Research and Development of Broadband Wireless Access Technologies

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Abstract

This paper describes research and development of broadband wireless access technologies aiming at mobile/nomadic/fixed broadband wireless access systems. It introduces key technologies detailed in the other selected papers in this issue, including SDM-COFDM (space division multiplexed, coded orthogonal frequency division multiplexing) over MIMO (multiple input multiple output) channels, broadband wireless access systems using quasi-millimeter wave, mesh-type wireless systems, and a ubiquitous network concept for economical public LAN services.

1. Introduction

It is widely recognized that the significant advantage of wireless communications is "mobility", which enables telecommunications "anytime and anywhere with anyone and anything". This advantage has been driving the explosive increase in mobile phone subscribers and the rapid deployment of wireless Internet access such as i-mode in the last decade in Japan, and mobile wireless communications is expected to continue to grow. Japan led the world with the commercial introduction of a third-generation mobile telecommunication system, IMT-2000 (International Mobile Telecommunications-2000), in 2001 [1]. IMT-2000 can provide high-speed data services for multimedia in addition to voice services, i.e., 144 kbit/s in mobile environments, 384 kbit/s at walking speed outdoors, and 2 Mbit/s indoors [2], [3].

On the other hand, Internet services are becoming more and more popular, and the demand for broadband Internet access services is increasing. This demand is also driving the rapid growth of ADSL (asymmetric digital subscriber lines) and FTTH (fiber to the home) in Japan. The number of broadband service subscribers reached 13 million in 2003. As wireless access is being used for Internet access, it is quite natural that wireless systems are required to provide 10- to 100-Mbit/s-class services, equivalent to wired Internet access, i.e., 10Base-T/100Base-T Ethernet. To meet the increasing demand for broadband access services, nomadic wireless access services in hot-spots have been introduced using emerging broadband wireless local area network (WLAN) technologies [4].

The increasing demand for ubiquitous broadband services forced the ETSI (European Telecomunications Standards Institute)-project BRAN (broadband radio access networks) in Europe, MMAC (multimedia mobile communication systems promotion council) in Japan, and IEEE 802.11 in the U.S. to develop broadband WLAN standards. These include HiperLAN/2 (high-performance radio LAN), HiSWANa (high-speed wireless access networks type a), and IEEE802.11a for enterprise, home, and public WLAN networks [5]-[7]. They can provide up to 54 Mbit/s with an average of 20 Mbit/s using the 5-GHz band. IEEE802.11b and .11g using 2.4 GHz are being widely used for wireless Internet access due to their low cost. To meet further demand for broadband wireless access, the IEEE802.11n group has recently been formed to create a new WLAN standard to enable over 100 Mbit/s by wireless.

The recommendation for "Systems beyond IMT-2000" has been recently approved by ITU-R, SG8. This recommendation envisages the research target of 4th generation cellular (4G cellular) being 100 Mbit/s and that of the next-generation WLAN being 1 Gbit/s. Thus, "Systems beyond IMT-2000" has become an

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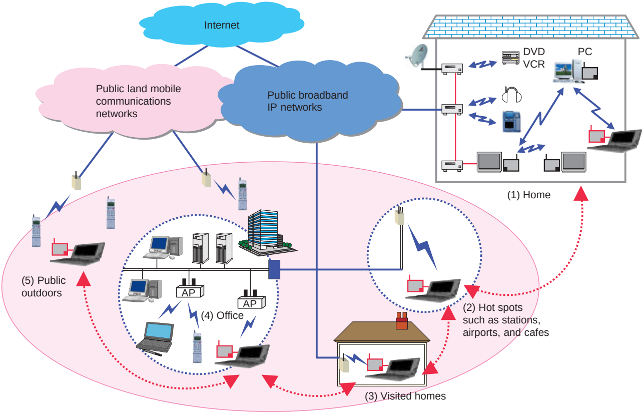
important research area [8]-[10]. One scenario for using future broadband mobile communications is illustrated in **Fig. 1**, where various mobile/nomadic wireless communication systems are deployed according to the user environments such as outdoor cellular, so-called hot spots such as coffee shops and airports, offices, and homes. These wireless communication systems will be used to supplement each other. In outdoor public environments, broadband cellular systems will be deployed for services up to 100 Mbit/s, while private WLANs will mainly be used in office and home environments for higher rate services. Hot spots will be covered by either public WLANs or private WLANs. A wireless user moving across these environments will be able to stay connected to the broadband backbone network. Many research projects aiming at “Systems beyond IMT-2000” have been launched.

This paper overviews research and development that NTT Network Innovation Laboratories has been conducting on broadband wireless access technologies aiming at mobile/nomadic/fixed broadband wireless access systems, and the R&D approach to enable high-capacity broadband access at over 100 Mbit/s by wireless. It also outlines key technologies, such as SDM-COFDM (space division multiplexed, coded orthogonal frequency division multiplexing) over MIMO (multiple input multiple output) channels, broadband wireless access systems using quasi-millimeter wave, mesh-type wireless systems, and seamless networking techniques, which are explained in more detail by other selected papers in this issue.

2. Evolutional scenario of wireless access systems

A scenario for evolution toward future ubiquitous broadband wireless access is illustrated in **Fig. 2**, where the cellular systems including both enhanced IMT-2000 i.e., HSDPA (high-speed downlink packet access), and 4G cellular evolves toward 100 Mbit/s in



AP: access point
IP: Internet protocol

Fig. 1. Scenario for using future broadband mobile communications networks.

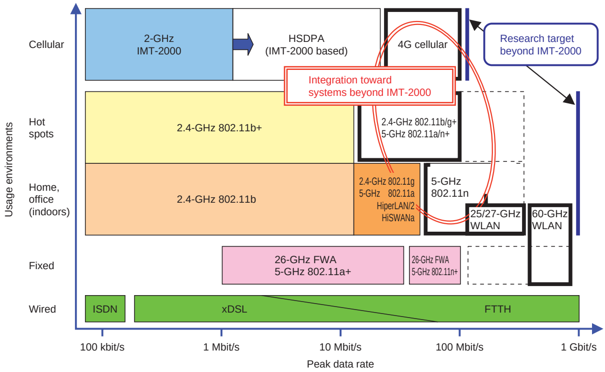


Fig. 2. Scenario for evolution toward future ubiquitous broadband wireless access.

outdoor environments with high mobility, i.e., a large cell size. On the other hand, WLAN is expected to evolve toward 100 Mbit/s early in this decade and to 1 Gbit/s later in indoor office, home, and hot-spot environments with low mobility, i.e., a small cell size. They are expected to complement each other by roaming over various wireless systems according to the user environments. The collaboration between cellular systems and WLAN will enable ubiquitous wireless access for broadband services.

Though the possible frequency band for 4G cellular will be discussed in WRC (World Radio Conference) 2007, WRC 2003 decided to allocate 455 MHz for mobile services, mainly for WLAN applications, on a global basis. As far as WLAN is concerned, 2.4, 5, 25/27, and 60 GHz bands are available in Japan. WLAN using the 5-GHz band will be able to provide over 100 Mbit/s, then 25/27 GHz will be used to provide 100 to 400 Mbit/s or to provide higher system capacity.

Fixed wireless access (FWA) is also playing an important role in the economical deployment of broadband services in rural areas, where FTTH is not deployed and the user density is low. FWA is also expected to evolve toward over 100 Mbit/s and later to 1 Gbit/s. Wireless PANs (personal area networks) and RFID tags are also hot topics nowadays, but this scenario does not include them because they are not ways to access a broadband network, but are means to connect personal computers to miscellaneous devices such as hard disk drives or to collect information from many RF tags.

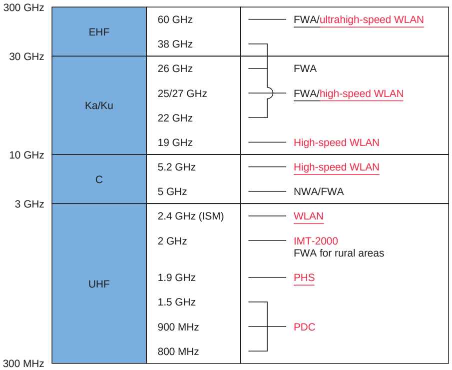
3. R&D approaches to broadband wireless access

3.1 R&D approaches from the viewpoint of frequency

Figure 3 shows the frequency spectrum assigned to wireless access in Japan. The lower frequency bands are allocated to mobile services and the higher frequency bands to fixed services. The main technical reasons for allocating low-frequency bands to mobile services are the smaller shadowing and propagation losses and the lower Doppler frequency*1 for mobile use.

Let us consider broadband wireless access systems and a suitable frequency band for them. In general, a wider frequency spectrum is available in the higher

*1 Doppler frequency, which is given by the mobile receiver speed divided by the wavelength, represents the fading frequency in the multi-path fading environments.



Note: Red indicates mobile services, black fixed services, and underline unlicensed services.
NWA: nomadic wireless access

Fig. 3. Current frequency spectrum assignment to wireless access in Japan.

frequency band. Thus, a high-frequency band can more easily provide high-speed transmission, which needs a wide frequency spectrum. However, a higher frequency band suffers from larger propagation loss, larger diffraction loss resulting in severe shadowing, and larger Doppler frequency for mobile use. Although a lower frequency band is well suited to mobile use because of its smaller shadowing loss and smaller Doppler frequency, the lower the frequency band, the smaller the frequency spectrum. Thus, there are two approaches to broadband mobile/nomadic wireless access: i) developing countermeasures to overcome the severe shadowing loss and high transmitting power required when the higher frequency band is used and ii) developing technologies to improve frequency utilization efficiency, which is expressed in bit/s/Hz assuming no interference and bit/s/Hz/cell assuming cellular deployment of wireless systems resulting in inter-cell interference.

3.2 Required performance improvement for broadband mobile/nomadic wireless access

The performance improvement required to achieve broadband wireless access is expressed as a function of propagation loss including shadowing effects and the required EIRP (equivalent isotropic radiated power) if the modulation and coding are the same. This required performance improvement R in dB to achieve the bit rate B is given by

$$R = 10\log\left(\frac{B}{B_r}\right) + \alpha\log\left(\frac{f}{f_r}\right),$$

where f_r is the reference frequency, B_r is the reference bit rate, and α is the propagation factor for frequency. The value of α is 33.4 according to the COST 231 Hata-model and 20 for free-space propagation [11].

Assuming IMT-2000 as a reference system, we have, for example, B_r=2 Mbit/s and f_r=2 GHz. **Figure 4** shows R as a function of f to achieve 100 Mbit/s with α=35 for a severe case, where the antenna gain is the same. If we use the 5-GHz band for its wide frequency spectrum advantage, R must be 30 dB in the severe case to keep the same coverage. On the other hand, R is 6.5 dB for 1 GHz. The above discussion implies that we can keep the same cell radius by increasing EIRP by 6.5 dB if 1 GHz is used, though

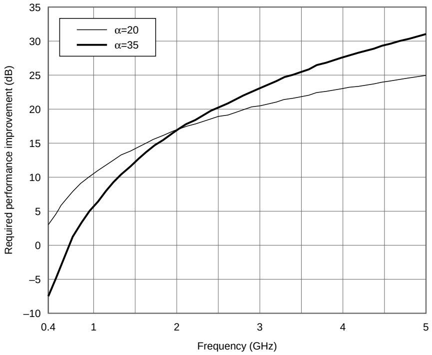


Fig. 4. Required performance improvement to achieve 100 Mbit/s from 2 Mbit/s at 2 GHz as a function of frequency.

we need to achieve very high frequency utilization efficiency. However, if we go to from the 2-GHz band to the 5-GHz band, we need to achieve a 30-dB improvement, for example an EIRP increase of 30 dB. Otherwise we need to shorten the cell radius. It should be noted that the overall system cost is proportional to the number of access points and entrance links to connect the access points to the backbone network. Thus, the cost of access points and entrance links will be much lower for 1 GHz compared with 5 GHz. The discussion will be similar when we compare WLANs using 5 and 25 GHz.

In conclusion, if we need to go to a higher frequency band for broadband wireless access, we must accept a shorter cell radius resulting in an increase in the number of access points, i.e., the system cost will be higher. Therefore, we should use a higher frequency to achieve a significant increase in system capacity by employing a micro-cell or pico-cell architecture with a shorter cell radius than current systems. On the other hand, if the service area coverage is more important than system capacity, then a lower frequency should be used by developing advanced technologies to achieve greater frequency utilization efficiency. Therefore, to achieve wide area coverage as well as high system capacity simultaneously, we should take a combined approach by using both lower frequency to cover a wide area and higher frequency to increase the system capacity. This multi-layered cellular concept (**Fig. 5**) seems essential for future broadband mobile/nomadic communication systems.

4. Overview of enabling technologies

4.1 CDMA and OFDM for broadband mobile/nomadic wireless systems

One of the key challenges facing broadband nomadic/mobile wireless communications is to develop advanced wireless access technologies to achieve high-speed and high-quality transmission at over 100 Mbit/s in severe fading channels with high frequency utilization efficiency. There are two major technical streams for broadband mobile/nomadic wireless access: CDMA (code division multiple access) used in IMT-2000 and OFDM (orthogonal frequency division multiplexing) used in 2.4/5-GHz-band WLANs.

(1) CDMA

CDMA is used in the IMT-2000 standards because of its excellent performance in multi-path fading environments and high frequency utilization efficiency for cellular deployment. Each user is assigned a unique code sequence (spreading code) to spread his/her data by encoding. Assuming low cross-corre-

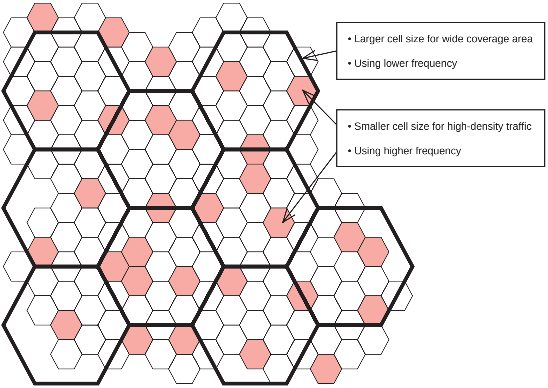


Fig. 5. Multi-layered cell concept for high-capacity and broadband mobile/nomadic systems.

lation between the code assigned to the desired user and the codes assigned to other users, the receiver can recover the data by de-spreading. Though precise and fast control of the transmitting power is essential to solve the near-far problem in the uplink of the DS-CDMA (direct sequence-CDMA) system, CDMA has the following advantages for broadband wireless access:

- High link quality under frequency selective fading by rake reception and powerful forward error correction (FEC)
- Robustness against interference and jamming
- Single frequency cellular deployment resulting in simple frequency spectrum management and high frequency utilization efficiency in terms of bit/s/Hz/cell

W-CDMA can support up to 2 Mbit/s using a 5-MHz channel spacing. To meet the increasing demand for high-speed mobile internet services, HSDPA has recently been developed as part of 3GPP standard release 5 to support up to 14.4 Mbit/s using a 5-MHz channel spacing [12].

(2) OFDM

OFDM is a multi-carrier transmission technique in which discrete Fourier transform (DFT) is used for frequency division multiplexing and de-multiplexing instead of banks of sub-carrier filters and frequency converters. If the OFDM symbol timing synchronization is perfect, then inter-symbol interference caused by a delay spread less than the guard interval can be eliminated. Therefore, OFDM can eliminate the inter-symbol interference due to multi-path propagation.

In OFDM, frequency domain interleaving is usually used to avoid the burst errors that significantly degrade the FEC coding gain. The combination of OFDM and frequency domain interleaving makes it possible to achieve high FEC coding gain by using a powerful FEC such as convolutional coding and Viterbi decoding*2. Furthermore, the OFDM approach can further improve the link quality by employing sub-carrier-by-sub-carrier-based diversity and achieve higher transmission rate by using multi-level modulation schemes such as 16QAM and 64QAM.

*2 Viterbi decoding is one of the decoding schemes for convolutional encoding error correction. It is very powerful for random errors, so many wireless systems have already installed it. The name is derived from the name of inventor, Dr. A. J. Viterbi.

OFDM was selected in the WLAN standards (such as IEEE802.11a/g, HiperLAN/2, and HiSWANa) because of its excellent performance under frequency selective fading, transmission rate scalability, and reasonable complexity for low-cost terminal implementation. The 5-GHz WLAN standards support 6 to 54 Mbit/s using a 20-MHz channel spacing, where link adaptation techniques are used to maximize the system throughput according to the C/N+I (carrier-to-noise ratio plus interference) condition.

4.2 Technologies for improving frequency utilization efficiency

As mentioned in section 3, one approach to enable broadband wireless access is to develop technologies for achieving high frequency utilization efficiency in terms of bit/s/Hz and/or bit/s/Hz/cell. There are two major problems in broadband mobile communications: i) frequency selective fading due to multi-path propagation and ii) severe inter-cell interference. An appropriately designed OFDM system can achieve excellent performance, i.e., low packet error rate under severe frequency selective fading. On the other hand, CDMA can achieve good transmission performance in severe interference environments. Thus, both these major problems seem to have been almost solved.

One of the most promising technologies for improving bit/s/Hz is space division multiplexing (SDM) over MIMO channels using multiple transmitting and receiving antennas. In an additive white Gaussian noise (AWGN) channel, the channel capacity C is given by

$$C = \log(1+\gamma),$$

where γ is the signal-to-noise ratio. The MIMO channel capacity is given by

$$C = \log\left[\det\left(I_{N_R} + \frac{\gamma}{N_T} H \cdot H^H\right)\right],$$

as the parallel channel capacity, where I is an n-by-n identity matrix, H is a channel matrix, N_T and N_R denote the number of transmitting and receiving antennas, and $(\ )^H$ denotes the complex conjugate transpose. This equation indicates that the channel capacity can be increased in proportion to the number of antennas if N_T=N_R [13]. This possible capacity increase in terms of bit/s/Hz is why SDM/MIMO is attracting a significant amount of attention these days. NTT has been making efforts to develop SDM/MIMO technologies based on OFDM, taking advantage of its robustness against frequency selective fading. Details are given in the next paper in this issue [14].

When link C/N+I is low under severe interference, the spreading/de-spreading of CDMA is a useful technique for improving channel quality. Thus, the combination of OFDM and CDMA looks promising to improve frequency utilization efficiency for cellular environments with severe inter-cell interference. A lot of R&D effort has also been expended on multi-carrier CDMA, i.e., OFDM employing channel spreading over both the frequency and time domains. An example of this approach is OFCDM (orthogonal frequency and code division multiplexing) [15]. The above observation implies that the OFDM/CDMA approach combined with “link adaptation” (i.e., adaptive modulation and coding) and SDM over MIMO channels should maximize the channel capacity for a given C/N+I. The proposed OFDM/CDMA/SDM concept is illustrated in **Fig. 6**, where the transmission rate can be maximized according to the C/N+I conditions [16].

4.3 Technologies for using a higher frequency band

The other approach to enable broadband wireless access is to use a higher frequency band such as the quasi-millimeter and millimeter wave bands. However, there are many problems such as severe shadowing and large propagation loss for mobile/nomadic applications. The expense of RF components and monolithic microwave integrated circuits (MMICs) is also a problem.

NTT has been conducting research and development of 25/27-GHz wireless access systems, because the 1-GHz in 25/27 GHz band is available for WLAN and FWA applications on an unlicensed basis in Japan. For WLAN applications, it is very important to clarify the propagation characteristics, especially in indoor environments. As multi-path fading is also encountered in 25/27 GHz, we assume the use of OFDM to combat the multi-path fading the same as for 5-GHz WLANs. For economical hardware implementations, one possible approach is to re-use the chip set developed for 2.4/5-GHz-band WLANs. The third paper in this issue covers wireless access systems using the 25-GHz band and describes experimental results for OFDM transmission in indoor environments [17]. The fourth describes an active directional antenna system designed to improve the

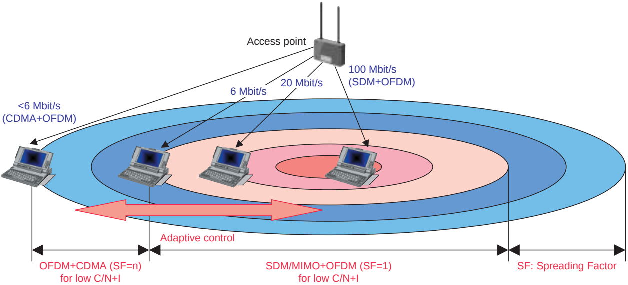


Fig. 6. Example of OFDM-based wireless access system using both SDM/MIMO and CDMA to maximize the frequency utilization efficiency.

receiver sensitivity and increase the EIRP by reducing the loss between antenna and RF circuits [18].

4.4 Technologies for increasing the system capacity of FWA

FWA is intended to supplement xDSL*3 and FTTH in deploying broadband access networks. It is expected to be used for rural/urban areas containing few users and/or for buildings in urban areas where FTTH installation is difficult due to the high construction cost.

Current point-to-multipoint and point-to-point FWA systems mainly use the quasi-millimeter and millimeter bands. If we consider dense deployment of FWA systems for broadband services to many users, we need to further improve the frequency utilization efficiency. In addition, FWA using these bands needs a clear line of sight (LOS) between the base station and user station. However, LOS is difficult to obtain as the user station is located far from the base station. One promising way to solve the above-mentioned problems is to employ mesh type multi-hop wireless networks, where both user and base stations use directional antennas to reduce the interference, resulting in an increase in system capacity. Furthermore, user stations without LOS can be covered by relaying the signals in a multi-hop manner. A feasibility study of this mesh type FWA concept is reported in [19].

*3 xDSL refers to a generic digital subscriber line, including ADSL.

4.5 Technologies for economical public WLAN services

WLAN is growing rapidly in home and office environments with the expansion of xDSL and FTTH. To provide WLAN users with seamless connectivity to the Internet outside their homes and offices, public WLAN services have been recently launched for broadband nomadic wireless access. The service operator must install a large number of access points because each one covers only a small area. In the early stage of the business, an operator must make a large investment to deploy access points and the entrance network to win customers. Therefore, it is important to develop a new framework for economical access point deployment, especially for public WLAN services. NTT has been studying a network concept with the aim of establishing a cost-effective ubiquitous network combining wired access links and wireless networks, in which a public network is constructed from private networks using advanced authentication and network resource control techniques. This is described in [20].

5. Concluding remarks

This paper described research and development of broadband wireless access technologies for mobile/nomadic/fixed broadband wireless access systems and technical approaches to enable high system capacity and broadband wireless access over 100 Mbit/s. Some key technologies were briefly introduced. Details are given in the following papers.

"Systems beyond IMT-2000" will be a combination of 4G cellular and next-generation WLAN according to the global consensus for next-generation mobile communications. There are two key words: broadband and seamless. Thus, in addition to the advanced wireless access techniques for broadband over 100 Mbit/s, it is important to develop seamless networking technologies, enabling seamless wireless access over various wireless access networks using various frequency bands available for wireless access.

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