The Future Generations of Mobile Communications Based on Broadband Access Technologies

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ABSTRACT

The forthcoming mobile communication systems are expected to provide a wide variety of services, from high-quality voice to high-definition videos, through high-data-rate wireless channels anywhere in the world. The high data rate requires broad frequency bands, and sufficient broadband can be achieved in higher frequency bands such as microwave, Ka-band, and millimeter-wave. Broadband wireless channels have to be connected to broadband fixed networks such as the Internet and local area networks. The future-generation systems will include not only cellular phones, but also many new types of communication systems such as broadband wireless access systems, millimeter-wave LANs, intelligent transport systems, and high altitude stratospheric platform station systems. Key to the future generations of mobile communications are multimedia communications, wireless access to broadband fixed networks, and seamless roaming among different systems. This article discusses future-generation mobile communication systems.

INTRODUCTION

There has been an evolutionary change in mobile communications systems every decade. The first-generation (1G) in the 1970s and second-generation (2G) cellular systems in the 1980s were used mainly for voice applications and to support circuit-switched services. 1G systems were implemented based on analog technologies; however, 2G systems are digital systems such as the Global System for Mobile Communications (GSM), IS-54 Digital Cellular, Personal Digital Cellular System (PDC), and IS-95 [1]. These systems operate nationwide or internationally, and are today's mainstream systems. The data rates for users in air links of these systems are limited to less than several tens of kilobits per second. International

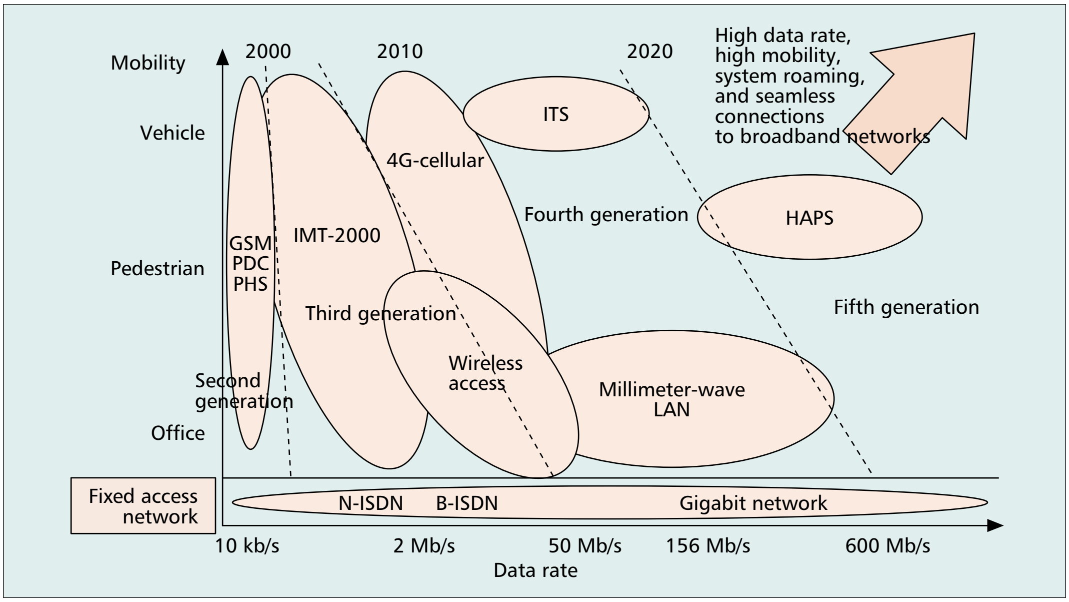

Figure 1. *Mobile communications systems.*

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Mobile Telecommunications 2000 (IMT-2000), which will be introduced at the beginning of the 21st century as the third-generation (3G) cellular systems [2], can provide 2 Mb/s and 144 kb/s in indoor and vehicular environments, respectively. However, demands for higher access speeds for multimedia communications will be unlimited.

In the coming century, society and the economy will greatly depend on computer communications in digital format. Almost all information will become digital data instead of real-time voice. Another trend is that communications will make human activities free of spatial and time restrictions. Advanced personal communication devices will lead people to be *nomadic*, a concept first introduced by Mr. Attali [3]. Mobile communications will become an essential part of our daily life, yet be transparent much like the air itself. It will be everywhere and commonplace, but people will not be aware of it. Key to the future generations of mobile communications are multimedia communications, wireless access to broadband fixed networks, and seamless roaming among different systems.

In this article, future generations include the fourth (4G) and fifth generations (5G), and 4G is used, in a broad sense, to include several systems; not only cellular phone systems, but also many new types of communication systems such as broadband wireless access systems, millimeter-wave LANs, intelligent transport systems (ITSs), and high altitude stratospheric platform station (HAPS) systems. When 4G systems are used in a narrow sense as cellular systems, they will be specified as 4G-cellular. Generations of mobile communications, and their key words and typical systems are shown in Table 1.

Figure 1 shows a future trend of mobile communications. It is very clear that they have to satisfy the demands of high data rate, high mobility, and seamless coverage. However, it is very hard to give a clear vision of future-generation systems. In principle, it is difficult to realize the system, which has both a high data rate and high mobility. In addition to this, system performance (e.g., cell size and transmission data rate) greatly depends on frequency bands. Taking these technical problems into account, future systems will include several different systems. Some will have high performance in providing high data rates, others in service coverage or high mobility.

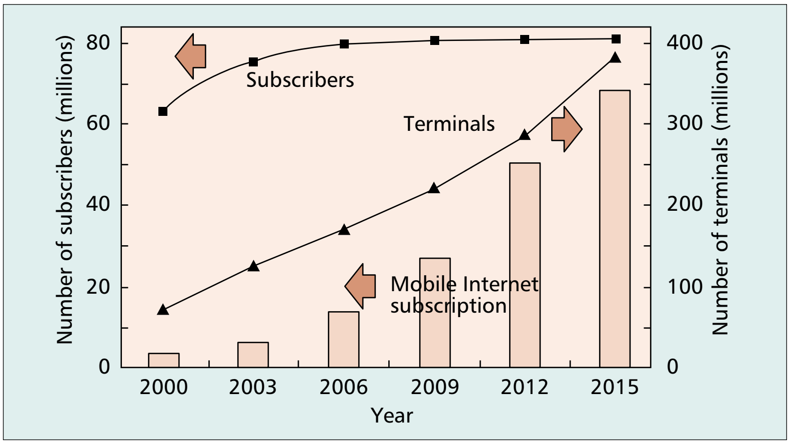


Figure 2. *The mobile communications market forecast for Japan.*

If these systems are integrated with other systems, there will be possible uses to enjoy both high data rate and high mobility. As candidates for future systems, 4G-cellular, broadband wireless access systems, ITSs, and HAPS systems have been attracting much interest in the mobile communication field. In future systems, seamless roaming among these different systems is a very important concept.

Seamless roaming among different systems will be added to high data rate, high mobility, and connection broadband fixed networks.

This article discusses not only so-called 4G-cellular systems, but also other broadband access systems as future generation systems.

Market Forecast

A forecast of the mobile communications market is shown in Fig. 2 for Japan, as an example. The number of mobile communication subscribers is expected to reach 81 million by the year 2010 [4]. The dark line in the figure represents the number of mobile telephone subscribers. As the figure shows, from the current increasing ratio, this number will be saturated around 2006 with a penetration rate of approximately 70 percent.

Although the number of subscribers will be saturated, traffic will still increase. The bars represent a forecast number of mobile Internet users as an example of new service subscribers.

	1980s	1990s	2000s	2010s	2020s
Generation	First	Second	Third	Fourth	Fifth
Keywords	Analog	Digital personal	Global world standards	High data rate High mobility IP-based	High data rate High mobility IP-based
Systems	Analog cellular	Digital cellular	IMT-2000	4G-cellular	5G-cellular
		GSM, IS-54, PDC	(3G-cellular)	Broadband access	Broadband access
	Analog cordless	Digital cordless		ITS, HAPS	ITS, HAPS
		DECT, PHS	Max data rate	Mini data rate	Mini data rate
			2 Mb/s	2–20Mb/s?	20–100 Mb/s?
		Mobile satellite			
		Iridium, Inmarsat-M			

Table 1. *Generations of mobile communications and their keywords and typical systems.*

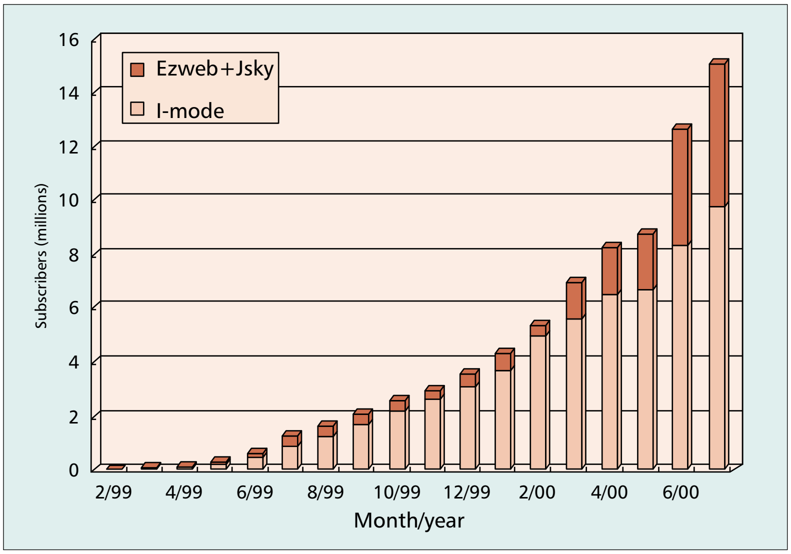


Figure 3. *The growth of mobile Internet services.*

The number of mobile Internet users will continue to grow through the 2000s. In Japan, a new mobile Internet service called i-mode started in February 1999 [5], and other operators followed to provide similar IP access services called EZweb and J-sky. In these services, users can access Web sites and banking services, and send e-mail using mobile phones. As shown in Fig. 3, the increase has been remarkable. The number of total subscribers reached approximately 15 million at the end of July 2000. This shows that the "second wave" in mobile communications has arrived, and its main service will shift from real voice to Internet access communications. Mobile access to both the Internet and intranets will become increasingly popular and essential. Data size will continue to increase year by year, and higher-speed mobile communications systems will be required in order to satisfy user demands. This trend will be accelerated by new types of applications such as electric tags on luggage, wallets, or even animals. The number of mobile terminals will continue to increase after 2010 to several times the number of subscribers.

Therefore, we expect that mobile communications traffic will expand considerably. Future mobile communications systems should accommodate increased multimedia traffic in the 2010s. It should be not only high-speed but also high-capacity, with low bit cost.

Traffic Forecast

When developing a new wireless system, one of the most fundamental issues is to obtain the frequency spectrum necessary to accommodate the forecast traffic. This spring, the International Telecommunication Union —Radiocommunication Standardization Sector (ITU-R) task group TG 8/1 forecast future traffic and the necessary spectrum for IMT-2000 [6].

The calculation results for Region 3 are shown in Fig. 4, where future traffic is compared in bits with traffic in 1999, which is considered one unit.

From 1999 through 2010, voice-oriented services, which were the main services in the first and second-generation systems, are expected to grow by 1.5 times in the number of subscribers and double in amount of traffic. However, growth is not expected after that, and voice-oriented services will level off after 2010. After 2010, multimedia services, which will be widely introduced in the third-generation system, are expected to expand considerably. The ratio between voice and multimedia traffic in 2010 will be approximately 1:2 for total up- and downlinks.

Assuming that multimedia traffic grows by 40 percent a year after 2010, it will be 23 times the current level, and the ratio between multimedia and voice traffic will be 10:1. This growth rate assumption of 40 percent is based on the fact that the expansion rate of storage cell capacity, such as the memory and hard disks of personal computers which process information, as well as the number of pixels in CCDs on which information is captured, is around 40 percent, and the number of Internet Web sites is growing at an annual rate of 40 percent in Japan and other countries.

The conclusion of the ITU-R TG 8/1 document was that additional frequency assignment will be necessary for 3G (IMT-2000) to accommodate the growing demand. The bandwidth to be added is assumed to be 160 MHz in 2010. However, the added bandwidth greatly depends on the growth ratio of traffic per subscriber, and traffic will continue to increase after 2010. Therefore, study of high-capacity 4G-cellular systems with improved spectrum efficiency and a new frequency band is necessary to accommodate growing traffic in 2010 and thereafter.

System Requirements

High-Data-Rate Transmission

The 3G system covers up to 2 Mb/s for indoor environments and 144 kb/s for vehicular environments. The 5 GHz band wireless LAN and wireless broadband access systems being developed in Japan (MMAC) [7], Europe (Hiperlan2), and United States (IEEE 802.11) have transmission speeds of approximately 20–30 Mb/s. The user data rates of future generations will range from 2–600 Mb/s depending on the systems. The minimum target speed of 4G-cellular will be 10–20 Mb/s, and at least 2 Mb/s for moving vehicles.

High Mobility

4G-cellular may be required to provide at least 2 Mb/s for moving vehicles. Although realization of high mobility with high-data-rate systems is very difficult, it will be realized by intelligent transport systems, which will be operated in 5.8 GHz in the first phase. The ITS mentioned below is a dedicated system for transportation in the first phase; however, it will be expanded to cover pedestrians. The second phase of ITS will provide high-data-rate services with 50–200 Mb/s in millimeter-wave bands.

A Wide Coverage Area and Seamless Roaming among Different Systems

Since the target data rate of future systems is more than two orders of magnitude higher than that of present systems, the cell radius will be

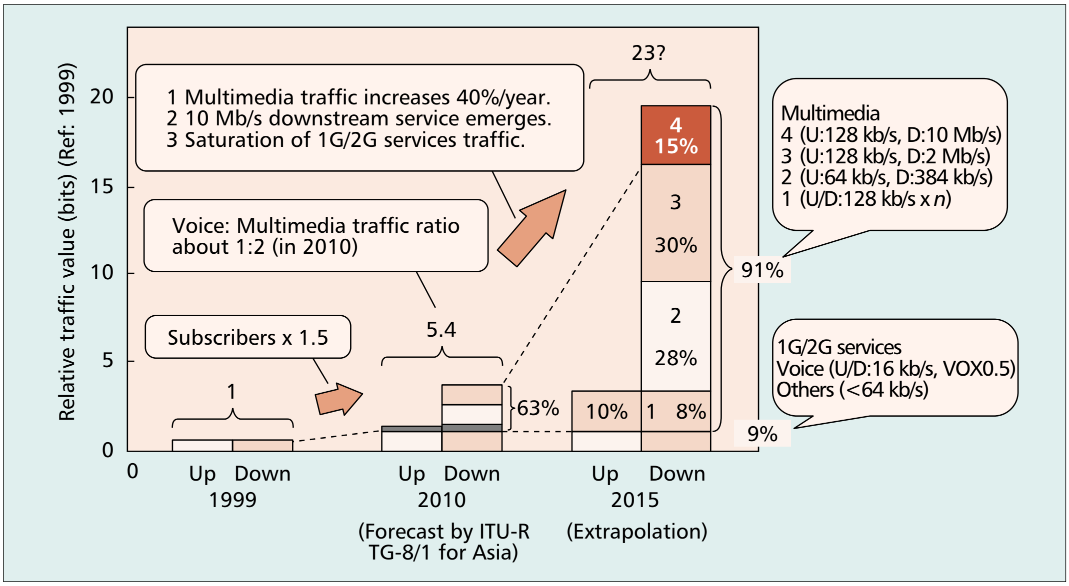


Figure 4. *Forecast traffic for Region 3 in 2010 and after.*

Smooth handover to other systems, such as indoor wireless LANs, outdoor broadband access systems, and intelligent transport systems, is a very important function for future systems.

decreased, resulting in a small coverage area. One option may be to use high altitude platform station (HAPS) systems, which use large airships as communication platforms in a stratospheric layer 20 km above the ground. To extend penetration into buildings, wide-range variable-speed transmission is necessary. Smooth handover to other systems such as indoor wireless LANs, outdoor broadband access systems, and ITSs is a very important function for future systems. This concept can be called roaming among different systems. It may be the first step in realizing system roaming by constructing networks based on Internet Protocol (IP) technology. Supporting the next-generation Internet, including IPv6 and multicast, is important because every consumer electronic device can be connected to the network.

Higher Capacity and Lower Bit Cost

3G cellular system capacity will not be sufficient to handle the explosively growing multimedia traffic of the 2010s. Capacity per unit area for 4G-cellular systems should be at least 10 times that of 3G cellular systems. The bit cost should be dramatically cut so that people can use it without worrying about communication charges.

Wireless QoS Resource Control

For Internet services, best effort service is very attractive because it has the potential to lower service cost. However, wireless systems use limited radio resources (frequency bandwidth and transmitting power) and suffer from congestion. Therefore, wireless quality of service (QoS) resource control is necessary to maintain the service quality, and to support various applications and service classes.

Candidates for Future-Generation Systems

In this section, several candidates for future systems such as 4G-cellular, broadband wireless access, LANs, ITSs, and HAPS systems are introduced. A concept of system roaming by system handover among different systems is shown in Fig. 5.

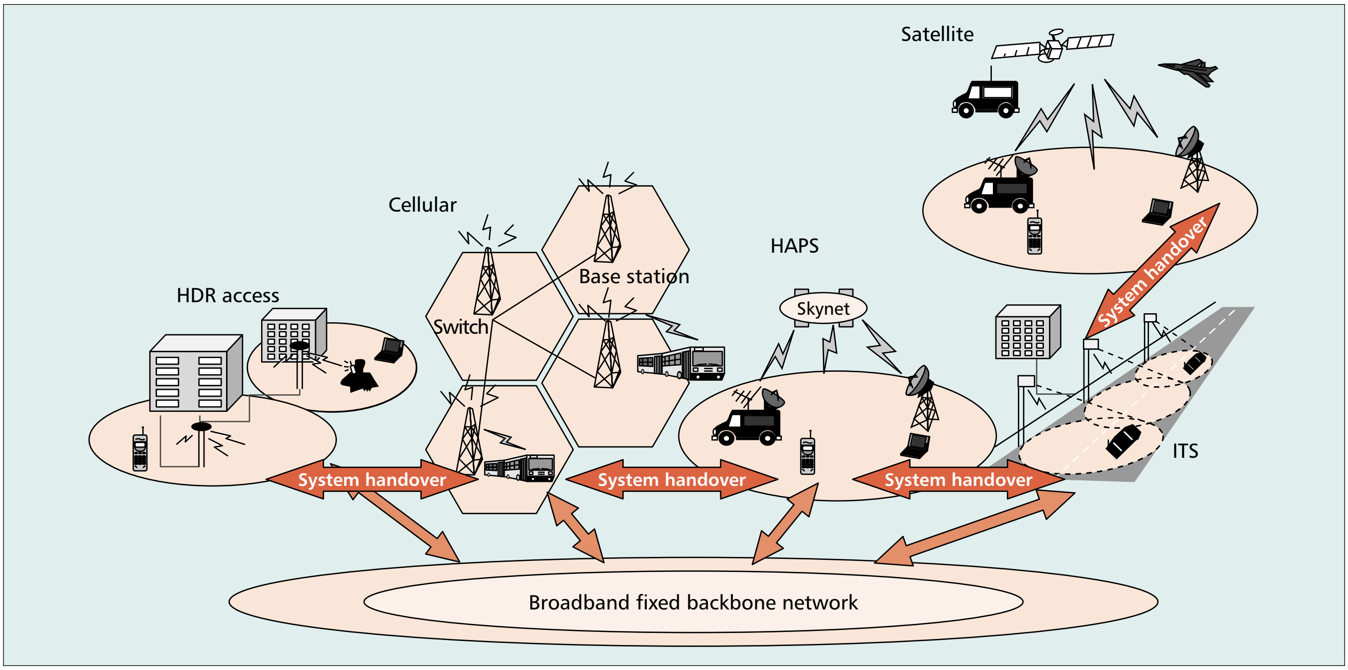
4G-Cellular Systems

4G-cellular systems should not only be high-speed but also high-capacity, with low bit cost and the ability to support the services of the 2010s. In order to achieve high capacity with reasonable frequency bandwidth, the cell radius of 4G-cellular systems shall be decreased from that of present cellular systems. However, current cellular radio access network (RAN) structures are not optimized for microcellular networks. Thus, a new revolutionary RAN structure with reduced bit cost should be studied.

By constructing networks based on IP technology, seamless connection between 4G, 3G, wireless LANs (W-LANs), and fixed networks will be possible. Not only the RAN structure but the entire network structure should be considered to support various application services of the 2010s. The basic network structure concept for 4G-cellular is shown in Fig. 6. The relationship between the network and applications in 4G can be divided into three layers. The physical network provides access and routing functions in an integrated format for both radio and core networks. The middleware environment acts as a bridge between the application and physical network. It provides functions such as QoS mapping, address conversion, plug and play, security management, and an active network. The interface between the physical network and the middleware environment will be an open IP interface. The interface between the middleware environment and applications will also be open interfaces, enabling third parties to develop and provide new applications and services easily.

Broadband Wireless Access and Local Area Networks

Broadband wireless access systems using 5 GHz and millimeter-wave bands have been developed. In 1996 Japan started a new R&D program called Multimedia Mobile Access Communication



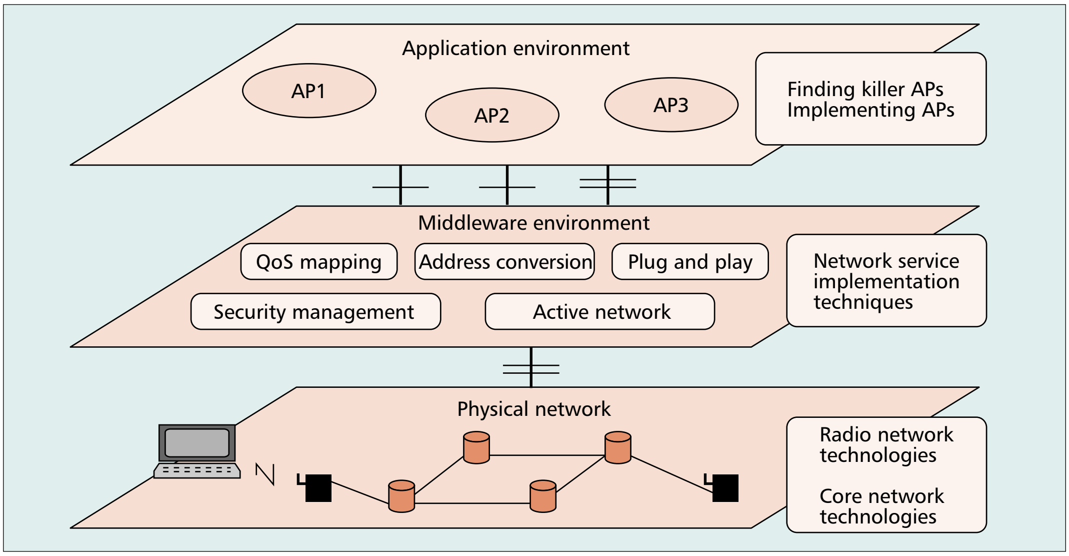
■ **Figure 5.** *The concept of future-generation mobile communications.*

(MMAC) Systems. An MMAC is a high-performance wireless system to be used after IMT-2000, which allows any person to communicate "anytime, anyplace" [7]. The MMAC will provide two categories of high-speed wireless access communications. The first will be serviced both outdoors and indoors. This is a broadband mobile communications system, which can transmit up to 30 Mb/s using 5.2 GHz, which will operate starting in 2001. The second will provide ultra-high-speed WLANs indoors, which can transmit high-speed signals (up to 600 Mb/s) using the millimeter-wave radio band (e.g., 60 GHz). 5 GHz MMAC systems are similar to other systems in the world, and user data rates of these systems are very high, up to 30 Mb/s. These systems cannot provide wide coverage areas; nor can they provide services in vehicle environments, and the main application is limited to a "hot spot" (i.e., covering indoors and premises). Prototype systems of millimeter-wave wireless LANs have been developed to demonstrate feasibility of 60 GHz WLAN systems with asynchronous transfer mode (ATM) or 100-base Ethernet interfaces operating at data rates up to 155 Mb/s [8, 9].

Intelligent Transport Systems

The ITS is a new transport system, which comprises an advanced information and telecommunications network for users, roads, and vehicles [10, 11]. The ITS is greatly expected to contribute much to solving problems such as traffic accidents and congestion. Not only solving such problems, ITS will provide multimedia services for drivers and passengers.

The ITS consists of nine development areas, including advances in navigation systems, electronic toll collection system (ETC), assistance for safe



■ **Figure 6.** *4G-cellular system architecture.*

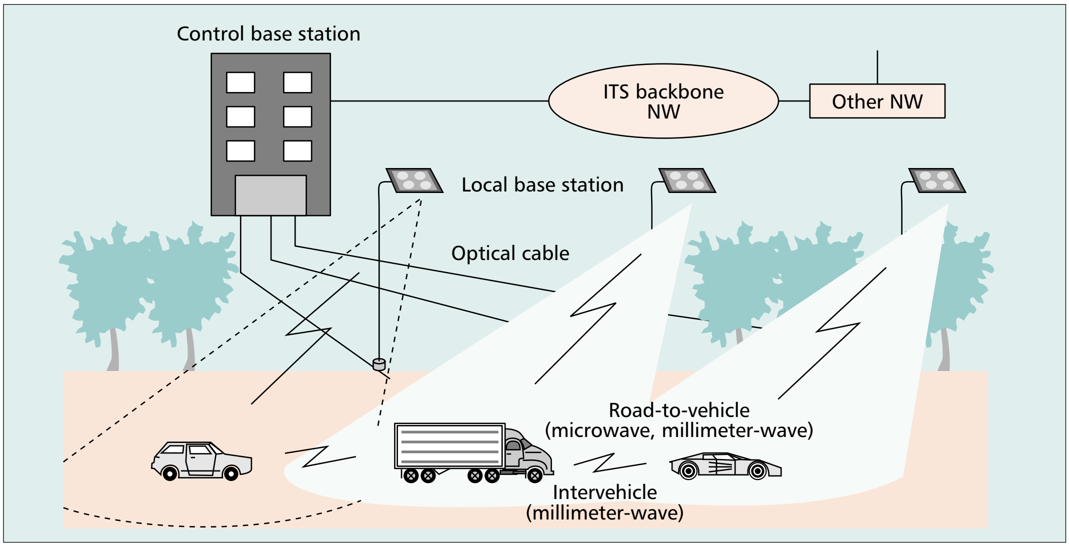


Figure 7. *The basic concept of ITS communications.*

The intelligent transport system (ITS) is a new transport system, which is comprised of an advanced information and telecommunications network for users, roads and vehicles

driving, and so forth. The first step of the ITS is ETC, which is a nonstop toll collection system using two pairs of 5.8 GHz bands. The ITS is appreciated as one of the most promising multimedia businesses, and the potential market is estimated at about 50 trillion yen. Telecommunications systems related to the ITS are divided into *road-vehicle communications* and *intervehicle communications*. The most important infrastructure is road-vehicle communications, in which many base stations are equipped along the trunk road in order to communicate with vehicles, and several control stations manage these base stations. Figure 7 shows the basic concept of ITS communications. Along the roadside, optical fiber networks will be implemented to convey high-speed data to access points, which will connect fiber and wireless links for moving vehicles. In ITSes, radio on fiber is one of the most important key technologies.

High Altitude Stratospheric Platform Station Systems

A concept of a high-data-rate wireless access network using HAPS is shown in Fig. 8. The HAPS system is very attractive for multimedia communications. It has the potential to become the third communications infrastructure after terrestrial and satellite communications [12, 13]. The platforms keep their positions at about 20 km high in the stratosphere. By optical intercommunication links, they make a mesh-like network in the sky.

A broadband access link is the link between the platform station and the user station. The frequency band of the access link is expected to use a millimeter-wave band. At the recent World Radio Congress (WRC) in Geneva, Switzerland, November 1997, a 600 MHz bandwidth in a 48/47 GHz band was allocated for the fixed services of high-altitude stations.

This system can support various types of user terminals, fixed terminals, portable terminals, and mobile terminals. The typical bit rate of the access link is 25 Mb/s for most fixed and portable terminals, while a several hundred megabits per second link is available for limited fixed terminals with antennas larger than the typical ones. Because of using millimeter-wave bands, a small antenna with high gain is feasible. For example, a bit rate of 144 kb/s can be provided for vehicles by only a 5 cm dish antenna with 20 dBi gain.

Key Technologies

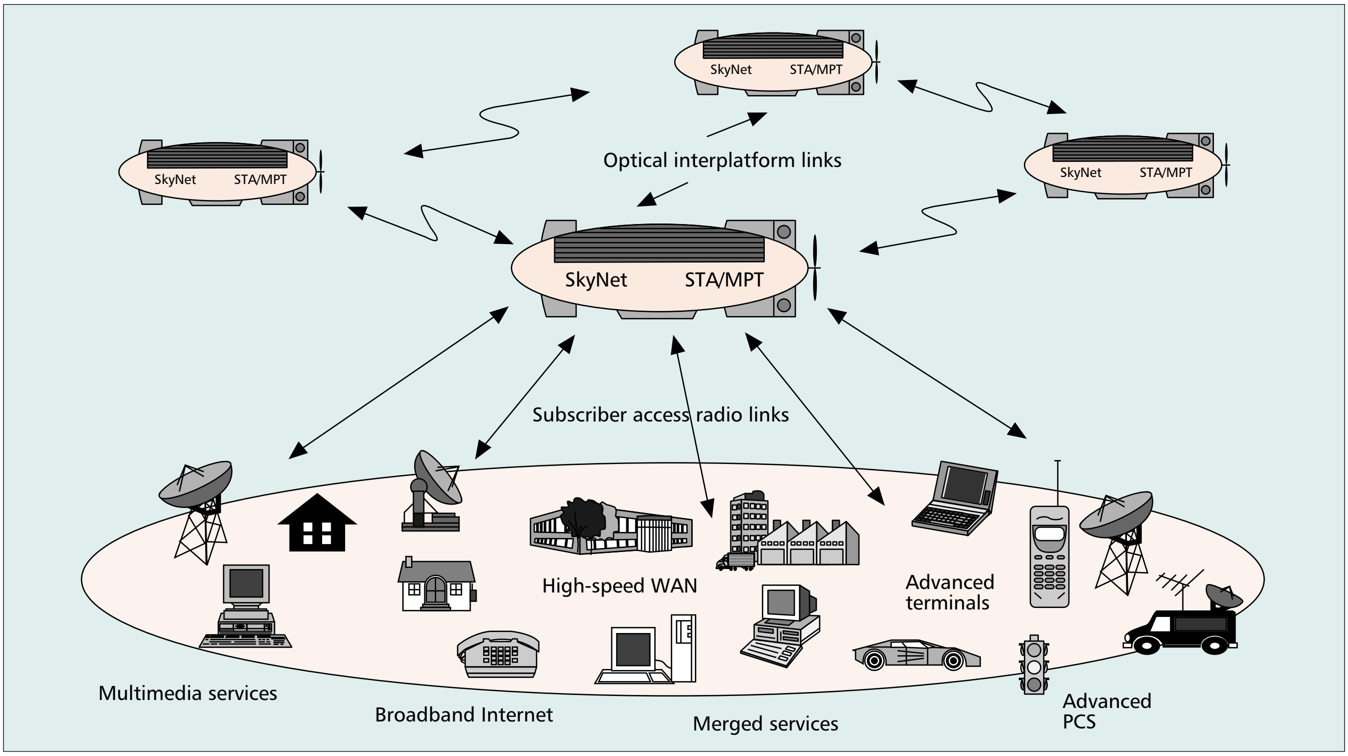
In this section, key technologies of future systems are mentioned and summarized in Fig. 9.

Modulation and Signal Transmission

High-speed mobile transmission in higher frequency bands suffers severely from frequency-selective fading. Robust modulation/demodulation schemes should be studied to find a way to withstand frequency-selective fading. Multiple carrier modulation schemes, including orthogonal frequency-division multiplex (OFDM) and single-carrier modulation with adaptive equalizers, are candidates [14]. Another important demand for high-speed transmission is an extremely low required E_b/N_0 value. Since the noise bandwidth at the receiver is wide in a high-speed system, low E_b/N_0 values are required to achieve reasonable area coverage. High-speed transmitter power control (TPC) to mitigate Rayleigh fading and a pilot-added fast-tracking coherent demodulator are effective ways to achieve this goal [15]. Frequency domain anti-fading measures such as RAKE combining spread spectrum receivers or frequency hopping techniques are also necessary. High-performance forward error correction (FEC) such as turbo-coding [15], automatic repeat request (ARQ), and diversity are important factors in establishing high-speed large-capacity networks. All these measures to improve the required E_b/N_0 value are also effective in increasing capacity.

Propagation

In radio propagation and link budget design, the mobile propagation characteristics of microwaves to consider for use in the future and broadband signal transmission characteristics with the maxi-



■ **Figure 8.** *The concept of a HAPS wireless access network.*

mum of 20 Mb/s are subjects for further study. Propagation studies at 60 GHz to analyze the characteristics of indoor multipath propagation found that the use of circular polarization and a directive antenna is effective to suppress the effects of multipath and therefore significantly improve high-speed digital transmission characteristics [16]. In addition to these indoor multipath propagation experiments, measurements for characterizing various indoor construction materials have also been conducted in order to study their reflection and transmission characteristics, required for analyzing indoor multipath characteristics and modeling indoor propagation [17]. Rain attenuation probability characteristics in the sub-millimeter-wave band are research subjects.

SOFTWARE RADIO

Software radio technology is one solution in order to realize coexistence of several mobile telecommunication services. Software programs describe all telecommunication components in digital signal processing language, and adequate software programs are downloaded to digital signal processing hardware (DSPH) such as field programmable gate arrays (FPGAs) and digital signaling processors (DSPs) in accordance with the users' favorite wireless telecommunications system. By using software radio technologies, we may use only one terminal in different systems [18]. However, in order to realize such a software radio technology, there remain several problems, including the following:

- The large volume of software depends on the required telecommunication systems.
- In the implementation of the software in DSPH, many proprietary techniques exist. If a download-type-software radio system is realized, all these confidential techniques will leak out.

In order to overcome these problems, a new configuration method for software radio systems has been proposed, which is called a *parameter-controlled* software radio system [19]. Moreover, an experimental prototype, which realizes three mode real-time radio communication systems — ETC, Global Positioning System (GPS), and Personal Handyphone System (PHS) — was developed using the proposed scheme, and evaluated the transmission and configuration performance [20].

SMART ANTENNAS

Smart antennas have intelligent functions such as suppressions of interference signals, auto tracking of desired signals, and digital beamforming with adaptive space-time processing algorithms. Because of these characteristics, smart antennas have been considered key technologies for future mobile communications [21, 22] One type of smart antennas, adaptive array antennas (AAAs), are expected to reduce interference and lower transmission power [23]. Interference canceling with an AAA and an interference canceling equalizer (ICE) is promising to increase capacity. One problem in making these candidates feasible is implementing a fading channel estimation circuit. Since channel estimation requires many calculations, the estimation algorithm and processor configuration are important issues to address.

RADIO ON FIBER

Radio on fiber (ROF) technologies have been considered very attractive and important subjects of R&D, especially in implementing the road-vehicle communications systems of the ITS. By

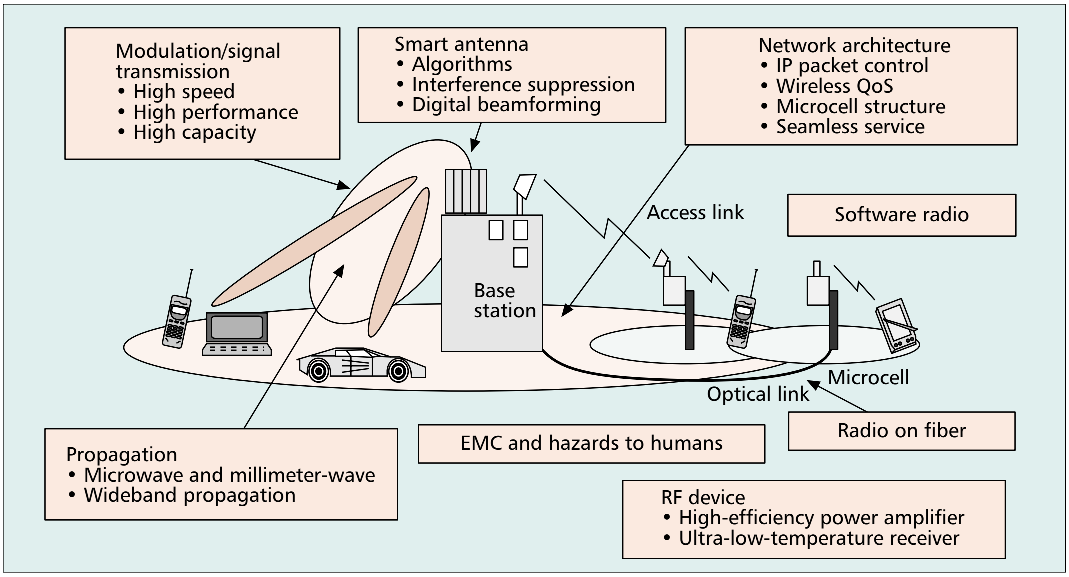


Figure 9. *Key technologies in wireless access networks.*

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using ROF, we can transmit a broadband radio signal with low loss. Until now, a 60 GHz radio signal can be transmitted through the optical fiber. By using ROF technologies, we transmit multiservice radio signals through an optical fiber. In Japan many wireless services are available, such as digital cellular (PDC) on 800 MHz and 1.5 GHz bands, PHS on 1.9 GHz, VICS service on 2.5 GHz band, FM commercial radio on 76–90 MHz, TV broadcasting on 90–770 MHz, and ETC on 5.8 GHz. In order to decrease the number of air interfaces, a new transmitting technique based on ROF has been proposed [24].

Network Architecture and Protocol

The main subjects here include an air interface protocol suitable for IP packet transmission, location registration, and base station network configuration, wireless QoS control, network configuration that facilitates the introduction of microcells, and integrated seamless service control with 3G cellular and wireless LANs.

In order to accommodate the enormous amount of traffic in dense urban areas, a spatial frequency reuse strategy is key. At this point, seamless geographical coverage with a microcellular structure is better than a hot-spot coverage strategy because the former can avoid geographical concentration of traffic.

Intelligent wireless resource management is a key technique in handling multimedia traffic. For high-speed mobile communications, not only the spectrum resource, but also the transmission power available in the base station and mobile station restricts the user's transmission speed. A wireless resource manager should check the available resources, the quality of the forward and reverse links, the application type and user class in QoS services, and then assign the appropriate forward and reverse link speeds and transmitting power to the user.

The IP-technology-based network structure can handle IP packet traffic efficiently and at low cost. It can also easily provide the broadcast and multicast functions essential for push-type information services. The key issue is a routing/handover scheme and an authentication strategy that does not affect mobility or throughput.

Devices

Important components in high-frequency systems are RF circuits such as high-efficiency power amplifiers, ultra-low-temperature compact receiver amplifiers, and antennas. In particular, realization of millimeter-wave communication systems greatly depends on whether suitable devices are available for operation in high-frequency bands. Millimeter-wave components traditionally have been based on two-terminal devices and waveguide as active elements and transmission media, respectively. However, waveguide has disadvantages of bulkiness, heaviness, and rigidity. A remarkable technical advancement of high-speed three-terminal devices in millimeter-wave bands in the last two decades has changed components to integrated-circuit-based planar structures. Compared with a waveguide, they have advantages of compactness, light weight, and suitability for commercial production.

Indium phosphate (InP)-based high-electron-mobility transistors (HEMTs) have achieved a record high maximum oscillation frequency (fmax) of 600 GHz [25] and superior low-noise performance from the microwave to millimeter-wave frequency ranges [26]. Multistage millimeter-wave low noise amplifiers (LNAs) have shown high performance (1.7 dB NF at 62 GHz) [27].

Antennas operating in millimeter-wave bands are also key devices in future mobile communications. To avoid large attenuation in feed circuits in millimeter-wave bands, various types of antennas have been investigated and developed. Examples are a circularly polarized omnidirectional cylindrical slot-array antenna for base stations, and a dielectric loaded Gaussian beam antenna integrated with MMICs [28].

EMC and Hazards to Humans

Evaluations of electromagnetic compatibility (EMC) and hazards to humans are very important

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in frequency bands, especially in higher frequency bands such as microwave and millimeter-wave.

CONCLUSION

This article discusses future-generation mobile communications systems and key technologies. The forthcoming mobile communications systems are expected to provide a wide variety of services, from high-quality voice to high-definition video through high-data-rate wireless channels anywhere in the world. High data rates require broad frequency bands, and sufficient broadband can be achieved in higher frequency bands such as microwave, Ka-band, and millimeter-wave. These broadband wireless channels have to be connected to broadband fixed networks such as the Internet and local area networks.

Future generations of systems will include not only cellular phones, but also many new types of communications systems. The future systems under discussion are 4G-cellular, microwave and millimeter-wave broadband access, intelligent transport systems, and high altitude platform station systems. The key terms in future generations of mobile communications are multimedia communications, wireless access to broadband fixed networks, and seamless roaming among different systems.

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