Emerging Wireless Technologies and the Future Mobile Internet

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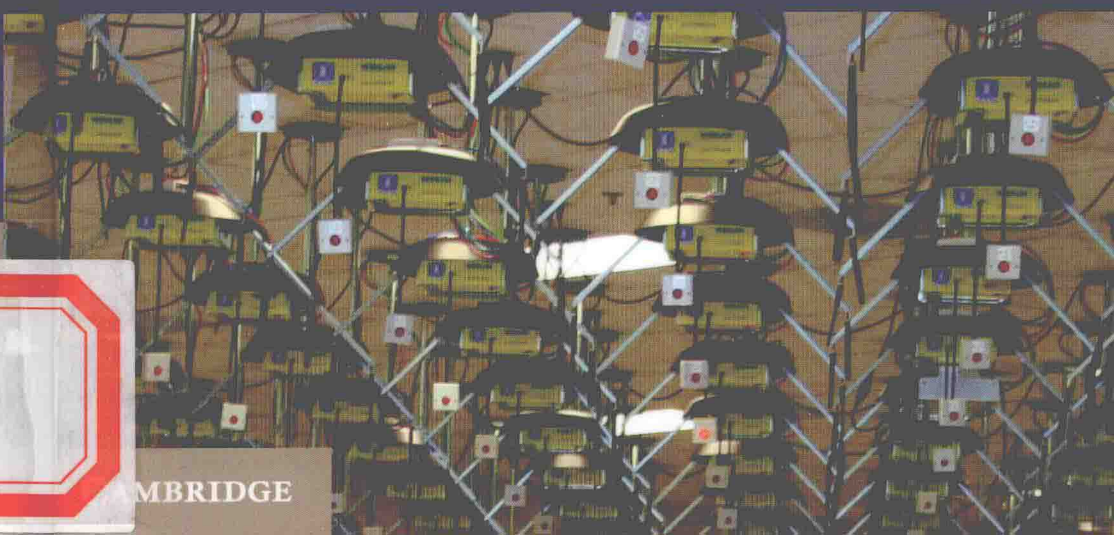

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Emerging Wireless Technologies and the Future Mobile Internet

This book provides a preview of emerging wireless technologies and their architectural impact on the future mobile Internet. The reader will find an overview of architectural considerations for the mobile Internet, along with more detailed technical discussion of new protocol concepts currently being considered at the research stage.

The first chapter starts with a discussion of anticipated mobile/wireless usage scenarios, leading to an identification of new protocol features for the future Internet. This is followed by several chapters that provide in-depth coverage on next-generation wireless standards, ad hoc and mesh network protocols, opportunistic delivery and delay-tolerant networks, sensor network architectures and protocols, cognitive radio networks, vehicular networks, security and privacy, and experimental systems for future Internet research. Each of these contributed chapters includes a discussion of new networking requirements for the wireless scenario under consideration, architectural concepts, and specific protocol designs, many still at the research stage.

Dipankar Raychaudhuri is Professor-II, Electrical and Computer Engineering and Director, Wireless Information Network Lab (WINLAB) at Rutgers University. WINLAB's research scope includes topics such as RF (Radio Frequency)/sensor devices, cognitive radio, dynamic spectrum access, 4G systems, ad hoc mesh networks, wireless security, future Internet architecture, and pervasive computing. Raychaudhuri is widely recognized as a leader in the future Internet research field and has lectured extensively on the topic at both national and international forums. During 2005–2007, he organized and co-hosted the NSF (National Science Foundation) "Wireless Mobile Planning Group" (WMPG) workshops that inspired and set the stage for much of the content in this book.

Mario Gerla is a Professor in the Computer Science Department at the University of California, Los Angeles. He has led the ONR (Office of Naval Research) MINUTEMAN (Multimedia Intelligent Network of Unattended Mobile Agents) project, designing the next-generation scalable airborne Internet for tactical and homeland defense scenarios and two advanced wireless network projects under U.S. Army and IBM funding. Dr. Gerla is an active participant in future Internet research activities in the United States, co-hosting the NSF WMPG workshops from 2005 to 2007. His research group is an active contributor to the emerging field of vehicular networking and is credited with the "CarTorrent" protocol for peer-to-peer file transfer between vehicles.

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FOREWORD

The current Internet is an outgrowth of the ARPANET (Advanced Research Projects Agency Network) that was initiated four decades ago. The TCP/IP (Transmission Control Protocol/Internet Protocol) designed by Vinton Cerf and Robert Kahn in 1973 did not anticipate, quite understandably, such extensive use of wireless channels and mobile terminals as we are witnessing today. The packet-switching technology for the ARPANET was not intended to support real-time applications that are sensitive to delay jitter. Furthermore, the TCP/IP designers assumed that its end users – researchers at national laboratories and universities in the United States, who would exchange their programs, data, and email – would be trustworthy; thus, security was not their concern, although reliability was one of the key considerations in the design and operation of the network.

It is amazing, therefore, that given the age of the TCP/IP, the Internet has successfully continued to grow by supporting the ever increasing numbers of end users and new applications, with a series of ad hoc modifications and extensions made to the original protocol. In recent years, however, many in the Internet research community began to wonder how long they could continue to do "patch work" to accommodate new applications and their requirements. New research initiatives have been launched within the past several years, aimed at a grand design of "a future Internet." Such efforts include the NSF's FIND (Future Internet Design) and GENI (Global Environment for Network Innovations), the European Community's FP 7 (Frame-network Program, Year 7), Germany's G-Lab, and Japan's NWGN (New Generation Network).

It is therefore extremely timely that Drs. Raychaudhuri and Gerla are publishing this book at this juncture, because better understanding of rapidly evolving wireless technologies and emerging new applications will be crucial in deciding the right architecture for the future Internet. It is not clear at this point which approach among several alternatives proposed or being pursued – ranging from so-called clean-slate architectures to continuous enhancements of the current IP network – will eventually prevail, but there is no question that the *future Internet* architecture must be built with wireless technologies as its major components, and mobility of end users/terminals and security of applications and services must be adequately supported.

The conventional architecture of treating a wireless network as an L-2 level *access* network connected to the core network (i.e., L-3 layer) through a gateway is becoming outdated. As pervasive computing in smart devices and wireless sensors/actuators attached to numerous things are expected to become predominant end users/devices in a future network, a novel network architecture and protocols with end-to-end control and routing, including heterogeneous wireless subnetworks as an integrated part of the entire network, will be called for to provide mobility services with satisfactory performance, security, and scalability. Up to now, wireless technologies have been largely treated as synonymous with wireless *communication* links, where a wireless channel serves merely as an interface between the end mobile user and the core network. In the future network, however, we anticipate that in-network *computing* (or *processing*) of data from sensors and *storing* (or *caching*) of data based on its content ought to be performed.

The introductory chapter of this book presents a variety of emerging wireless networking scenarios and identifies requirements for a new architecture and protocol for each of the mobile networking scenarios. These requirements are then aggregated into a number of key protocol features. Technical issues associated with implementing these wireless/mobility requirements into a unified comprehensive future Internet architecture protocol are then discussed. In the concluding chapter, Drs. Raychaudhuri and Gerla review the overall challenge of evolving the current Internet to meet these mobile networking needs and provide a roadmap for the future.

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Dr. Raychaudhuri would like to acknowledge sabbatical leave support from his home institution, Rutgers University, during the academic year 2008–2009, when much of this book was planned and organized. Thanks are also due to the Clean Slate Program at Stanford University (led by Prof. Nick McKeown) for providing him with office space and other resources during his sabbatical visit in 2008. Finally, he would like to express his gratitude to his wife, Arundhati Raychaudhuri, for her encouragement and support throughout the course of this project.

Dr. Gerla would like to acknowledge the support of the NSF grant "The Health Guardian – A Gateway to Networked Wellness" and of the NSF-GENI grant "Campus Vehicular Testbed" that helped him focus on mobile and vehicular communications. Also, the International Technical Alliance project (led by IBM) supported some of the time dedicated to the research that went into this book. Finally, Dr. Gerla wishes to express his gratitude to his doctoral student, Eun Kyu Lee, for his outstanding editorial work during the final and very critical phase of integrating all the chapters to a consistent manuscript.

CONTENTS

1

Introduction

Dipankar Raychaudhuri and Mario Gerla

1.1 Background

Over the next ten-to-fifteen years, it is anticipated that significant qualitative changes to the Internet will be driven by the rapid proliferation of mobile and wireless computing devices. Wireless devices on the Internet will include laptop computers, personal digital assistants, cell phones (more than 3.5 billion in use as of 2009 and growing!), portable media players, and so on, along with embedded sensors used to sense and control real-world objects and events (see Figure 1.1). As mobile computing devices and wireless sensors are deployed in large numbers, the Internet will increasingly serve as the interface between people moving around and the physical world that surrounds them. Emerging capabilities for opportunistic collaboration with other people nearby or for interacting with physical-world objects and machines via the Internet will result in new applications that will influence the way people live and work. The potential impact of the future wireless Internet is very significant because the network combines the power of cloud computation, search engines, and databases in the background with the immediacy of information from mobile users and sensors in the foreground. The data flows and interactions between mobile users, sensors, and their computing support infrastructure are clearly very different from that of today's popular applications such as email, instant messaging, or the World Wide Web.

As a result, one of the broad architectural challenges facing the network research community is that of evolving or redesigning the Internet architecture to incorporate emerging wireless technologies – efficiently, and at scale.[1] The Internet's current TCP/IP protocol architecture was designed for static hosts and routers connected by wired links. Protocol extensions such as mobile IP have been useful for first-generation cellular mobile services involving single-hop radio links from mobile devices to base stations or access points.[2] However, incremental solutions based on IP are inadequate for dealing with the

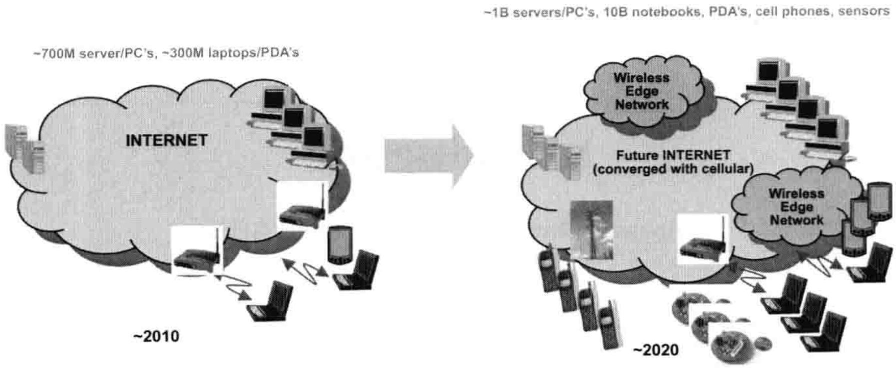

Figure 1.1. Migration of Internet usage from fixed PCs and servers to mobile devices and sensors.

requirements of fast-growing wireless usage scenarios such as multihop mesh,[3] peer-to-peer,[4] disruption-tolerant networks (DTN),[5] sensor systems,[6] and vehicular applications.[7] These emerging wireless scenarios motivate us to consider "clean-slate" network architectures and protocols capable of meeting the needs of these and other emerging wireless scenarios. In the next section (1.2), we present an overview of these emerging wireless networking scenarios, identifying new architecture and protocol requirements for each of these usage cases. These mobile network architecture requirements will then be aggregated into a number of key protocol features in Section 1.3 that follows. Technical challenges associated with implementing these new wireless/mobility requirements into a unified comprehensive future Internet architecture protocol will then be discussed briefly in Section 1.4. Each of the emerging wireless technology scenarios identified in this introductory chapter will then be discussed in greater depth in each of the chapters that follows. In the concluding chapter, we will review the overall challenge of evolving the current Internet to meet these mobile networking needs, and provide a brief view of the road ahead.

1.2 Wireless Technology Roadmap

Wireless and mobile networks represent an active research and new technology development area. The rapid evolution of core radio technologies, wireless networks/protocols, and application scenarios is summarized for reference in the technology roadmap given in Figure 1.2. It can be seen from the chart that in addition to 2.5G/3G cellular data and WLAN systems developed during the 1990s, emerging wireless scenarios include personal-area networks, wireless peer-to-peer (P2P), ad hoc mesh networks, cognitive radio networks, sensor networks, RFID systems, and pervasive computing.

Each of the previously mentioned wireless technologies or usage scenarios is associated with unique network architecture and service requirements that

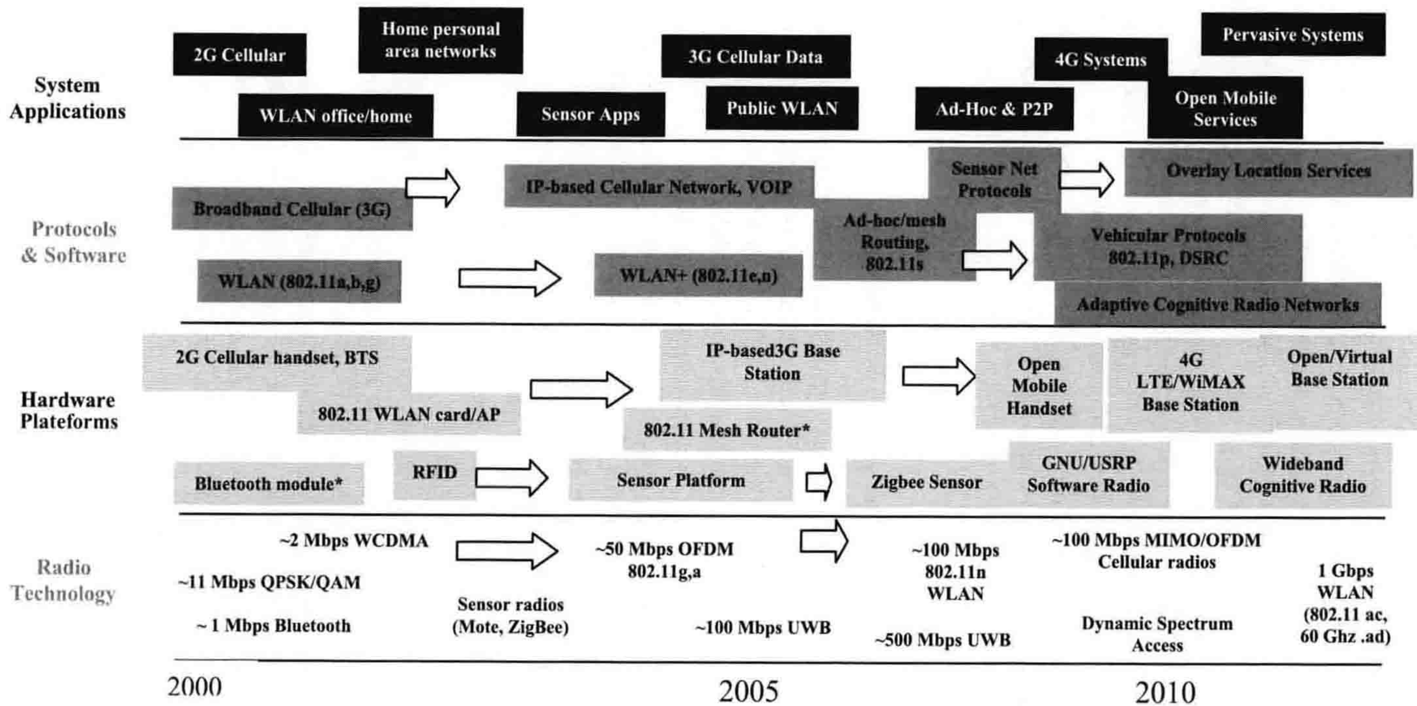

Figure 1.2. Wireless technology roadmap.

affect both the access and infrastructure portions. The default approach adopted by most of the research community is to treat the wireless access portion as a "layer 2" local area network connecting to the Internet (i.e., layer 3 IP) through a gateway. This approach is pragmatic, but it precludes uniform dissemination of control and routing information through the entire network and creates a potential processing bottleneck at the gateway. A more integrated end-to-end control and routing architecture is important for optimizing mobile/wireless service features such as location management, dynamic handoff, quality-of-service (QoS) or cross-layer transport. Also, a local-area wireless network may contain one or more routing elements, which can create inconsistencies in protocol layering and addressing. If compatibility with the current IP network is not viewed as an essential constraint, it may be possible to develop a clean-slate network architecture that can accommodate emerging wireless networks in a single unified protocol structure.

1.3 Wireless Networking Scenarios

The most important wireless technology in use today is the cellular network that provides mobile phone and data services on handheld devices. Cellular networks are ubiquitous in all parts of the world, with almost 4 billion cell phones in use worldwide at the time of writing of this book. Cellular networks have evolved from first-generation analog systems (such as the AMPS system used in the United States prior to 1990) to second-generation digital systems (such as GSM and CDMA[8] used in most parts of the world between 1990 and 2005), and then to third-generation, or 3G, systems such as CDMA2000 and UMTS/WCDMA in use since about 2005. Second-generation cellular systems such as GSM are capable of supporting packet data services at bit-rates of ~100 Kbps, whereas 3G systems such as UMTS or CDMA2000 can deliver between ~300 Kbps – 2 Mbps, depending on signal quality. Further evolution from 3G to 4G cellular systems with the goal of supporting service bit-rates in the range of ~10–100 Mbps is planned by the industry over the next three to five years. Examples of 4G systems are LTE and WiMAX/IEEE 802.16.

From a network architecture point of view, cellular has always been built as a separate custom network with its own set of protocols for key interfaces, such as mobile terminal to base station and base station to mobility service gateways such as the MSC and GGSN. These networks were initially built for integration with the telephone network that was based on a set of signaling protocols defined by the ITU. More recently, 3G networks have been migrating toward integration with the IP network using voice-over-IP (VoIP) protocols such as SIP[9] for signaling and mobility protocols such as mobile IPv6.[2] As data services for mobile devices continue to grow, this may be expected to lead to a gradual migration of mainstream cellular services to the Internet. However, gradual migration of cellular networks to the Internet involves the use of overlays and gateways for interfacing between mobile network features such as authentication, addressing, and mobility – an approach that has scalability and performance limitations.

In addition to cellular, a number of short-range wireless data technologies such as WiFi, Bluetooth, and Zigbee have started to penetrate the market for enterprise and home networks starting in the late 1990s. Of these technologies, WiFi (based on the IEEE 802.11 standard) is the most ubiquitous as an Internet access link, with more than 500 million devices in use today, with the number expected to grow to a billion by 2012.

Most of these WiFi devices are used as wireless local area networks (WLAN) that connect to the Internet as "layer 2" networks similar to the widely used Ethernet LANs. When WiFi is used as a home or office LAN, it is the last hop for Internet access, but does not provide mobility or global roaming features associated with the cellular network. As we will see in later chapters, 802.11 WLAN technology is also being used in the ad hoc mode to build new kinds of networks such as peer-to-peer (P2P), vehicular networks (V2V and V2I), and mesh networks. In addition to 802.11 radios, there are several short-range radio standards such as Bluetooth and Zigbee that are used to provide short-range access to devices such as wireless speakers and sensors/actuators. Power and size limitations on the sensor devices imply the need for a more general wireless network architecture that provides connectivity to a range of heterogeneous radios with different transmission ranges. In contrast to the cellular network, the emerging wireless network will incorporate multiple radio technologies operating under a decentralized control framework.

This is illustrated in Figure 1.3, which shows that the overall network architecture is evolving from the separate special-purpose cellular and WiFi networks toward a more general, heterogeneous wireless access network with multiple radio technologies, opportunistic ad hoc association, self-organization, multihop routing, and so on. The long-term architectural goal would be to evolve the Internet architecture to seamlessly meet all the requirements associated with the general wireless "network of networks" shown in the right-hand side of the figure.

Next, let us consider some of the key wireless networking scenarios of importance to the future Internet architecture. The first and most well-understood emerging wireless service scenario is that of anytime, anywhere access to the Internet from personal mobile devices. As shown in Figure 1.4, this scenario implies the need for a network addressing and routing scheme capable of handling roaming and continuous mobility across multiple points of attachment.

User mobility of this sort is handled quite effectively in today's cellular network using the concepts of a "home network" and "visited network." In particular, users of the network have a permanent address to which all communication is initially addressed, and a forwarding (or visiting) address used to temporarily forward connections during mobility outside the home area. A modified form of this approach has been used in the mobile IP specification