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FRONTIERS OF WIRELESS AND MOBILE COMMUNICATION

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ABSTRACT

The field of wireless and mobile communication has a remarkable history that spans over a century of technology innovations from Marconi's first transatlantic transmission in 1899 to the worldwide adoption of cellular mobile services by over four billion people today. Wireless has become one of the most pervasive core technology enablers for a diverse variety of computing and communications applications ranging from third-generation/fourth-generation (3G/4G) cellular devices, broadband access, indoor Wi-Fi networks, and vehicle-to-vehicle (V2V) systems to embedded sensor and radiofrequency identification (RFID) applications. This has led to an accelerating pace of research and development in the wireless area with the promise of significant new breakthroughs over the next decade and beyond. This paper provides a perspective of some of the research frontiers of wireless and mobile communications, identifying early stage key technologies of strategic importance and the new applications that they will enable. Specific new radio technologies discussed include dynamic spectrum access (DSA), white space, cognitive software defined radio (SDR), antenna beam steering and multiple input–multiple-output (MIMO), 60-GHz transmission, and cooperative communications. Taken together, these approaches have the potential for dramatically increasing radio link speeds from current megabit per second rates to gigabit per second, while also improving radio system capacity and spectrum efficiency significantly. The paper also introduces a number of emerging wireless/mobile networking concepts including multi-homing, ad hoc and multi-hop mesh, delay tolerant routing, and mobile content caching, providing a discussion of the protocol capabilities needed to support each of these usage scenarios. In conclusion, the paper briefly discusses the impact of these wireless technologies and networking techniques on the design of emerging audiovisual and multimedia applications as they migrate to mobile Internet platforms.

Keywords: Ad Hoc and Mesh Networks, Audiovisual Communication, Broadband Services, Cognitive Radio, Delay-Tolerant Routing

I. INTRODUCTION

The field of information and communications technology (ICT) is currently undergoing a fundamental transformation from the era of personal computers and wired Internet services to a new paradigm based on portable devices connecting wirelessly to the emerging B mobile Internet. The mobile Internet represents the second wave of the wireless revolution which started with the remarkable adoption of cellular phones estimated to exceed four billion users worldwide at the time of this writing in 2011. Cellular technology started migrating

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towards data and Internet services with the introduction of so-called third-generation (3G) and fourth-generation (4G) services starting around 2005, enabling a wide range of new anytime/anywhere computing and multimedia applications ranging from navigation and search to mobile video streaming. Mobile data services are currently experiencing rapid growth because of the popularity of Internet applications on mass-market mobile platforms including smart phones, net books, and laptops. An authoritative industry report [1] predicts that mobile generated traffic will exceed that from fixed personal computers (PCs) by 2015, underscoring the fact that most ICT services may be expected to migrate to mobile devices over the next few years. This trend toward mobile platforms has significant implications for radio technology and wireless networks, which will enable this paradigm shift, as well as for the wide variety of Internet applications currently supported on fixed network devices such as PCs and televisions. In particular, large-scale delivery of Internet applications on mobile devices will require faster radio access bit rates, significantly improved spectrum efficiency, higher access system capacity, seamless protocol integration with the Internet, and robustness in presence of wireless channel impairments and disconnection, improved security for the open radio medium, and many others[2][3]. Much of the research and development in the wireless field today is aimed at addressing these issues, which will be discussed in further detail in the sections that follow. Clearly, the trend toward mobility will also result in major technical challenges as well as new opportunities in the design of audiovisual and multimedia applications, which are the focus of these proceedings of the IEEE special issue. In the rest of this paper, we provide a review of the state-of-the-art and future research challenges in the field of wireless and mobile communications with the goal of providing the reader with an understanding of the technology direction and its impact on future audiovisual applications. Section 2 provides a roadmap for emerging wireless technologies and usage scenarios, summarizing recent developments in the field and identifying potential future directions, both in terms of technology development and potential applications. This is followed in Section III by a review of recent technical developments in the field, including summary coverage of core radio systems and platforms, wireless communication algorithms, and mobile/wireless network protocols. Section IV discusses the implications for audiovisual and multimedia communications and computing considering issues such as robustness to wireless channel properties, capacity scaling, quality-of-service/quality-of-experience (QoS/QoE), and the potential for new classes of applications. Finally, some concluding remarks are given in Section V.

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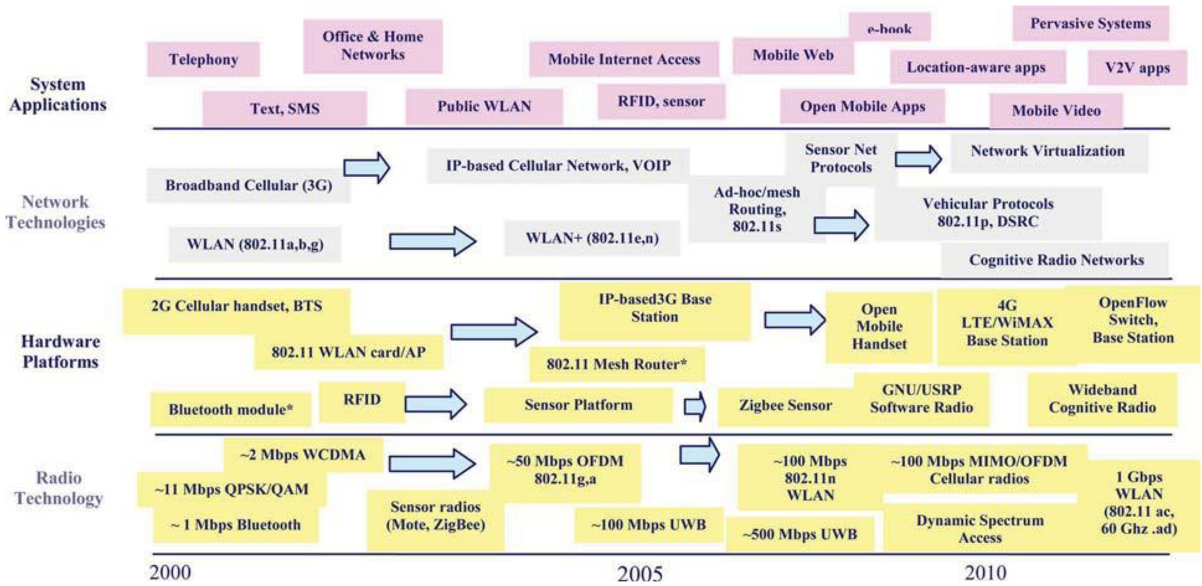

Figure 1 Wireless Technology Road Map

II. WIRELESS TECHNOLOGY ROADMAP

Wireless technology has progressed significantly during the past decade, with many new research ideas and product innovations currently in the pipeline. Fig. 1 shows a summary roadmap for wireless technology, identifying some of the important innovations during the period 2000–2010. The diagram is organized into four layers: radio hardware platforms, wireless physical layer technologies, network protocols and software, and mobile systems/applications [4][5]. At the hardware platform level, it is observed that there has been a proliferation of new radio equipment during this period including 3G, 4G, Wi-Fi, Bluetooth, open mobile handsets, software-defined radio, and most recently, open virtualized access points and base stations [5][6]. In terms of the radio physical layer, it can be seen that cellular radio link speed has increased from about 2 Mb/s with early 3G systems in the year 2000 to 100 Mb/s with 4G (LTE and Wi-Max) systems using multiple-input–multiple-output (MIMO) radio technology. Similarly, short-range Wi-Fi radio speeds have increased from 11 Mb/s 802.11b in the year 2000 to 300 Mb/s with 802.11n [7][9]. Thus, wide-area cellular and short-range radio have become 30–50 times faster over this period, roughly matching Moore's law advances in computing speed; see Fig. 2, which shows approximately exponential increases over the past 20 years. The bit-rate trajectories in Fig. 2 also show future increases in 4G and Wi-Fi speeds to 200 Mb/s and 1 Gb/s by taking advantage of wideband dynamic spectrum allocation or new higher frequency bands such as 60 GHz being considered for the gigabit per second 802.11ad standard. Clearly, we are currently in the midst of historic increases in wireless bit rate and system capacity to levels needed to support large-scale delivery of audiovisual and rich media applications [10][11]. Moving to the network protocol layer in Fig. 1, we observe that cellular networks are evolving from their telecom roots to become more Internet protocol (IP)-based (as in 4G systems such as Wi-Max and LTE), and are expected to further converge into the future mobile Internet protocols over the next decade [10][12]. Wi-Fi technologies that started out as local area networks with limited indoor coverage have also been extended to incorporate ad hoc and mesh networking protocols for wide-area outdoor deployments in areas without wired infrastructure [9].There is also an emerging 802.11p/DSRC standard for peer-to-peer (P2P) ad hoc communication between vehicular radios. Cognitive radio networking protocols are also expected to emerge over the next few years to enable coordination between multiple systems sharing the same white space band. It is noted here that convergence of cellular and Internet services will drive further integration of cellular network protocols and the next-generation of IP protocols into a more unified mobile Internet architecture [8][9]. It may also be expected that these mobile networks will provide new service features such as location, context and content-aware routing and enhanced multicasting capabilities [6][7]. Finally, at the mobile systems and application level, we observe an evolution from early 3G cellular, WLAN, and personal area network (PAN) systems to public wireless local area network (WLAN) and mesh, ad hoc and P2P and sensor network applications [8][9]. Streaming video and voiceover-IP (VOIP) applications have also emerged recently on cellular devices now that broadband data service is being offered on 3G and 4G systems. Location-aware applications such as traffic navigation and targeted advertising represent another important and growing usage scenario for cellular devices [4][5]. Looking ahead, wireless systems will support new classes of pervasive computing applications involving observation and control of the physical world [6]. This class of pervasive or ubiquitous applications ranges from simple views of physical world resources [as in navigation systems or radio-frequency identification (RFID) based inventory management] to more complex ones such as augmented reality and healthcare monitoring [7][8]. While it is impossible to predict which specific applications will become popular, it may be expected that successful ones will involve context or location-aware delivery of more general forms of audiovisual and multimedia information.

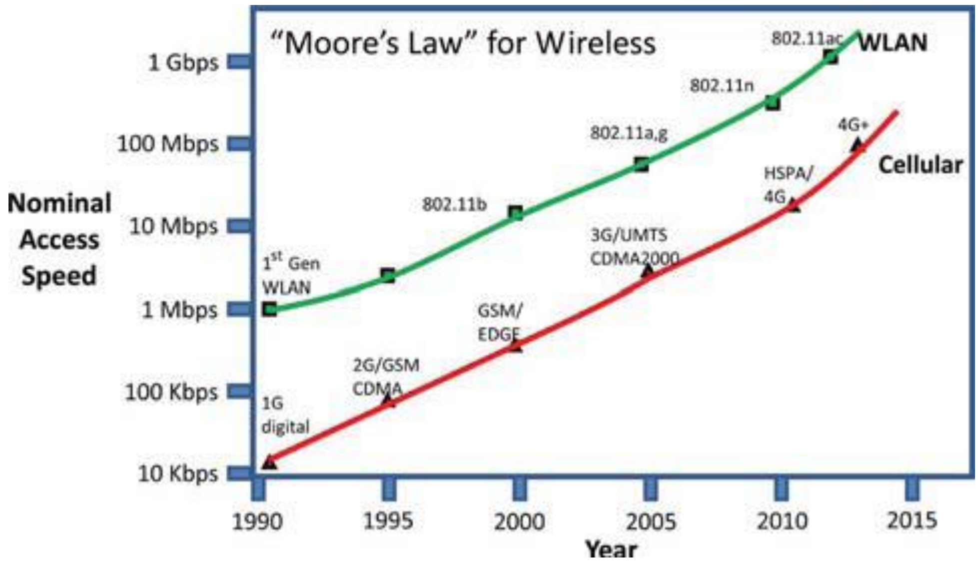

Figure 2 Exponential increases in WLAN and cellular access speeds over past 20 years

III. ADVANCES IN WIRELESS AND MOBILE TECHNOLOGY

3.1. Radio Technologies and Platforms

A variety of radio technology standards have been proposed over the last 20 years in order to meet the needs of diverse applications ranging from PANs to LANs and wide area cellular services. Radio technologies are generally classified in terms of their modulation and coding method along with the medium access control (MAC) technique. The vast majority of digital cellular systems in use today are based on the Global System for Mobile Communications (GSM) standard which uses generalized minimum shift keying modulation, block coding, and time-division multiple access (TDMA) to achieve circuit switched bit rates 16 kb/s, and packet data rates 100 kb/s [2]. The corresponding second-generation (2G) U.S. digital cellular standard still in use today is known as code-division multiple access (CDMA) or IS-95, using spread spectrum modulation, convolutional coding, and CDMA to achieve roughly similar bit rates as GSM [3]. Both GSM and CDMA migrated to the so-called B3G [standards known as the Universal Mobile Telecommunication System (UMTS) in Europe and CDMA-2000 in the United States. These 3G standards use wideband spread spectrum, adaptive modulation, convolutional coding, and CDMA to achieve peak service bit rates of up to 2 Mb/s [4]. In parallel to these cellular standards, the widely adopted 802.11 specification for WLAN started out with direct sequence spreading (DSS), quadrature phase shift keying (QPSK) modulation, and CSMA/CA MAC (in the 802.11b standard) at 1 Mb/s, later adding the option of higher order adaptive quadrature amplitude modulation (QAM) without spreading to achieve up to 11 Mb/s. Fig. 2. Exponential increases in WLAN and cellular access speeds over past 20 years [11]. Subsequent high-speed cellular and WLAN standards (i.e., 4G cellular including Wi-MAX and LTE, and 802.11a,g,n) have migrated to a single modulation technology called orthogonal frequency division multiplexing (OFDM), which offers higher spectral efficiency and performance [5]. Fourth-generation cellular systems using OFDM also employ a different type of MAC protocol based on dynamic FDMA/TDMA in which time-frequency slots are allocated to each subscriber on a frame-by-frame basis. Both LTE and Wi-Max use OFDMA with FDMA/TDMA to achieve basic service bit rates in the range of 10–20 Mb/s. With the addition of multiple antennas, MIMO signal processing [6] and wider band channels, it becomes possible to increase peak bit rates to the range of 100 Mb/s in both LTE and Wi-Max systems [7]. Similar OFDM/ MIMO technologies have been used in WLAN systems to achieve significantly higher bit ratesV802.11n has a peak bit rate of 300 Mb/s using OFDM with higher order adaptive modulation and MIMO along with multiple channel (B channel bonding techniques [8]. Note that the faster 802.11 standards based on OFDM differ from wide-area cellular radios in the sense that they continue to use CSMA/CA at the MAC layer in order to maintain compatibility with previous versions of the standard and to limit implementation complexity. Table 1 summarizes the PHY/MAC technology, operating frequency bands and bit rates for different generations of the cellular and WLAN systems.

Technology	PHY	MAC Protocol	Frequency band	Channel spacing	Service Bit-Rate (downlink)
			Cellular		
2G(GSM)	GMSK	TDMA/FDMA	850MHz &1.9GHz	200kHz	22.8 Kbps
2G(IS95)	QPSK	CDMA	825-849 MHz	1.25MHz	115 Kbps
2.5G (Edge)	GMSK/ 8PSK	FDMA/ TDMA	850MHz &1.9GHz	200kHz	236.8 Kbps
3G (UMTS)	DQPSK	WCDMA	1.8 – 2.5 GHz	5MHz	384- 2048 Kbps
3G+ (CDMA 2000)	BPSK/ QPSK	CDMA	1.8 – 2.5 GHz	5 MHz	2.5 – 15.7 Mbps
3G+ (HSPA)	BPSK/QPSK	CDMA	1.8 – 2.5 Ghz	5 Mhz	22-56 Mbps
4G(LTE)	64QAM/ MIMO	OFDMA/ SC-FDMA	2 - 8 GHz	20MHz	100 Mbps
			WLAN		
802.11a/g/n	64QAM	OFDM	5/2.4/5 GHz	20/20/40 MHz	54/54/200 Mbps
802.11b	DQPSK	FDMA	2.4 GHz	20MHz	11 Mbps
802.11ac	256QAM/ MU-MIMO	OFDM/ SDMA	5 GHz	80MHz	500 Mbps
802.11ad	64QAM	OFDM	60GHz	2160MHz	1 Gbps

Table 1 Radio Technologies for Local and Wide Area Networks

Technology	PHY	MAC Protocol	Frequency band	Channel spacing	Service Bit-Rate (downlink)
Bluetooth	GFSK	FHSS	2.4 GHz	1 MHz	1 Mbps
UWB	BPSK/QPSK	DS-UWB/ MB-OFDM	3.1-10.6 GHz	500MHz-7.5GHz	54-1024 Mbps
ZigBee	BPSK/ O-QPSK	DSSS	868/915MHz/ 2.4 GHz	0.3/0.6 MHz 2 MHz	250 Kbps

Table 2 Radio Technologies for Short-range Communication

Looking ahead, it is anticipated that both cellular and Wi-Fi standards will continue along the OFDM track for the physical layer, with enhancements to achieve higher speeds approaching 300–500 Mb/s for cellular and 1 Gb/s for WLAN. Proposed enhancements include the use of dynamic spectrum access (DSA) and non contiguous OFDM (NC-OFDM) to achieve wideband operation, increasing numbers of antennas or beams, network MIMO involving cooperative signal processing between base stations and cooperative communication techniques [3][4]. With modulation efficiency reaching its practical limits, a key enabler for higher speed data will be the availability of wideband channels using advanced DSA and cognitive radio techniques. More detail on these emerging methods for faster and more spectrally efficient radio systems will be provided in Section III-B. While cellular and WLAN are perhaps the most visible wireless technologies for end users, there are also several widely used standards for embedded applications including short-range device connectivity and machine-to-machine communication [5][7]. The most widely used standard is Bluetooth (802.15.4), which supports 1-Mb/s service rate using frequency-hopped spread spectrum modulation in the 2.4-GHz unlicensed band. Bluetooth is a relatively slow radio technology but has widespread adoption for short-range connectivity between consumer devices, and is often used to support audio streaming from cellular phones to other devices [4][7]. Although the Bluetooth standard does have some planned speed enhancements in its roadmap, new technologies for high-speed PANs to support high definition video between consumer devices have also been proposed. One of the notable proposals is ultra wide band (UWB), a technology in which data are spread to a very wide band signal over multiple gigahertz spanning existing bands [6][9]. UWB has extremely low power density so as to avoid interfering with existing services while still being able to achieve 100–500 Mb/s at short range (G 10 m). UWB products based on the Wi-Media Alliance specification are now reaching the market typically intended to provide connectivity between TVs and other home devices such as video cameras and PCs. Another short-range wireless technology of interest is the Zigbee standard, which was designed to support low bit rate and power efficient wireless data transfer for embedded devices such as sensors or M2M [6][7]. A comparative summary of these technologies is presented in Table 2. There is also an ongoing effort to migrate indoor WLAN and WPAN networks toward less congested higher frequency unlicensed spectrum bands such as 60 GHz. There are significant propagation-related differences between the 60-GHz band and the lower frequency unlicensed Wi-Fi bands at 2.4 and 5.0 GHz. Several standardization bodies have been working on the 60-GHz PHY and MAC protocols approaching 1-Gb/s service rate. These include the IEEE 802.11ad and Wireless Gigabit Alliance (Wi-Gig) for WLAN, and IEEE 802.15.3c, and Wireless HD for short-range PANs [4][6]. The IEEE 802.15.3c standard defines a central controlled network topology and TDMA-based MAC protocol for 60-GHz wireless PANs. The IEEE 802.11ad draft standard introduces a new network architecture named Personal Basic Service (PBSS) without an access point in which each station can serve the role of a central coordination point which supports a combination of random access CSMA access and scheduled TDMA access modes [7][9]. There are still a number of open research issues related to 60-GHz networks such as MAC-layer support for beam switching, diversity techniques to overcome propagation impairments, cooperative relaying, and so on. Overall, 60-GHz technology is expected to mature during the next three to five years and will provide an important option for high-speed indoor connectivity associated with applications such as device docking and HD video. In terms of hardware technologies, wireless PHY and MAC technologies discussed in this section involve considerable signal processing complexity generally requiring Application Specific Integrated Circuit (ASIC) implementation in order to achieve the 100-Mb/s and higher speeds associated with modern radio standards [8][9]. The high cost of chip development implies the need for mass-market standards with significant volume in order for a new product concept to be viable. This in turn results in relatively long product development cycles of seven to ten years in the wireless industry, as compared with three to five years in the computer industry, which relies on processors, memory, and other generic components that do not require completely new architectures for each generation [6][7]. This has motivated research work on software defined radio (SDR) starting in the mid-1990s with the goal of developing a generic programmable hardware

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architecture for radios capable of supporting a wide range of standards and being able to upgrade functionality after the product has been shipped [5][6]. SDR technology is of even greater interest today because it is viewed as the most appropriate hardware solution for cognitive radios, which are capable of dynamically adapting their operating parameters based on actual spectrum availability. A number of research prototypes for SDR platforms have been developed over the past few years, including the WARP board from Rice University, the GNU/USRP and USRP2 platforms from Ettus Research, and the GENI SDR platform at Rutgers University (see Fig. 3). These research prototypes still use field-programmable gate arrays (FPGAs) and are therefore costly and consume significant amounts of power with thus, the current state of the art in SDR is more suitable for base stations (low production volume, higher power available) than for consumer-level mobile devices and data cards [3][4]. Further work will be required to approach the goal of a fully programmable radio implemented on a low-cost chipset with an example of a research project with the goal of designing software radios suitable for ASIC implementation is the WiNC2R prototype. When such a mass-market generic SDR becomes available, it will have a major impact on the industry by enabling adaptive/cognitive radio techniques, speeding up wireless system design cycles and making it easier to deploy new radio standards [6][8].

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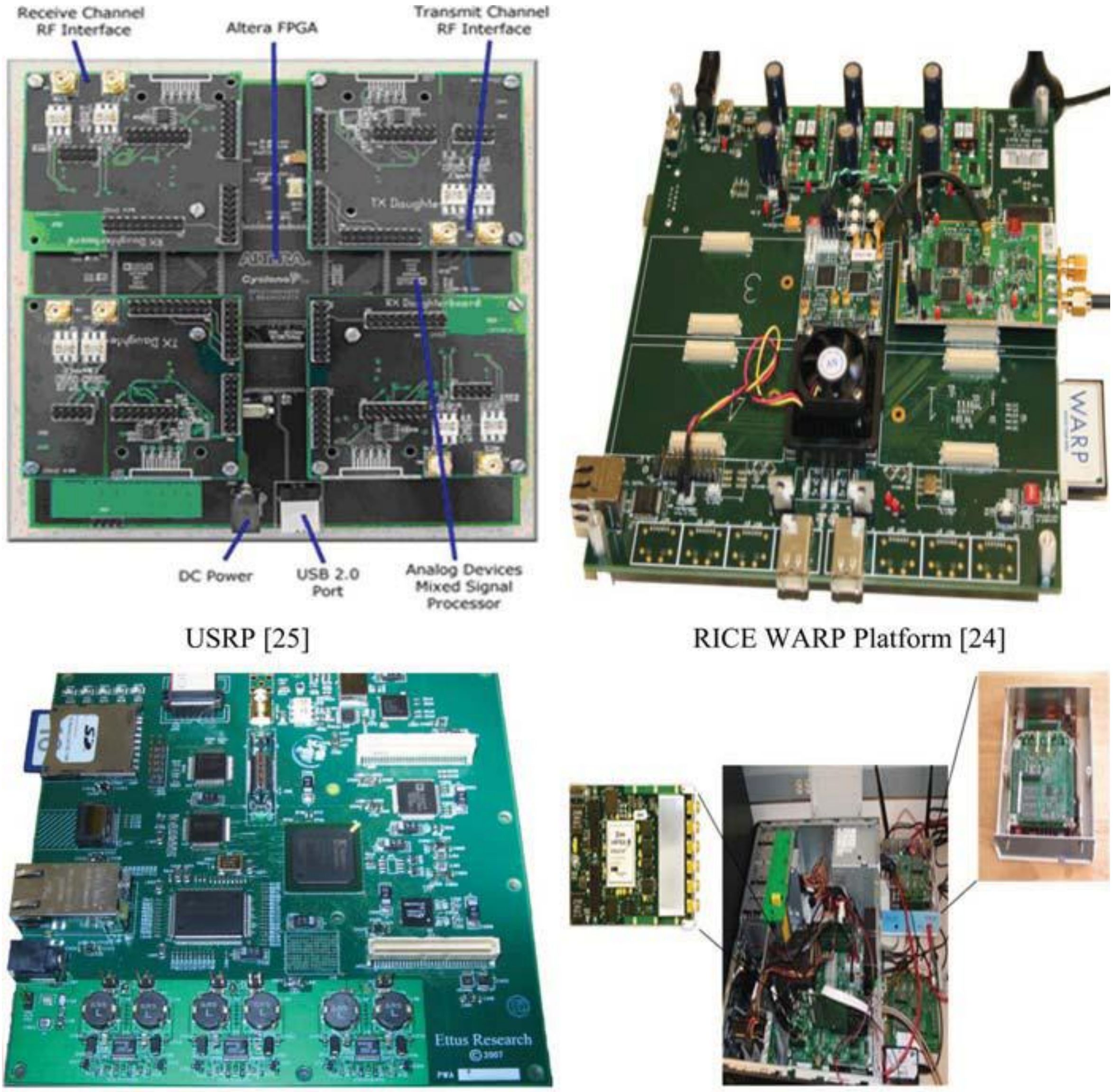

USRP2 [25] WINLAB WINC2R System [27]

Figure 3 Photographs of Experimental Cognitive Radio Platforms

3.2. Mobile/Wireless Networks

In the preceding sections, we have discussed advances in core radio technologies, which serve as the foundation for all wireless systems. Here we discuss networking, which is the next layer of the protocol stack needed to build a complete system with applications running on top [3][5]. Wireless network protocols add considerable value since a point-to-point wireless link is of limited value, while the existence of a network makes it possible to extend the range of coverage and connect to a multiplicity of devices and applications. Mainstream wireless networks for cellular and Wi-Fi applications have been built by extending the capabilities of wired networks incrementally adding new protocol features required to handle mobile service requirements such as authentication, link encryption, and user mobility [6][9]. Radio access networks in 2G cellular systems were built as extensions of digital telephony systems incorporating incremental features for support of dynamic mobility (handoff, roaming, authentication), while access networks used for Wi-Fi are extensions of Ethernet

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LANs typically used in offices and homes. The convergence of cellular and Internet applications on mobile smart phones is driving greater integration between these two networks. The B3GPP [cellular network standard is steadily migrating toward the concept of an all IP cellular network with telephony signalling protocols replaced by Internet protocols for multimedia support such as the Session Initiation Protocol (SIP) and the IP multimedia system (IMS), while user mobility is directly supported by the IP network using protocols such as mobile IPv6 [5][7]. There is also a recognized need to support heterogeneous radios in the same mobile network, for example, smooth migration between 3G or 4G cellular and Wi-Fi hot spots, known as vertical or intersystem handover, These trends point to a gradual B flattening [of the radio access network into which different kinds of radio access points and base stations can simply be plugged in with enhanced Internet protocols handling all the networking and mobility requirements [6][9]. Mobility extensions to the Internet protocol have been proposed since the early 1990s. The original mobile IPv4 protocol was designed to provide mobile nodes with a permanent (home) address while rerouting packets when the node roams into other networks [7][9]. Mobile IP with route optimization was proposed to improve scalability and reliability and reduce signalling overhead. Micro mobility was proposed for mobility within a small region. Jain et al. and Aura et al. among others extend basic mobile IP to avoid the need of a unique home network [7][9]. Mobile IP has not been widely adopted for mobility in the global Internet due to a number of technical and operational reasons, so that there is continued interest in a general architectural solution to the problem of terminal mobility [10][11]. An alternative approach under consideration is based on the separation of names from addresses, with the network attached devices and objects being assigned a permanent name with a name resolution service to provide dynamic binding between the name and the current network address. An example of this approach is the Host Identity Protocol (HIP) specified by the Internet Engineering Task Force (IETF). An alternative approach to supporting mobility without changes to the routing protocol is to dynamically migrate the end-to-end transport layer connection as the mobile device moves from one network address to another [11][12]. In particular, the mobile node sends its new address to its communicating parties and then both sides simultaneously adjust the connection information to keep the connection alive on the move [14][16]. Instances of connection reconfiguration and migration approaches are the Stream Control Transmission Protocol (SCTP) and the Transmission Control Protocol (TCP) migration. The SIP used for voice and video services has also been proposed to support terminal mobility. Mobile nodes register their addresses with their SIP register. Location updates for ongoing connections are done by sending a new SIP INVITE message to the corresponding node [16][17]. Storage-aware networking has also been proposed as a mechanism for dealing with disconnection and channel impairments associated with wireless access and mobility. The Infostation mobile content cache concept was proposed in 1998 as a networking feature that enables opportunistic delivery of media files to mobile devices which pass through high bandwidth hot spots while roaming through multiple networks. The idea is to store large media files at Infostation caches and deliver these to mobile users passing through a hot spot in order to alleviate traffic load on lower speed wide area cellular networks[18][19]. This concept was further developed in the cache-and forward (CNF) architecture in which storage is integrated into network routers, access points, and base stations utilizing a storage-aware routing protocol that handles large content files on a hop-by-hop basis [15][17]. The CNF routers make forwarding or storage decisions based on routing algorithm that considers both short-term and long-term path quality, preferring to store when the short-term path quality is poor while the long-term path quality is good. The results for CNF show that significant performance and capacity gains can be achieved with storage aware routing, particularly for scenarios involving delivery of large media files to mobile users [19][20]. Another important dimension of wireless networking research has been aimed at enabling infrastructure less (or ad hoc) networking between mobile devices in physical proximity [21][22]. The ad hoc mode of networking was originally proposed for emergency response and tactical military networks known as mobile ad hoc networks (MANETs) where a group of first responders or soldiers participate in a self-organizing network with multi hop routing of messages between radio nodes [18][19]. Ad hoc wireless network technologies have also been applied commercial usage scenarios such as multi hop mesh networks for low-cost broadband access networks in both urban and rural areas [15][18]. Ad hoc or mesh networks can also be used to provide P2P connectivity between short-range media and computing devices inside the home or office without the need for in-building wiring [13][15]. Variations of ad hoc and mesh network protocols have also been applied to sensor network scenarios where low power sensor devices inherently require multi hop communication modes to overcome short transmission range [19][21]. Multi hop wireless networks can potentially achieve high service bit rates by using multi hop communication between high-speed commodity radios such as 802.11a or g. Ad hoc and mesh networks differ from conventional cellular and Wi-Fi systems in the sense that there is no hierarchy of clients and access points, and each radio node is required to serve as a mobile router that forwards packets based on a suitable dynamic routing protocol [20][22]. A number of on-demand protocols suitable for this scenario have been proposed over the past ten years, most notably ad hoc on demand distance vector routing (AODV) and dynamic source routing (DSR) which are specified in the IETF MANET standard [17][18]. Ad hoc and mesh network protocols generally require cross-layer awareness (i.e., holistic knowledge of key parameters across the entire protocol stack) in order to deal with interactions between radio link quality, MAC layer congestion, and routing, and this remains a topic of investigation in the research community [12][14]. Delay-tolerant networks (DTNs) represent another innovation in wireless networking as applied to ad hoc and heterogeneous radio access scenarios, which are characterized by occasional disconnections. The main concept behind DTNs is to be able to deliver a message without the requirement for a contemporaneous end-to-end path to the destination. Early work on routing in these environments assumed that connectivity between nodes was either scheduled or could be estimated, and hence worked on enhancing shortest path algorithms, such as Dijkstra’s algorithm, to account for links changing predictably with time [16][17]. It became clear, however, that mobility patterns in many target environments, such as emergency response, are anything but predictable. Epidemic dissemination, the DTN equivalent to flooding, quickly became a baseline protocol when mobility was unpredictable [14][16]. Efficiency and overhead considerations led to a series of enhanced epidemic protocols with intelligent buffer management, such as prioritized epidemic routing (PREP) [21][22]. Many of these protocols, such as Prophet, Max Prop and RAPID have taken advantage of generalized mobility trends and attempted to capture meeting probabilities and other inter node meeting characteristics. When node mobility is fairly high and resources are constrained, another approach researchers have taken is to utilize the high degree of node mixing instead of relying solely on replication, as in the spray-and-wait protocol [13][16]. Generalizations of DTN protocols combined with storage-aware routing mentioned earlier are currently being considered for mainstream mobile Internet scenarios with the goal of achieving robustness in the presence of fluctuating link quality and disconnection. In particular, the National Science

Foundation's Future Internet Architecture (FIA) program includes a project called Mobility First where the goal is to design and validate a comprehensive new architecture with efficient and robust support of mobility and wireless access scenarios across a range of emerging usage scenarios including hybrid cellular Wi-Fi, ad hoc and mesh networks, vehicular networks, and sensor networks [16][17]. The baseline network protocol being considered in the Mobility First architecture includes a generalized storage-aware routing (GSTAR) protocol which unifies features from CNF and DTN protocol outlined earlier to achieve good performance in a seamless manner across both wired and wireless networks [13][15]. The Mobility First architecture also incorporates a clean separation of names from network addresses by introducing the concept of a globally unique identifier (GUID) for all network objects including hosts, content and context 16][19]. In contrast to mobile IP, mobility is handled by introducing a fast global name resolution service (GNRS), which provides dynamic bindings between network objects and their current point of network attachment [20][21]. These and other future mobile Internet protocol ideas (for example, Accountable Internet Protocol (AIP) or Hierarchical Architecture for Internet Routing (HAIR) are still at an early stage of research and it may be expected that some of the techniques under consideration (storage, DTN, global name resolution service etc.) will influence mainstream networking standards over the next five to ten years [19][20].

IV. CONCLUSION

Wireless has become one of the most pervasive core technology enablers for a diverse variety of computing and communications applications ranging from 3G/4G cellular devices, broadband access, indoor Wi-Fi networks, and vehicle-to-vehicle (V2V) systems to embedded sensor and RFID applications. It is also of central importance to the future of mobile pervasive audiovisual and multimedia applications. This has led to an accelerating pace of research and development in the wireless area with the promise of significant new breakthroughs over the next decade and beyond. We have provided a perspective of some of the research frontiers of wireless and mobile communications and identified early stage key technologies of strategic importance and the new applications that they will enable. Specific new radio technologies discussed include DSA, white space, cognitive software-defined radio (SDR), antenna beam steering and MIMO, 60-GHz transmission, and cooperative communications. Taken together, these approaches have the potential for dramatically increasing radio link speeds from current megabit per second rates to gigabit per second, while also improving radio system capacity and spectrum efficiency significantly. We also introduced a number of emerging wireless/mobile networking concepts including multi-homing, ad hoc, and multi-hop mesh, delay-tolerant routing, and mobile content caching, and provided a discussion of the protocol capabilities needed to support each of these usage scenarios. Moreover, the global Internet itself is now going through a basic paradigm shift as it migrates from fixed server/PC applications to mobility services at large scale. Emerging wireless technologies and mobility scenarios will be of growing importance for the holistic design of future audiovisual applications that will be accessed over the mobile Internet.

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