

Broadband radio LANs and the evolution of wireless beyond 3G

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The wireless communication landscape will continue to develop at a rapid pace over the next few years. New systems and standards are on the horizon which enable broadband wireless communication in the office, at home, and “on the move.” They will finally bring the information services provided by the Internet and the World Wide Web to mobile users, together with a variety of new multimedia entertainment services. In this paper we give an overview of key developments in wireless communication systems. The emerging third-generation (3G) cellular systems and the growing importance of wireless local- and personal-area networks are discussed. The physical and medium-access control (MAC) layers are described for the new broadband wireless local area networks (LANs), which enable “hot-spot” data and multimedia services in airports, hotel lobbies, and a variety of other “public” places. We present an outlook toward a future fourth-generation wireless communication system. It can be integrated with the Internet protocol (IP) backbone network and can provide quality-of-service (QoS) support for multimedia applications. It supports dynamic scheduling, link adaptation, and frequency selection as well as full mobility. We conclude by describing some of the underlying technology developments driving the wireless evolution.

1. Introduction

Cellular radio technology has transformed voice communication and messaging in a spectacular way. However, the low data rates of a few kb/s have so far prevented mobile users from enjoying the full benefits of Internet and World Wide Web services, but this is changing rapidly. The emerging third-generation (3G) mobile cellular systems (UMTS, IMT-2000) are designed for data rates up to 2 Mb/s [1]. In Japan and Europe, where additional capacity for voice communication and multimedia-enriched message services is urgently needed, deployment of 3G has already begun. Third-generation systems will have a hierarchical cell structure with suburban macrocells, urban microcells, “hot-spot” picocells, and possibly also a satellite overlay. Seamless coverage, ubiquitous roaming, and operation at vehicular

speeds up to 200 km/h (120 mph) will be supported in macrocells and microcells for data rates up to 64 kb/s (cf. **Figure 1**). A richer variety of wireless services, at least for slower-moving platforms, will become available with the deployment of 384-kb/s data services which will finally bring many of the Internet and Web services to the mobile user. In particular, multimedia services such as MPEG audio and video streaming are expected to unlock new revenue streams for the cellular operators. However, cellular networks will have to compete with new wireless broadcasting networks based on the digital audio broadcast (DAB) and digital video broadcast (DVB) standards. In addition, the 3G standard defines a high-speed 2-Mb/s mode for stationary hot-spot services.

A second wave of radio technology has recently begun to penetrate our offices and homes. Indeed, very short-

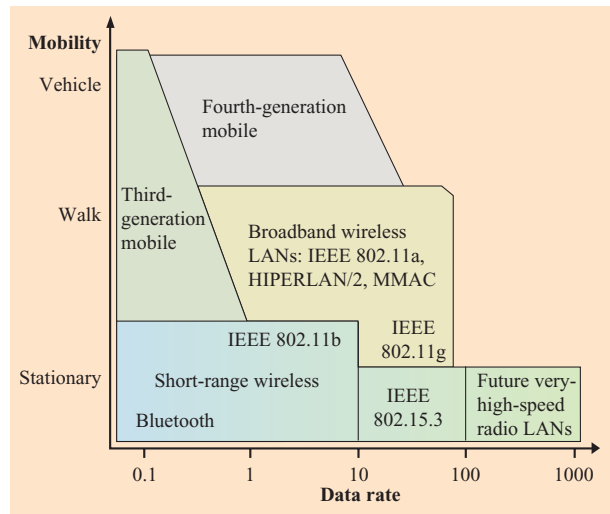


Figure 1

Mobility and data rate of wireless systems.

range wireless systems, in particular IEEE 802.11b radio LANs [2] and “Bluetooth” [3], may soon rival cellular systems in ubiquity. Bluetooth is a system that enables the coexistence of a small number of low-cost radio links for voice or data communication within a range of up to 10 meters, allowing wireless access to a plethora of devices and appliances and a variety of new personal area network (PAN) scenarios. Bluetooth was standardized in IEEE 802.15.1 and operates at 1 mW in the worldwide license-free 2.4-GHz industrial, scientific, and medical (ISM) frequency band. It uses frequency hopping to transmit data at a rate of 1 Mb/s—sufficient for three 64-kb/s voice links or for asynchronous data up to 723 kb/s.

IEEE 802.11b radio LANs have recently achieved spectacular market growth. They typically operate at 100 mW in the same license-free 2.4-GHz ISM band, supporting asynchronous data up to 11 Mb/s. The 802.11 MAC allows two modes of operation, either using an access point (base station) that is typically connected to a wired backbone network, or operating in *ad hoc* networking mode without a base station. In addition to their traditional use in office environments, 802.11b systems are rapidly penetrating the home networking market, where wireless operation is particularly attractive for connecting entertainment devices. In addition, 802.11b base stations increasingly serve as access points for delivering Internet access in airports, hotel lobbies, and other “public” places. Integrating such 802.11b hot spots into the emerging 3G networks may prove to be more cost-efficient than deploying the 2-Mb/s data service defined in the 3G standard. Indeed, as we describe later

in this paper, wireless LANs will play a key role in the further evolution of wireless communications.

The evolution of 2.4-GHz wireless LANs and PANs toward higher data rates and richer functionality is underway: IEEE 802.11g has drafted a higher-speed wireless LAN for data rates of up to 55 Mb/s. It is backward-compatible with 802.11b, which uses complementary code keying (CCK) for 11 Mb/s. For higher data rates, orthogonal frequency-division multiplexing (OFDM) and, as an option, packet binary convolutional coding (PBCC) are employed [4]. IEEE 802.11e is working on an enhanced MAC with QoS provisions, and 802.11i on enhanced security functionality. Similarly, 802.15.3 is pursuing a high-speed wireless PAN for data rates as high as 55 Mb/s using trellis-coded modulation [5]. The MAC supports *ad hoc* networking and QoS provisions. Concerns about the coexistence of the various systems operating in the 2.4-GHz band are addressed by yet another group. Nevertheless, the 2.4-GHz ISM band has a bandwidth of only about 80 MHz and is also shared by a number of industrial, scientific, and medical users. More bandwidth for short-range radio transmission is available at higher frequencies, notably between 5.1 and 5.8 GHz.

In Section 2 we address the standards for 5-GHz broadband radio LANs and describe the standardization activities in the United States (IEEE 802.11a), Europe (ETSI HIPERLAN/2), and Japan [ARIB Multimedia Mobile Access Communication (MMAC)]. The significance of the convergence of the physical layers toward a future worldwide broadband short-range radio standard and the relevant modulation and coding schemes are explained [6]. The differences among the MAC schemes and their relevance for asynchronous data communication and isochronous multimedia services are discussed. The paper continues with some thoughts about a future broadband MAC that supports *ad hoc* networking, isochronous multimedia services, and dynamic link adaptation.

In Section 3 we explore the evolution of wireless systems beyond 3G, currently being addressed by the Wireless World Research Forum (WWRF) [7], and discuss a future fourth-generation (4G) mobile communication system that can be integrated with an IP-based backbone network [8]. The paper concludes with a discussion of recent advances in circuit technology and an assessment of their impact on the evolution of wireless communications.

2. Broadband radio LANs

Standards overview

In the U.S., wireless LANs have been standardized by the IEEE 802.11 committee. The MAC and physical-layer

characteristics are specified in [9]. Originally, three physical-layer transmission schemes for data rates up to 2 Mb/s were defined: two radio-based techniques, both operating in the 2.4-GHz ISM frequency band and employing either Frequency-Hopping Spread-Spectrum (FHSS) or Direct-Sequence Spread-Spectrum (DSSS), and one infrared scheme. Subsequently, the 802.11b group extended the DSSS scheme with Complementary Code Keying (CCK) to increase the data rate to 5.5 and 11 Mb/s.

A second high-rate extension with a new physical layer was approved by the 802.11a task group in September 1999 [10]. This physical layer operates in the 5-GHz frequency band, where the FCC allocated 300 MHz of spectrum in the lower, middle, and upper Unlicensed National Information Infrastructure (U-NII) bands for wireless transmission (see **Figure 2**). The 802.11a physical layer uses OFDM with variable-rate coding allowing selectable user data rates between 6 and 54 Mb/s.

In Europe, broadband radio LANs have been standardized by the ETSI workgroup Broadband Radio Access Networks (BRAN). The HIPERLAN/1 standard (1997) specifies an 802.11-like radio LAN operating at 5 GHz with a data rate of up to 19 Mb/s. Single-carrier modulation is used, requiring a complex equalizer to handle delay spread. HIPERLAN/2, HIPERACCESS, and HIPERLINK support access to IP, ATM, and UMTS core networks. HIPERLAN/2 [11] is a broadband radio LAN for wireless access to a core network. It offers data rates from 6 to 54 Mb/s and supports multimedia applications. Like 802.11a, the physical layer uses OFDM transmission. HIPERLAN/2 operates at 5 GHz in a band of 455-MHz bandwidth (Figure 2) that is license-exempt for the use of radio equipment complying with the relevant ETSI HIPERLAN/2 standard. Two bands are provided, one for indoor use with a power limit of 200 mW, and one for outdoor use with a maximum transmit power of 1 W. HIPERACCESS provides remote access to an IP or ATM backbone network and is intended for use in a wireless local loop (WLL). HIPERLINK is a high-rate interconnect between HIPERACCESS and HIPERLAN/2 networks.

In Japan, broadband radio LANs are standardized by the ARIB MMAC group [12]. Like the European standard, MMAC defines a broadband wireless LAN with access to an IP or ATM backbone network. The MMAC radio LAN standard is OFDM-based and foresees data rates up to 25 Mb/s for licensed operation at 5 GHz within a bandwidth of 100 MHz.

In the following sections, we give an overview of the 802.11a physical layer specification, point out differences between 802.11a [10] and HIPERLAN-2 [11], and discuss some implementation issues.

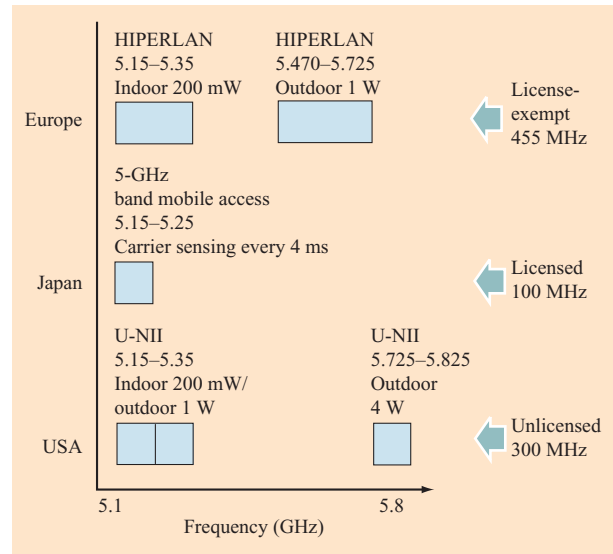


Figure 2

Spectrum allocation for broadband radio LANs.

Table 1 Parameters of OFDM physical layer [10].

Variable data rate	6, 9, 12, 18, 24, 36, 48, 54 Mb/s
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Coding	Convolutional code: rate = 1/2 Puncturing: rate = 2/3 and 3/4
Subcarriers	52
FFT/IFFT	64 points
Pilots	4
OFDM symbol duration	4 μ s
Guard interval	800 ns
Channel spacing	20 MHz
Subcarrier spacing	312.5 kHz
Sampling rate	20 MHz

IEEE 802.11a physical layer

The physical layer of an 802.11a broadband radio LAN employs OFDM transmission. The data stream is split into parallel streams of reduced rate, with each substream modulating a separate subcarrier. Appropriate subcarrier spacing ensures orthogonality, so that some spectral overlap between subchannels can be permitted. This leads to better spectral efficiency than using simple frequency-division multiplexing. OFDM offers good performance in indoor and outdoor multipath environments as long as the delay spread is smaller than the guard interval that is added between successive OFDM symbols. The main physical-layer parameters are given in **Table 1**.

The 802.11a physical layer supports user-selectable data rates between 6 and 54 Mb/s with a variable-rate modulation and coding concept which uses a punctured

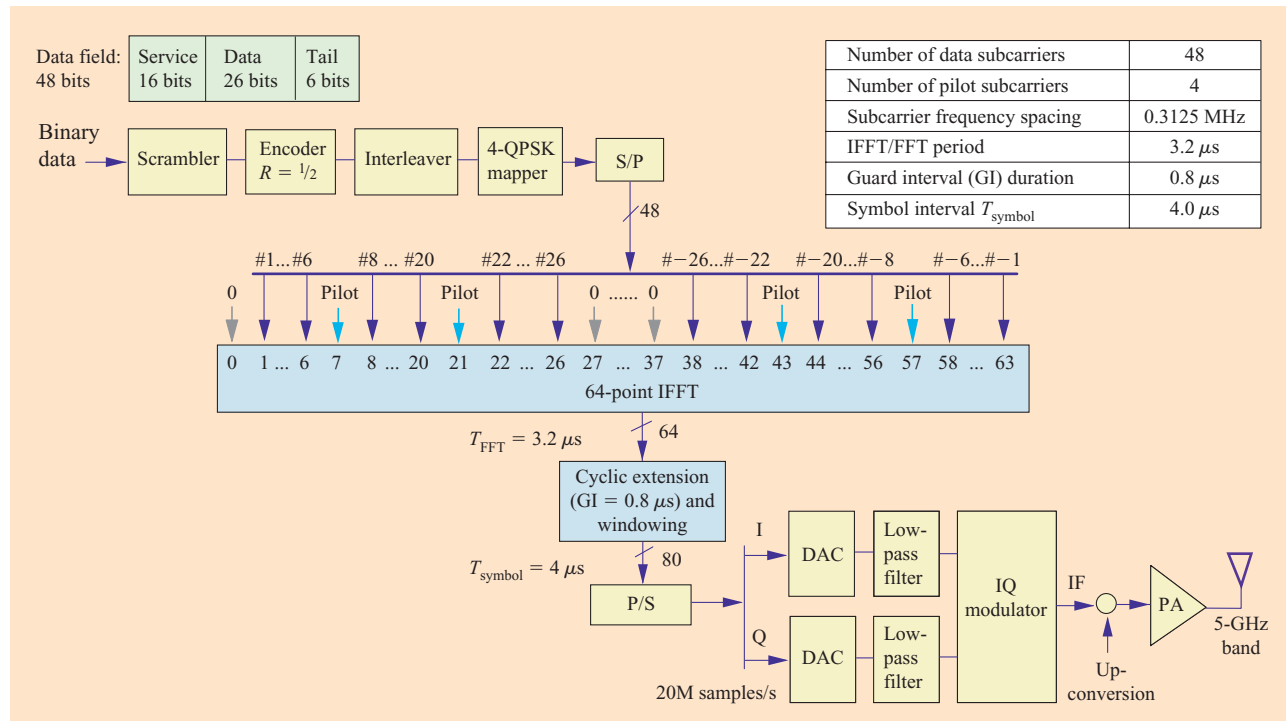


Figure 3

IEEE 802.11 OFDM physical layer: Transmitter operating at 12 Mb/s.

Table 2 Parameters of rate-dependent physical layer [10].

Data rate (Mb/s)	Modulation	Coding rate	Coded bits per subcarrier	Coded bits per OFDM symbol	Data bits per OFDM symbol
6	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24	16 QAM	1/2	4	192	96
36	16 QAM	3/4	4	192	144
48	64 QAM	2/3	6	288	192
54	64 QAM	3/4	6	288	216

convolutional code with generator polynomials $g_0 = 1338$ and $g_1 = 1718$, and several signal constellations. Depending on the selected data rate, data packets are encoded with rate $R = 1/2$, $2/3$, or $3/4$. For the lower data rates, the encoded data is modulated with binary phase shift keying (BPSK) or quadrature phase shift keying (QPSK). Quadrature amplitude modulation (QAM) with 16 or 64 signal constellation points is used for the higher rates. **Table 2** summarizes the resulting rate-dependent physical layer parameters.

A block diagram of an OFDM transmitter operating at a data rate of 12 Mb/s is shown in **Figure 3**. A 48-bit

data packet is scrambled, encoded with the half-rate convolutional code, interleaved, mapped into a sequence of 48 QPSK samples, and parallelized by a serial-to-parallel (S/P) converter. Each sample is subsequently modulated onto one of 64 subcarriers, four pilot samples are inserted to facilitate coherent reception, and the remaining 12 subchannels remain empty. After a 64-point inverse fast Fourier transform (IFFT) is performed, the number of samples is subsequently increased to 80 by cyclic extension into the guard interval (GI), and windowing is performed. Cyclic extension makes the system more robust to multipath propagation, while

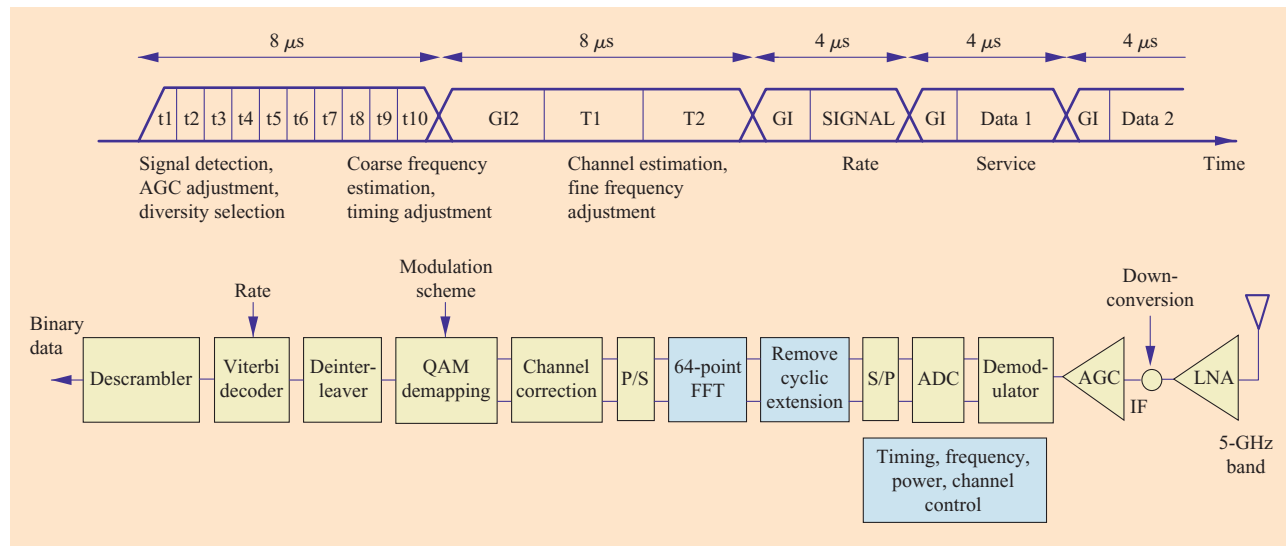


Figure 4

IEEE 802.11 OFDM physical layer: Receiver operating at 12 Mb/s.

windowing narrows the output spectrum. The samples are serialized by a parallel-to-serial (P/S) converter and pass through a digital-to-analog converter (DAC). The resulting analog signal is modulated with an intermediate frequency (IF) and up-converted to the 5-GHz frequency band, passes through a power amplifier (PA), and is transmitted over the air by the antenna.

The corresponding receiver block diagram is shown in **Figure 4**. The received signal is amplified with a low-noise amplifier (LNA), down-converted to IF, scaled in amplitude by an automatic gain control (AGC) circuit, demodulated, and digitized by an analog-to-digital converter (ADC). The digital samples are then processed with the inverse signal processing operations performed in the transmitter in order to reconstruct the transmitted user data packet: After S/P conversion and removal of the cyclic extension, a 64-point fast Fourier transform (FFT) is carried out. The 48 complex samples containing the data are extracted and sent to a P/S converter. A QAM demodulator then reconstructs the transmitted signal-constellation values, which are deinterleaved, and a Viterbi decoder performs hard- or soft-decision maximum-likelihood decoding. Finally, the resulting binary information bits are descrambled.

The receiver is trained with the help of a preamble which consists of two 8- μ s frames (Figure 4). From the received signal and the known training symbols in the preamble, the receiver derives the AGC gain, the frequency offset between transmit and receive clock, and the OFDM symbol timing. Later, a control loop tracks

phase drift by monitoring the pilot signals transmitted on four of the subcarriers. After the preamble, a field containing information about packet length and user data rate is sent [10]. Finally, the user data is transmitted as a sequence of OFDM symbols, each with a duration of 4 μ s.

Only minor differences exist among the physical layer specifications of IEEE 802.11a [10], HIPERLAN-2 [11], and MMAC [12]. For example, HIPERLAN/2 does not support 24 Mb/s. Instead, it provides 27 Mb/s with rate 9/16 encoding, which allows a 54-byte ATM packet to be fitted into an integer number of OFDM symbols. Also, while 802.11a specifies a single preamble for all logical channels, HIPERLAN/2 uses different preambles for broadcast, downlink, uplink, and random-access channels.

Physical layer implementation challenges

The complexity of the 802.11a physical layer is substantially greater than that of the 802.11b because of the OFDM signal processing and coding (64-point FFT, Viterbi decoder). However, OFDM transmission is more efficient in handling large delay spreads than conventional single-carrier transmission modulation, which requires a large equalizer [13]. Equally important, FFT and Viterbi decoder can be implemented very efficiently in dedicated hardware or with appropriately optimized DSPs [14].

OFDM also offers significant challenges for the radio front-end designer. Recent advances in SiGe technology offer substantial benefits for minimizing power consumption at 5 GHz [15]. Amplifiers with good linearity

Table 3 Comparison of functions provided by the 802.11 standard, HIPERLAN/2, and Bluetooth.

	802.11	HIPERLAN/2	Bluetooth
<i>Medium access control—media sharing</i>	Decentralized/centralized control—CSMA/CA	Centralized control—TDMA/TDD	Centralized control—TDMA/TDD
<i>Connectivity</i>	Connectionless	Connection-oriented	Speech: synchronous connection-oriented link; Data: asynchronous connectionless link
<i>Multicast</i>	Broadcast, multicast	Broadcast, multicast	Broadcast only
<i>Channel selection</i>	Single carrier with fixed frequency selection	Single carrier with dynamic frequency selection	Frequency-hopping sequence
<i>Authentication</i>	Yes	Yes	Yes
<i>Encryption</i>	40-bit RC4	DES, 3 DES	“Bluetooth” encryption
<i>Fixed network support</i>	802.1, IP	802.1, IP, ATM, UMTS, IEEE 1394	IP, GSM
<i>Power management</i>	Yes	Yes	Yes
<i>Radio link quality control</i>	Monitoring	Monitoring and dynamic link adaptation	Monitoring
<i>QoS support</i>	No	ATM (RSVP)	Synchronous service
<i>Ad hoc network support</i>	Yes	No	Yes
<i>Isochronous service support</i>	No	Yes	Yes

receiver address, the transmitter address, and the basic service set ID. The sequence control field contains the segment and fragment numbers. The frame control field contains the protocol version to allow for proper protocol selection. The type field indicates the type of frame: management, control, or data frame. Within each type there exist several subtypes indicated by the subtype field. Several flags are provided to indicate, for example, the power management mode of the transmitting station, that more data are buffered at the AP, or that the content of the frame body has been processed with the WEP algorithm. The frame body is optional and contains the MAC payload.

The HIPERLAN/2 protocol is connection-oriented and based on a time-division multiple-access (TDMA) scheme. It employs centralized control; i.e., a device may transmit frames either when an access point requests a frame transmission in the next time slot or when a regular frame transmission has been scheduled in advance. It offers QoS support and isochronous services (voice, multimedia), which is not the case for 802.11. However, HIPERLAN/2 does not support the *ad hoc* networking mode offered by 802.11. A more complete comparison of the MAC functionalities is given in **Table 3**. Also listed are the corresponding functions provided by Bluetooth.

Unification of the three regional standards 802.11a, HIPERLAN/2, and MMAC into a single worldwide

standard will be of key importance if broadband radio LANs are to succeed in the marketplace as 802.11b has succeeded. Indeed, members of the IEEE, ETSI, and ARIB standardization groups are working on the harmonization of the physical layer and MAC specifications in the 5-GHz Industry Advisory Group. This effort could produce a new broadband radio LAN standard that combines the best features of 802.11a, HIPERLAN/2, MMAC, and Bluetooth to meet the short-range wireless networking, application, and service requirements of the future: high-speed Intranet and Internet access, high-quality speech service(s), QoS support for a variety of multimedia services, adequate security provisions, and handover/roaming support. There will probably be a requirement for a new MAC protocol which is capable of supporting *ad hoc* networking, isochronous data services, and dynamic link adaptation for QoS support.

3. Outlook toward a future fourth-generation wireless system

In 2001 the Wireless World Research Forum (WWRF) was formed to bring together experts from industry and academia to investigate the future of wireless systems beyond 3G. Work is underway in the WWRF to shape the outlines of a future 4G mobile wireless communication system [7]. A consensus is forming that mobile communication systems beyond 3G will integrate several

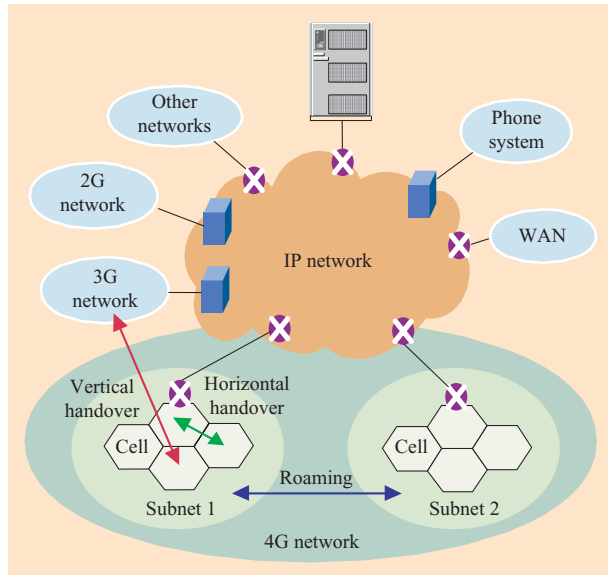


Figure 6

Future broadband wireless system.

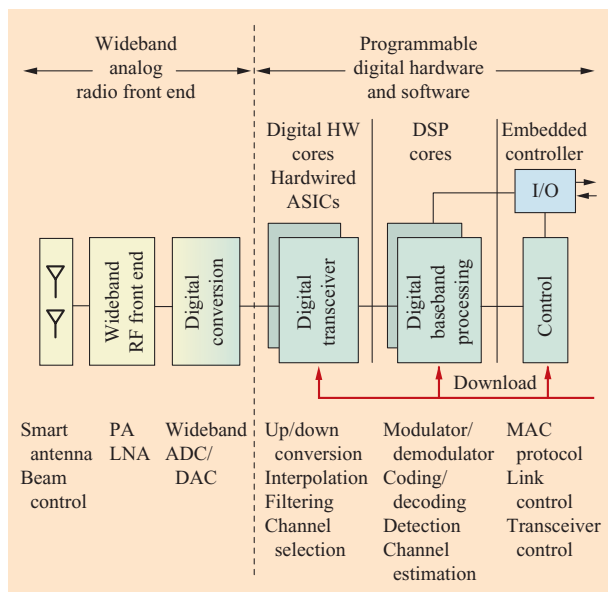


Figure 7

Software-defined radio.

types of wireless access systems with a common IP-based backbone network (Figure 6). Wireless access to the IP backbone will be provided by broadband radio LANs, low-cost wireless PANs, and, of course, by second- and third-generation cellular systems.

The IP backbone network will provide most of the services and applications because of its cost-efficiency and scalability. It will support roaming between subnets of the emerging 4G broadband wireless network as well as “vertical handover” between 4G and the legacy 2G and 3G networks. However, there remain some challenges for the IP network in areas such as throughput, mobility management, and QoS support. Future 4G wireless systems will also be challenged to provide not only QoS support and dynamic scheduling of bandwidth, but also dynamic link adaptation and frequency selection. Broadband radio LANs such as 802.11a appear to be especially well positioned for meeting these challenges and serve as stepping stones in the evolution toward 4G systems. However, 3G systems themselves are likely to evolve further. Indeed, evolutionary versions of 3G are already being explored which employ advanced modulation and diversity techniques to achieve better spectral efficiency and higher data rates [7, 18]. Future very-high-speed wireless LANs (Figure 1) operating at 60 GHz and above are another challenging research area. Also, radically different air-interface techniques such as ultra-wideband (UWB) radio transmission may challenge OFDM as the preferred transmission concept for future broadband radio communication systems [19]. UWB radio transmission employs ultra-low-power signals and large bandwidth generated, for example, by very short pulses.

Future mobile devices will run multiple concurrent applications and support multiple wireless standards, which translates into a need for multimode and multiband operation. The evolution of wireless systems beyond 3G is therefore intimately linked to the rapid advances in digital and analog device technology. The implementation of programmable and/or configurable analog radio front ends with multiple, adaptive antennas will make it possible to cope with the spectral regulatory requirements in different countries and regions. Minimizing power consumption will be a key requirement for which the advantages of SiGe technology can be exploited [15]. Integrating the analog front end with the digital baseband functions and the controller on the same chip or substrate remains the ultimate goal.

Moore’s law dictates that the time is rapidly approaching when the complete set of digital signal-processing and control functions of an advanced cellular or radio LAN transceiver can be integrated on a single chip. The corresponding hardware architecture is often referred to as *system-on-a-chip*. In the future, software-defined radios (Figure 7) with multiple baseband functionality and/or firmware cores will be implemented on a single chip and will function as *configurable silicon* (multiple cores that are switched on and off on demand) or as *programmable silicon* (digital processors that first

download and then run a required set of functions corresponding to a particular standard or protocol [20]).

4. Conclusions

The number of different standards and systems is likely to remain high during the continuing evolution of wireless systems. Innovative new concepts will continue to be introduced to improve spectral efficiency, performance, and power consumption, and to increase the functionality of wireless platforms and devices. A single-standard wireless system which integrates or replaces all present systems and spans the globe is thus likely to remain a dream for some time to come.

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