Beyond 3G: Vision, Requirements, and Enabling Technologies

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ABSTRACT

This article introduces the vision and requirements for future development of mobile communications systems, and discusses several key enabling technologies considered important to realize this vision in real-world systems.

INTRODUCTION

The third-generation (3G) International Mobile Telecommunications 2000 (IMT-2000) has started to be deployed, and its service has just begun in some countries. However, even before its deployment, its enhancement activity had already started and has been actively pursued in the Third Generation Partnership Project (3GPP) [1]. Furthermore, in various fora and organizations for wireless research, such as the Wireless World Research Forum (WWRF) and International Telecommunication Union (ITU), there have been active discussions about systems beyond 3G to be deployed around 2010 [2, 3]. These recent activities are quite appropriate when we recall that research in 3G systems began more than 10 years ago, and consider the explosive growth rate of the mobile communication market in recent years. According to [3], the number of mobile subscribers worldwide increased from 300 million in 1997 to 800 million in 2001, as shown in Fig. 1. It is predicted that by 2010 there will be 1700 million subscribers worldwide.

Such growth is driven by increasing user expectations for mobile services. Users will demand more multimedia services, and expect new applications and services that are ubiquitous and customized to individual needs. In order to meet rising expectations, telecommunications services will be integrated and converged in the future. For example, digital broadcasting and commercial wireless services will be integrated to create new value-added services and bring enormous benefits to both end users and service providers. To achieve this goal, the next-generation mobile telecommunications system will migrate in two ways: evolution and revolution. Evolution corresponds to an upgraded IMT-2000 system, while revolution corresponds to newly developed systems. The vision required for such services and systems has already been suggested in ITU — Radiocommunication Standardization Sector (ITU-R) and Telecommunication Standardization Sector (ITU-T) reports, and will guide research and development of the next-generation wireless communications system.

In this article, we briefly review the ITU-R's vision and summarize its requirements. We then discuss some key enabling technologies important for future developments of mobile communications: modulation and multiple access schemes, multiple antenna techniques, and an IP-based network.

VISION AND REQUIREMENTS

The ITU-R Assembly recently approved Question ITU-R 229/8 on the future development of IMT-2000 and systems beyond IMT-2000 [3]. According to its vision, IMT-2000 will continue to evolve and support new applications, products, and services. It is anticipated that the capabilities of the IMT-2000 terrestrial radio interfaces will be extended up to approximately 30 Mb/s by around 2005. In addition to this evolutionary development of IMT-2000, ITU envisions a new system, possibly based on a *new* radio access technology, called systems beyond IMT-2000 around 2010. This will complement the enhanced IMT-2000 systems and other radio systems. The new radio access will support up to approximately 100 Mb/s peak data rate for high mobility and up to approximately 1 Gb/s for low mobility. These data rates will be shared among all active users connected to the same radio resource. It is possible that the peak data rate in the upstream will be different from that in the downstream. Due to the high data rate requirements, additional spectrum will be needed in the future. It is anticipated that new spectrum for systems beyond IMT-2000 will be identified at WRC '07 if WRC '03 approves it for the WRC '07 agenda.

The ITU-R vision also describes how various radio access systems will coexist in a harmonious way to provide integrated services. In the vision,

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relationships in communications are classified into three different levels: personal area networks (PANs), immediate environments, and communications via networks. Furthermore, satellite, wireless LAN (WLAN), digital broadcast, cellular, and other access systems will be connected to provide integrated and seamless services via a common IP-based core network. The different access systems are organized in a layered structure according to their application areas, cell ranges, and radio environments. This allows a flexible and scalable environment for system deployment. Seamless interworking between the different access systems will be performed by vertical handover or session continuation. The different layers correspond to the distribution layer comprising digital broadcast systems, the cellular layer comprising several cell layers, the hot spot layer for very high data rate applications, the personal network layer for short-range communications, and the fixed layer for the fixed access system.

In order to satisfy the above vision, requirements for the future wireless communications systems can be summarized as follows:

- High data rate and reduction of data transmission cost per bit
- IP-based network
- Seamless connections
- Service integration
- Short delay in handover and packet transmission

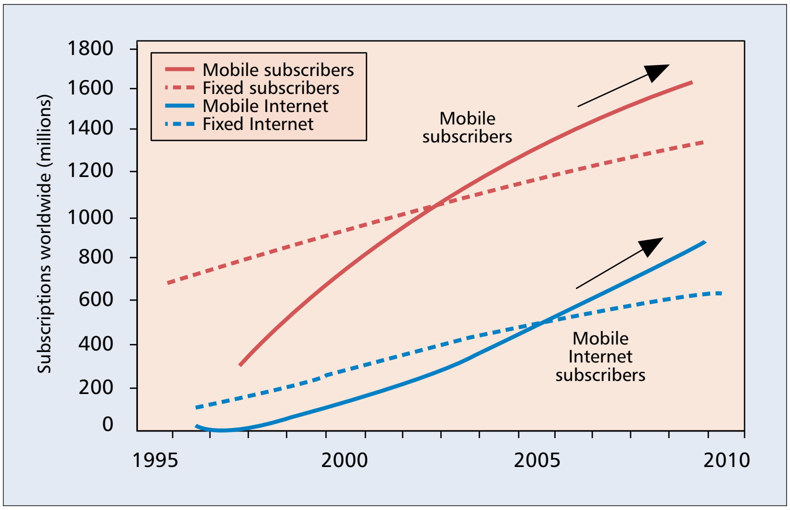


Figure 1. *Global growth of mobile and fixed subscribers [3].*

Enabling Technologies

In order to satisfy the high data rate requirement and efficiently support multimedia services, the modulation and multiple access scheme must be much more spectrally efficient and flexible than those used in current mobile systems, with greater immunity against severe frequency selective fading of broader signal bandwidth. Also, multiple antenna technologies are considered indispensable in achieving high spectral efficiency. Finally, a scalable network based on IP is key to supporting seamless connection and service integration.

Modulation and Multiple Access Scheme

The broadband channel undergoes severe multipath fading, and the equalizer in a conventional single-carrier modulation scheme becomes prohibitively complex to implement. Orthogonal frequency-division multiplexing (OFDM) is robust against severe multipath fading and can be efficiently implemented [4]. In OFDM, the entire signal bandwidth is divided into a number of narrow bands or orthogonal subcarriers, and the signal is transmitted in the narrow bands in parallel. This is done by performing an inverse discrete Fourier transform (IDFT) on the data stream at the transmitter. A cyclic prefix is inserted at each IDFT block to prevent interference between blocks in received signal and preserve orthogonality of subcarriers. Also, the IDFT size is chosen such that each narrow band undergoes flat fading. After performing DFT on the received signal, one tap equalizer for each subcarrier is sufficient to compensate for multipath fading. OFDM has been chosen as a standard method in digital audio/video broadcasting and broadband WLAN applications.

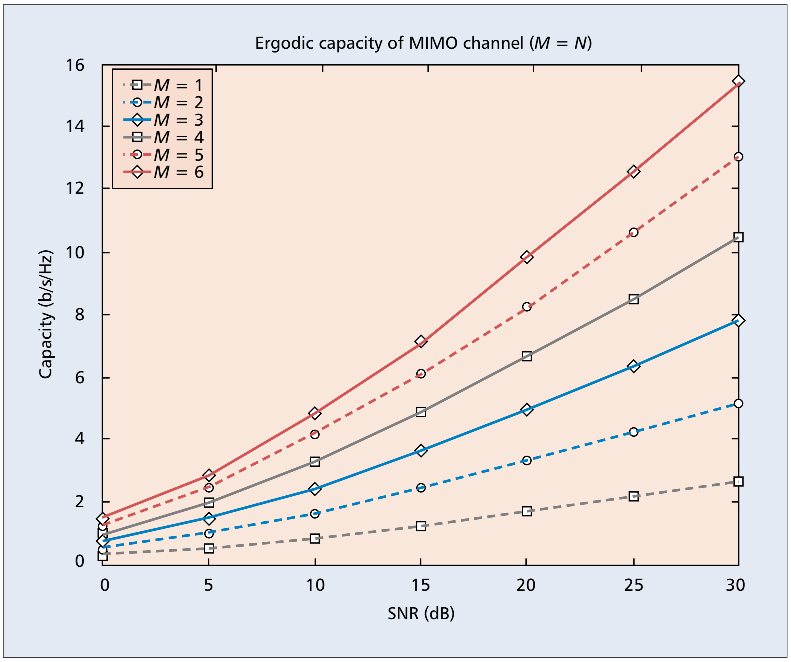
The multiple access scheme for systems beyond IMT-2000 must be highly flexible and efficient in order to support multimedia services with various quality of service (QoS) requirements and attain a frequency reuse factor of one. To this end, various methods of combining OFDM with multiple access concepts such as code-division multiple access (CDMA) and/or time-division multiple access (TDMA) have been investigated; among them, multicarrier CDMA (MC-CDMA) and frequency hopping OFDMA (FH-OFDMA) are two most promising candidates for future-generation mobile communications [5].

In MC-CDMA, user data are spread by different orthogonal or near orthogonal codes over the frequency domain, and more than one user occupy the same set of frequencies at the same time. The spreading helps improve immunity against intercell interference and obtains a frequency diversity effect. However, while the orthogonality of the code for different users can be preserved in the downlink, the orthogonality breaks up completely in the uplink because different user signals undergo different multipath fading.

In FH-OFDMA, users within the same cell are allocated a disjoint set of subcarriers. The hopping patterns for different users are usually designed in such a way that they are mutually orthogonal within the same cell, and interference from other cells is maintained below some levels. Therefore, an FH-OFDMA system does not suffer from intracell interference under an ideal frequency and timing synchronization condition. Furthermore, frequency hopping offers frequency diversity and intercell interference averaging effects. The intercell interference can be reduced even further when information about the status of adjacent cells is combined with frequency hopping.

Multiple Antenna Techniques

Teletar demonstrated the fact that using multiple antennas at both transmitter and receiver can dramatically increase channel capacity while



■ **Figure 2.** *Ergodic capacity vs. SNR, where* M *denotes the number of antennas at transmitter and receiver [6].*

the total transmit power is held constant, as shown in Fig. 2 [6]. Since his investigation, many methodologies with multiple antennas have been researched.

Bell Laboratories' layered space time (BLAST) technique attempts to obtain a theoretical capacity limit under a rich scattering environment [7]. The multiple antenna channel forms, in effect, independent information paths or spatial multiplexing channels. Its capacity increases linearly with the number of spatial multiplexing paths formed. However, when the channels of the individual antennas are correlated with one another, the independent information paths are reduced in number and capacity, reducing the overall channel capacity. Therefore, for an outdoor environment where line of sight (LOS) exits, since the channels tend to be highly correlated, this scheme may not achieve the high data rate hoped for. Furthermore, this technique is sensitive to channel estimation errors.

As an alternative, diversity methods have been developed. In wireless communications, the diversity effect can be obtained from temporal, frequency, and antenna diversities. The basic idea of antenna diversity is to send replicas of a signal in each antenna in a coordinated way so that the detrimental effect of a weak signal channel is reduced. Among a number of antenna diversity methods, the Alamouti method is very simple to implement and does not need any channel information at the transmitter [8]. This is an example of space-time block code (STBC) for two transmit antennas, and the simplicity of the receiver is attributed to the orthogonal nature of the code. However, it is shown that for three or more antennas with complex signal constellations, no orthogonal STBC design exists that does not sacrifice either the data rate or the diversity effect [9]. Thus, for a large number of transmit antennas, other approaches have been developed by combining various channel codes. These methods achieve coding gain in addition to diversity gain. When the transmitter already knows the channel, the diversity can also be achieved by precompensating for the channel at the transmitter. For a frequency-division duplex (FDD) system, how to efficiently implement the transmitter diversity concept under a given feedback constraint is important.

By carefully controlling the signal phase of each antenna, a directed beam can be formed in multiple transmitter or receiver antennas. The direction of the beam can be controlled to point toward the desired signal and at the same time reject interference signals, so overall signal-to-interference and noise ratio (SINR) can be improved [10]. Transmitter beamforming also requires feedback of the channel state information to the transmitter, and its performance deteriorates when the channel varies quickly.

Until now, the use of multiple antennas to increase the throughput in the standardization of 3G systems has been of limited extent. However, in order to attain the high data rate target of systems beyond IMT-2000 with scarce bandwidth resources, we will have to utilize more antennas at both transmitter and receiver. In this case, the various multiple antenna techniques must be chosen carefully by considering the communication environment. In indoor environments with rich scattering effects, the channel is well suited to multiplexing techniques such as BLAST. In high-speed outdoor systems with high Doppler spread, where channel estimation error is high and feedback of channel state information is difficult, space time coding is preferred. However, since the diversity gain of space time code is saturated for more than four antennas, a careful combination of diversity and multiplexing techniques is more advantageous in attaining higher throughput [11]. In addition, a noncoherent detection scheme is also promising under high Doppler spread [12], and multi-user diversity can increase cell capacity by communicating with users via best instantaneous channel conditions [13].

NETWORKS

Various wireless communications systems will coexist and interwork in the future. Wireless communications systems will be more heterogeneous, and seamless integration of these heterogeneous wireless systems will be important to enable interworking among them. Several proposals have been made to integrate heterogeneous wireless systems based on an IP network. Examples of the proposed IP-based network architectures are the all-IP network in the 3GPP standard, Broadband Radio Access for IP-Based Networks (BRAIN), and Multimedia Integrated Network by Radio Access Innovation (MIRAI). In this subsection we briefly introduce the main characteristics of these architectures, and suggest a new network architecture.

The all-IP network in the 3GPP standard is based on the General Packet Radio Service (GPRS) protocol that was developed to provide packet services to the Global System for Mobile Communications (GSM) [13]. The GPRS serving node utilizes GSM registration and authentication to verify the identity of the data user. The 3GPP access network is interfaced to the core network by a serving GPRS gateway node. Although general IP protocols are employed in the core network, the access network requires private protocols for access network functions.

The BRAIN project is an Information Society Technologies (IST) program [14]. The BRAIN network architecture consists of a BRAIN access network (BAN), BRAIN mobility gateways (BMGs), a BRAIN access router (BAR), and an IP-based core network. The network components are imported from standard Internet Engineering Task Force (IETF) protocols to facilitate network evolution and flexibility. The access network is based on IP, and the access router interfaces the mobile node and access network. The gateway is placed between the access network and the core network.

MIRAI is a Japanese national project under the e-Japan plan for seamless integration of heterogeneous wireless systems [15]. MIRAI architecture is composed of four major building blocks: a mobile host, radio access networks (RANs), a common core network (CCN), and an external IP network. The CCN contains a resource manager (RM) and a mobility manager (MM) for resource and mobility management in the network. Gateway routers act as the interface between the CCN and the external IP network.

All the above networks are currently under development, and are expected to be available by 2010. However, they are based on private RANs to connect user and core networks. Certainly, a private access network can be built to satisfy the QoS requirements of the control and user data, but a private network has several drawbacks that hinder seamless integration of wireless communications systems. The private network undoubtedly requires a high cost for installation and maintenance. The protocol stacks on the control plane are different from one private network to another. Therefore, the network requires a conversion step at gateways between the networks. This can induce a severe communication bottleneck at the gateway, and undermines scalability and seamless integration of a wireless communications system.

To solve these problems, an open architecture based on the public IP network is considered. The open architecture consists of a public IP network, an authentication, authorization, and accounting (AAA) server, a home agent (HA), and radio access points (RAPs), and the network components form a virtual private access network within a public network, as shown in Fig. 3. Functionalities of each component are:

- HA: registration of subscribers and location management of mobiles
- AAA server: management of subscribers' authentication, authorization, and accounting
- RAP: connection point between router and mobile terminal, termination point of radio link function

Control signals between the network components are encapsulated and transmitted in a secure way by, for example, using a virtual private network (VPN) and Resource Reservation Protocol (RSVP), while user data are transmitted directly by the Internet. By communicating through the Internet protocol, the network components perform various control functions such as handover, admission control, resource management, and AAA. For example, each base station has information about its neighboring base stations in a database and can exchange the information with its neighboring base stations for radio resource management and mobility management. A service provider can add a new access point directly to the Internet when necessary and make virtual connections to other access points using a VPN. In this way, a private network is established based on IP without having to build a completely new network and new protocol. In this manner, the network architecture is scalable, and the cost of building a private network is minimized.

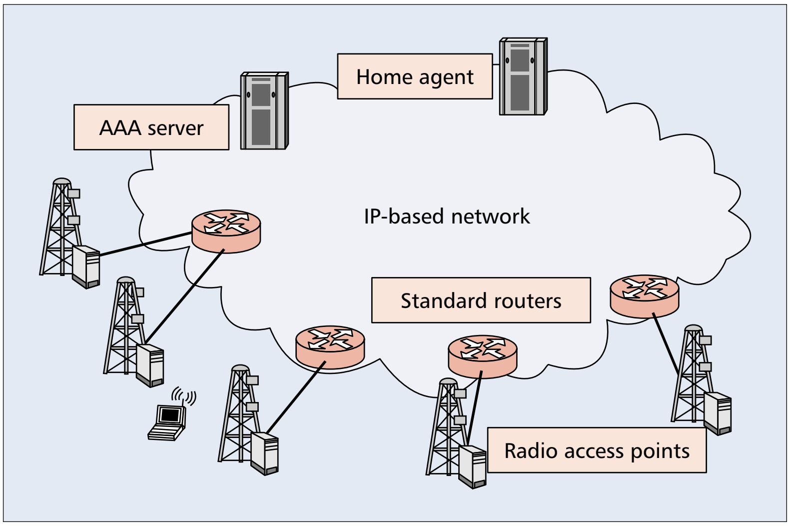


Figure 3. *Open network architecture.*

Conclusions

The future mobile communication systems will develop in two ways: evolution and revolution. The goal of these developments is to provide enhanced services with high data rates, and integrated and converged services with IP-based seamless networks. Some key technologies needed to achieve this goal are discussed: modulation and multiple access schemes, multiple antenna techniques, and a scalable network architecture based on IP.

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