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Challenges of Wireless Communications—IMT-2000 and Beyond—

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SUMMARY Mobile radio and Internet communications services are penetrating our society at an exponential rate of growth. The Internet is the most important driving force towards establishing a multimedia society. Mobile communication systems add an important capability to our communications society, i.e., mobility. The third generation mobile communications system called IMT-2000 is expected to play an important role in this soon-to-arrive multimedia society. Wideband mobile services based on IMT-2000 will soon become a reality (early 2001). First, we look at the trends of wireless access technologies, centering on IMT-2000. Wideband direct sequence code division multiple access (W-CDMA) will be a major component of a global IMT-2000 standard. Then, we address advanced wireless techniques, i.e., interference cancellation and employing an adaptive antenna array, which can enhance W-CDMA at a later date. Finally, requirements are discussed for future wireless techniques that will support a fully mobile multimedia communications society.
key words: *wireless communications, mobile communications systems, IMT-2000, DS-CDMA*

1. Introduction

The rate at which mobile radio and Internet communications services have proliferated throughout our society is striking. Before the introduction of mobile communications systems, communications were only possible from/to fixed places, i.e., houses and offices. Mobile communications have enhanced our communications networks by providing an important capability, i.e., mobility. Mobile communications service started in December 1979 in Japan. For the first 10 years, its growth rate was very low. However, through the liberalization of mobile communications services (1988) and terminal markets (1994), the growth rate of mobile communications services accelerated (Fig. 1).

An important factor that should not be overlooked is the increased utilization efficiency of portable phones (lighter weight, longer talk time, easier-to-use terminals, etc.) made possible by advanced LSI technology (Fig. 2). At the end of July 1999, the number of subscribers of cellular (mainly digital) and Personal Handyphone System (PHS) services exceeded 50 million; this number is equivalent to a penetration rate of 40%. On the other hand, the number of fixed telephone users has declined to 58 million (its peak was 61 million in 1997). The number of mobile communications users is expected to overtake that of fixed telephone users within a year. Similar rapid growth rates in mobile communications services are evident worldwide. People want to communicate with people not with places. This is only possible through the aid of mobile communications technology. Mobile communications is now a necessity, particularly for our younger generation.

The Internet has proven itself to be a true driving force towards establishing a multimedia society. The third generation mobile communications system, called International Telecommunication Systems (IMT)-2000 in the International Telecommunication Union (ITU), is expected to play an important role in this soon-to-arrive multimedia society.

This paper discusses the trends of wireless access techniques, centering on IMT-2000. Wideband direct sequence code division multiple access (Wideband DS-CDMA or W-CDMA) will play a major role in establishing a global IMT-2000 standard. W-CDMA will be briefly overviewed. This paper also addresses interference cancellation and employing an adaptive antenna array, which can enhance W-CDMA at a later date. Finally, requirements for future wireless techniques supporting a full mobile multimedia communications soci-

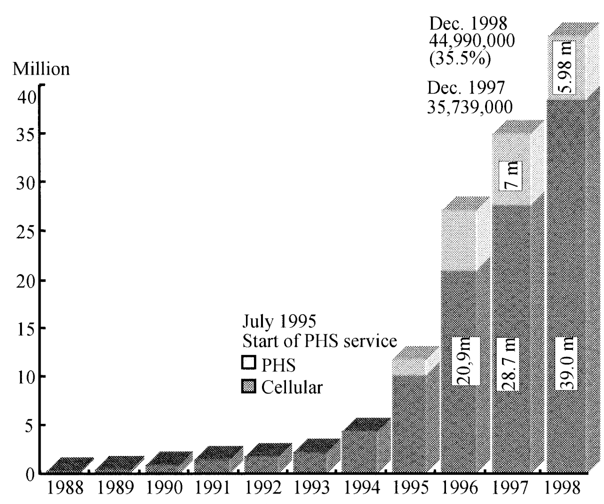

Fig. 1 Growth of mobile communications in Japan.

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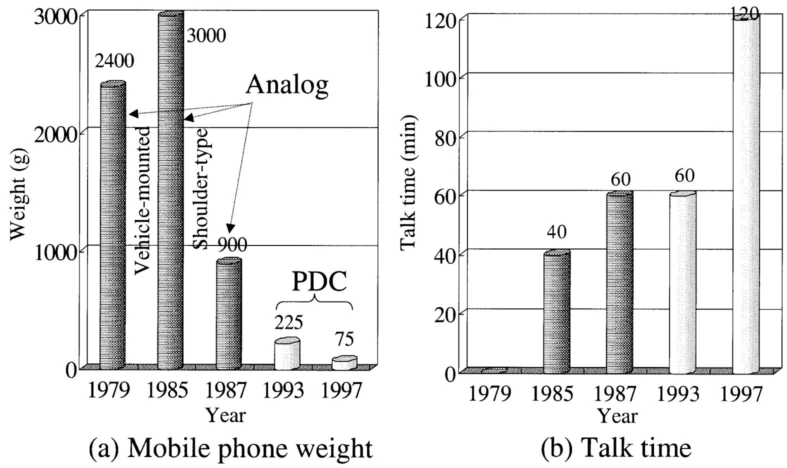

Fig. 2 Weight and talk time of mobile phones [1].

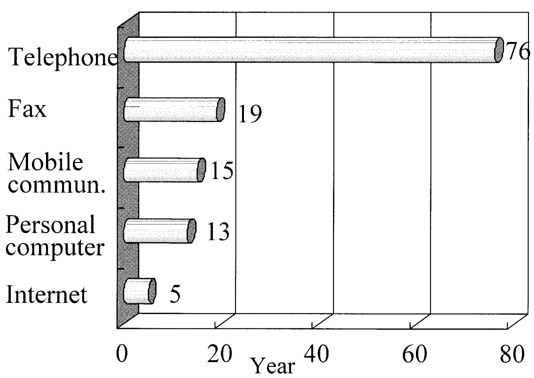

Fig. 3 Time taken to arrive at 10% penetration (household) point [2].

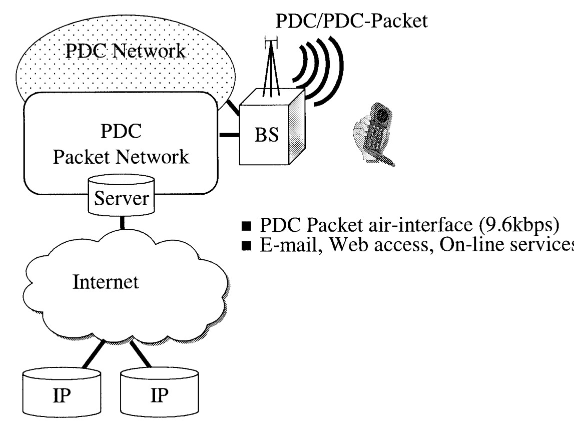

Fig. 4 Multimedia-type "*i*-mode service" over PDC-Packet Networks [3].

ety are discussed.

2. Bridging the Expanse of Mobile Multimedia

In fixed networks, voice conversation was a long-time dominant service, but the introduction of Internet communications services has changed or is changing our society. In Japan, the amount of Internet traffic is expected to surpass that of telephone traffic in 2001. Through the Internet, users can easily access WWW sites to retrieve various types of information including images, enjoy on-line shopping and trading services, and instantly exchange electronic mail messages instead of using traditional postal services. Information casting services represent another type of promising service. Internet services have been gaining popularity in our society with the aid of advancements in computer and data communication technologies.

Figure 3 shows just how fast mobile, personal computers, and the Internet have grown in Japan [2]. It is evident that Internet services have spread throughout our society at a much faster speed than the other services. Internet services took only 5 years to approach the 10% penetration (household) mark from the start of its commercial service (penetration rate was 11% by March 1999), while personal computer took 13 years (Fig. 3) to reach the same level.

Recently, mobile communications services have shifted their focus from only voice conversation to electronic mailing and Internet connections in line with the increasing popularity of Internet communications in fixed networks. Our ultimate goal is to communicate any information with anyone, at anytime, from anywhere. It is clear that a combination of mobile communications, personal computers, and Internet services will drive our society to evolve into a mobile multimedia communications society in the 21st century.

The first steps toward bridging the expanse from today's society to the mobile multimedia communications society of the 21st century is seen in a new Internet access service called "*i*-mode service," which is provided over PDC-Packet Networks (Fig. 4) [3]. Its services include e-mailing, Web browsing, and various types of on-line services ranging from transactions to entertainment (Fig. 5). Since its introduction in Feb.

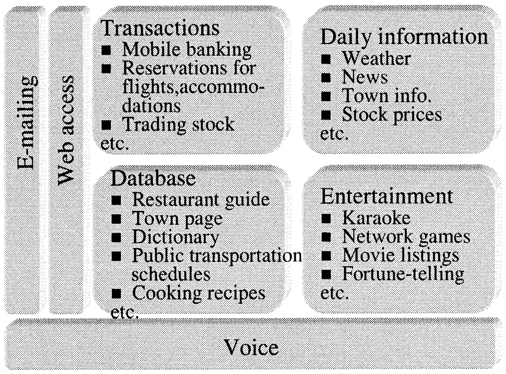

Fig. 5 "*i*-mode service" contents [3].

Table 1 Second generation systems.

	PDC	GSM	TIA(USA)	
Frequency (MHz)	800/1500	800/1900	900/1800/1900	
Wireless access	TDMA	TDMA	TDMA	CDMA
Carrier spacing (kHz)	25	200	60	1250
No. of ch/ carrier	6	8	3	Max. 64 (DL)
Speech codec (kbps)	5.6	22.8	13	8 (variable rate)
			IS54/136	IS95

1999, its popularity has blossomed (over 1 million users in July 1999). Now, it seems that a mobile phone is not just for conversation, but will become a communication tool that enables various types of electronic communications for private as well as business use.

3. Trends in Wireless Access Technology

Looking back through mobile communications history, we see the initial deployment of the first generation mobile communications systems, AMPS, TACS, NTT, etc., around 1980. They employed analog FM wireless access using frequency division multiple access (FDMA) with the channel spacing of around 25–30 kHz [4]. Then, the second generation systems, IS54, GSM, and PDC, were deployed in the 1990's, all of which adopted time division multiple access (TDMA) with the channel spacing ranging from 25 to 200 kHz [4]. Table 1 lists the second generation digital cellular systems. Later, a new wireless access technique, DS-CDMA, appeared [5]. Its channel spacing is much wider, i.e. 1250 kHz, compared to other second generation systems. In DS-CDMA, unlike in FDMA and TDMA, all users share the same frequency-band and time, but employ different spreading code sequences to separate each user.

Wireless DS-CDMA has numerous advantages over FDMA and TDMA, e.g., single frequency reuse, soft and softer hand-off, and exploitation of multipath fading through Rake combining. Since the appearance of the wireless DS-CDMA technique, a heated debate has continued regarding which access technique, TDMA or DS-CDMA, provides a larger link capacity (it is quite a difficult task to conclude this debate since the link capacities offered by these techniques are different under different assumptions).

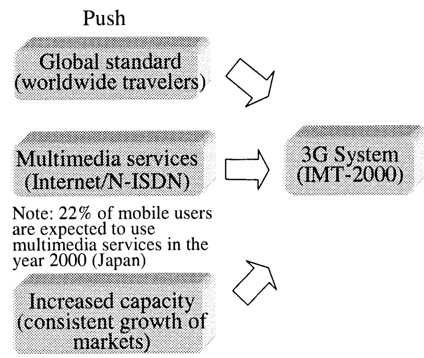

Fig. 6 Preparing for a wireless multimedia society.

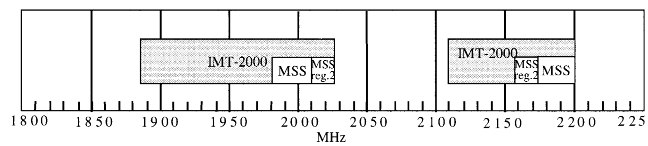

Fig. 7 Frequency allocation by ITU.

All of the first and second generation systems are designed so that they can be optimized for basic services, i.e., voice, facsimile, and voice-band data. However, in the coming multimedia communications society, supporting multi-rate communications (the data rate range of which is significantly wide, e.g., as low as 8 kbps to a couple of Mbps) is a paramount requirement. In order to cope with the still-continuing rapid growth of mobile communications, the important issue of capacity must also be addressed. Furthermore, establishing a global standard is becoming increasingly important in the 21st century, when more and more people will travel around the world for businesses and leisure (second generation system standards are, more or less, regional standards).

In summary, there are three strong reasons for developing the third generation mobile communications IMT-2000: mobile multimedia, higher capacity, and a global standard (Fig. 6). The frequency bands allocated to the IMT-2000 by the ITU are indicated in Fig. 7. The 2-GHz bands are used. IMT-2000 is expected to be deployed worldwide starting around 2001–2002. Information rates of up to 2 Mbps and the same quality as fixed networks are its target, but it is a quite difficult challenge to realize these in harsh mobile communications channels.

Figure 8 summarizes the evolution path from the first to third generation systems. Interestingly, every

1980's 1st Gen.	1990's 2nd Gen.	2000's IMT-2000
Analog	Digital	Wideband digital
Voice	Voice/data	Voice/multimedia
2.4kbps	9.6-28.8k	144k; vehicular 384k; pedestrian 2000k; indoor
	GSM, PDC, IS95, IS54/136, etc.	Global standard

Fig. 8 Evolution path.

decade, new technology has appeared that enhances the communications capability.

4. W-CDMA Wireless Access

Major services provided by the IMT-2000 system will shift from voice to multimedia communications over the Internet, as indicated by the "*i*-mode service" [3], but at much higher transfer rates. These services will be high-speed Internet/data access and video/high-quality images as well as basic services (voice, fax, and voice-band data). To realize such a system, a new wideband wireless access technique incorporating as many recent technological achievements as possible is necessary. It is commonly accepted that DS-CDMA is quite flexible in providing multi-rate services and can well combat multipath fading (or can exploit the frequency selectivity of multipath channels to improve the transmission quality). For the above reasons, W-CDMA [7] has attracted strong interest over the last 5 years and has been under intensive development [8].

In Japan, the Association of Radio Industries and Businesses (ARIB) started in 1995 a selection process for a wireless access technique and chose W-CDMA in January 1997. Since then, the ARIB has been actively promoting W-CDMA worldwide for its acceptance as a global standard [8]. Table 2 shows the W-CDMA proposal (June 1998) to the ITU. Meanwhile, in Europe, the European Telecommunications Standards Institute (ETSI) arrived at an historic decision in January 1998 to adopt W-CDMA for frequency division duplex (FDD) bands and a hybrid solution of TDMA and CDMA called TD/CDMA for time division duplex (TDD) [7]. Since then, W-CDMA has been recognized as the strongest candidate and its development has been accelerated throughout the world. Eight out of ten proposals submitted to the ITU for terrestrial access technique were based on DS-CDMA.

Intensive harmonization studies are currently under way to establish a global IMT-2000 standard. There will be three operation modes in DS-CDMA: FDD single-carrier, FDD multi-carrier, and TDD. The FDD single-carrier mode will be based on W-CDMA but with a chip rate of 3.84 Mcps. The global IMT-2000 standard will be finalized by the end of 1999 [22].

The important concepts of the original W-CDMA

Table 2 Japan's W-CDMA proposal to the ITU (June 1998).

Bandwidth (MHz)		1.25/ 5/10/20
Chip rate (Mc/s)		1.024/4.096/8.192/16.384
Duplex scheme		FDD and TDD
Spreading	Code	Orthogonal multi-SF code + scramble code
	Modulation (FL/RL)	QPSK/QPSK
Data modulation (FL/RL)		FDD: QPSK/BPSK TDD: QPSK/HQPSK
Data detection	FL:forward link	Coherent detection based on FDD/TDD:TCH dedicated time-multiplexed PL
	RL: reverse link	Coherent detection based on FDD: I/Q multiplexed pilot TDD: Time-multiplexed pilot
Frame length		10 ms
Multi-rate		Variable SF and multicode
Channel coding		Convolutional codes (R=1/3 and 1/2, K=9) Turbo codes
Inter-cell timing		FDD: Asynchronous (Synch. possible) TDD: Synchronous

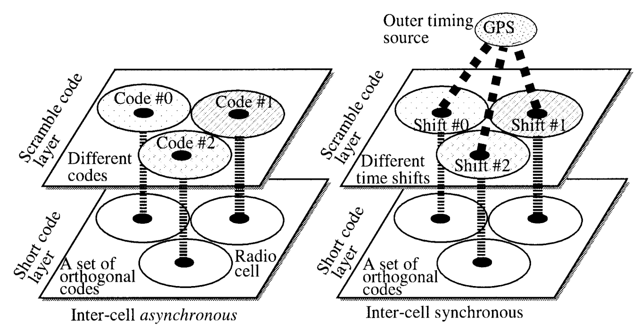

Fig. 9 Inter-cell asynchronous mode.

proposal are the introduction of an inter-cell *asynchronous* mode and the pilot channel associated with each data channel. The former allows easier system deployment from outdoors to indoors because no external timing source, such as the Global Positioning System (GPS) as used in the inter-cell synchronous system (i.e., IS95), is required (Fig. 9). Unlike inter-cell synchronous systems, each different cell site has a unique scramble code sequence assigned to its forward link. The pilot channel makes coherent detection possible on the reverse link. Furthermore, introducing the pilot channel makes it easier to adopt interference cancellation and adaptive antenna array techniques at a later date.

The unique technical features developed thus far for W-CDMA are summarized below.

- Fast cell search algorithm for inter-cell *asynchronous* mode [9].
- Design of orthogonal variable spreading factor (OVSF) codes on forward links [11], [12].
- Coherent Rake receiver design on reverse and forward links [13].
- Signal-to-interference ratio (SIR)-based fast transmit power control (TPC) scheme on reverse and forward

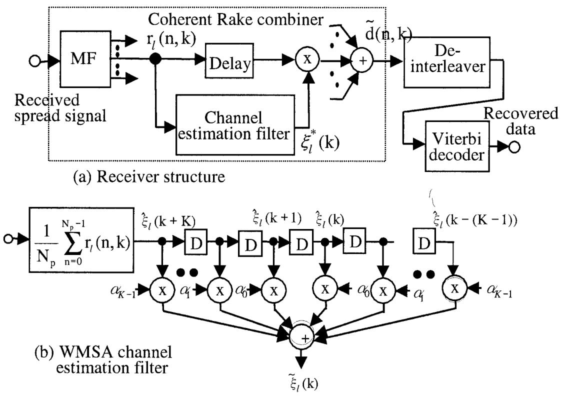

Fig. 10 Coherent Rake receiver.

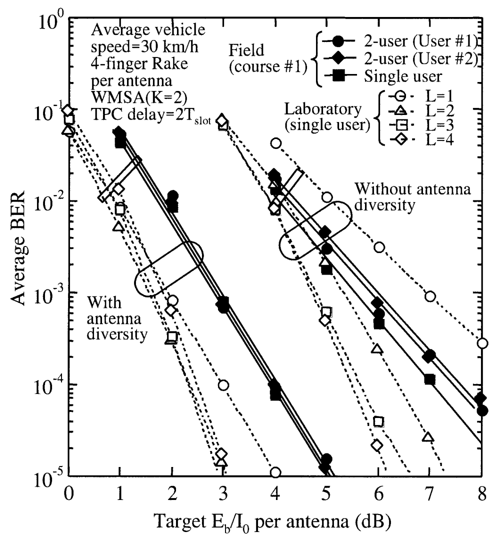

Fig. 11 BER performance with fast TPC and Rake.

links [14].

- Variable rate transmission scheme with blind rate detection [15].

The coherent Rake receiver structure using a 2K-tap weighted multi-slot averaging (WMSA) channel estimation filter [13] is illustrated in Fig. 10. Combined use of fast TPC and coherent Rake yields the greatest improvement in the transmission performance in frequency selective fading environments. Furthermore, SIR-based fast TPC can always minimize the mobile and cell site transmit powers according to variations in the traffic load. Thus, interference to other users in other cells can be reduced, thereby increasing the link capacity.

The measured BER performance (4.096 Mcps, $SF = 64$) of the reverse link plotted in Fig. 11 clearly indicates superior performance of W-CDMA, which increases the link capacity and coverage. By employing antenna diversity reception at the cell site, the average $BER = 10^{-3}$ can be achieved at the required E_b/I_0 of as low as 3 dB per antenna.

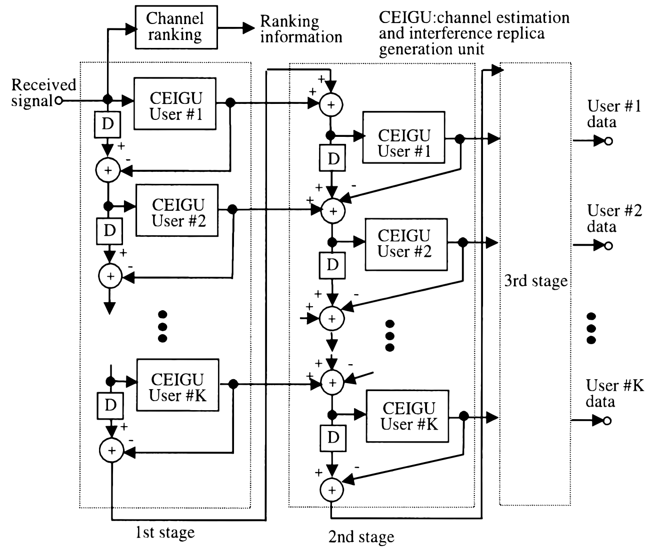

Fig. 12 Multistage IC receiver structure.

In general, the inter-cell asynchronous mode increases cell search time (time spent before finding the best cell site to access). According to our measurements, the 3-step algorithm in [9] allows the cell search to be accomplished within 960 ms at a 90% probability for 512 scramble codes [10].

5. W-CDMA Enhancement

In W-CDMA, the links are interference-limited. Severe multi-access interference (MAI) is produced by high rate users. The most powerful and promising techniques to reduce interference from other users are, probably, interference cancellation and the use of an adaptive antenna array [16]. For the last decade, many theoretical studies have been devoted to these techniques. Now, it is time to implement real hardware to demonstrate their capabilities under real mobile radio propagation channels.

5.1 Interference Cancellation (IC)

Figure 12 illustrates the simplified structure of the multistage IC receiver, which we are developing. Interference replica generation and subtraction are done successively in decreasing order of received signal powers and the channel estimation for each user is updated at succeeding stages to yield improved BER performance [17].

The measured average BER performance (1.024 Mcps, $SF = 16$) plotted in Fig. 13 indicates that, as the average E_b/N_0 increases, the average BER with the IC receiver monotonically falls, while that with the MF receiver approaches an error floor. Even when $K = 16$ users exist (which equals the value of SF), an average BER below 10^{-3} can be achieved at the average E_b/N_0

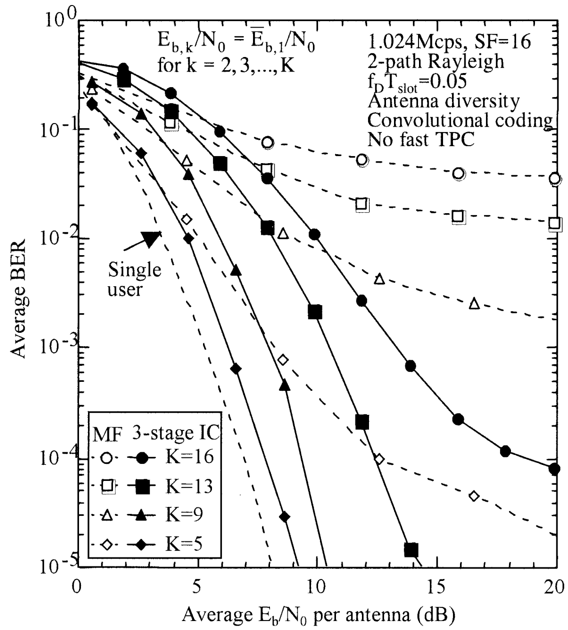

Fig. 13 Measured BER performance with 3-stage IC.

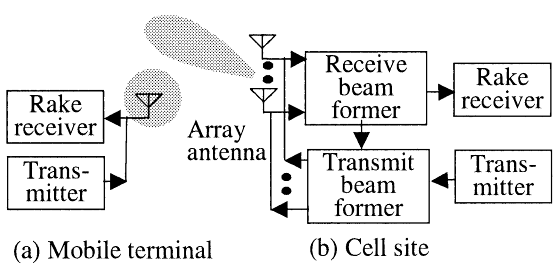

Fig. 14 Adaptive antenna array at cell site.

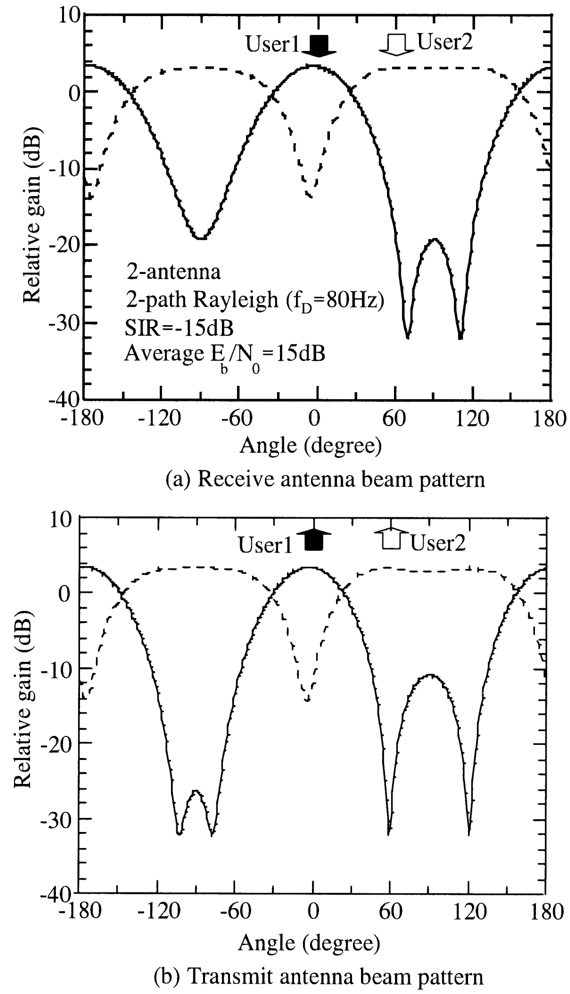

Fig. 15 Receive and transmit antenna beam patterns.

per antenna of about 14 dB. The regenerated interference replica is perturbed by the channel estimation error. Weighting (by a factor of less than one) the regenerated interference replicas before subtraction from the received signal can further improve the BER performance [18].

5.2 Adaptive Antenna Array

Employing the adaptive antenna array is known as space-time processing. In general, this technique requires very complicated signal processing and may not be practical at the present time. The conceptual structure of the W-CDMA adaptive antenna array as a pragmatic solution is illustrated in Fig. 14 [19].

Our design concept completely separates space domain processing and time domain processing. The former is of course, adaptive beam forming and the latter is Rake combining. Furthermore, the adaptive antenna array is adopted only at the cell site. The generated antenna beams need to track only slow changes in the arrival angles and the average powers of the desired and interfering signals so that the average received SIR corresponding to each user can be maximized. It is the Rake combiner's task to track the fast changes in the received signals due to multipath fading and coherently combine the resolved desired signal components to maximize the instantaneous SIR.

One important issue is how to form proper antenna beam patterns for the forward link. Since no instantaneous information regarding the multipath channel parameters is involved in beam forming (thus, its carrier frequency-independent characteristic), the forward link beam forming can use adaptively generated reverse link antenna weights. However, appropriate calibration due to RF circuit amplitude/phase differences among different antenna branches is required.

The measured receive (reverse link) and transmit (forward link) antenna beam patterns are plotted in Fig. 15 for W-CDMA (4.096 Mcps, $SF = 64$). Beam nulls are directed toward the interfering users. Average BER measurements confirmed that adaptive antenna array reception yields superior performance to antenna space diversity reception (reverse link) [20], and adaptive antenna array transmission improves the forward link performance.

6. Beyond IMT-2000

Figure 8 predicts that the fourth generation system will appear around 2010. A major objective is to offer mobile users broadband multimedia services, which will soon be in full force in fixed networks based on next generation Internet technology. Information transferred over the Internet will become increasingly rich, most of the information may contain high-quality still and moving images, and thus, a very high-speed wireless access is necessary.

The fourth generation system should be a broadband wireless system, probably with maximum rates of more than 2 Mbps in a vehicular environment and 10–20 Mbps in stationary-to-pedestrian environments [21]. However, this is quite a difficult technical challenge since wireless channels become quite adverse due to dense multipath environments. The appearance of the dynamically changing microscopic structure of the channel makes high quality data transmission very difficult ("broadband" means as wide as 100 MHz and time resolution is 10 ns equivalent to 3 m in distance). Then, the question here is which wireless access should be adopted.

A debate similar to that concerning IMT-2000 wireless access will undoubtedly occur again. We must consider the significant difference between forward and reverse link rates. This may lead to different wireless access techniques in the forward and reverse links. One promising candidate is hybrid access of orthogonal frequency division multiplex (OFDM) and DS-CDMA combined with packet capability, because both provide a good degree of robustness against multipath fading while ensuring flexibility of multi-rate services. For flexible transmission of various types of data at different rates and different QoS, packet transmission is the most appropriate.

The frequency bands for the fourth generation systems will seem to lie above 3 GHz. We must remember that propagation loss is in proportion to 2.6th power to the carrier frequency, i.e., $\propto f_c^{2.6}$. Therefore, the radio links are not only interference-limited but also severely power-limited. The adaptive antenna array plays a key role in abating this power problem. MAI (or collision) also limits the packet throughput, so packet interference rejection or employing a packet IC receiver is also an important technique. Furthermore, a micro-cell or even a pico-cell structure must be adopted due to the power limitation, requiring the adoption of a relatively fast handoff procedure. It is highly likely that an intelligent packet routing algorithm can resolve this issue.

Due to the micro/pico-cell structure, it is quite difficult for the fourth generation system to provide nationwide coverage. Only high-traffic areas may be covered. Close cooperation with other systems, e.g., IMT-2000 system is thus, necessary. This requires so-called software radio technology to allow a single mobile terminal to access both third and fourth generation systems.

7. Conclusion

This paper overviewed the trends of wireless access techniques and the mobile communications evolution path towards the realization of the mobile multimedia communications society at the beginning of the 21st century. The third generation mobile communications system, IMT-2000, is expected to play an important role in this soon-to-arrive multimedia society.

Also discussed were the technical issues for the fourth generation system, which is expected to emerge around 2010. Broadband wireless access that allows very high-speed packet data transmission, in the order of several tens of Mbps, in dense multipath and vehicular environments is necessary. Since the expected frequency bands are above several GHz, wireless links are not only interference-limited but also severely power-limited, resulting in pico-cell systems. The most promising techniques to lessen this problem are employing the adaptive antenna array and interference cancellation techniques. These are under extensive development for W-CDMA IMT-2000; however, they must be operated under packetized signal conditions.

We will face very difficult but interesting technical challenges in the coming years.

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