Evolution Towards Broadband Wireless Systems

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Abstract

Convergence of wireless communications, computing and Internet is on the way. This will be the driving force towards a wireless multimedia society. In this paper, we will overview today's standards of 3G cellular and wireless LAN systems. There are two trends complementing each other: enhancing the cellular technology (3G WCDMA, cdma2000, etc) and enhancing the wireless LAN technology (HiperLAN, IEEE802.11, HiSWAN, etc). More or less, these two technologies have been evolving independently, but now, coordination between these two have been considered viable to realize broadband communication era. Recently, discussions on 4th generation (4G) wireless systems have been intensified. We will foresee how wireless systems will evolve into global 4G wireless systems. In global 4G wireless, cellular and wireless LAN systems architectures may become closer and will work together via IP core network. Difference between them may be that the former offers seamless handoff for real-time services but the latter offers seamless roaming for nomadic services, focusing on very high-speed data communications close to 1Gbps.

Keywords

Broadband, wireless, cellular, wireless LAN

1. Introduction

Our ultimate goal is to communicate any type of information with anyone, at anytime, from anywhere. This is only possible with the aid of wireless technology. For the last two decades, wireless communication technologies have enhanced our communication networks by providing an important capability, i.e., mobility. There are two types of wireless communications networks; one is the cellular network, which has evolved from mobile telephone, and the other is wireless local area network (LAN), which has emerged from computer network.

The growth rate of cellular services accelerated over the last 10 years. In Japan, the total number of subscribers of cellular and Personal Handyphone System (PHS) services reached close to 57 million by March 2000 and exceeded the number of fixed analog telephone circuit lines. This clearly shows that people want to communicate with people, *not with places*. In line with the increasing popularity of Internet (multimedia) communications in fixed networks, cellular systems are evolving from simply providing traditional voice and fax communications services to providing Internet services. In 2002, about 70% of cellular phones in Internet services. In 2002, about 70% of cellular phones in Japan are equipped with Internet communication functions. Now, it seems that a cellular phone is not just for voice conversation, but is a communication tool for private as well as business use. Local area networks (LAN) for computer communications in business offices, factories, schools, etc., have evolved into wireless LAN to expand their service areas, as cordless phones have been used as wireless replacements for fixed phones. Recently, wireless LAN with much faster data transport and roaming capabilities is also gaining popularity for nomadic services. Wireless LAN covers hot spot areas, e.g., homes, shopping areas, railway stations, airports, hotels, for accessing Internet.

Convergence of wireless communications, computing and Internet is on the way. This will be the driving force towards a wireless multimedia society. Most important are the International Mobile Telecommunication (IMT)-2000 Systems [1], or the 3rd generation (3G) cellular systems, wireless LANs, and wireless IP networks. Present 3G cellular systems and wireless LANs are designed to provide data rates up to 2Mbps (currently 384kbps in service) and 54Mbps. However, their data rate capability will sooner or later become insufficient to cope with the ever-increasing demands for rich multimedia services (broadband communications).

In this paper, we will overview today's standards of 3G cellular and wireless LAN systems. Recently, discussions on 4th generation (4G) wireless systems have been intensified [2]. We will foresee how wireless systems will evolve into global 4G wireless systems.

2. Evolution Into Wideband Communication Era

There are two trends complementing each other to realize the wireless wideband communications era: enhancing the 3G cellular technology (WCDMA, cdma2000, etc) and enhancing the wireless LAN technology (HiperLAN, IEEE802.11, HiSWAN, etc). More or less, these two technologies have been evolving independently, but now, close coordination between these two have been considered viable to realize broadband communications era.

2.1 Cellular standards

It was more than 20 years ago that analog cellular systems (1G cellular systems) appeared, followed by digital cellular systems (2G cellular systems) that are currently used. In a cellular system, service area is covered by many distributed base stations that are controlled by radio network controllers (RNCs). User locations are tracked and their information is stored in location registers.

The data transfer rates in 2G cellular systems are too slow, e.g., less than 64kbps, for retrieving rich information comprising text and images. However, a significantly wide range of data-rates were in demand, e.g., from as low as 8kbps to a couple of megabits per second. This led to the 3G cellular standards. Figure 1 illustrates a simplified architecture of the 3G WCDMA systems. Several base stations are controlled by RNC, which is in turn connected to the core network. Minimum requirements in terms of data transport rates and quality for different communication environments are:

- Indoor: 2Mbps with bit error rate (BER)=10^{-6}
- Pedestrian: 384kbps with BER=10^{-6}
- Vehicular: 144kbps with BER=10^{-6}

Wideband (5MHz bandwidth) direct sequence code division multiple access (DS-CDMA) technology has been adopted as one of the wireless access techniques [3] since it has many advantages over its counterpart, time division multiple access (TDMA) technology:

- Single-frequency reuse
- Flexible transmission/multiplexing of different services with wide range of data rates by just changing the spreading factor of spreading codes
- Multiple simultaneous transmission of several bit-streams with different quality of service (QoS) requirements
- Robust signal transmission against multipath fading through Rake combining
- Graceful degradation of quality and no hard limit in capacity (soft capacity)
- Soft handoff to reduce shadowing effects

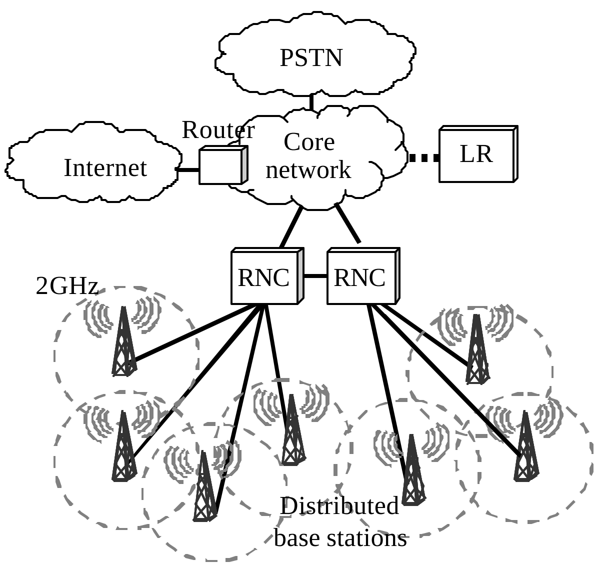

Fig. 1 3G WCDMA cellular architecture.

There are two alternatives: one is WCDMA and the other cdma2000. Now, the shift to 3G systems is on going. The introduction of WCDMA services took place in Japan in 2001. This will be continued in Europe. Meanwhile, WCDMA will continue to evolve to meet the demands for packet-data services and substantially strengthen its downlink data rate capability, resulting in high-speed (8~10Mbps) downlink packet access (HSDPA) for best effort packet data services. The major technical features of HSDPA include [17]:

- Adaptive modulation and coding to vary the modulation level and channel coding rate according to the received signal quality
- Fast hybrid ARQ to provide implicit link adaptation to instantaneous channel conditions
- Fast cell selection for a mobile to be served by the best cell rather than by multiple cells (unlike soft handoff)

The evolution of cellular systems is shown in Fig. 2. New systems have appeared every decade according to advancements in wireless technologies and changes in user demands.

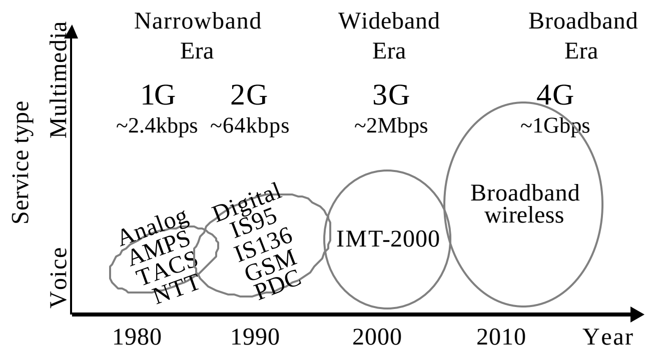

Fig. 2 Evolution of cellular systems.

2.2 Wireless LAN standards

Different versions of wireless LAN standards exist in the 2.4GHz and 5GHz bands. Figure 3 illustrate a simplified structure of wireless LAN system. A wireless terminal accesses servers distributed in LAN and Internet via nearby access point (AP). Today's wireless LAN standards include: ETSI-BRAN HiperLAN/2 (5GHz), IEEE802.11a (5GHz) and b (2.4GHz), and ARIB high-speed wireless access network (HiSWAN) and CSMA (5GHz), etc. The 5GHz wireless LAN standards are more or less identical, with OFDM modulation, 20MHz channel spacing, data rates up to 54Mbps, while IEEE802.11b uses DS-CDMA and provides ~11Mbps data rate in the 2.4GHz band. Two types of multiple access techniques are adopted in wireless LANs. They are CSMA/CA and TDMA-TDD/DSA; the former is the distributed control and the latter the central control. Since wireless LANs provide significantly higher data rates but have a shorter-range coverage (100~150m but 500m~1km in LOS condition) than 3G cellular systems, Wireless LANs and 2/3G cellular systems are considered to be complement each other.

ARIB 5GHz wireless LAN standards, HiSWANa and CSMA, are compared in Table 1 [4]. The former has many commonalities with HiperLAN/2 while the latter IEEE802.11a HiSWAN can accommodate a maximum of 256 users per AP and efficiently handle asymmetric traffic between uplink and downlink due to the dynamic assignment of the TDMA/TDD slots between them. Link adaptation is employed that changes the combination of OFDM subcarrier data modulation level and coding rate according to changes in propagation environments. Since HiSWANa utilizes the central control, QoS control is possible. There are three QoS classes: best effort class using ARQ with guaranteed minimum bandwidth, fixed guaranteed bandwidth class using ARQ, and fixed guaranteed bandwidth class without ARQ. HiSWANa was originally designed to have an interface with ATM networks but now with 3G cellular systems by adding the convergence layer to wireless LAN protocol stacks.

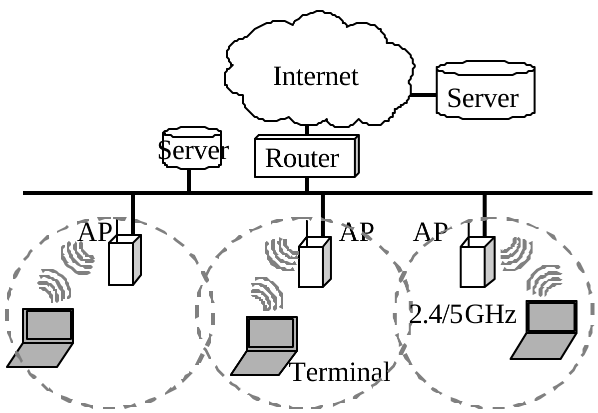

Fig. 3 Wireless LAN architecture.

Table 1 ARIB 5GHz wireless LAN standards

	HiSWANa	CSMA
Frequency band	5.15~5.25GHz 20MHz channel spacing	
Modulation	Coded OFDM	
Data rate	6~54Mbps	
Multi-access	TDMA-TDD/DSA (centralized control)	CSMA/CA (de-centralized control)
QoS	Guarantee Best effort	Best effort
Network interface	Ethernet/IP/ATM/ IMT2000	Ethernet
Related standards	ETSI HiperLAN/2	IEEE 802.11a

Recently, a move of coordination between cellular communications and wireless LANs is under way. Since most of the traffic will be data transport between the terminal and Internet via APs, the central access control seems to be efficient even in wireless LAN. CSMA/CA used in ARIB CSMA standard (also in IEEE802.11) is a distributed control. In wireless environments, there may arise the well-known hidden terminal problem if the links are not in LOS environment, this may significantly reduce the wireless LAN throughput. Roaming functions are necessary in wireless LANs to support nomadic services. Wireless LANs provide much faster data rate capability but lacks nationwide mobility support (although handoff within the own wireless LAN is possible). This may be only possible by close coordination with cellular networks that equip location registers.

3. Evolution Into Broadband Communication Era

Broadband multimedia services will soon be in full force in fixed networks based on next generation Internet technology. Information transferred over the Internet will become increasingly rich. It is quite difficult to predict which services will become popular in the coming 10 years. However, most of the services may contain high resolution and shorter delay streaming video combined with audio. An important issue to be discussed is whether extremely high data rates are necessary everywhere. Perhaps, small hot spot areas, e.g., homes, shopping areas, railway stations, airports, hotels, etc., require such extremely high data rates. However in future, the requirement of high data rate services at all places will be a trend.

The most important objective of the global 4th generation (4G) wireless systems (global 4G wireless includes cellular and wireless LAN) is to offer both cellular and nomadic users broadband multimedia services everywhere. The so-called 4G cellular systems (expected to emerge around 2010) provide nationwide coverage but will support much increased data rates than 3G cellular systems (WCDMA, cdma2000). On the other hand, wireless LANs will only cover hot spot areas with extremely high data rates, but will strengthen its roaming and handoff capabilities. However, to provide a seamless nationwide broadband services, close coordination of 3/4G cellular systems and wireless LANs is necessary, as indicated in [17].

3.1 Evolution path

In line with an explosive expansion of Internet traffic, demands for broad ranges of services (in terms of data rate, quality, traffic type, …) are becoming stronger. It may be almost impossible to build a single super wireless system to meet all the demands. Therefore, it may be wise to construct a virtual global system that can efficiently connect many dedicated wireless systems using broadband internet technology, each optimized to each communications environment as indicated by Fig. 4.

The virtual global system allows each wireless system to evolve independently of each other. Seamless roaming and handoff capabilities among cellular systems, wireless LAN systems, and other wireless systems will be of paramount importance. This will be an important task of IP mount importance. This will be an important task of IP based core network.

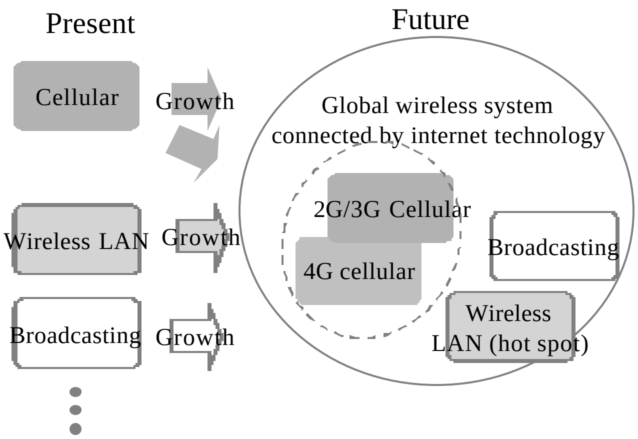

Fig.4 Global 4G wireless system.

3.2 Close to 1Gbps wireless will be required at hot spot areas

Demands will become stronger and stronger for downloading of ever increasing volume of information. Tremendous long transport time over the air is necessary with today's wireless technology. In case of cellular communications, a 1MB still image needs 14 min at 9.6kbps of 2G technologies to download. The transport time will be significantly reduced to 4s with 2Mbps of 3G cellular technologies. But, sooner or later, much richer images (streaming video combined with audio) will appear on Web sites distributed worldwide. Furthermore, the asymmetry between forward (base-to-mobile) and reverse (mobile-to-base) wireless link traffic is increasing. More than several dozen times higher rates will be required for forward links for downloading of images from a Web site. On the other hand, today's wireless LANs cannot provide nationwide roaming services for nomadic users.

Global 4G wireless systems need be fully packet-based. Giga-bit wireless technology (up to 1G bps) will be required that is optimized to broadband IP packet transport over the air. Flexible data multiplexing of much broader range of information rates than today's 3G and wireless LAN is required. Significantly asymmetric traffic between forward and reverse links is foreseen. For wireless access, a mixture of random and reservation packet access and much flexible wireless resource assignment between forward and reverse links will be required. A 100M~1Gbps class wireless access (we call this technology *Giga-bit wireless*) may be necessary with best effort type transmission but keeping minimum required quality. The Global 4G wireless system requirements for the air interface may be:

- Global and seamless roaming between different wireless systems
- Hot spots and pedestrian environments: 100M~1Gbps
- Vehicular environments: ~100Mbps
- Spectrum efficiency: ~10 bps/Hz

The 4th requirement is of paramount importance because of very limited available bandwidths. For achieving this, multiple-input multiple-output antenna systems (MIMO) will play an important role.

3.3 Cellular network structure will become closer to wireless LAN

As one may expect, IP packet traffic will dominate over the circuit switched traffic in the near future. 3G systems have a much higher data transport capability and can handle IP packet traffic more efficiently than any other 2G systems. However, 3G core networks seem to be only slowly evolving from 2G by taking advantage of their legacy and therefore, 3G core networks may not be fully optimized to the IP packet traffic.

It should be emphasized again here that the global wireless system would consist of broadband 4G cellular systems, 2G/3G cellular systems, wireless LANs, and probably broadcasting systems. The 4G cellular systems will be used for nationwide and hotspot areas coverage, while evolved wireless LANs will cover only hot spot areas. Broadcasting systems may have nationwide coverage to provide cellular and nomadic users with one-way streaming video programs and high-fidelity music programs, etc. Wireless network architecture completely different from 2G/3G cellular systems is thus, necessary. An advanced IP networks will connect wireless access network components of the aforementioned systems to each other.

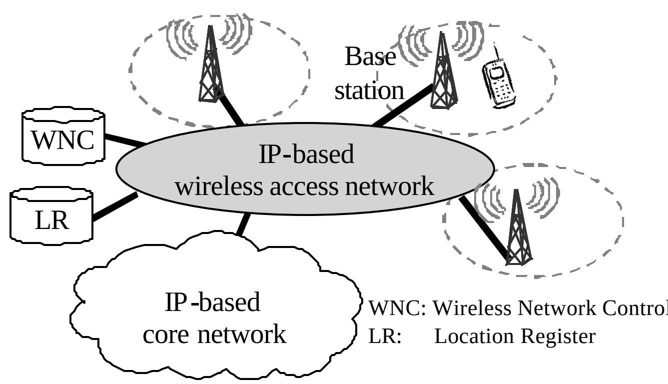

Fig. 5 Conceptual configuration of 4G cellular systems.

Table 2 Comparison of 1G ~ 4G cellular systems

	1G	2G	3G	4G
Wireless Access	Analog	Digital	Digital	Up to 1 Giga bit/s
	FDMA	TDMA, DS-CDMA	DS-CDMA	OFDM, CDMA based access
Major Services	Voice	Voice	Voice	Broadband rich Internet
		Internet (text only)	Internet (text, images)	
Core-network	Circuit-switched	Circuit-and packet switched	Circuit-and packet-switched	Broadband IP-based

Figure 5 illustrates a conceptual configuration of 4G cellular systems (which is one component of the global 4G wireless system). The cellular systems will be based on all IP-based wireless access and core networks, through which different wireless systems are connected to support seamless services. The wireless part of 4G cellular systems will become closer to a wireless LAN, but with wide area mobility management as in the 2G/3G cellular systems. Table 2 shows how 1G to 4G cellular systems are different. Cellular systems require many call control functions and distributed database, and quick and stable connections between these are necessary. These will be embedded in the IP-based wireless access networks based on a virtual leased line concept. Voice traffic can be transferred as IP packets, i.e., VoIP, but how to guarantee different QoS requirements and reduce latency is a major technical issue.

4. Wireless Challenges

Technology target of 4G wireless is shown in the mobility-data rate plain of Fig. 6. Giga-bit wireless for broadband packet access is one of the core technologies for global 4G wireless systems. It may be necessary to develop common wireless technology to be used in cellular and wireless LAN systems. Then, it is relatively easy to develop software defined wireless terminals that can access both cellular and wireless systems (even broadband broadcasting systems). Below we focus our discussions on broadband wireless access techniques.

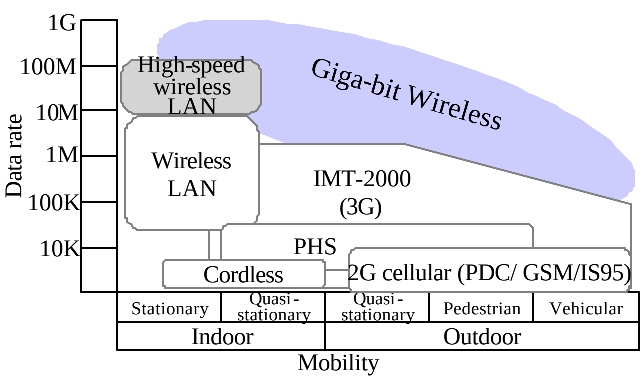

Fig. 6 Mobility-data rate map.

For wireless access, today's 3G cellular standards adopt DS-CDMA while high-speed wireless LAN standards employ CSMA/CA or TDMA-TDD/DSA combined with OFDM. A simple use of 3G DS-CDMA technologies seems to experience significant degradations in a severe frequency selective fading channel. Any wireless technique has its own limitations: too long propagation delays to equalize in TDMA, too weak propagation paths to coherent Rake combine in DS-CDMA, and no multipath diversity and large peak-to-average power ratio when using OFDM. Proper choice of wireless access techniques is important. In OFDM, many narrowband channels are used in parallel, leading to small performance degradations in a severe frequency selective channel. Recently, a combination of OFDM and CDMA techniques is extensively studied as 4G wireless access. The challenge is to transmit data packets of as many users as possible with high quality at high speed (close to 1Gbps) under severe frequency-selective fading environments. A debate similar to that concerning 3G wireless access will undoubtedly occur again. An interesting question is: whether to spread as in 3G or not to spread as in 2G? There will be two approaches to realize Giga-bit wireless: from DS-CDMA [3] and from MC-CDMA [5], [6], [7]. The former uses time-domain spreading sequences, while the latter uses frequency-domain spreading sequences, as understood from Fig. 7.

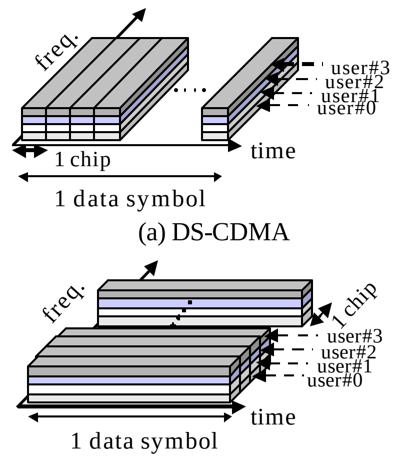

Fig. 7 DS-CDMA and MC-CDMA.

4.1 DS-CDMA approach

The spreading factor (SF) can control the transmission data rate and the number of simultaneously transmitting users. For packet data services, ARQ combined with DS-CDMA (spread ARQ) seems to be the most appropriate error control scheme. However, spread ARQ alone cannot perform satisfactorily in a severe frequency selective channel. Spread ARQ can be combined with forward error control technique to form spread hybrid ARQ, in which the information data is first forward error coded and then spread to transmit.

One promising solution is to use spread type-II hybrid ARQ with rate compatible punctured turbo (RCPT) coding and coherent rake combining [8]. Spread type-II hybrid RCPT ARQ transmits only additional parity bits in response to a retransmission request. Combined use of present and previously received packets forms a lower rate code. Code combing [9] or time diversity (TD) combining [10] is also utilized. The computer simulated performance of spread type-II hybrid RCPT ARQ in a four-path (L=4) frequency selective Rayleigh channel is plotted in Fig. 8. In multi-user environment, the throughput obtained with and without spreading is found to be almost the same when RCPT codes are used as the error correction code.

Interesting question with respect to spread type-II hybrid RCPT ARQ is: what should be the spreading factor? We need to consider the pros and cons for a spread system and a non-spread system.

(a) When spread: Spreading allows multiple users to communicate at the same time. Each user is provided continuous transmission but the time taken for transmission is longer. Total throughput is divided among the users; hence, each user's throughput is lower. This may be optimum for real time communication with a constant data rate.

(b) When not spread: High throughput is given to a single user at each moment. After completing the transmission of one user, channel is assigned to another user. Users need to wait for channel being assigned. This scheme may be optimum for non-real time data communications.

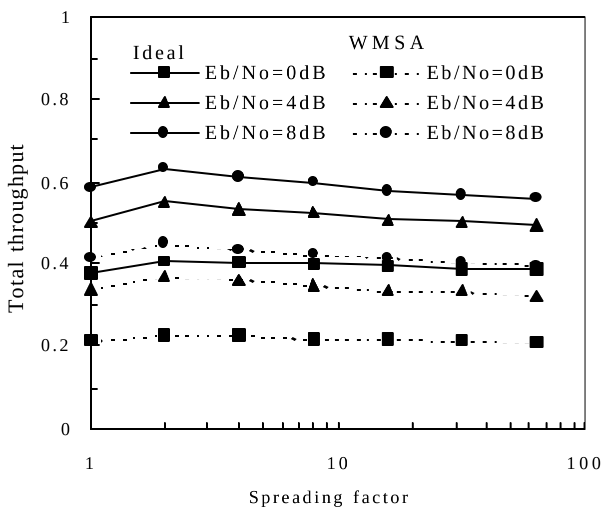

Fig. 8 Downlink total throughput of spread type-II RCPT hybrid ARQ. N=SF users and L=4-path Rayleigh channel.

Then, is it necessary to spread? Both can be used. The use of orthogonal variable spreading factor (OVSF) spreading code [11], [12] allows construction of spread and non-spread systems. A possible non-spread wireless system may be a random TDMA system with appropriate scheduling, while a possible spread system is just an extension of present 3G cellular system based on DS-CDMA. Real time and non-real time services with relatively low data rate per user are provided in cellular system with SF>1. On the other hand, in hot spot areas, non-real time services with very high data rates are provided with SF=1. An SF=1 system requires a fast scheduling mechanism to determine which user to transmit in the given time interval. Since higher priority of services is given to users in better channel conditions, a certain degree of fairness among users should be kept. The SF=1 system can be extended to a cellular system with the aid of fast selection of transmit cell and adaptive antenna array. Note that, in areas with too severe frequency-selective channel environments, this approach may not be optimal.

4.2 MC-CDMA approach

MC-CDMA wireless access can cope with severe frequency-selective fading and allows multi-rate transmission using OVSF spreading codes (when orthogonal sub-carriers are used, it is called OFDM-CDMA). MC-CDMA can fill the gap between OFDM and DS-CDMA [13]. The former can overcome frequency-selective fading by adopting a relatively low-complexity receiver (a simple one-tap equalizer per sub-carrier), while the latter gives multi-access capability, multi-rate transmission, single-frequency reuse, etc. The received signal suffers from severe frequency distortion and thus, partial orthogonality destruction is produced, thereby producing large multi-user interference (MUI). A number of multi-user interference suppression techniques have been proposed: orthogonal restoration combining (ORC), controlled equalization combining (CEC), minimum mean square error combining (MMSEC) and threshold detection combining (TDC) [5], [6], [7], [14]. The computer simulated BER performances of MC-CDMA achievable with ORC, CEC, TDC, and MMSEC are compared with that of DS-CDMA in Fig. 9. MC-CDMA achieves better BER performance than DS-CDMA.

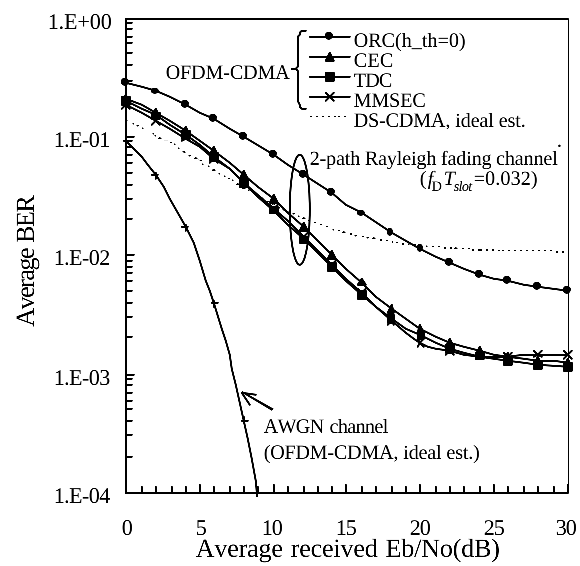

Fig. 9 Downlink BER performance of MC-CDMA. N=128 users and L=2-path Rayleigh channel.

It allows flexible system design between cellular system and single cell system. The use of SF>1 allows single-frequency reuse similarly to 3G, while SF=1 can be used to cover hotspot areas, resulting in a single-cell system using OFDM [13], as illustrated in Fig. 10 (similar design can be applied to DS-CDMA). To significantly increase the data rate within limited bandwidth under severe frequency-selective environments, the combination of MC-CDMA approach with MIMO plays an important role.

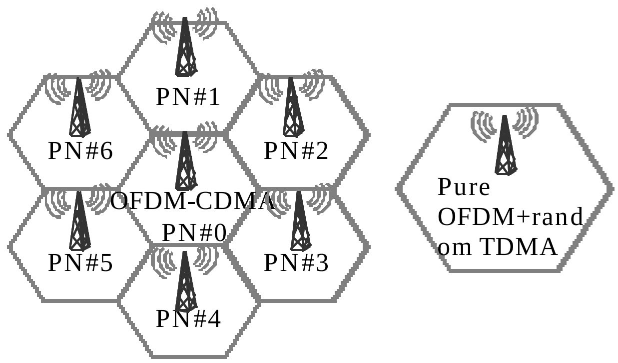

Fig. 10 OVSF DS-CDMA and MC-CDMA systems.

4.3 Virtual cell

The frequency bands for the global 4G wireless systems will most likely lie above 5 GHz. One important question is whether extremely high data rate can be designed on the basis of today's 3G cellular and wireless LAN system architectures. Since the propagation loss is in proportion to 2.6^{th} power to the carrier frequency [15], the links are not only interference-limited but also become severely power-limited. This suggests that a nano-cell or even a pico-cell structure must be adopted. As mentioned earlier, it is almost impossible for 4G cellular and wireless LAN systems to provide nationwide coverage; only hot spot areas with high multimedia traffic can be covered. In hot spot areas, data transport needs be done almost instantly at speeds of 100M~1Gbps. In other areas, however, data transport can be done using conventional cellular systems.

Due to the nano/pico-cell structure, propagation statistics are strongly influenced by microscopic structure of nearby propagation environments and dynamically change from cell to cell according to the movement of a user. This makes use of adaptive antenna array quite attractive not only in the base stations but also in mobile terminals. However, additional gains achievable by adaptive antenna array may be 10~20dB at most and may not be sufficient to offset the significant increase in the path loss. The introduction of adaptive (modulation level and code rate to the time-varying channel conditions) best-effort transmission is necessary but with guaranteed minimum data rate of e.g. 30Mbps; faster transmission rates if closer to base stations or better propagation conditions. The above discussions imply that 4G wireless systems may need to be designed apart from the cellular concept that relies on the statistical properties of propagation channels.

One idea to cope with increasing path loss is to adopt virtual cell concept [16]. This is illustrated in Fig. 11. Each virtual cell consists of many distributed small base stations with extremely high data rate capability. This is similar to an ad hoc network, e.g., wireless LAN, but with central administration (central station). Most of the cellular system research is focused on centralized systems. This virtual cell concept is particularly suitable to non-real time IP packet transport, which obviously does not require transmit and receive functions at the same base station. Hence, the receive-only stations can be distributed in each virtual cell together with conventional transmit & receive stations.

The small base stations can be similar to existing wireless LANs, e.g., HiperLAN, IEEE802.11, HiSWAN, etc, but most importantly having dynamic network topology, autonomous routing to the central station, fast handoff, fluctuating link capacity. Each small base station can be connected based on wireless multi-hopping technology. i.e., each small base stations with short communication ranges may be used and the user data can be relayed via small base stations to the central station. They can be installed where needed and removed when not needed; they are connected to each other in a self-configuring way to transport IP traffic. For the ad hoc networking, it may be difficult to guarantee the fixed QoS. QoS control, security, routing and mobility management are important research issues.

Central base stations with large transmit powers can be co-located with the base stations of 2G/3G cellular systems. Since coverage areas of virtual cells cannot overlap each other, close cooperation with 2G/3G systems is necessary. The 3G cellular radio access network (RAN) can be overlaid with the above virtual cell networks in the hot spot areas. This requires inter-system mobility management between the 3G and virtual cell networks, a dynamic IP routing algorithm, and the so-called software defined radio technology. The last is to make a single mobile terminal access different radio components of global 4G wireless systems.

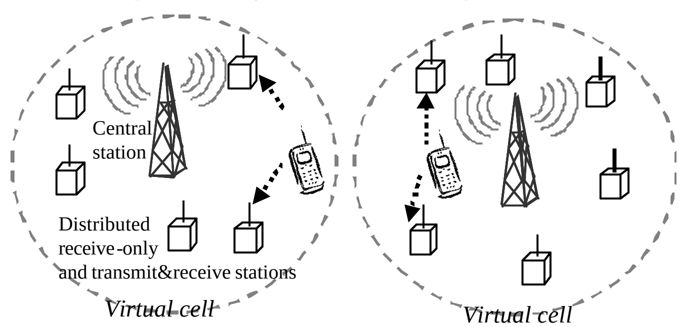

Fig. 11 Virtual cell using ad hoc and multi hop networks.

5. Conclusion

Wireless is becoming more and more important. Wireless systems are now becoming an important infrastructure of our society. It may be almost impossible to build a single super wireless system to meet demands for broad ranges of Internet services (in terms of transmission rate, quality, traffic, …) to cellular and nomadic users. A virtual global system is a good solution that can efficiently connect many dedicated wireless systems including 2~4G cellular systems, wireless LAN, broadcasting systems, etc., each optimized to each communications environment.

In this paper, we overviewed today's wireless standards of 3G cellular systems and wireless LANs and discussed technical issues for the realization of global 4G wireless systems. The core network will be fully IP-based. Gigabit wireless and virtual cell concept were presented. The expected frequency bands are above several GHz and data throughput over the air will be close to 1Gbps. Cellular and wireless LAN system architecture may become closer and will work together based on IP core network. Difference between them may be the former offers seamless handoff for real-time services but the latter offers seamless roaming for nomadic services, focusing on very high-speed data communications close to 1Gbps. In case of cellular systems, since wireless links are severely power-limited for such a Giga-bit wireless, adoption of the well-known and long-time used cellular concept may not be a good idea. Adoption of virtual cell concept that allows flexible installation of distributed base stations may be a better solution. The receive functions can be separated from the base station and can be geographically distributed to make it possible to reduce the transmit power of portable phones. Virtual cell concept adopts ad hoc and multi-hop networking to provide extremely high data rate services with reasonable transmit power.

Before the realization of the wireless society, very difficult but interesting technical challenges are waiting for us.

REFERENCES

[1] Special issue, *IMT-2000: Standards efforts of the ITU*, IEEE Personal Commun., Vol. 4, Aug. 1997.

[2] "Fourth generation wireless networks and interconnecting standards," IEEE Personal Commun., vol. 8, Oct. 2001.

[3] Special issue, *Wideband CDMA*, IEEE Commun. Mag., Vol. 36, Sept. 1998.

[4] T. Hattori and M. Fujioka, ed, *Wireless broadband lecture book*, (in Japanese) IDG Japan, 2002.

[5] M. Helard, R. Le Gouable, J.-F. Helard, and J.-Y. Baudais, "Multicarrier CDMA techniques for future wideband wireless networks," Annals of Telecommunications, Vol. 56, pp. 260-274, May-June 2001.

[6] S. Hara and R. Prasad, "Design and performance of multicarrier CDMA system in frequency-selective Rayleigh fading channels," IEEE Trans. Veh. Technol., Vol. 48, pp. 1584-1595, Sept. 1999.

[7] S. Hara and R. Prasad, "Overview of multicarrier CDMA", IEEE Commun. Mag., pp.126-144, Dec. 1997.

[8] D. Garg and F. Adachi, "Effect of limited number of retransmissions of RCPT hybrid ARQ for DS-CDMA mobile radio," Proc. 5th International Symposium on Wireless Personal Multimedia Communications, Hawaii, Oct. 27-30, 2002.

[9] D. Chase, "Code combining- a maximum likelihood decoding approach for combing and arbitrary number of noisy packets", IEEE Trans. Commun., Vol COM-33, pp. 385-393, May 1985.

[10] F. Adachi, S. Ito, and K. Ohno, "Performance analysis of a time diversity ARQ in land mobile radio", IEEE Trans. Commun., Vol. 37, pp.177-183, Feb. 1989.

[11] F. Adachi, M. Sawahashi, and K. Okawa, "Tree-structured generation of orthogonal spreading codes with different lengths for forward link of DS-CDMA mobile radio," IEE Electron. Lett., Vol. 33, pp. 27-28, Jan. 1997.

[12] K. Okawa and F. Adachi, "Orthogonal forward link using orthogonal multi-spreading factor codes for coherent DS-CDMA mobile radio," IEICE Trans. Commun., Vol.E81-B, pp. 777-784, April 1998.

[13] H. Atarashi and M. Sawahashi, "Variable spreading factor orthogonal frequency and code division multiplexing (VSF-OFCDM)," 2001 Third International Workshop on Multi-Carrier Spread Spectrum (MC-SS 2001) & Related Topics, pp.113-122, Oberpfafenhofen, Germany, Sept. 26-28, 2001.

[14] T. Sao and F. Adachi, "Pilot-aided frequency-domain equalization with threshold detection for OFDM-CDMA downlink transmissions in a frequency selective fading channel," IEICE Trans. Commun., to appear.

[15] M. Hata, "Empirical formula for propagation loss in land mobile radio services," IEEE Trans. Veh. Technol., Vol. VT-29, No. 3, pp.317-325, Aug. 1980.

[16] F. Adachi, "Wireless past and future - evolving mobile communications systems," IEICE Trans. Fundamentals, Vol. E84-A, pp.55-60, Jan. 2001.

[17] H. Honkasalo, K. Pehkonen, M. T. Niemi, and A. T. Leino, "WCDMA and WLAN for 3G and beyond," IEEE Wireless Commun., Vol. 9, pp. 14-18, April 2002.