INVITED PAPER

Frontiers of Wireless and Mobile Communications

The authors of this paper describe how wireless transmission has reached billions of bits per second and mobile services have become Internet based.

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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 WiFi networks, vehicle-to-vehicle (V2V) systems to embedded sensor and radio-frequency 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 multihoming, ad hoc and multihop 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; future Internet; MIMO; mobile multimedia; radio access networks; software-defined radio; wireless communication; 3G and 4G mobile communication

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 "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 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, netbooks, 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

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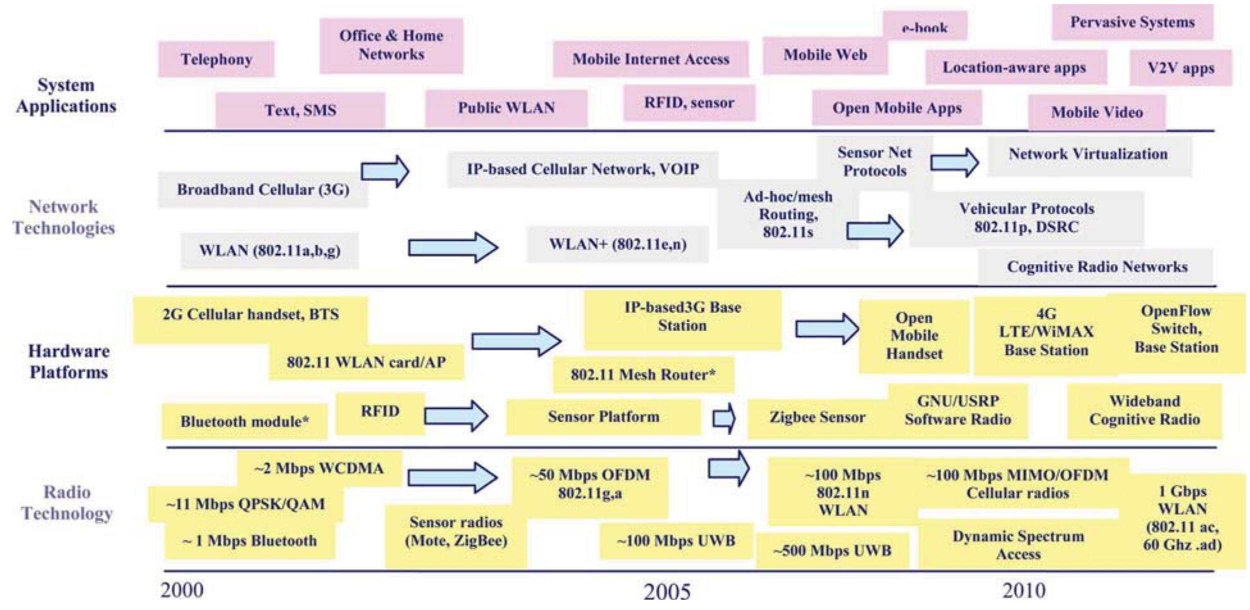

Fig. 1. *Wireless technology roadmap.*

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, robustness in presence of wireless channel impairments and disconnection, improved security for the open radio medium, and many others. 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 this 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[1] with the goal of providing the reader with an understanding of the technology direction and its impact on future audiovisual applications. Section II 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.

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. At the hardware platform level, it is observed that there has been a proliferation of new radio equipment during this period including 3G, 4G, WiFi, Bluetooth, open mobile handsets, software-defined radio, and most recently, open virtualized access points and base stations. 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 WiMax) systems using multiple-input–multiple-output (MIMO) radio technology. Similarly, short-range WiFi radio speeds have increased from

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[1] The terms "wireless" and "mobile" are used in this paper to distinguish between core radio access technologies/systems and mobile communication services, respectively. Although these terms can sometimes be used interchangeably, note that all wireless systems do not necessarily support mobility, while mobile services may involve a broader class of network technologies in addition to wireless access.

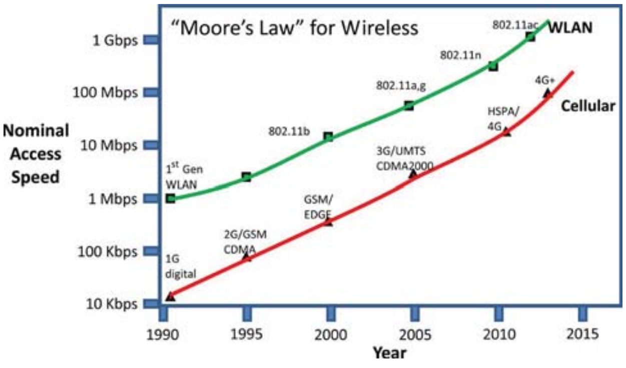


Fig. 2. *Exponential increases in WLAN and cellular access speeds over past 20 years.*

11 Mb/s 802.11b in the year 2000 to 300 Mb/s with 802.11n. 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 WiFi 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.

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 WiMax and LTE), and are expected to further converge into the future mobile Internet protocols over the next decade. WiFi 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. 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. 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.

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. Streaming video and voice-over-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. Looking ahead, wireless systems will support new classes of pervasive computing applications involving observation and control of the physical world. 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. 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.

III. ADVANCES IN WIRELESS AND MOBILE TECHNOLOGY

A. Radio Technologies and Platforms

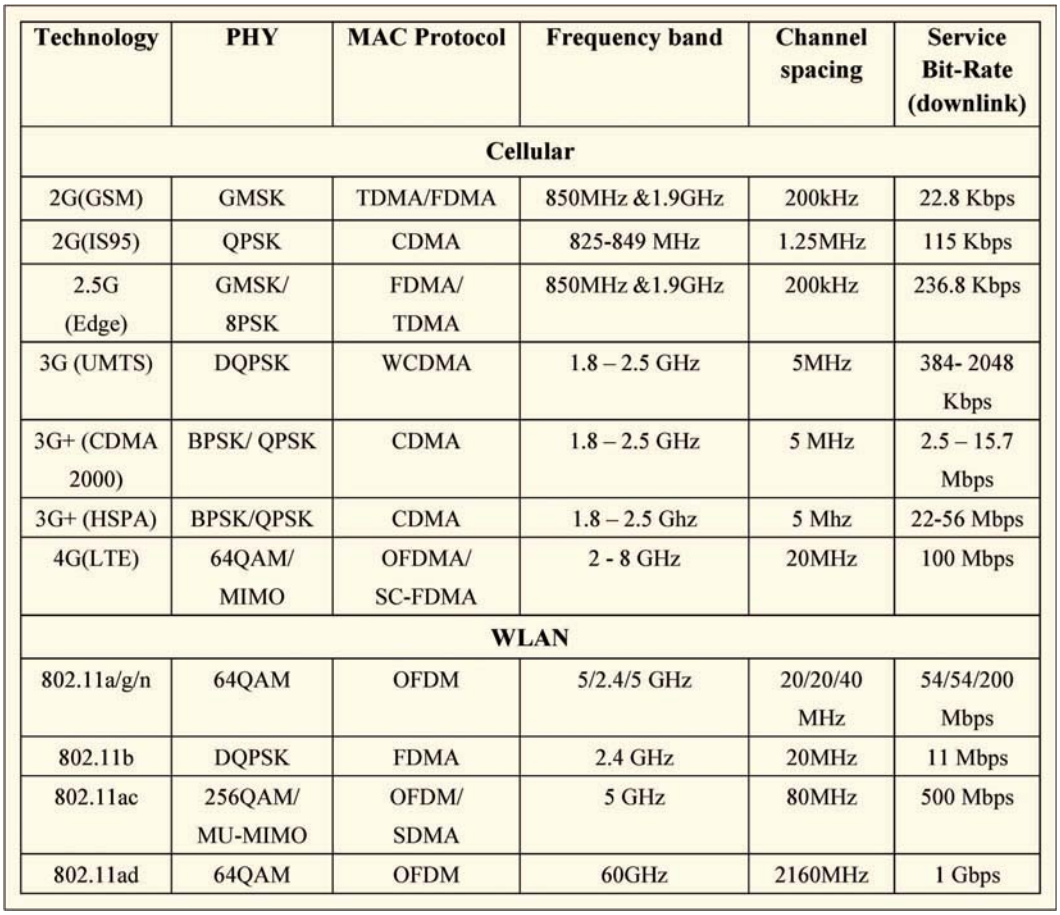
A variety of radio technology standards have been proposed over the last 20 years in order to meet the needs of diverse applications ranging from PANs to LANs and wide-area cellular services. Radio technologies are generally classified in terms of their modulation and coding method along with the medium 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 "3G" 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.

Subsequent high-speed cellular and WLAN standards (i.e., 4G cellular including WiMAX 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 WiMax 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 WiMax systems [7]. Similar OFDM/MIMO technologies have been used in WLAN systems to achieve significantly higher bit rates—802.11n has a peak bit rate of 300 Mb/s using OFDM with higher order adaptive modulation and MIMO along with multiple-channel ("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.

Looking ahead, it is anticipated that both cellular and WiFi 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 noncontiguous OFDM (NC-OFDM) to achieve wideband operation [9], increasing numbers of antennas or beams [10], network MIMO involving cooperative signal processing between base stations [11], and cooperative communication techniques [12]. 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.

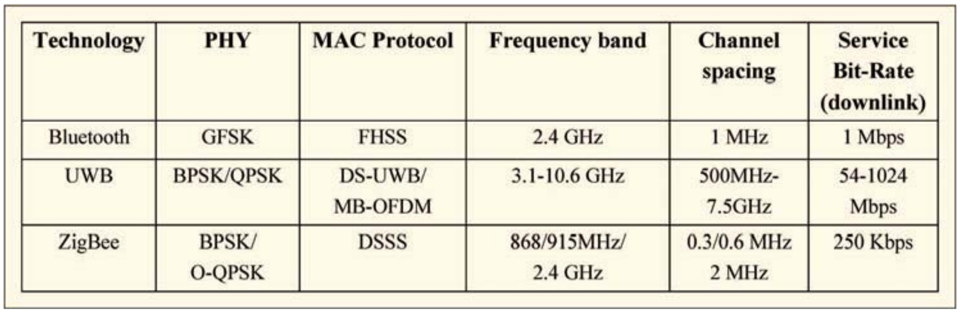
While cellular and WLAN are perhaps the most visible wireless technologies for end users, there are also several widely used standards for embedded applications including short-range device connectivity and machine-to-machine

Table 1 Radio Technologies for Local and Wide Area Networks



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 2 Radio Technologies for Short-Range Communication

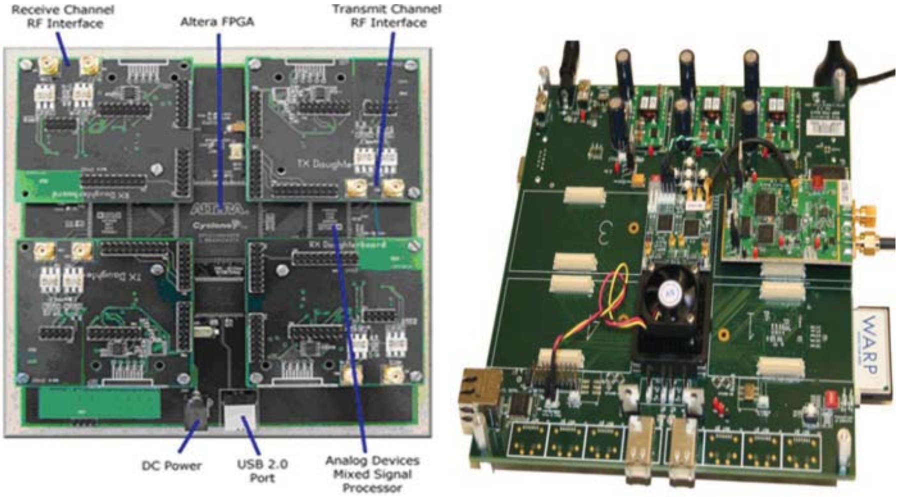


Technology	PHY	MAC Protocol	Frequency band	Channel spacing	Service Bit-Rate (downlink)
Bluetooth	GFSK	FHSS	2.4 GHz	1 MHz	1 Mbps
UWB	BPSK/QPSK	DS-UWB/ MB-OFDM	3.1-10.6 GHz	500MHz- 7.5GHz	54-1024 Mbps
ZigBee	BPSK/ O-QPSK	DSSS	868/915MHz/ 2.4 GHz	0.3/0.6 MHz 2 MHz	250 Kbps

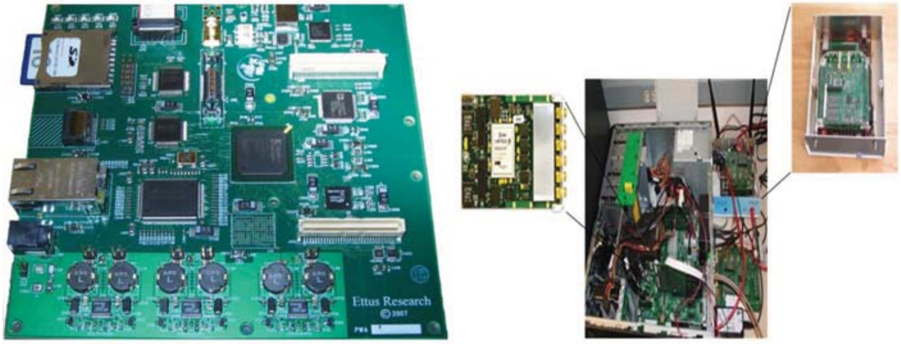
communication. The most widely used standard is Bluetooth (802.15.4), which supports ~1-Mb/s service rate using frequency-hopped spread spectrum modulation in the 2.4-GHz unlicensed band [13]. Bluetooth is a relatively slow radio technology but has widespread adoption for short-range connectivity between consumer devices, and is often used to support audio streaming from cellular phones to other devices. 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 ultrawide band (UWB) [14], a technology in which data are spread to a very wide band signal over multiple gigahertz spanning existing bands. 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 (< 10 m). UWB products based on the WiMedia Alliance specification [15] 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 [16], which was designed to support low bit rate and power-efficient wireless data transfer for embedded devices such as sensors or M2M. 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 WiFi bands at 2.4 and 5.0 GHz [17], [18]. 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 (WiGig) for WLAN, and IEEE 802.15.3c, and Wireless HD for short-range PANs. The IEEE 802.15.3c standard defines a central controlled network topology and TDMA-based MAC protocol for 60-GHz wireless PANs [19]. 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. 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 [20]–[22]. 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. 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. This has motivated research work on software-defined radio (SDR) [23] starting in the mid-1990s with the goal of developing a generic programmable hardware architecture for radios capable of supporting a wide range of standards and being able to upgrade functionality after the product has been shipped. 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 [24], the GNU/USRP and USRP2 platforms from Ettus Research [25], and the GENI SDR platform [26] 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—thus, the current state of the art in SDR is more suitable for base stations (low



USRP [25] RICE WARP Platform [24]



USRP2 [25] WINLAB WINC2R System [27]

Fig. 3. ***Photos of experimental cognitive radio platforms.***

production volume, higher power available) than for consumer-level mobile devices and data cards. Further work will be required to approach the goal of a fully programmable radio implemented on a low-cost chipset—an example of a research project with the goal of designing software radios suitable for ASIC implementation is the WiNC2R prototype [27]. 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.

B. Wireless Communication Algorithms

1) MIMO: For several emerging wireless data services and requirements, the application of multiple-antenna systems appears to be one of the most promising solutions leading to even higher data rates and/or the ability to support greater number of users. Multiple transmit and multiple receive antenna systems that embody an implementation of the MIMO concept in wireless systems [28]–[30] have been shown to be able to provide the necessary

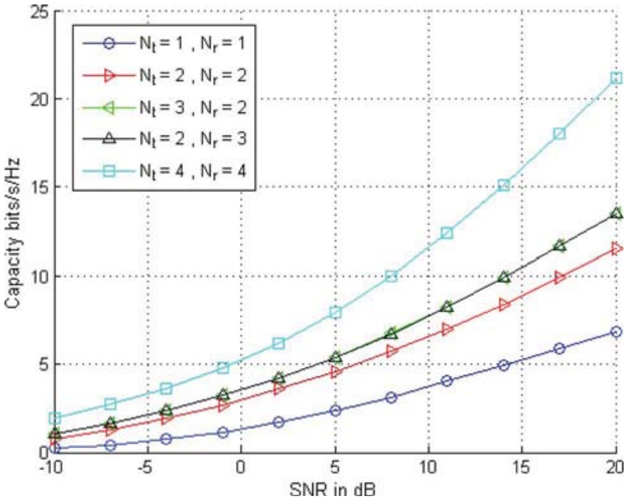


Fig. 4. ***Illustration of the capacity increase with N_t antennas at the transmitter and N_r antennas at the receiver.***

capacity and also flexibility required for supporting a variety of high data rate applications. As shown in Fig. 4, theoretical capacity gains in a single-user system scale (approximately) linearly in the number of antennas and this has further fueled studies related to various aspects of MIMO systems: propagation, detection, space–time coding, implementation aspects, and multiuser systems [31]–[35].

The potential and promise of multiple-antenna techniques has now resulted in widespread proposals for the use of these in a variety of contexts: for wide area wideband wireless transmission in next-generation cellular systems; for local area hot-spot data service overlays in cellular systems; for emerging short-range WLAN networks; for promoting efficient spectrum sharing in the unlicensed bands; and a variety of collaborative techniques in wireless *ad hoc* networks. A key attribute required of any multiple-antenna technique to be successful in any of the above contexts is the need for reliable and efficient channel state information (CSI). Such CSI is absolutely necessary at the receiver to realize the potential capacity gains that are promised in such systems. Further, the CSI is also necessary at the transmitter in the case of transmitter optimization techniques used in conjunction with multiple antennas.

The challenges in estimating CSI in MIMO channels (compared to single-antenna systems) are not only greater because of the large number of parameters that have to be estimated, but they are further exacerbated by the need to support higher data rates for video, mobility, and the migration of future wireless data services to higher carrier frequencies. For example, use of higher carrier frequencies results in more spatial variations of the electromagnetic field, while higher data rates result in greater frequency selectivity. The fundamental limits of the performance of multiple-antenna systems have been characterized in terms of unreliable and/or absent CSI [36], [37]. There have also been efforts in relating such fundamental limits to the specifics of signal processing algorithms required for enabling knowledge of CSI. A few efforts in this direction have been presented in [38]–[41]. The specific issues considered in these works include the impact of power allocation, channel correlations, and feedback delays on MIMO capacity, and all of those point to the need for efficiently acquiring reliable CSI. Further, the capacity gains due to transmitter optimization in multiple-antenna multiuser wireless systems also rely heavily on the availability of the CSI at the transmitter. Therefore, in addition to reliability in CSI information, the feedback of such information will also have to be fast and frequent for audio/video (AV) applications.

2) Cooperative Communications: Advances in radio technology have enabled radios that can manage their power, time, and bandwidth resources in ways that share the available spectrum more efficiently. Many of these cooperative algorithms and techniques could be employed independently or even competitively as terminals strive to maximize their own performance. Other techniques involve cooperation between terminals, and are often viewed as providing another form of diversity, namely "user-cooperation diversity" [12], [42]. These techniques are in themselves diverse, and include such approaches as collaborative signal processing, cooperative coding, relaying, and forwarding. It is perhaps not surprising that cooperative techniques can often lead to a better overall result than independent or competitive techniques, and a good deal of important research in this area has occurred.

A related aspect that has also been considered extensively in research studies is that cooperation may involve significant costs, and that the greatest immediate benefits will not necessarily go to the users that bear the greatest immediate cost. For example, cooperation may require that a terminal delay its own transmissions and use its limited energy budget to relay messages for other terminals. Over time, such costs and benefits may equalize, but there is no reason to assume that users will willingly bear an immediate cost for a speculative future benefit. In the case of spectrum shared by autonomous terminals, however, as is typical in the ISM and U-NII bands, protocols are relatively unconstrained and the assumption of a selfless, cooperative sharing of the spectrum resource may not be realistic. Several mechanisms have been proposed to facilitate cooperation among autonomous nodes. These mechanisms can be roughly classified as reputation-based, credit-based incentive, network-assisted pricing mechanisms, and mechanisms based on forwarding (or *ad hoc*) games [43]–[46]. These prior efforts often mimic the operation of a complex economy and in doing so they illustrate the inherent difficulty of such an approach. Such approaches may be sometimes more complex than is warranted for this problem and simpler approaches based on the mechanisms of barter and exchange have also been considered. Bandwidth, stored battery energy, and data are the tangible assets of a radio resource manager, and will be the basis for our barter-exchange economy. Bandwidth and data can be traded directly between nodes, and energy can be saved by one or both on the basis of their cooperation [47].

We note that such cooperative techniques can also help to improve power efficiency and hence are applicable to emerging "green" information technology initiatives. While current projections for carbon emissions due to information and communication technologies are about 2%–4% of the total [118], [119], rapidly increasing demand for wireless data services has motivated efforts toward improving energy efficiency in wireless networks. In modern cellular systems, approximately 80% of the energy costs are incurred at the base station, and a further 80% of this cost is incurred in the operation and support of the power amplifiers used in the transmitter [120]. Cooperative forwarding by relays has been proposed for reducing cellular base station transmit power while also improving coverage and capacity. Preliminary results [121] demonstrate gains of about 2.5-dB savings in peak transmit power and 3-dB savings in average transmit power.

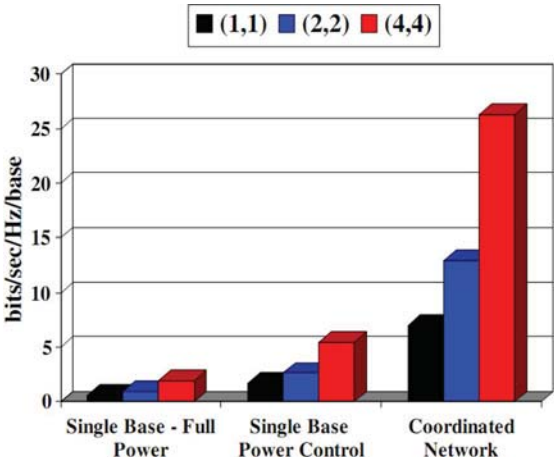


Fig. 5. ***Spectral efficiency of power control scheme with different number of antennas systems.*** (N_t, N_r) ***denotes antennas at the transmitter and the receiver, respectively [48].***

In a managed system such as cellular, such issues may not be significant—the system operator has the power to embody cooperative strategies in the protocols that control the behavior of users. The downlink capacity of cellular wireless networks is limited by intercell interference. In conventional cellular systems, each base station transmits signals intended for users within its cell coverage. Depending on the users' channel conditions, interference caused by the neighboring cell transmissions can sharply degrade the received signal quality. Fortunately, since the base stations can be connected via a high-speed backbone, there is an opportunity to coordinate the base antenna transmissions so as to minimize the intercell interference, and hence to increase the downlink system capacity. Such coordinated base station transmissions also referred to as network MIMO [11], [48] can help to eliminate intercell interference, and result in a great capacity improvement on the downlink cellular networks (see Fig. 5 reproduced from [48]). The challenges of obtaining and managing network/channel state information are indeed multifold compared to MIMO discussed earlier, but the potential gains capable by employing network MIMO are tremendous and provide a means of supporting the increasingly high data rate demands of AV applications.

3) Dynamic Spectrum Access (DSA): The sharing of spectrum, in its many forms, has been at the heart of effective regulation and efficient system design since the earliest days of wireless. Historically, it has driven advances as disparate as tighter filtering to create more channels and cellular architectures to reuse them more frequently. State-of-the-art radio techniques, protocols, and algorithms (e.g., evolving cellular and WLAN technologies) are typically limited to static, contiguous allocations ranging from a few megahertz to tens of megahertz. These technologies require contiguous spectrum availability and do not allow dynamic spectrum adaptation or modulation that will be required for open access under varying spectrum availability. The emerging cognitive radio technologies on the other hand enable DSA. In their simplest embodiments (which are by no means simple to implement) cognitive radios can recognize the available systems and adjust their frequencies, waveforms, and protocols to access those systems efficiently. Such dynamic access hinges on the development of cognitive protocols and algorithms that exploit temporal and spatial variability in the spectrum via: 1) initial cooperative neighbor discovery and association; 2) spectrum quality estimation and opportunity identification; and 3) radio bearer management. These, in turn, imply a framework that senses "neighborhood" conditions to identify spectrum opportunities for communication by building an awareness of spectrum policy, local network policy, and the capability of local nodes (including noncooperative "legacy nodes").

In concept, cognitive radios [49] extend the SDR framework to include multiple domains of knowledge, model-based reasoning, and negotiation. The knowledge and reasoning can include all aspects of any radio etiquette such as radio-frequency (RF) bands, air interfaces, protocols, and spatial as well as temporal patterns that moderate the use of the radio spectrum. Negotiation implies strategy-directed communication with peers about the use of radio spectrum over the dimensions of space, time, and frequency. The key to such an enablement of DSA lies in the ability to program such radios to become radio-domain aware and intelligent agents, and to provide the supporting structures which allow awareness and negotiation to take place. The PHY and MAC layer innovation that allows such seamless spectrum access is based on OFDM and access based on OFDMA [5]. The use of multiple carriers such as in OFDM techniques allows support of high date rate applications such as video without necessarily encountering frequency selective radio channels at the receiver, since the multiple carriers effectively present to the receiver a set of parallel flat fading channels. Further, the advent of noncontiguous OFDM techniques [9] also presents opportunities for flexible and versatile DSA where a transmitter can simultaneously and opportunistically transmit data over multiple frequency channels that are not adjacent (see Fig. 6).

4) Network Coding: In the last few years, the area of network coding has seen an explosive growth in research activity while being touted as the foundation on which several applications related to the robust operation of both wired and wireless networks can be built. The breadth of areas that have been touched by network coding is vast and includes not only the traditional disciplines of information theory, coding theory, and networking, but also topics such as algorithms, combinatorics, distributed storage, network monitoring, content delivery, and security. Since the

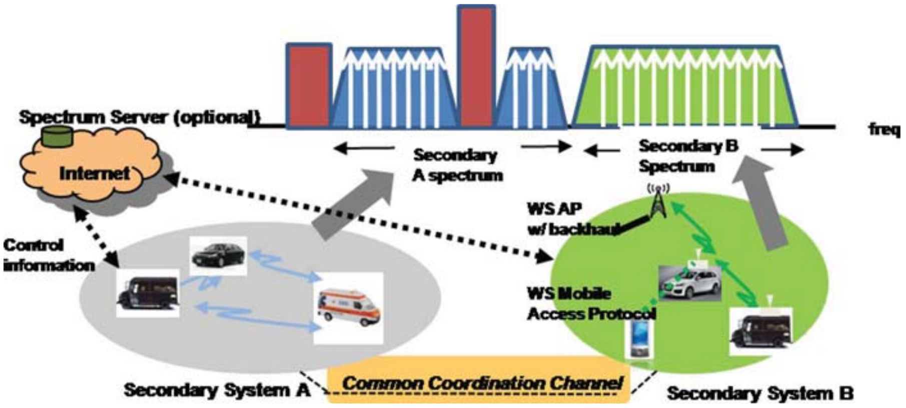


Fig. 6. ***White space usage scenario with multiple NC-OFDMA secondary signals.***

pioneering work by Ahlswede *et al.* [50] that established the benefits of coding in routers and provided theoretical bounds on the capacity of such networks, there have been many fine results for network coding strategies for multicast traffic, as well as their design and implementation in polynomial time. In fact, it can be said that for multicast traffic, linear codes achieve the maximum capacity bounds and can be done in polynomial time. Further, the above is true even when routers perform random linear operations. The above results have been extended to various situations in wireless networks and also in the context of content distribution, distributed storage, and secrecy [51]–[53]. More recently, there has also been an equally excellent body of work that has focused on implementation aspects of network coding [54]. In its simplest embodiment, under the assumption of an underlying MAC protocol, random network coding requires all nodes in a network to linearly combine received packets and retransmit them to other nodes, which in turn execute the same procedure. The net result is that over time all intended destination nodes in the network would have received all the intended packets for them as shown in the illustrative example in Fig. 7. This effective network level technique can provide the robustness necessary to support QoS requirements for AV content distribution.

C. 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. 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 WiFi 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. Radio access networks in 2G cellular systems were built as extensions of digital telephony systems incorporating incremental features for

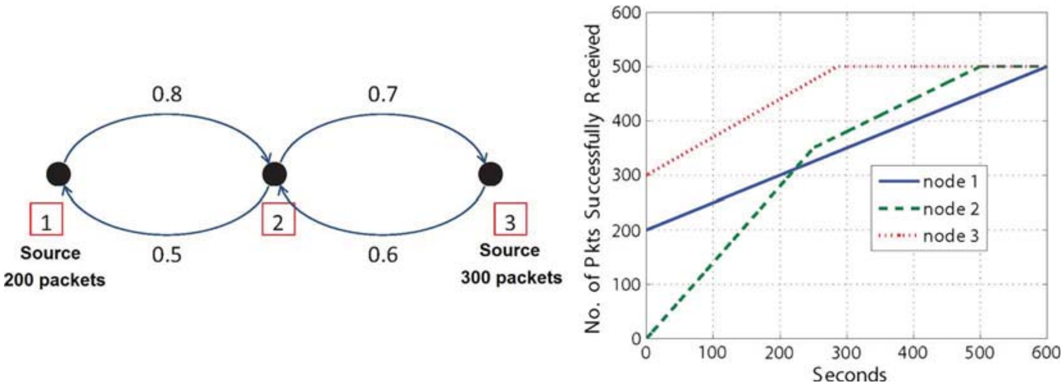


Fig. 7. ***Number of packets successfully received in a three-node wireless network (with link probability shown) using random network coding.***

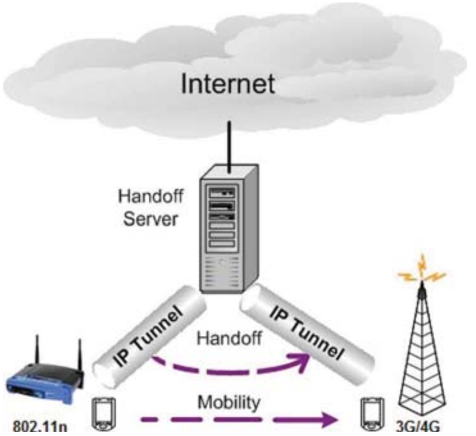


Fig. 8. *Universal seamless vertical handoff architecture [117].*

support of dynamic mobility (handoff, roaming, authentication), while access networks used for WiFi are extensions of Ethernet 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 "3GPP" cellular network standard is steadily migrating toward the concept of an all-IP cellular network with telephony signaling protocols replaced by Internet protocols for multimedia support such as the Session Initiation Protocol (SIP) and the IP multimedia system (IMS) [55], while user mobility is directly supported by the IP network using protocols such as mobile IPv6. 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 WiFi hot spots, known as vertical or intersystem handover [56] (see Fig. 8). These trends point to a gradual "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.

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. Mobile IP with route optimization [57] was proposed to improve scalability and reliability and reduce signaling overhead. Micromobility [58] was proposed for mobility within a small region. Jain *et al.* [59] and Aura *et al.* [60] among others extend basic mobile IP to avoid the need of a unique home network. 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. An alternative approach under consideration is based on the separation of names from addresses, with 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)" [61] 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. 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. Instances of connection reconfiguration and migration approaches are the Stream Control Transmission Protocol (SCTP) [62] and the Transmission Control Protocol (TCP) migration [63]. The SIP used for voice and video services [64] 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.

Storage-aware networking has also been proposed as a mechanism for dealing with disconnection and channel impairments associated with wireless access and mobility. The "Infostations" mobile content cache concept was proposed in 1998 [65] 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. This concept was further developed in the cache-and-forward (CNF) architecture [66] 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, as depicted in Fig. 9. 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. Results for CNF show that significant performance and capacity gains can be achieved with storage-aware routing [67], particularly for scenarios involving delivery of large media files to mobile users.

Another important dimension of wireless networking research has been aimed at enabling infrastructureless (or "*ad hoc*") networking between mobile devices in physical proximity. The *ad hoc* mode of networking was originally proposed for emergency response and tactical military networks known as mobile *ad hoc* networks (MANETs) [68]–[70] where a group of first responders or soldiers participate in a self-organizing network with multihop routing of messages between radio nodes [71]. *Ad hoc*

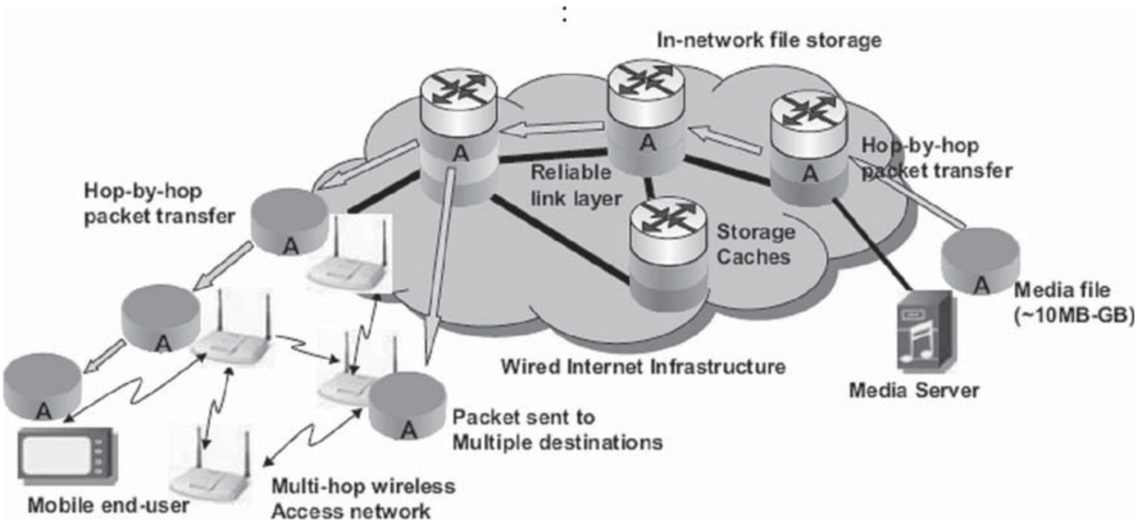


Fig. 9. *Conceptual view of the CNF network with storage routers and hop-by-hop transport [66].*

wireless network technologies have also been applied commercial usage scenarios such as multihop "mesh networks" for low-cost broadband access networks in both urban and rural areas [72]–[74]. *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 [75], [76]. Variations of *ad hoc* and mesh network protocols have also been applied to sensor network scenarios where low-power sensor devices inherently require multihop communication modes to overcome short transmission range [77]. Multihop wireless networks can potentially achieve high service bit rates by using multihop communication between high-speed commodity radios such as 802.11a or g [78], [79]. *Ad hoc* and mesh networks differ from conventional cellular and WiFi 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. 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) [80] and dynamic source routing (DSR) [81], which are specified in the IETF MANET standard [82]. *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.

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 [83]. 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 [84]. Efficiency and overhead considerations led to a series of enhanced epidemic protocols with intelligent buffer management, such as prioritized epidemic routing (PREP) [85]. Many of these protocols, such as Prophet [86], MaxProp [87], and RAPID [88], have taken advantage of generalized mobility trends and attempted to capture meeting probabilities and other internode 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 [89].

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 [90] includes a project called "MobilityFirst" [91] 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-WiFi, *ad hoc* and mesh networks, vehicular networks, and sensor networks. The baseline network protocol being considered in the MobilityFirst architecture includes a generalized storage-aware routing (GSTAR) protocol [92] which unifies features from CNF and DTN protocol outlined earlier to achieve good performance in a seamless manner across both wired and wireless networks. The MobilityFirst 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. 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 [93]. These and other future mobile Internet protocol ideas (for example, Accountable Internet Protocol (AIP) [94] or Hierarchical Architecture for Internet Routing (HAIR) [95]) 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.

IV. IMPLICATIONS FOR AUDIOVISUAL COMMUNICATIONS AND MULTIMEDIA APPLICATIONS

The emergence of wireless as the *de facto* mode of communications to and from end-user devices is one of the most notable technology trends of this decade. This has significant implications for the development and deployment of audiovisual and multimedia applications which just ten years ago were supported on relatively large, static platforms such as PCs, TVs, and stereo systems most with wired network or broadcast network connectivity. This is in sharp contrast to the current model of network delivery of all types of content to portable wireless devices, such as smartphones, tablet computers (pads), and electronic books. Because these devices are inherently portable, they must access the Internet through one or more radio access technologies discussed in the previous sections. For example, a typical smartphone or tablet computer will have three radio interfaces including 3G/4G, WiFi, and Bluetooth radios—the 3G/4G and WiFi radios are intended for long-range outdoor and short-range indoor access, while the Bluetooth radio is meant for *ad hoc* pairing with nearby devices. All three of these radio technologies have reached a point where they can support a reasonable set of audiovisual applications at quality levels acceptable for personal mobile devices, though some technical challenges remain.

One of the major problems with wireless delivery of multimedia is caused by the fact that wide-area cellular access (even after the introduction of 3G) remains relatively slow and the actual radio link bandwidth and channel error rate can fluctuate across a wide range of parameters. Although the introduction of 4G technologies such as WiMax and LTE offers the prospect of significantly higher nominal bandwidth (~1–10-Mb/s peak rate per user versus ~0.1–1 Mb/s), these newer cellular networks continue to exhibit large variations in channel quality due to the fundamental nature of the wide-area radio channel (see Fig. 10, which plots the bit-rate variation at a mobile WiMax device during pedestrian mobility in a suburban/office environment). For the audiovisual application developer, this means that higher bandwidth applications such as video streaming must be able to continually adapt the encoded stream's bit rate as the channel quality fluctuates in order to avoid decoder starvation. Techniques for video rate adaptation have been developed earlier for the wired Internet [96]–[98], which still exhibits variations in available stream bit rate, though not at the same short time scales as mobile wireless channels. These techniques involve the use of transport layer protocols such as the Real-Time Control Protocol (RTCP) [99] to estimate achievable bit rate and then use this information along with receiver buffer status to adjust video encoding quality and rate. More recent work on video rate adaptation for wireless channels has also considered the use of cross-layer feedback (for example, radio link rate and quality information from the base station or access point) to further improve end-to-end performance [100], [101]. Further QoS gains can be achieved with cross-layer scheduling of traffic at intermediate network nodes such as edge routers and base stations, of course, at the cost of increased complexity relative to simpler end-to-end rate adaptation [102]. Although we have discussed the case of streaming video, similar considerations apply to high-quality digital audio which require bit rates in the region of ~100–500 kb/s. In general, rate adaptation of audiovisual streams implies an increasing need for real-time A/V transcoding capabilities within the network or "cloud" as services migrate to mobile platforms.

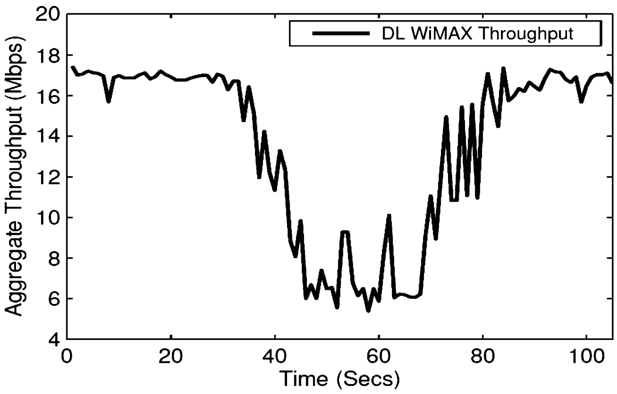


Fig. 10. ***Measured sample variation of WiMax downlink bit rate during pedestrian mobility [108].***

A second key barrier to widespread adoption of high-quality media services over cellular networks is that of limited network capacity. While the most recent 4G cellular systems can achieve peak bit rates ∼10–100 Mb/s, the realistic total network throughput for a single cell is no more than ∼5–10 Mb/s due to the fact that peak bit rates can only be achieved at a small subset of mobile users with excellent channel propagation, while the majority of devices operate at a much lower speed hence pulling down the overall network capacity. Considering typical urban and suburban population densities along with the coverage area of a 3G or 4G base station, it is observed that a single base station is expected to serve between ∼100 and 500 potential users, with perhaps 20% activity during busy hour. This means that if the practical capacity of a single 4G cell is 10 Mb/s, this bandwidth must be shared by 20–100 active users, resulting in a dedicated per user capacity of just 100–500 kb/s, insufficient for rich media applications at a majority of end-user devices. Some solutions to the capacity problem are: 1) multicasting of media streams as in the commercial MediaFlo system [103]; this approach offers significant capacity gains for broadcast television but is not particularly applicable to individual media viewing as is the case for most mobile services; 2) addition of WiFi hot spots to offload traffic in densely populated areas; this hybrid WiFi/cellular approach mentioned earlier in Section III has become quite popular with cellular operators and is a low-cost approach that can provide significant capacity gains; and 3) content caching at mobile devices and inside the network; this approach is somewhat different in that streaming of content is avoided in favor of delivering video blocks/files in anticipation of user needs, utilizing low traffic periods and/or WiFi hot spots to avoid use of network resources during the peak hour. Caching at mobile devices is becoming increasingly feasible due to declining semiconductor memory costs, and significant effective capacity gains have been demonstrated in various studies on this topic [65]. System capacity can be further improved by enabling in-network caching of content as in the CNF architecture proposed in [66], [67], and [104].

The problem of maintaining a reliable QoS for media applications can also be addressed by the emerging technology of network virtualization [105]–[107]. Virtualization techniques aim to partition hardware, processing, and bandwidth resources at shared network elements such as routers and base stations into distinct "slices" while also providing the software programmability necessary to customize network routing and higher layer protocols to the service carried on each slice. Virtualization methods have been applied to wireless systems (such as WiFi or WiMax access networks considered in [108] and [109]), providing for improved isolation between traffic from distinct services such as video and data. Each virtual network can employ its own customized queue scheduling algorithm which considers the specific needs of the application (for example, most AV services require low delay and predictable bandwidth in preference to high peak throughput). Service-specific admission control and bandwidth pricing strategies [110] can also be used to improve overall QoS of audiovisual applications such as video streaming.

Our discussion so far has focused on the cellular network, which is a critical enabler (as well as potential bottleneck) for mobile multimedia services. There is another important scenario for media delivery over wireless for in-building distribution of high-quality media between devices such as set-top boxes, DVRs, PCs, HD displays, etc. Making the distribution network completely wireless has many advantages for the consumer relative to wired networks, so this goal has been widely endorsed by the consumer electronics industry. While some progress has been made on very high-speed short-range radios ∼100–500 Mb/s such as UWB [15], this is still an emerging technology without common industry-wide standards. In addition, the technology is relatively short range (a few meters), limiting more general uses in homes and offices. High-speed 802.11n has proved to be a competitive alternative for in-home media distribution, but there are still some issues with range and stability of high-bit rate modes that need to be addressed. The emerging 802.11ac and ad standards (the latter at 60 GHz) mentioned in preceding sections are intended to address this important usage case by providing stable gigabit per second links with moderate range (∼10–20 m).

The above discussion shows that there will be improving wireless technology for both mobile content delivery and indoor media distribution applications, but also that these systems remain imperfect in terms of fluctuating bit rate and limited system capacity. This means that audiovisual application developers cannot treat the wireless delivery medium as a "bit pipe" and must instead improve coding methods and application structure to effectively deal with the characteristics of wireless networks. Future audio and video coding standards [111]–[113] will need to incorporate rate adaptivity and resilience, while further increasing compression factors to address the capacity constraints in cellular mobile systems. At the application level, developers should explore alternatives to streaming which can exploit opportunistic access and do not require continuous allocated bandwidth—these include techniques such as near-real-time file delivery, content caching, and mobile P2P. Future applications may require even more creative methods for retrieval or delivery of media content from mobile users and real-world sensors—examples of these are collaborative viewing [114] in mobile social networks, immersive video sensing, and augmented reality [115], [116].

V. CONCLUDING REMARKS

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 WiFi networks, 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 multihoming, *ad hoc*, and multihop 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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