Broadband Packet Wireless Access

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Abstract

Packet access in the radio access network (RAN) is essential to reduce network costs and achieve high-capacity multimedia mobile communications capable of supporting services such as high-resolution video communication. This article presents targets and key techniques for the broadband packet wireless access system that we propose, which enables seamless support of both cellular systems and isolated-cell environments, such as hotspot areas and indoor offices, using the same air interface for efficient packet access. It also describes efficient packet access techniques for guaranteeing the quality of service (QoS), including handover in the RAN on both the data-link layer and the physical layer.

1. Introduction

A maximum information bit rate of 2 Mbit/s or greater has been specified as the requirement for third-generation (3G) mobile communications called international mobile telecommunications-2000 (IMT-2000) in the radiocommunication sector of the international telecommunication union (ITU-R). We have experimentally demonstrated high-speed data transmission above 2 Mbit/s with high quality at an average bit error rate of less than 10^{-6} using a 5-MHz frequency bandwidth in the downlink, applying three-code multiplexing with a spreading factor (SF) of 4 using two-branch antenna diversity reception. Meanwhile, the third-generation partnership project (3GPP) has completed specifications focusing on high-speed packet data transmission in the downlink called high-speed downlink packet access (HSDPA) based on an air interface using wideband code division multiple access (W-CDMA) [1]. In HSDPA, a much higher peak throughput than 2 Mbit/s is possible with low latency and high efficiency by employing adaptive modulation and channel coding (AMC) including 16 quadrature amplitude modulation (QAM), hybrid automatic repeat request (H-ARQ) with packet-combining in the medium access control (MAC) layer, and fast packet scheduling (i.e., user diversity). Moreover, we have shown that a peak throughput of nearly 10 Mbit/s is possible with a 5-MHz bandwidth by using a multipath interference canceller or chip equalizer even in a multipath fading channel. However, to meet the current huge increases in the amount of data traffic and further ones expected in the future, new broadband wireless access methods must provide broadband packet transmission with a maximum throughput above 100 Mbit/s in the downlink using a bandwidth of approximately 50 to 100 MHz (note that the target throughput corresponds to an approximately 10-fold increase over that achievable in HSDPA with a 5-MHz bandwidth). In addition, this broadband wireless access must flexibly support both isolated-cell environments (such as hotspot areas and indoor offices) and cellular systems from the standpoint of further reducing the cost of radio access networks (RANs). Furthermore, since it is presumed that the signal format in the wireless channel is a packet format, the service being offered is basically a best-effort type according to the channel condition of each user and traffic conditions within the cell, where minimum throughput is guaranteed with the required quality of service (QoS), e.g., delay and residual packet error rate.

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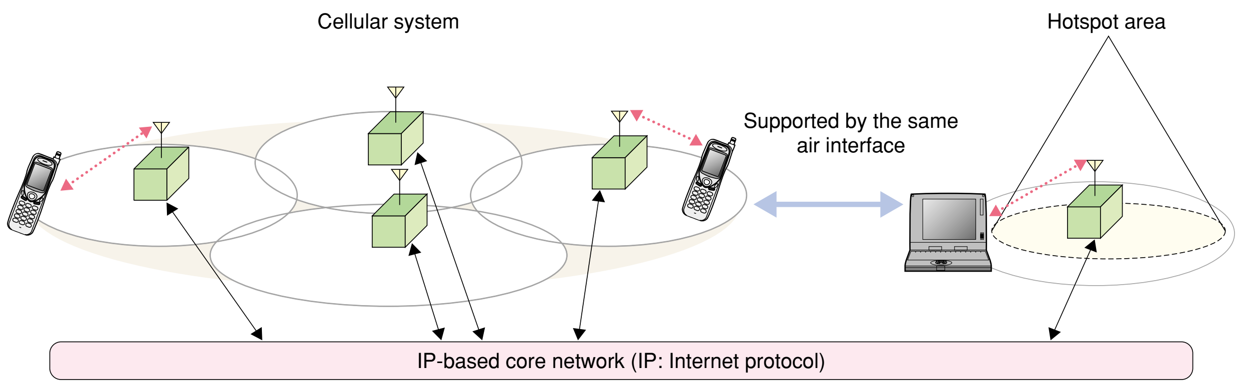


Fig. 1. Concept of the broadband packet wireless access system supporting a cellular system and local areas by the same air interface.

In this article, we present targets for a broadband packet wireless access system, which is for the systems beyond IMT-2000, and overview key techniques for it. Section 2 describes the targets of broadband packet wireless access. Section 3 then explains the RAN configuration that we propose, and section 4 presents broadband packet wireless access techniques focusing on wireless access schemes. After that, section 5 briefly presents efficient packet access techniques, and section 6 discusses multiple-antenna transmission methods, which are essential for enabling wider coverage area and improving the achievable throughput.

2. Targets of broadband wireless access

Figure 1 shows the concept of the proposed broadband packet wireless access system. In the future RAN, further decrease in the network cost is a very important requirement for offering rich multimedia services to customers via wireless communications. Therefore, the proposed concept can support both a cellular system with a multi-cell configuration and local areas (such as hotspot areas and indoor office environments) by the same air interface (i.e., the same carrier frequency, frequency bandwidth, radio frame structures, etc.). Only the main radio parameters such as spreading factor, data modulation scheme, and channel coding rate need to be changed. By changing them according to the cell configuration, channel load, and channel condition of each user, we can achieve the maximum system capacity based on the same air interface, that is, the same broadband wireless access scheme.

In our broadband packet wireless access system, the target of the peak throughput for the downlink in a cellular environment is 100 Mbit/s, which is approximately ten times the peak throughput forecast for HSDPA using a 5-MHz frequency bandwidth. Achieving a throughput of 100 Mbit/s will of course help to reduce network cost, but it will also enable large-capacity data downloads and high-resolution video communication services among multiple users. However, local areas (generally, short-distance and short-time-dispersion environments) will probably require throughput in excess of 100 Mbit/s to support large amounts of data traffic. We therefore aim for a maximum throughput of 1 Gbit/s (frequency efficiency: 10 bit/s/Hz) for these types of areas and intend to support throughput flexibly for various environments using the same air interface.

For the uplink, the target for frequency efficiency for hotspots and indoor environments is 7 bit/s/Hz. This comes to a maximum throughput of approximately 300 Mbit/s for a frequency bandwidth of 40 MHz. For a cellular environment, the target is a maximum throughput of 20 Mbit/s per sector[*1].

In the broadband wireless access system, all signals are transmitted by a packet configuration in the RAN, i.e., to transmit both realtime and non-realtime traffic data as packet signals. Here, channels can be allocated to multiple users in a cell on the basis of time-division multiplexing using a shared-channel packet format. This will significantly reduce the number of physical radio devices making up base-station equipment compared with the circuit-switching transmission system that allocates a dedicated physical channel to each user.

*1 Sector: Cells are split into sectors for greater efficiency.

3. Radio access network configuration in broadband wireless access

3.1 Inter-cell synchronization

A broadband wireless access system must be able to support a seamless service area covering not only a cellular environment but also hotspots in underground shopping centers, airports, hotel lobbies, and indoor environments like offices. To achieve flexible deployment, especially to indoor environments, an inter-cell asynchronous system is advantageous over an inter-cell synchronous system based on time synchronization.

A mobile terminal needs to establish a wireless link with the base station that provides the minimum path loss. In a wireless access system that supports a multi-cell cellular system, this criterion is nearly the same as the criterion of finding the reference signal in the downlink with the highest received power level (in W-CDMA, the common pilot channel is used for this purpose). Thus, in W-CDMA, the cell or sector whose common pilot channel in the downlink has the highest received power is selected as the optimal cell/sector. The situation is somewhat different, however, in a broadband wireless access system that supports both cellular and isolated cells, as shown in **Fig. 2**. Specifically, the base-station transmission power of cellular cells differs from that of hotspot cells, which means that the cell with the highest received power level of the common pilot channel in the downlink is not necessarily the cell with the lowest path loss between the base station and mobile terminal. In the example shown in the figure, the received power of the pilot channel from an outdoor cellular cell is highest, but the cell with the lowest path loss is an indoor hotspot. Establishing a wireless link with the indoor cell leads to the maximum reduction in the transmission power required by the mobile terminal.

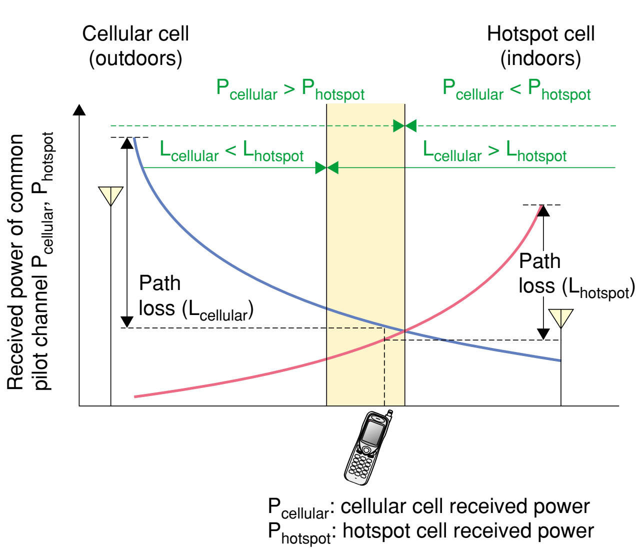


Fig. 2. Cell selection when cellular cells and hotspot cells coexist.

In the manner described above, a search must be performed for the cell/sector having the lowest path loss between the base station and mobile terminal in a system where isolated environments coexist with a cellular environment. This cell search can be divided into three types: (1) initial cell search, (2) cell search in active mode, and (3) cell search in idle mode. For cell searches in the active and idle modes, and standby searches, the currently connected cell (sector) informs the mobile terminal about the transmission power and cell type (cellular or isolated) of neighboring cells so that the terminal can find the optimal cell having the lowest path loss between itself and the base station.

For the initial cell search, two methods can be considered. In the first method, which is similar to the method used in conventional cellular systems, the mobile terminal first establishes a wireless link with the cell whose downlink pilot channel has the highest received power. The terminal then receives and decodes a report on neighboring cells from that cell. If there is a neighboring cell with lower path loss than the currently connected cell, the terminal switches its wireless link to it. In the second method, each cell is allocated beforehand a unique scrambling code indicating a cellular or hotspot cell [2]. As a result, a mobile terminal in an initial cell-search stage can identify the cell type and thus search for the optimal cell with the lowest path loss simply using the processing in the physical layer.

Of these three types of cell searches, the initial cell search takes the longest time. To reduce the search time, three-step cell search algorithms have been proposed using orthogonal frequency and code division multiplexing (OFCDM) or orthogonal frequency division multiplexing (OFDM) [3], [4]. In the first step, the system detects the OFCDM or OFDM symbol timing. In the second step, it detects the group to which a cell-specific scrambling code belongs as well as the frame/slot timing. To detect this information, a method that uses a synchronization channel [3] and one that uses a time-multiplexed common pilot channel [4] have been proposed. In the third and final step, the system detects the scrambling code of the optimal cell among the scrambling-code candidates belonging to the scrambling-code group detected in the sec-

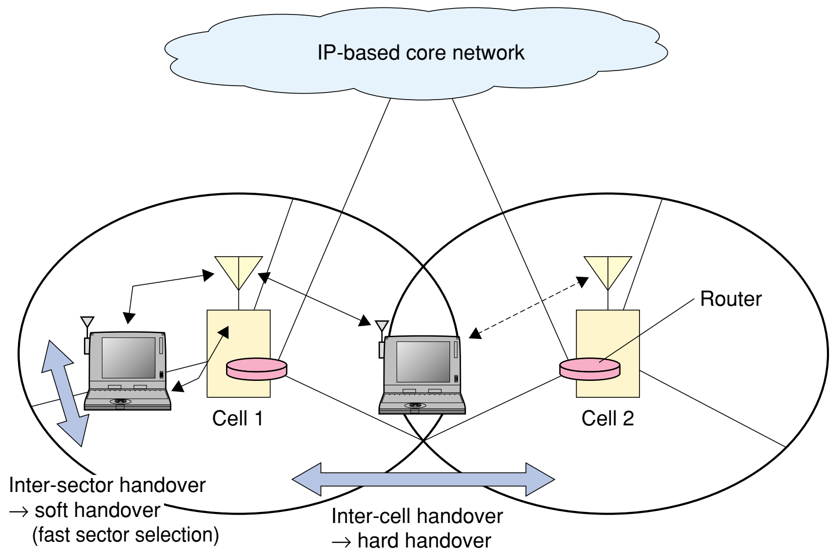


Fig. 3. Handover control.

ond step.

3.2 Handover

In addition to handover between cells/sectors in a cellular system, a function for achieving handover between a cellular cell and an isolated cell is essential to achieving seamless cell deployment. A handover operation on the data-link or lower layer is called inter-cell or inter-sector macro-diversity*2, and the required QoS on these layers is guaranteed by employing the macro-diversity. On higher application layers, both the data delay via wired transmission based on the Internet protocol (IP) network in the system and the control signaling delay corresponding to the mobility of the mobile terminal must be taken into consideration. In W-CDMA, the mobile terminal sets up dedicated channels with multiple cells/sectors and obtains a diversity effect by performing a soft handover in which the same information is transmitted to the mobile terminal via multiple cells/sectors on the downlink and received by multiple cells/sectors on the uplink. This macro-diversity effect between cells/sectors in a soft handover results in high-quality transmission in circuit-switching mode.

A broadband wireless access system, however, employs transmission-slot allocation (packet scheduling) and ARQ, which means that an optimal handover algorithm on the data-link layer or below must take into account the effects of packet scheduling and ARQ. In this regard, a study has been performed on throughput performance versus cell selection interval during inter-cell macro-diversity reception for OFCDM on the downlink [5]. For a cell selection interval of more than 500 ms, cell-selection updating cannot follow the shadowing variation. This results in the selection of a cell with a small signal-to-interference power ratio (SIR), i.e., a large path loss, and an increase in the required ratio of the signal energy per bit to noise power spectrum density (E_b/N_0).

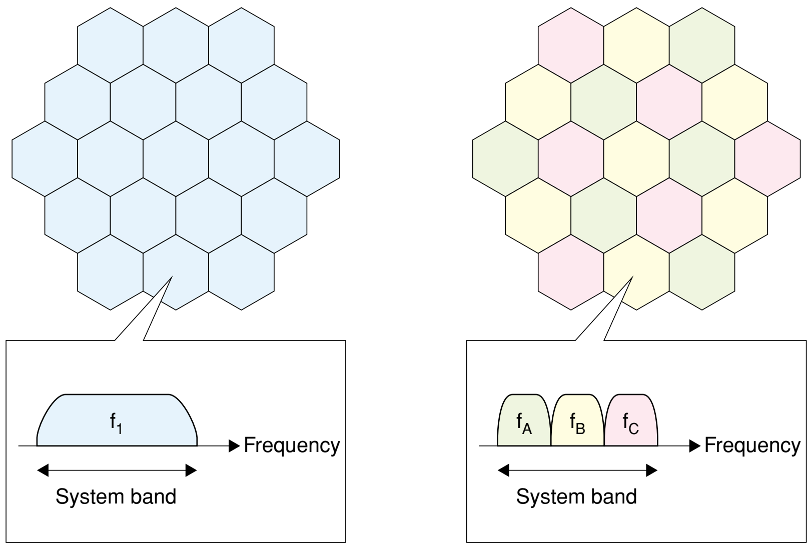
Figure 3 shows the proposed method of handover control for the data-link layer and below. When taking into account fast packet scheduling and ARQ, fast hard handover with a cell selection interval of about 100 ms is considered to be appropriate for inter-cell handover. A hard handover can simplify the control of the core network between different cells compared with a soft handover. As for inter-sector handover, processing within the base station makes it easier to distribute and combine data sequences. A soft handover (including fast sector selection on the downlink) is therefore expected to have a traffic-dispersion effect when traffic becomes concentrated in a particular sector.

4. Broadband wireless access schemes

4.1 Duplexing

Two well-known duplexing schemes are frequency division duplexing (FDD) and time division duplexing (TDD). TDD has the advantage of not requiring a pair of frequency bands, although it does require base stations to be synchronized (frame synchronization) for application to a cellular system. In an isolated-cell

*2 Macro-diversity: Improvement obtained by combining the signals received at multiple cells (or sectors).



(a) One-cell frequency reuse
(b) Three-cell frequency reuse

Fig. 4. Comparison of one-cell and three-cell frequency reuse.

environment, moreover, TDD can perform flexible slot allocation for each link by varying the transmission/reception slot-allocation ratio on the uplink and downlink using the same frequency band. However, in a cellular system, uplink/downlink slot allocation ratio needs to be same among a cluster of neighboring cells. FDD, on the other hand, while requiring a pair of frequency bands for the uplink and downlink, does not require base-station synchronization, so it is considered to be preferable to TDD from the viewpoint of flexible cell deployment. While both will probably have to be supported in the end, a system configuration based on a single wireless interface (frame configuration) is desirable.

4.2 Cell frequency reuse

Figure 4 shows the frequency usage efficiency in a cellular system for one-cell and three-cell frequency reuse. With one-cell frequency reuse (Fig. 4(a)), the transmitted signals are spread over the whole system band by spreading in the time or frequency domain while the despreading process decreases interference and noise components by the inverse of the spreading factor on average, which means that a spreading gain can be expected. In ordinary time division multiple access and frequency division multiple access, however, three-cell frequency reuse (Fig. 4(b)) is necessary to reduce co-channel interference. As a result, the frequency bandwidth per cell/sector is 1/3 of the full system band. In short, one-cell frequency reuse is an essential condition for increasing system capacity in a cellular system.

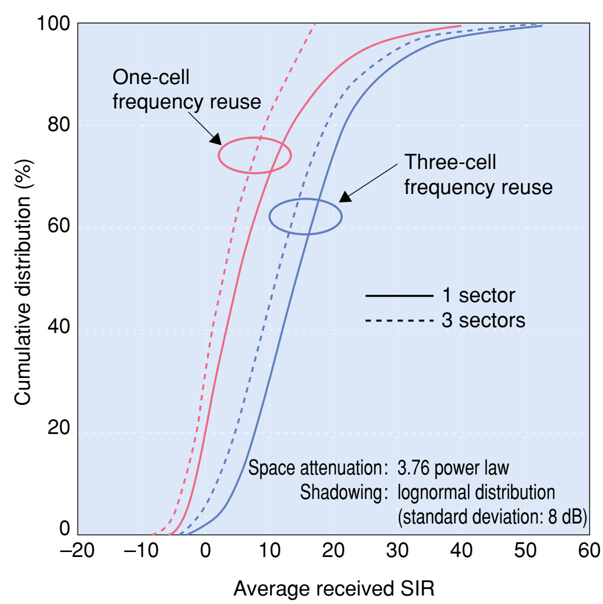


Fig. 5. Cumulative distributions of average received SIR for one-cell and three-cell frequency reuse.

Figure 5 shows cumulative-distribution of average received SIR (equal to the ratio of desired-signal power to interference power from neighboring cells in this case) for one-cell and three-cell frequency reuse on the downlink of a cellular system. It is assumed here that the cell radius is the same for all cells and that the transmission power is the same for all sectors. Distance-dependent path loss follows a 3.76 power law, while shadowing variation follows a lognormal distribution with a standard deviation of 8 dB. The 50% values of these cumulative-distribution plots show that the received SIR for one-cell frequency reuse is about 10 dB less than that for three-cell frequency reuse, which means that one-cell frequency reuse needs "gain" to suppress about 10 dB of interference from neighboring cells. Spreading of the time or frequency domain can easily achieve one-cell frequency reuse by effectively reducing interference from neighboring cells. In addition, to prevent each symbol from being affected by same-pattern interference from neighboring cells in one-cell frequency reuse, it is essential to employ cell-specific (or user-specific) scrambling code.

4.3 Downlink wireless access scheme: VSF-OFCDM

Table 1 compares broadband wireless access systems on the downlink and **Fig. 6** compares DS-CDMA and multicarrier transmission systems on a broadband channel. These systems can be roughly divided into those that perform spreading using cell-specific spreading codes and those that do not.

In a broadband wireless channel, a large number of delayed paths are observed. If spreading is applied to the broadband wireless acess scheme based on the time-domain-spreading approach taken by DS-CDMA, the number of paths that can be resolved increases. However, at the same time, paths having different delay times generate interference (multipath interference), which offsets the Rake diversity effect.

Table 1. Comparison of wireless access systems on the downlink.

Access system	Single/multicarrier DS-CDMA	OFCDM	OFDM	Single/multicarrier TDMA
Spreading	Yes	Yes	No	No
Number of carriers	1 or a few	Many	Many	1 or a few
Effects of multipath interference	Degrades the Rake diversity effect	Robust against multi-path interference	Robust against multi-path interference	Degrades signal due to inter-symbol interference
Frequency reuse	One-cell frequency reuse	One-cell frequency reuse	Cell frequency reuse basically needed	Cell frequency reuse basically needed

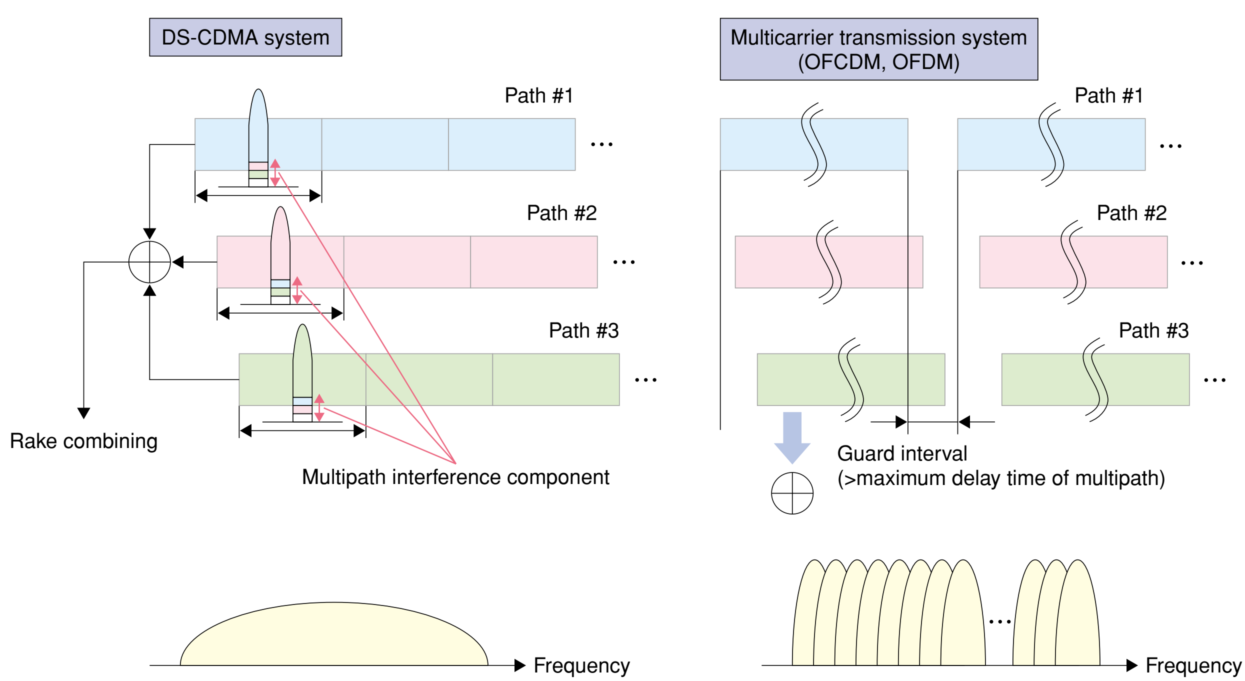


Fig. 6. Comparison of wireless access systems in a broadband channel.

If the SIR of each despread path is very small, the signal after Rake combining cannot achieve the required SIR. Therefore, a wireless access system robust against multipath interference is therefore essential to achieving high-quality signal transmission in a broadband channel. In this regard, a multicarrier transmission scheme first subjects a high-speed data stream to a serial-parallel conversion generating many subcarrier signals whose symbol length is sufficiently longer than the multipath propagation delay time. It then proceeds to transmit these low-symbol-rate data streams in parallel. In other words, in multicarrier transmission, the frequency band is divided into a large number of narrow-band signals resulting in a small bandwidth per subcarrier. This means that amplitude and phase variations within a subcarrier can be treated as flat fading and that the effects of waveform distortion caused by frequency-selective fading can be reduced. Even if there is a subcarrier whose received power has dropped due to fading, its decoded error can be compensated for by applying error-correction channel coding across multiple subcarriers whose received power has not dropped, resulting in high-quality reception.

On the downlink of a cellular system, OFCDM, which is based on multi-carrier CDMA (MC-CDMA) [6], [7], can reduce the effects of multipath interference while obtaining a frequency diversity effect by spreading and mapping channel-coded symbols across multiple subcarriers. For this reason, OFCDM is more suitable for increasing capacity than other wireless access systems [8], [9]. Thus, in addition to being robust against multipath fading, which is a characteristic of multicarriers, OFCDM can achieve one-cell frequency reuse in a flexible manner and increase system capacity by applying spreading in either the time or frequency domain. In an isolated-cell environment, however, interference from neighboring cells is small and system capacity can generally be increased by not using spreading. The reason for this is that when spreading in the frequency domain is used, code orthogonality among multiplexed code channels collapses due to frequency-selective fading caused by multipath interference. Similarly, when spreading in the time domain is used, amplitude fluctuation occurs in the time domain in a high-speed Doppler environment, giving rise to intercode interference that in turn destroys the orthogonality in the time domain. In either case, it is difficult to multiplex as many code channels as corresponds to the spreading factor.

To deal with the above situation, OFCDM with a variable spreading factor (VSF-OFCDM) has been proposed [10], [11]. This system adapts the variable spreading factor in the OFCDM time and frequency domains according to the cell configuration, propagation conditions (delay spread, maximum Doppler frequency, and interference from other cells), channel load, radio parameters (data modulation scheme and channel coding rate), and other conditions. **Figure 7** shows the concept of VSF-OFCDM with two-dimensional spreading. Here, one data modulation symbol

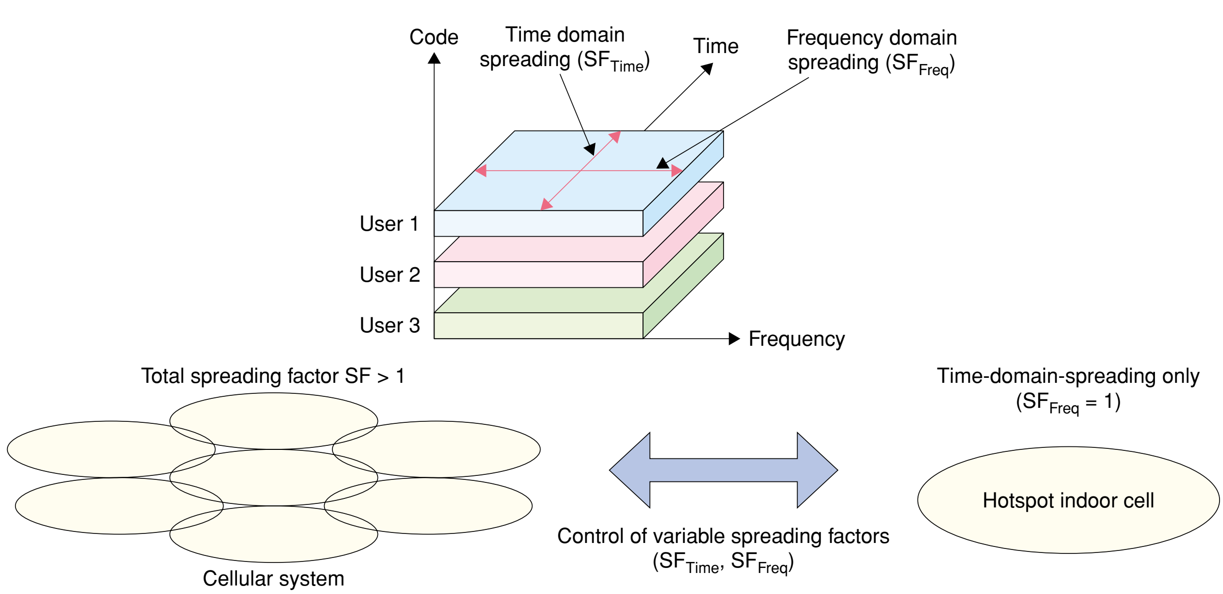


Fig. 7. Concept of VSF-OFCDM using two-dimensional spreading.

Table 2. Comparison of wireless access systems on the uplink.

Access system	Single/multicarrier DS-CDMA	OFCDM	OFDM	Single/multicarrier TDMA
Spreading	Yes	Yes	No	No
Number of carriers	1 or a few	Many	Many	1 or a few
Low power-consuming terminal	Low peak-power transmission possible by spreading	Large peak power	Large peak power	Large peak power
Large capacity	Performance improved by the Rake diversity	Accuracy of channel estimation degrades	Accuracy of channel estimation degrades	Signal degrades due to inter-symbol interference
Frequency reuse	One-cell frequency reuse	One-cell frequency reuse	Cell frequency reuse basically needed	Cell frequency reuse basically needed

will be spread across several consecutive OFCDM symbols and several consecutive subcarriers (these numbers are given by SF_{Time} and SF_{Freq}, which denote the spreading factor in the time and frequency domains, respectively) with the total spreading factor represented as the product $SF = SF_{Time} \times SF_{Freq}$. As indicated in Fig. 7, two-dimensional VSF-OFCDM can (i) control the total spreading factor in accordance with the cell configuration (the mobile terminal sets the spreading factor based on control information from the base station), (ii) adaptively control SF_{Time} and SF_{Freq} in accordance with propagation conditions, channel load, and radio parameters, and (iii) maximize channel capacity for both a cellular system and an isolated-cell environment.

4.4 Uplink wireless access scheme: VSCRF-CDMA

Table 2 compares broadband wireless access systems on the uplink. From the viewpoint of low mobile-terminal power consumption, the most important requirement on the uplink, the DS-CDMA approach is more advantageous than the multicarrier approach as in OFDM and OFCDM, which use many subcarriers having a large peak-to-average power ratio. The uplink, moreover, requires a dedicated pilot channel for each mobile-terminal physical channel to perform coherent detection and demodulation. Consequently, for OFDM and OFCDM, channel estimation must be performed for each subcarrier, and for the same pilot power condition, the pilot channel signal power per subcarrier is small compared with that of DS-CDMA. As a result, the DS-CDMA system has been reported to maintain more accurate channel-estimation, to reduce the received E_b/N_0 that satisfies the required packet error rate compared with multicarrier systems, and to be capable of increasing the link capacity [12]. Moreover, in DS-CDMA, there is a bandwidth that can minimize the required transmission power (i.e., received E_b/N_0). This optimal subcarrier bandwidth is determined based on the tradeoff between the Rake diversity and increasing multipath interference. When propagation conditions (such as delay profile shape and number of paths) and the spreading factor are given as parameters, the received E_b/N_0 required can be reduced the most by a subcarrier bandwidth from 20 to 40 MHz [12]. Accordingly, a multicarrier/DS-CDMA system configured on the basis of this optimal subcarrier bandwidth in accordance with the system band is a promising wireless access system from the viewpoint of link capacity.

The DS-CDMA system can achieve one-cell frequency reuse in a flexible manner through spreading in the time domain. The advantage of one-cell frequency reuse diminishes, however, in an isolated-cell environment for which interference from neighboring cells is small. Here, link capacity turns out to be 20-30% of the spreading factor when the voice activity factor is not used. To support a single air interface for both multi- and isolated-cell-environment DS-CDMA, the link capacity needs to be increased for isolated cells. Since interference from other users and multipath interference make it difficult to achieve orthogonalization in the code domain when the bandwidth is broadened, orthogonalization between simultaneous users in the frequency or time domain must be established.

Figure 8 shows the concept called variable spreading and chip repetition factors CDMA (VSCRF-CDMA) [13]. In a multi-cell environment, it is usual to perform spreading only in the time domain, which makes one-cell frequency reuse easy to achieve. In an isolated-cell environment, on the other hand, the principle of symbol repetition is applied to the spread chip sequence and chip repetition is performed. Here,

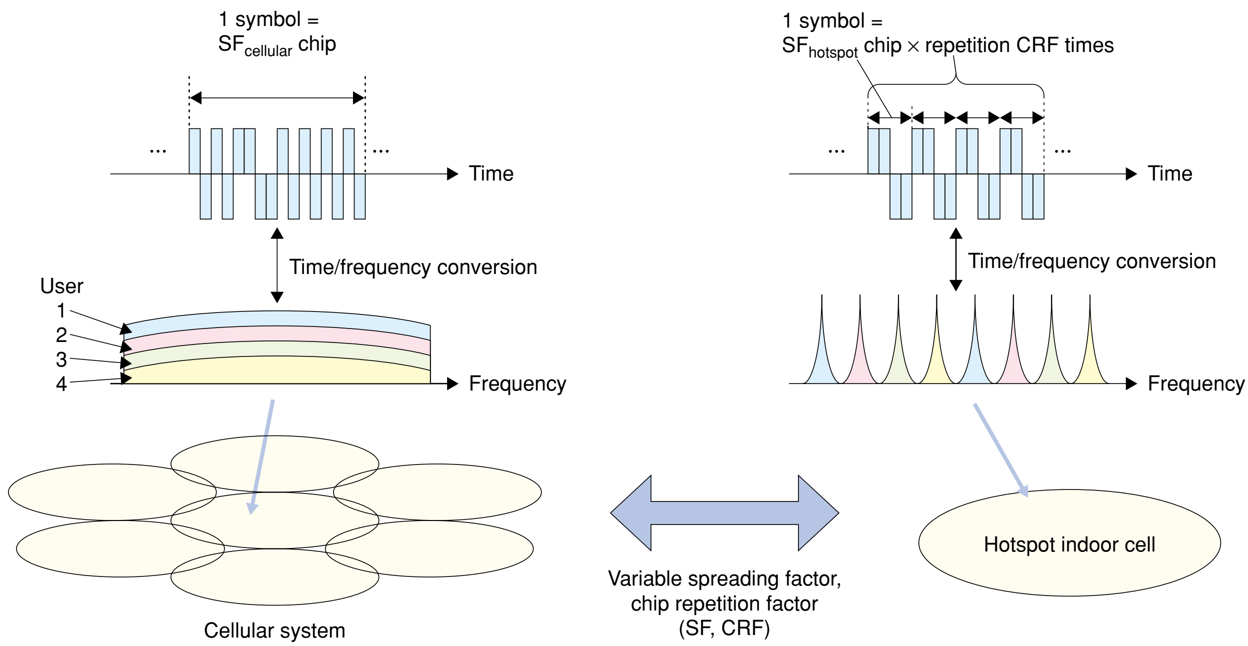


Fig. 8. Concept of VSCRF-CDMA.

SF denotes the spreading factor for total band broadening. Its value is determined by the symbol rate of the physical channel. In an isolated-cell environment, CRF is set to 1 or greater, and the time-domain spreading factor $SF_{hotspot}$ is made small based on the relationship $SF = SF_{hotspot} \times CRF$. This kind of control makes it possible to allocate received signals from a number of simultaneous users equal to CRF to a set of subcarriers that are mutually orthogonal in the frequency domain. In the method proposed here, CRF and $SF_{hotspot}$ are varied adaptively according to the cell configuration (multiple cells or an isolated cell), number of simultaneously accessed channels, and propagation condition (number of multipaths).

4.5 Physical channel configuration

Figure 9 shows the configuration of physical channels. First, the common control channel transmits broadcast and paging information at a fixed level of transmission power. This channel uses a fixed modulation scheme, quadrature phase shift keying (QPSK), and a low coding rate so that reception can be performed at the required quality and coverage within the cell. Next, the shared packet channel transmits high-speed packet data at a fixed level of transmission power. It applies AMC using a modulation scheme and channel coding rate appropriate for the received SIR and provides a maximum throughput that guarantees the required received-packet error rate. Finally, the associated control channel sends control information for the physical and data-link layers to facilitate high-quality transmission on the shared packet channel. It features a fixed modulation scheme (QPSK) and coding rate and applies transmission-power control to compensate for fluctuations in the received level caused by instantaneous fading.

5. Efficient packet access techniques

Table 3 lists realtime (RT) and non-realtime (NRT) traffic requirements [14], [15]. The transmission of RT traffic data such as audio and video broadcasts must provide guaranteed reception quality at or below the required residual packet error rate while meeting delay requirements. In contrast, NRT traffic data such as file transfer and WWW browsing must ensure the delay not more than a few seconds, which is a less stringent requirement than that of RT traffic data, but the data transmission must be error free within this delay. **Figure 10** shows packet control on the data-link and physical layers [16]. On these layers, scheduling is performed to satisfy the required delay and IP packet loss rate on the RAN in accordance with the traffic data in question. On the downlink, efficient transmission-slot allocation (scheduling) is performed according to the received SIR and type of traffic data (RT or NRT) of each mobile ter-

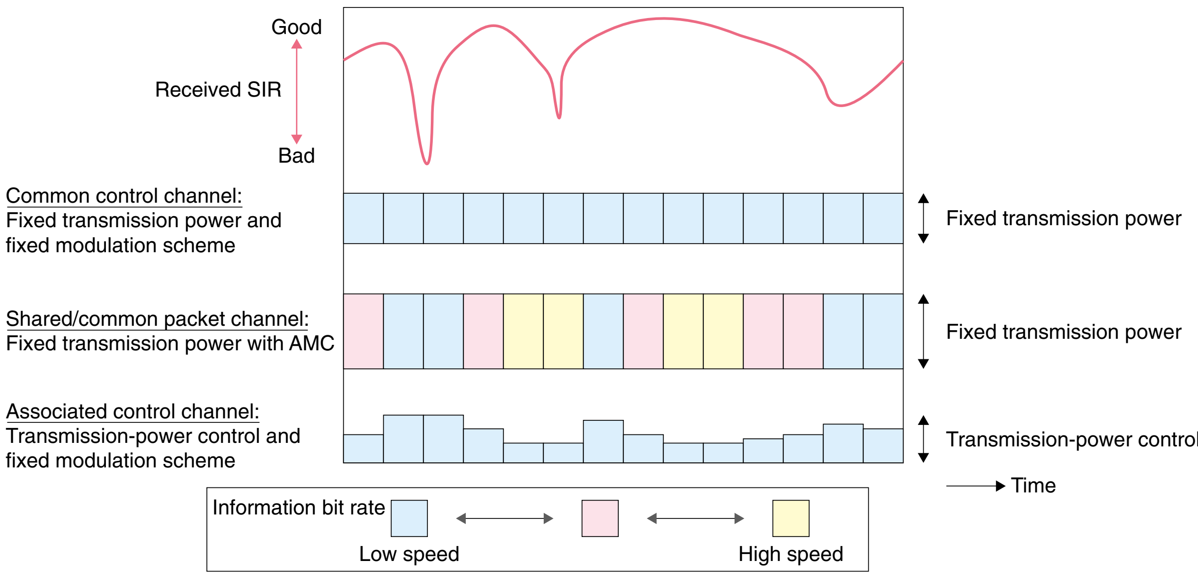


Fig. 9. Physical channel configuration.

Table 3. Traffic requirements.

Servise class	Example	QoS requirements (examples)	
		End-to-end delay	Pacekt loss rate
Realtime (RT)	Audio and video broadcasts	<150 ms	0.5% or less
Non-realtime (NRT)	File transfer, WWW browsing	<2-3 s	0%

minal. On the uplink, each terminal sends a reservation packet beforehand to report the QoS requirements of subsequent data packets, data size, channel conditions, etc., to the base station and the base station performs transmission-slot allocation on the data packet channel for each mobile terminal based on this information. The system also applies MAC-layer ARQ to the packet data channel according to the required delay time. The above approach can reduce the required transmission power through a time diversity effect, especially in the case of NRT traffic data [17].

6. Multi-antenna transmission/reception techniques

6.1 Configurations

A broadband wireless access system is expected to use a high carrier frequency to support high-speed transmission bit rates, and if such a service is to be provided to a wide area, small zones (micro-cells) and low required received E_b/N_0 will be indispensable. Therefore, it would be useful to have an adaptive antenna array that can generate directional beams in the angular direction of each user. At the same time, a multiple-input-multiple-output (MIMO), spatially multiplexed multi-antenna transmitting/receiving scheme is effective for increasing the throughput (frequency efficiency). This scheme uses multiple transmitting/receiving antennas and radio devices and transmits different data streams from each transmitter. On the downlink, VSF-OFCDM wireless access with a frequency bandwidth of 100 MHz enables a peak throughput of 200/300 Mbit/s to be achieved by combining 16QAM/64QAM data modulation and a channel coding rate of 3/4. A four-antenna MIMO, for example, might achieve 1-Gbit/s transmission (frequency efficiency: 10 bit/s/Hz) for a frequency bandwidth of 100 MHz in an isolated-cell environment. Below we discuss three multi-antenna transmitter/receiver configurations from the viewpoint of improving frequency efficiency. **Table 4**

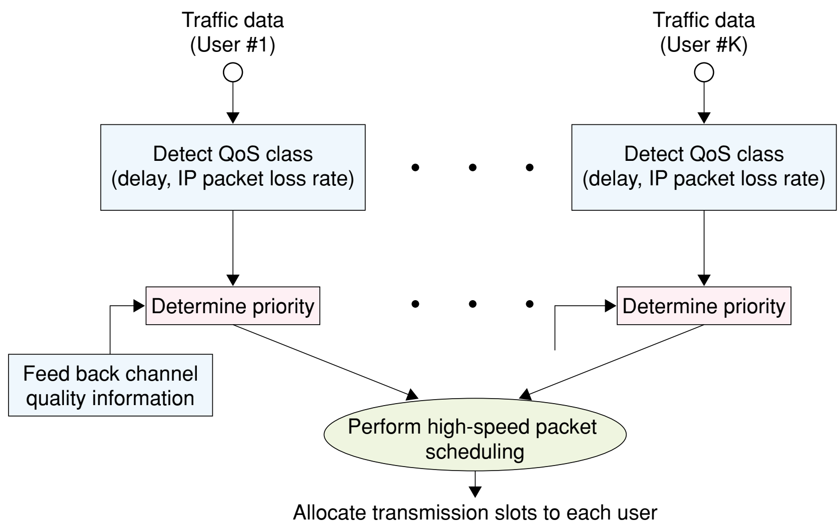


Fig. 10. Packet scheduling on the data-link and physical layers.

Table 4. Comparison of multi-antenna transmitter/receiver configurations.

		MIMO multiplexing	MIMO diversity	Adaptive-antenna-array transmission
Effect		Increases information bit rate	Increases diversity gain	Increases average received SIR
Required transmission-antenna interval		Large		Small
Inter-antenna fading correlation	Large	Small signal-separation ability	Small transmission-diversity gain	Large antenna gain
	Small	Large signal-separation ability	Large transmission-diversity gain	Small antenna gain
Own-cell/other-cell interference-suppression effect		No		Yes
RF circuit calibration		Unnecessary		Necessary

summarizes the comparison.

- MIMO multiplexing method: transmits different data streams on independent radio propagation paths using the same frequency band and time slot [18]
- MIMO diversity method: performs space-time coding and transmits data streams amongst multiple antennas [19]
- Adaptive-antenna-array transmission method: performs directional transmission using multiple transmitting antennas

(1) The MIMO transmitter/receiver configuration (MIMO multiplexing method) is shown in **Fig. 11(a)**. This method performs serial/parallel conversion on a modulated data stream to produce N separate streams and transmits them by spatial parallelism. Since different data streams are transmitted on the same frequency band and time slot, the received signals carrying these N data streams must be separated at the receiver. For this purpose, the following methods have been proposed .

- Separate signals by maximum likelihood detection (MLD)
- Combine received signals by weighting so as to minimize the mean square error
- Successively extract regenerated data replicas from the received signal (Vertical Bell Laboratories layered space time (V-BLAST)) [20]

(2) In the MIMO diversity method, the transmitter performs space time block coding (STBC) [19] after information bits have been channel encoded and data modulated and generates and transmits N streams of coded data. The receiver performs STBC decoding at each antenna and then performs antenna-diversity reception through maxi-

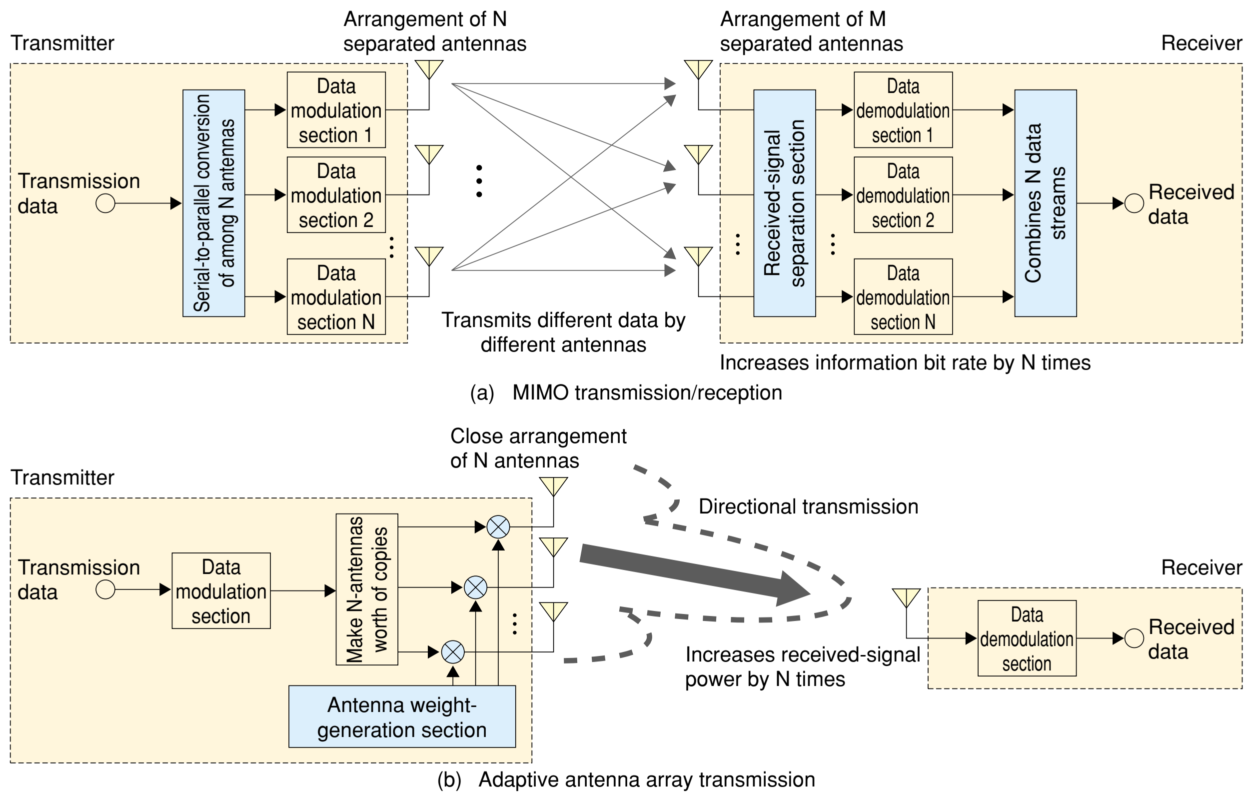


Fig. 11. Multi-antenna transmission/reception methods.

mal ratio combining (MRC).

(3) A transmitter/receiver configuration for performing adaptive-antenna-array transmission is shown in **Fig. 11(b)**. In this configuration, the system subjects a data stream to channel coding and modulation (including data modulation and spread modulation), copies the result N times corresponding to the number of antennas, and multiplies each stream by an antenna weight unique to each antenna branch. The antenna weights are generated adaptively by first estimating the direction of a signal received from the target user on the uplink and then computing them so that the main beam of the transmitting antenna pattern is directed toward the user [21]. On the receiving side, the system performs antenna diversity reception by MRC. This type of adaptive-antenna-array transmission can ideally increase antenna gain by N times, where N is the number of transmitting antennas.

6.2 Comparison of configurations for ultrahigh-speed signal transmission

As shown in Table 4, the MIMO multiplexing method, which transmits information in parallel via multiple transmitting antennas, can increase the information bit rate by simply increasing the number of transmitting antennas, unlike the other two methods. In MIMO diversity and adaptive-antenna-array transmission, the throughput can be increased by increasing either the modulation level or channel-coding rate. For VSF-OFCDM wireless access with a frequency bandwidth of 100 MHz, assuming four antennas for transmission and four for reception, the MIMO multiplexing method can achieve a high-speed, high-efficiency throughput of 1 Gbit/s (10 bit/s/Hz) using 16QAM or 64QAM data modulation. The MIMO diversity or adaptive-antenna-array transmission methods, on the other hand, would have to employ high-efficient multilevel modulation, so the achievable throughput performance is degraded due to the decrease in the minimum Euclidean distance. Overall, the MIMO multiplexing method, which transmits multiple data streams by spatial multiplexing, is the most appropriate method for achieving high-efficiency transmission such as 10 bit/s/Hz [22].

7. Conclusion

This article gave an overview of broadband wireless access technology featuring seamless support of various communication environments from cellular systems to isolated cells like hotspots and offices all by a single wireless interface. In future research, we plan to perform indoor and outdoor experiments to measure propagation characteristics and evaluate packet-signal transmission on a broadband channel.

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