology handover. Intersubnet handover potentially gives rise to packet loss and jitter because of the delay associated with transitions in layers 2 and 3.

**Intertechnology**

A mobile may be equipped with multiple interfaces, where each interface can support a different access technology (802.11 or CDMA). A mobile may prefer to communicate with only one interface at any time in order to conserve power. During the handover, the mobile may move out of the footprint of one access technology (e.g., 802.11) and into the footprint of a different technology (e.g., CDMA). This will warrant switching of the communicating interface on the mobile as well. This type of intertechnology handover is often called vertical handover, since the mobile makes a
movement between two different cell sizes. A vertical handover can be termed an upward or a downward vertical handover based on the direction of movement, namely from a smaller cell to a larger cell or vice versa as described by Stemm and Katz (1998). A mobile moving from an 802.11 network to a cellular network can be viewed as an upward vertical handover. An intertechnology handover may affect the quality of service of multimedia communication, since each access network may offer a different bandwidth.

**Intratechnology**

An intratechnology handover is defined as event when a mobile moves between two examples of the same type of access technology, such as between 802.11[a, b, n] and 802.11[a, b, n] or between CDMA1XRTT and CDMA1EVDO. In this scenario, a mobile may be equipped with a single interface (with multiple PHY types of the same technology) or with multiple interfaces. An intratechnology handover may involve intrasubnet or intersubnet movement and thus may need to change its layer 3 identifier, depending upon the type of movement. An intratechnology handover may involve networks with different access characteristics and thus may very well belong to the heterogeneous-handover category. However, a handover between two 802.11b networks, if these belong to the same subnet or domain, need not be termed a heterogeneous handover.

**Interdomain**

A domain can be defined in several ways. But, for the purposes of roaming, we define a domain as an administrative domain that consists of networks that are managed by a single administrative entity which authenticates and authorizes a mobile for accessing those networks. An administrative entity may be a service provider, an enterprise, or any organization. As a mobile moves between two administrative domains, it is also subject to intersubnet handover, as the two different domains exclusively have two different subnets. Thus, an interdomain handover will by default be subject to intersubnet handover and, in addition, it may be subject to either intertechnology or intratechnology handover. Interdomain handover will be subject to all the transition steps that a subnet handover goes through in addition to an authentication process. These extra steps contribute to additional delay on top of the delays due to regular subnet handover.

**Intradomain**

When a mobile’s movement is confined within an administrative domain, it is called intradomain movement. An intradomain movement may involve intrasubnet, intersubnet, intratechnology, and intertechnology handovers as well.

### 1.1.2 Personal Mobility

The concept of personal mobility was initially introduced as part of Universal Personal Telecommunications (UPT), as described by Zaid (1994). Personal mobility removes the fixed association between the terminal and the user, thereby allowing an additional degree of mobility over and above terminal mobility in mobile networks.

Figure 1.1 illustrates some fundamental differences between personal mobility and terminal mobility by showing the relationships between path identification, terminal identification, and user identification.¹

¹ These terms are defined in Appendix B.
For multimedia communication, personal mobility is a form of mobility by which a user can be reached at different terminals using the same logical address or resource identifier (Schulzrinne et al., 1996), regardless of the point of attachment of the mobile and the identifier that it obtains when it attaches to a network. As the mobile changes its point of attachment, it acquires a new identifier in the new network and updates this identifier by means of registration with a central authority, either in the home network or in the visited network. The central authority is often a SIP (Session Initiation Protocol) registrar (Rosenberg et al., 2002) that keeps a binding between the new terminal identifier and the Uniform Resource Identifier (URI) that is assigned to the mobile user and is unique for each mobile. A URI is typically a SIP URI and is of the form sip:alice@xyz.edu as defined by IETF RFC 2396 (Berners-Lee et al., 1998). Personal mobility can involve both 1-to-n mappings, where one address can be associated with many potential terminals, and m-to-1 mappings, where multiple addresses map to one device. Thus, by having a mapping between the terminal identifier and the resource identifier, it is possible to direct the data to one or more interfaces, where the interfaces can be part of the same device or multiple devices.

### 1.1.3 Session Mobility

Session mobility allows a user to continue an existing multimedia session or part of a session as the user moves from one device to another. For example, a user who is part of a multimedia session including voice and video on a cell phone can transfer the video to another device such as a TV, thus splitting the existing multimedia session over two devices. Similarly, an existing audio session can be transferred from a cell phone to a desktop phone. The MEGACO (Cuervo et al., 2000), third-party call control (Rosenberg et al., 2004), and REFER (Sparks, 2003) mechanisms are
some of the approaches that can be used to implement session mobility. Most recently, 3GPP (the Third Generation Partnership Project) has been following an approach called Voice Call Continuity (VCC) (Third Generation Partnership Project 2 and Telecommunications Industry Association 2007) that allows a user to move between an IP network and a cellular network. Shacham et al. (2008) and Shacham et al. (2007) discussed the technical details of session mobility and described how multimedia sessions can be transferred between different terminals.

1.1.4 Service Mobility

Service mobility allows a user to maintain their access to services even when changing devices and network service providers. In a VoIP (Voice over IP) environment, the typical services that users may wish to maintain include speed dial lists, address books, call logs, media preferences, buddy lists, and call-handling instructions. However, in order to be able to obtain the same service independently of the service provider, the mobile device may often require cross-provider relationships.

1.2 Performance Requirements

In order to provide the desired quality of service (QoS) for interactive VoIP and streaming traffic, one needs to limit the end-to-end delay, network jitter, and packet loss to an acceptable level. The performance requirements will vary based on the type of application and its characteristics such as delay and loss tolerance. Various standards organizations have defined limits for these metrics. For example, 3GPP TS23.107 (Greis, 2001) defines four application classes, namely conversational, streaming, interactive, and background (e.g., file transfer or email), each with different sets of end-to-end delay and QoS requirements. Based on the type of application (e.g., interactive, streaming, or data), these values may vary. For example, for the one-way delay, ITU-T G.114 (Time, 2000) recommends 150 ms as the upper limit for VoIP applications and considers 400 ms as a generally unacceptable delay. Similarly, the streaming class has a tolerable packet (SDU) error ratio ranging from 0.1 to 0.00001 and a transmission delay limit of less than 300 ms.

In general, the handoff process contributes to packet loss and network jitter and adversely affects the overall throughput of data traffic because of interruption and retransmission of data due to the change in the point of attachment to the network. A mobility event contributes to two kinds of delays that affect performance, namely the handoff delay and one-way delay of the packet. The handoff delay is defined as the time between when the last packet is received at the old point of attachment and when the first packet is received at the new point of attachment. The end-to-end delay (or one-way delay) consists of several components, namely the transmission delay, propagation delay, network delay, operating system delay, codec delay, and application delay. Wenyu and Schulzrinne have done a complete analysis of these delays (Jiang and Schulzrinne, 2000). Handoff contributes to the network delay component of the end-to-end delay.

During a mobile’s handoff process, in-flight transient traffic cannot reach the mobile. In-flight packets are defined as packets that are in transit during a mobile’s movement from one network point of attachment to another. Network jitter contributes to the variation in interpacket arrival time of consecutive packets at the receiver. This is caused by variation in the one-way transmission delay of the consecutive packets. These in-flight packets can be either lost or buffered. If the in-flight packets are lost, this contributes to the interpacket arrival delay between the last packet before handoff and the first packet after handoff. If the packets are buffered, packet loss is minimized, but there is additional...
jitter for the in-handoff packets when they are flushed after the handoff. Buffering during handoff avoids packet loss, but at the cost of additional one-way delay. A trade-off between one-way delay and packet loss is desired, based on the type of application. For real-time communication, if a packet is received after a certain delay threshold, it is also considered lost.

We have verified experimentally that in the absence of any optimization technique, a mobile can be subject to a handoff delay of between 4 and 17 s (Dutta et al., 2005c), resulting in transient service interruption and packet loss. This value varies depending upon the type of mobility protocol used; the type of handover, such as vertical (i.e., handover between different network types) or horizontal (i.e., handover between networks of the same type); and the type of access network, namely 802.11 or CDMA. Thus, it is desirable to conduct a formal analysis of the discrete events that constitute the handoff process; build a system model that can predict handoff performance; develop relevant optimization techniques for these operations; and analyze the dynamic behavior of the system during handoff, including resource utilization.

While several mobility protocols have been defined for different layers, to the best of our knowledge, there has been no formal analysis or system model that can study the basic operations associated with mobility events and various systems optimization techniques.

### 1.3 Motivation

The following are the key mobility issues that are covered in the book:

1. The existing mobility protocols affect the performance of real-time communication because of the sequence of discrete events associated with the handoff event.
2. The existing mobility optimization mechanisms are tightly coupled to the corresponding mobility management protocols and do not provide a generalized approach to optimization. For example, it is impossible to apply mobility optimization mechanisms designed for Mobile IPv4 (Perkins, 2002b) or Mobile IPv6 (Johnson et al., 2004) to MOBIKE (Eronen, 2006). Thus, it is desirable to develop a set of formal methodologies with specific design criteria to help formulate system optimization techniques that can be applied to any mobility management protocol and access technology.
3. The available mobility management techniques do not provide any systematic framework to formalize the different states and transition processes involved with a mobility event. Thus, it becomes difficult to study the behavior of a handoff event and evaluate the performance of any mobility protocol or to devise any improvements.
   (a) As far as we know, there has not been a systematic mobility system model that can analyze behavioral characteristics of a handoff event such as deadlock and help formulate systems optimization techniques for cellular or IP-based mobility management protocols.
   (b) The existing work does not provide a generalized mobility optimization framework that can support horizontal and vertical handovers across administrative domains.
   (c) There has not been any formal analysis of how a specific mobility optimization technique might affect other system resources in the network.

This book addresses the above issues. We analyze the basic operations associated with a mobility event in detail. We develop a formal systems model of mobility by representing the basic operations
associated with a handoff as a series of discrete events. We formalize the associated states and transitions in the form of a discrete-event dynamic systems (DEDS) model. We then analyze this DEDS-oriented mobility model using discrete timed-transition Petri nets (DTTP). Based on an analysis of the properties associated with a mobility event, we propose several systems optimization techniques for the basic operations associated with the handoff event. We demonstrate these techniques with models, experiments, and numerical analysis using a few network layer and application layer mobility protocols. We then apply these optimization techniques to a timed Petri net model and compare the results with experimental results. We perform a trade-off analysis between the utilization of systems resources and the handoff performance metrics obtained using these optimization techniques. Finally, we also use this model to study behavioral properties of the handoff such as deadlock and data dependency under conditions of systems and network resource constraints.

1.4 Summary of Key Contributions

The highlights of the key contributions of Chapters 2–12 are summarized in Table 1.1. For each chapter, we summarize the technical problems that are addressed, the details of the proposed mechanisms, and the key benefits, with experimental results.

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<th>No.</th>
<th>Chapter title</th>
<th>Summary of key contributions</th>
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<tr>
<td>2</td>
<td>Analysis of mobility protocols for multimedia</td>
<td>Comprehensive analysis and comparison of several generations of mobility protocols (e.g., 1G, 2G, 3G, and 4G) to extrapolate the common abstract functions for a mobility event.</td>
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<tr>
<td>3</td>
<td>Systems analysis of mobility events</td>
<td>Development of a new synthesis that derives a fundamental taxonomy of handover functions and their relationships. This taxonomy provides a basis for describing and characterizing optimization in each layer. Experimental analysis of the handoff delays for the application layer and network layer mobility protocols based on this handover taxonomy.</td>
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| 4   | Modeling mobility                      | • Data dependency analysis and resource analysis of the handover components based on the mobility taxonomy.  
• Design of the first mobility system model for handoff processes using deterministic timed-transition Petri nets based on data dependency and resource dependency.  
• Development of Petri-net-based mechanisms to predict the systems performance and behavior of a handoff system.  
• New mechanisms to investigate the opportunity for parallelism based on resource modeling. |
| 5   | Layer 2 optimization                   | • This chapter introduces a new handoff procedure that reduces the MAC layer handoff latency, in most cases to a level where VoIP communication becomes seamless. This new handoff procedure reduces the discovery phase using a selective scanning algorithm and a caching mechanism.  
• Using the selective scanning mechanism, it is possible to reduce the total handoff latency to an average value of 129 ms, and by using the caching mechanism it is possible to reduce the handoff latency to 3 ms. |

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<td>6</td>
<td>Discovery (Section 6.3)</td>
<td>Application layer discovery mechanism that discovers the network elements of the target networks in an access-independent manner. By discovering these elements proactively and caching some of these at the mobile, network discovery latency is reduced to 4 ms.</td>
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<td>Authentication (Section 6.4)</td>
<td>Network-layer-assisted layer 2 preauthentication mechanism that bootstraps the layer 2 authentication process in the neighboring networks by deriving preshared keys prior to the handover of the mobile. This mechanism reduces the authentication delay to 16 ms for both intersubnet and interdomain handover.</td>
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|     | Layer 3 configuration (Section 6.5)       | • Proactive IP address acquisition scheme that reduces the signaling exchange by obtaining the IP address from the target network over a secured tunnel before layer 2 handover.  
• Reactive router-assisted duplicate address detection mechanism, where the router multicasts the ARP cache at periodic intervals so that the mobile avoids ARP checking for duplicate address detection. |
|     | Layer 3 security association (Section 6.6)| • Anchor-agent-assisted layer 3 mechanism that maintains the layer 3 security context by hiding the change of network layer identifier address of the mobile and reduces the delay by avoiding the rekeying process.  
• Preregistration-based mechanism that establishes the security context prior to handoff by generating security keys. The handover delay due to layer 3 security association is completely eliminated. |
|     | Binding update (Section 6.7)              | • Reactive hierarchical binding update mechanism that uses a two-level hierarchy of addresses and an anchor agent to limit the global signaling update during mobility of the mobile within a domain. This mechanism achieves a reduction of about 70% in global signaling overhead for a 10 subnets/domain scenario.  
• Proactive binding update mechanism over a secured tunnel that eliminates the binding update delay completely at the cost of maintaining a proactive tunnel between the mobile and the target network. |
|     | Media rerouting (Sections 6.8 and 6.9)    | • Reactive forwarding mechanism that redirects the in-flight data from the previous network using an application layer mobility proxy in the previous network.  
• Mobile-controlled buffering mechanism that controls the buffering period dynamically based on handoff duration during proactive handoff.  
• Proactive multicasting mechanism that multicasts the in-flight data to the neighboring networks and reduces in-flight packet loss during handoff. |
|     | Route optimization (Section 6.10)         | • Packet-interceptor-assisted mechanism that modifies the source and destination addresses of the packets at the end hosts to maintain a direct path between the communicating hosts. This mechanism reduces transport delay by 50% for large packets.  
• Proxy-assisted packet interceptor that eliminates the trombone routing delay and reduces the signaling-related delay by 60% in an IMS (IP Multimedia Subsystem) environment. |
Table 1.1  (continued)

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<td></td>
<td>Media-independent cross-layer triggers (Section 6.11)</td>
<td>- First set of cross-layer triggers based on abstract primitives that can pass information across layers and expedite handoff-related operations independently of the access mechanism (e.g., CDMA or 802.11). These proposed cross-layer triggers were standardized in IEEE 802.21.</td>
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<td>7</td>
<td>Optimization with multilayer mobility protocols</td>
<td>Multilayer mobility management scheme that uses cross-layer triggers from data link layers and application layers and optimizes several handoff operations, namely address configuration, layer 3 binding update, and media traversal. The proposed mechanism increases the data throughput by 50% in a high-mobility scenario by reducing the binding update traversal.</td>
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| 8   | Optimization for simultaneous mobility | - Proposal of an analytical framework for simultaneous mobility that can predict the probability of simultaneous mobility based on interhandoff time and binding update latency.  
- Outlines solutions to the simultaneous mobility problem for network layer and application layer mobility protocols based on timer-based retransmission, forwarding, redirecting mechanisms, and simultaneous bindings. |
| 9   | Handoff optimization for multicast streaming | - Hierarchical scope-based multicast streaming architecture and implementation that offer local and global program management, and localized advertisement insertion using control information of real-time traffic (e.g., RTCP).  
- Reactive and proactive fast-handoff mechanisms using application layer triggering that reduce the join latency by a factor of 10 during subnet handover. |
| 10  | Cooperative roaming | - A novel approach, namely cooperative roaming, in which mobile nodes can collaborate with each other and share useful information about the network in which they move.  
- This achieves seamless L2 and L3 handoffs regardless of the authentication mechanisms used and without any changes to either the infrastructure or the protocol. |
| 11  | System evaluation | - Verification of experimental results from a few mobility systems that we built using optimization techniques for several handoff components that we developed, and validation of these results with results from corresponding Petri net models.  
- Behavioral analysis to study deadlocks and the effect of concurrency on handoff operations. |
| 12  | Conclusions and future work | We infer the best current practices for designing a mobility protocol based on the results obtained from our mobility taxonomy and systems optimization mechanisms. |