2 Wireless Access Technologies

2-1 Broadband Wireless Access System for Next Generation Seamless Mobile Communication

HARADA Hiroshi and FUNADA Ryuhei

In this article, we propose a new generation mobile communication system that can realize 100 Mbps carrier bit rate under high mobility environment and can access IP network easily. The new system is based on dynamic parameter controlled orthogonal frequency and time division multiple access (DPC-OF/TDMA) in which users share “slots” that use certain number of subcarriers and certain time. To access the slots, mobile stations use a packet-reservation-based protocol: packet reservation dynamic time-slotted multiple access (PR-DSMA). In addition, to avoid co-channel interference from adjacent cells and increase frequency utilization efficiency, we use an adaptive modulation scheme that is based on an interference detection algorithm. In this article, we mention the concept and the basic transmission performance of the proposed system.

Keywords
New generation mobile communication system, OFDMA, TDMA, Beyond 3G system, 1 cell reuse

1 Introduction

As clearly stated in the “e-Japan Project”, one of the most pressing issues for the near future is the realization of a new-generation (NG) mobile communication system[1] that allows wireless access to IP networks (as exemplified by the so-called “ultra-fast Internet”) and, at the same time, permits seamless handover with existing wireless network systems. Further, in the future, an enormous number of access points (AP) will be available and capable of establishing ultra-fast wireless connections to IP networks with carrier bit rates exceeding 100 Mbps. These APs will accommodate multiple mobile stations (MS) and will control high-speed handover by procedures coordinated using switches connecting the APs, which will also execute the processes required for switching between heterogeneous systems. The wireless transmission method adopted for this purpose should adapt to an AP environment using software-defined wireless technologies[1] to perform the appropriate selection of parameters concerning the wireless transmission—such as the frequency, bandwidth, and transmission method.

One of the most essential technologies in this NG mobile communication structure will be a high-mobility, broadband, wide-area access system that offers carrier bit rates exceeding 100 Mbps under high-mobility conditions, with anticipated transmission speeds of several hundred Mbps to 1 Gbps in near-stationary environments, and that allows as many users as possible to be accommodated on a single AP.

We may identify a number of specific requirements for such a high-mobility, broadband, wide-area access system: (1) the cell radius for the frequency band used should be extended to the full extent possible, which means increasing the number of users to the full extent as well; (2) the efficiency of frequency use should be maximally enhanced, to avoid unnecessary occupation of frequency bands when expanding the communication area; (3) low packet-error rates should be ensured in transmission, even under high-mobility conditions; (4) easy access must be offered to IP networks (such as the Internet); (5) the required band must be supplied to the user based on considerations such as user device environment, cost effectiveness, band limitations, etc. for all users—from those using PDAs to those using vehicle-borne devices; and (6) each of the layers (such as the seven layers of the OSI) must be distinguished and categorized, and the lower layers must be controllable from the upper layers.

In particular, a minimum carrier rate of several tens MHz (even under high-mobility conditions) and a maximum rate of 100 Mbps are required under condition (1) above, and so a frequency band of approximately 100 MHz must be secured. If we also take into consideration the expansion of the cell radius, then the frequency band used will mainly be in the microwave band of 3-10 GHz. However, availability in the microwave band is presently extremely low, and so the same frequency may have to be used for adjacent cells when expanding the communication area with the adoption of cellular systems. In such a case, the cell boundaries are subject to interference from multiple cells, and so countermeasures must be devised to counteract this interference. One method that has been examined for this purpose is referred to as Code Division Multiplexing (CDM). Another method is seen in OFCDM transmission[2], which offers advantages over CDM in the suppression of the frequency used; this method also adopts coded Orthogonal Frequency Division Multiplexing (or “coded OFDM”), which provides for sufficiently high transmission quality even under high-mobility conditions.

However, previous studies[3]-[5]—measuring received signal level, delay profile characteristics, and building penetration characteristics at microwave frequencies (4.9-GHz band) planned for use in NG mobile communication systems—were conducted under the following conditions: a reception antenna gain of 4.7 dBi (omnidirectional in the horizontal plane), a transmission power of 40 dBm, a transmission antenna gain of 9.7 dBi (omnidirectional in the horizontal plane), and a transmission antenna height of 40 m. According to the results, the radius of reception points at which the gain of the received signal level of -80 dBm can be obtained is 500 m at maximum; the median value of the delay profile is 300 ns, the 90 % value is 450 ns, and the maximum value is between 3,000 and 4,000 ns. The building penetration values are approximately 40-45 dB, and the areas in which interference arises between adjacent outdoor/outdoor cells and between outdoor/indoor cells are not large compared to that of second and third-generation mobile communication systems. Thus, we may conclude that the same frequency can be used in adjacent cells not only by adopting a method combining CDM and OFDM, but also by simply combining interference detection and circumvention methods with OFDM transmission.

In this article, we propose a Dynamic Parameter Controlled Orthogonal Frequency and Time Division Multiple Access (DPC-OF/TDMA) system, a high-performance system resulting in carrier bit rates exceeding 100 Mbps even in high-mobility conditions, and offering superior connectability to IP networks[6][7]. The proposed system has OFDM transmission as its core, and “slots” having prescribed lengths of frequency and time are shared between multiple mobile stations (MS). The method used to access these slots uses a protocol for packet reservation dynamic time-slotted multiple access (PR-DSMA) that is based on reserved dynamic slot allocation technology. Further, the system uses an interference detection and adaptation modulation method for interference control, with the aim of increasing transmission volume and efficiency of frequency use. In this article, we will focus on the basic concepts and features of the proposed system.

2 Outline of the system

The DPC-OF/TDMA has as its basic concept the adoption of the OFDM transmission method, as shown in Fig. 1. In order to carry out OFDM transmission, the subcarrier is divided into blocks having prescribed lengths. Each of these blocks will be referred to as sub-

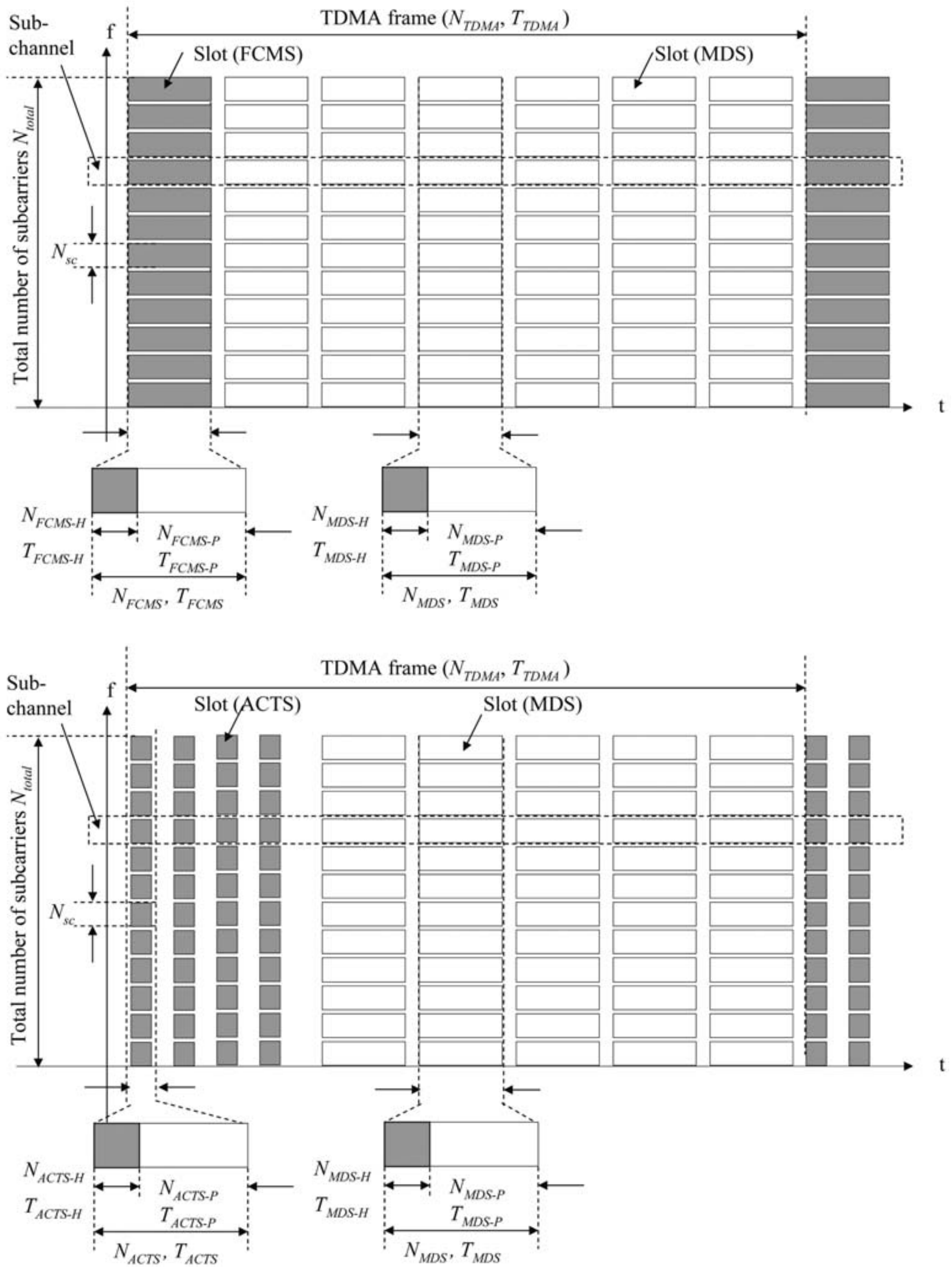

Fig. 1 *Frame configuration of the DPC-OF/TDMA for (a) downlink and (b) uplink*

channels in this article. Similarly, the time axis will also be divided into blocks of prescribed lengths. The blocked "subchannels" will be referred to as "slots", and these slots will be shared among multiple MS. When an MS establishes communication with APs, it registers its own station to the subchannel, and the slot-allocation controller of the AP allocates a time slot within the subchannel. The slot- allocation information of each subchannel is inserted periodically in the form of a Frame Control Message Slot (FCMS) in the time axis, as shown in Fig. 1. The slots between one FCMS and the next are referred to below collectively as the "TDMA frame".

In this method, an MS does not need to be able to access all subchannels, as shown in Fig. 2, and the number of subchannels accessed may be specified based on the scale, power consumption, and available service charge options for the MS. Moreover, even when it is possible to access all subchannels, the number of such actually used may be varied and controlled by parameters set according to conditions specified by the user—relating, for example, to power consumption of the MS device and service charges. Further, the modulation method for each slot may also be varied through parameter settings. Nevertheless, it will remain preferable that receiving ends on all MS be capable of receiving all subchannels so that these reception points may efficiently search through these subchannels for empty slots.

3 Configuration of the physical layer

Figure 3 shows the configuration of the physical layer of the receiver unit in the AP and MS. Below, transmission from the AP to the MS will be referred to as "downlink", and the reverse transmission will be referred to as "uplink".

During downlink, the AP receives a TDMA frame for each subchannel from the MAC layer and allocates each of these frames, as is, into the available subchannels. In addition to this allocation data signal, pilot signals for radio propagation path estimation and a

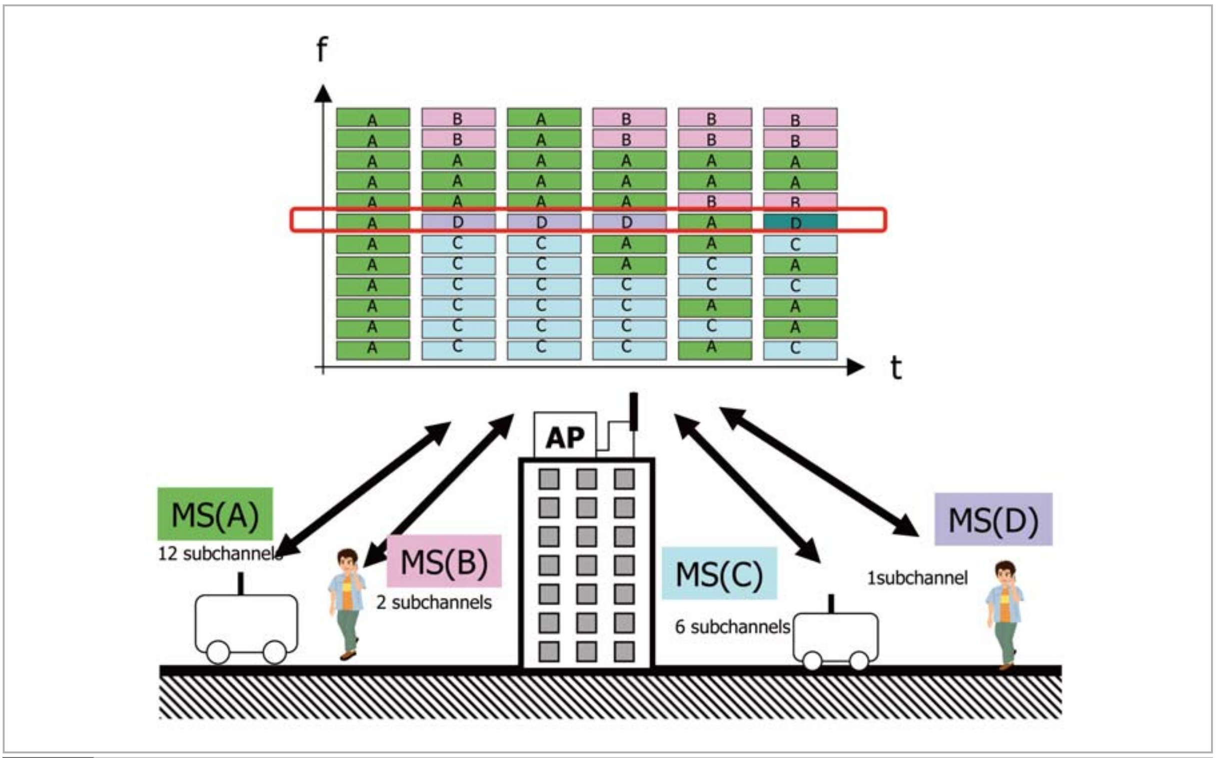

Fig.2 *Conceptual drawing of use of proposed system*

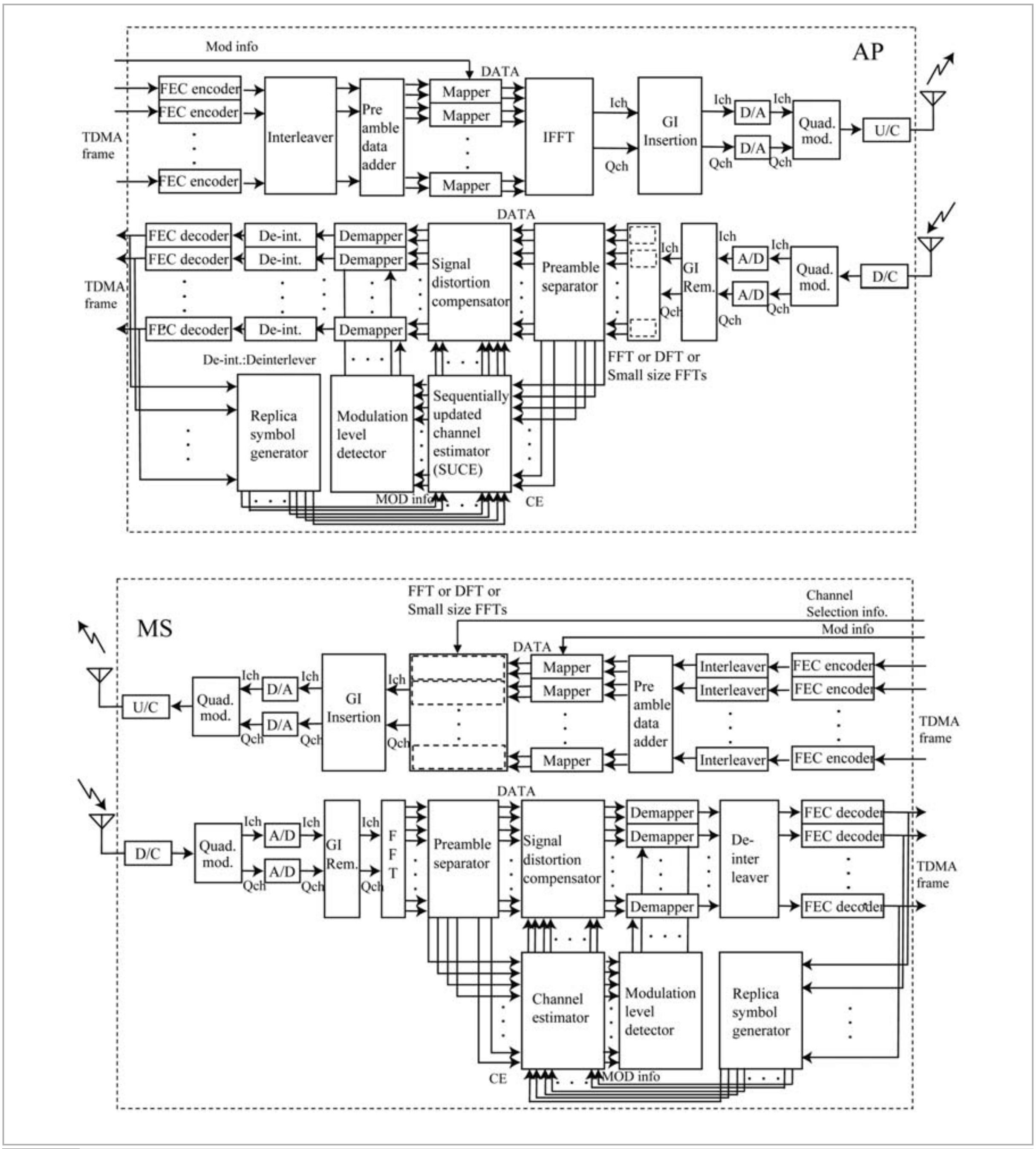

Fig.3 Configuration of the physical layer in the transmission and receiver unit ((a) AP and (b) MS)

preamble signal containing information on the modulation method will be inserted. The basic packet format will be as shown in Fig. 1. Next, each subcarrier will be subjected to modulation such as BPSK and QPSK (mapping) based on commands from the MAC layer, and the modulated signal for OFDM will then be created through the execution of IFFT. Guard intervals will then be inserted and the frame will be up-converted (U/C) into an analog signal and finally converted into signals in the given transmission frequency band, for transmission to each MS.

At the MS, the signal is down-converted (D/C) to the baseband and synchronized after digitization, and FFT is performed. The frequency divisionsignals are then divided and allocated among the subchannels. A radio propagation path estimation is then performed using the pilot channels within the preamble, and a correction to the transmitted signal is made based on the results of estimation. Subsequently, each subchannel signal is handed over to the MAC layer. The MAC layer receives the slot information for each subchannel based on the MAC protocol (which will be described in a later section) and receives the required information of the slot for each subchannel and sends the information to the higher layers.

During uplink, on the other hand, TDMA transmission is performed within the time prescribed by each MS based on the slot-allocation method for each subchannel in downlink. At each MS, the MAC layer receives the TDMA frame for each subchannel, and allocates each of these frames as is to the available subchannels. To this information the pilot signal and the preamble signal containing the modulation information are added, and modulation is then performed on each subcarrier in accordance with commands from the MAC layer. IFFT is then performed to create a modulated signal for OFDM. In this process, it is assumed that the numbers of subchannels and the IFFT are appropriate for the number of subchannels accessed by the MS, based on conditions such as scale, power consumption, and charge options applicable to the MS. However, it is possible to use an IFFT of the same scale on the transmission side of the AP.

The AP receives signals from multiple MSs. After the downlink slot information has been received, the uplink signals are transmitted within a prescribed length of time; however, export time may differ among the signals for each MS. Thus, synchronization is required to perform FFT on multiple signals having these different exportation times. Thus, the question of the size of the FFT used must be resolved. One method we may consider involves synchronization according to the earliest arriving signal, or according to the largest signal, and to perform batch FFT on each subchannel using an FFT of a scale sufficient to handle all subcarriers[8]. Another method is to prepare an FFT for each subchannel based on the allocated channel number, and then to perform the FFT. As shown in Fig.1, the configuration for each slot is basically the same as for the uplink case, except for certain differences in the parameters.

The APs must be capable of high-quality reception of information from high-mobility MS, or for the MS to receive information from the AP even in high-mobility environments. Since the symbol for channel estimation under DPC-OF/TDMA is located at the head of the transmitted packet, information located close to these symbols features relatively low error rates. However, with longer packets and higher mobility, the error rate increases for information located farther from the symbol. To resolve this problem, the DPC-OF/TDMA adopts a sequential channel estimation method[9][10]. Under this method, signals reproduced on the receiving end are used to create a replica of the received signal (after FFT), as shown in Fig. 3. This replica is then compared to the received signal after FFT to configure the channel characteristics estimated based on the packet header.

4 Architecture of the MAC layer

4.1 Basic architecture

As shown in the architecture of the MAC layer in Fig. 1, a common protocol is used for each subchannel. The protocol presently adopted is the PR-DSMA protocol, which is based on reserved dynamic slot allocation technology[11]. This protocol utilizes the FDD (Frequency Division Duplex) method, which uses different frequency bands for downlink and uplink. Further, the multiple access method is based on the TDMA method, in which the AP performs time slot allocation for each mobile station according to the traffic conditions.

4.2 Frame format

As shown in Fig. 1, the downlink frame consists of a single FCMS (Frame Control Message Slot) and a number n of MDS (Message Data Slot). The uplink frame consists of a single ACTS (Activation Slot) and several MDS (The number of ACTS plus the number of MDS will equal *n*). Here, the frame frequency for downlink and uplink is the same. Each of the various slot types will be described below in more detail.

(1) FCMS (Frame Control Message Slot)

This slot is specialized for downlink, and each frame will have one FCMS, which is normally located at the head of the frame. The slot elements are composed of the header component—which consists of the slot type, mode, version, slot count, sub slot count, source MAC address, destination MAC address, channel count, slot assignment term, propagation delay, transmit control, access point identification, and header CRC—and the payload component—which consists of the slot assignment information for downlink, slot assignment information for uplink, ACK information for uplink, and payload CRC[11].

(2) MDS (Message Data Slot)

One MDS slot (or more) is allocated to a single downlink or uplink frame. In the downlink, the AP performs the multiplexing, while in the in the uplink, multiple MSs do so. The MDS is used in normal data transmission, as well as for registration/deregistration requests by AP and connection establishment/release requests in the downlink. In the uplink, this slot is used for ACK transmission for downlink data. The slot elements are composed of a header component—which consists of the slot type, packet type, control, buffer count, source MAC address, destination MAC address, data length, data sequence number, ACK sequence number, and header CRC—and the payload component—which consists of the payload and payload CRC[11]. In this method, the PDU (packet data unit) from the higher hierarchy of the MAC layer is not sent directly by the MDS; instead, the PDU is divided into segments of a certain length, and the segments are then sent via MDS.

(3) ACTS (Activation Slot)

This slot is mainly allocated to an uplink frame, and serves as a randomly accessible slot used for transmitting requests for registration/deregistration by MS and connection establishment/release. As shown in Fig. 1, the slot in fact consists of several mini-slots; when the MS issues a request to the AP, a slot is selected randomly from these mini-slots and the requested packet is sent within the time selected. The slot elements are composed of the header component—which consists of the slot type, packet type, control, data length, source MAC address, destination MAC address, and header CRC—and the payload component—which consists of the payload and payload CRC[11].

4.3 Basic communication protocol[11]

Figure 4 is a block diagram of the MAC layer of each subchannel. In the AP, all of the IP data to be transmitted are divided into segments having a certain length according to the slot lengths, and stored in the transmission buffer of the AC according to the registered MS. In the slot allocation unit, the MDS data are created based on the specified slot allocation method, and combined with the FCMS data generated by the control data configuration unit to produce a TDMA frame. The frame is then sent to the MS.

At the MS, the FCMS is extracted from the TDMA frame sent from the AP in the slot extractor, and the downlink/uplink allocation status is checked for each subchannel. The traffic conditions are then detected. When performing downlink/uplink, the channel selector of the MS relays its intent to use the respective subchannel to the physical layer, and the signal from the MS registration signal generator is sent to the base station using ACTS. One example of the MS registration signal may be seen in the MAC address of the MS.

When the AP is able to receive the ACTS information, the AP, which has received the request to use a subchannel from the MS, issues the name of the authorized MS and the temporary address to all of the MS using the MDS for downlink. The relevant MS uses the address to initiate a session with the AP.

In this method of communication, a single

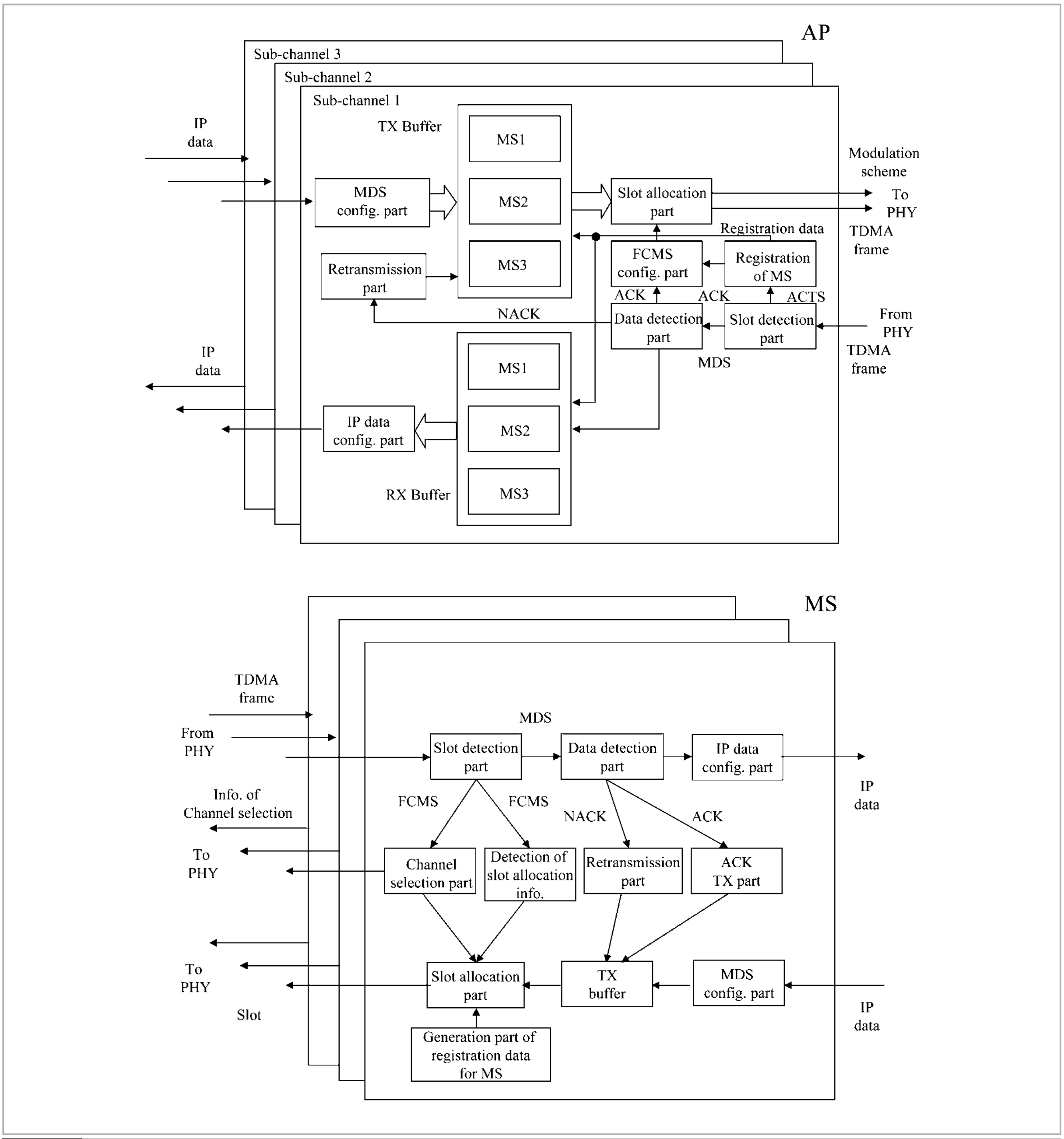

Fig.4 Architecture of the MAC layer transmission/reception unit ((a) AP and (b) MS)

MDS slot is allocated in a round-robin manner to the MS that is registered to the AP, regardless of the existence of the uplink transmission buffer. In this case, if the uplink transmission buffer status for the MS is 0 and no valid data has been sent by the MS within a certain length of time after the slot has been allocated, no slots will be allocated to for a given length of frame time. The MS will use this allocated uplink MDS slot to request and send information.

4.4 Slot allocation method

4.4.1 Downlink

Figure 5 shows the slot allocation method for the downlink. The TDMA frame used in the downlink contains slots for FCMS and MDS, and the FCMS will always be allocated a single slot at the head of the frame. The MDS consists of the MDS for MS data transmission and MDS for call-control data transmission, to send information required for call control. When call-control data needs to be

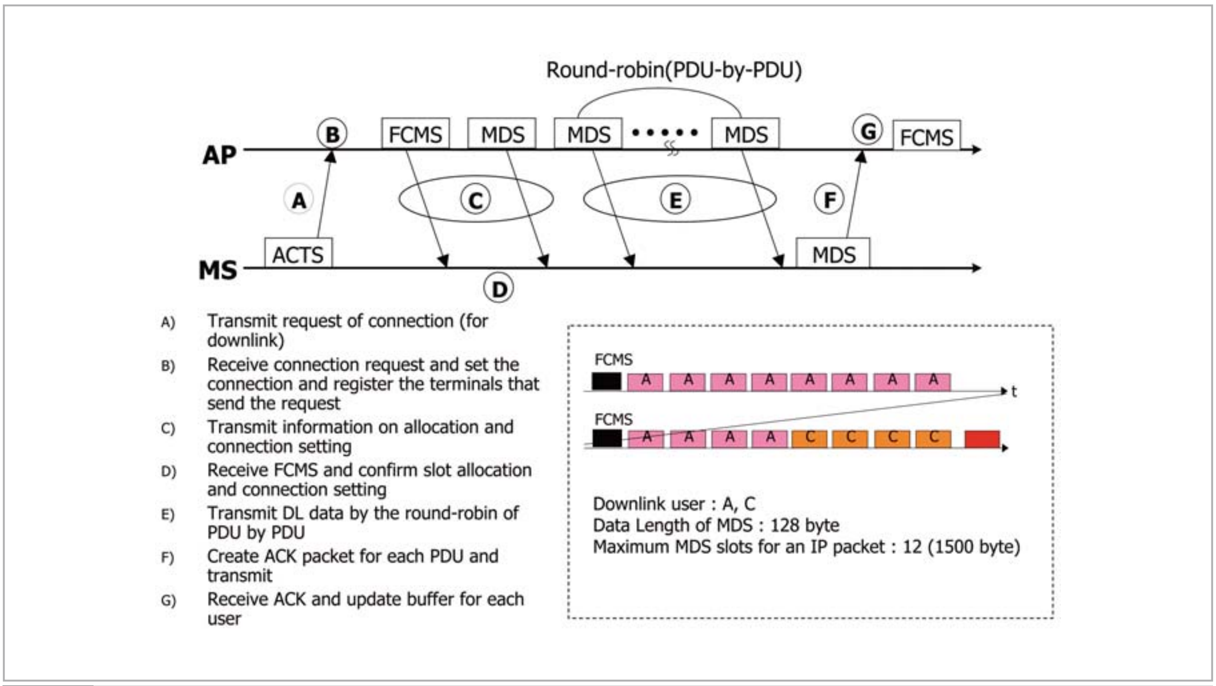

Fig.5 *Slot allocation method for downlink*

sent, these data will be preferentially be allocated slots from the head of the frame, relative to other MS data.

An MS that has entered the communication zone of a certain AP will first carry out registration with the AP using ACTS. When the AP has received the registration request, it is relayed by the FCMS, and at the same time, the request for communication is broadcast using the MDS. The slot allocation for the MS data transmission MDS is then made, according to the higher-layer PDU (packet data unit) length for each PDU, following the order of their entry into the transmission buffer. When there is no unsent data in the transmission buffer, no slots are allocated, and when one PDU is sent, an uplink MDS is allocated. This MDS is used to transmit ACK; thus constituting transmission of downlink information. Figure 5 shows a case in which allocation is made for downlink when a 1,500-byte PDU is sent to two MS, A and C. In this case, it is assumed that the volume of data transmitted by each MDS is 128 bytes.

4.4.2 Uplink

Figure 6 shows the slot allocation method for the uplink. The TDMA frame used in the uplink contains slots for ACTS and MDS, the latter of which can be categorized into that used for MS data transmission and that used for transmitting ACK for downlink data (ACK-data MDS). The slot allocation for ACK data MDS is always performed when the packet within the MDS sent in the downlink corresponds to the last segment in the higher-hierarchy PDU. The slot position assigned to ACK-data MDS will be later than that assigned to the slot for transmitting the last segment in the higher-hierarchy PDU in the downlink.

The slot allocation for the user-data MDS will use the slots remaining after the allocation to the ACK-data MDS. The slot-allocation management table will be referred to, and the slots will be allocated in a round-robin manner to the MSs that have established connections. The round-robin method here will not make allocations per PDU, as is the case in downlink, but will instead make allocations per segment. Figure 6 shows a case in which allocation is made for uplink when a 1,500-byte PDU is sent to three MS—B, D, and E. In this case, it is assumed that the volume of data transmitted by each MDS is 128 bytes.

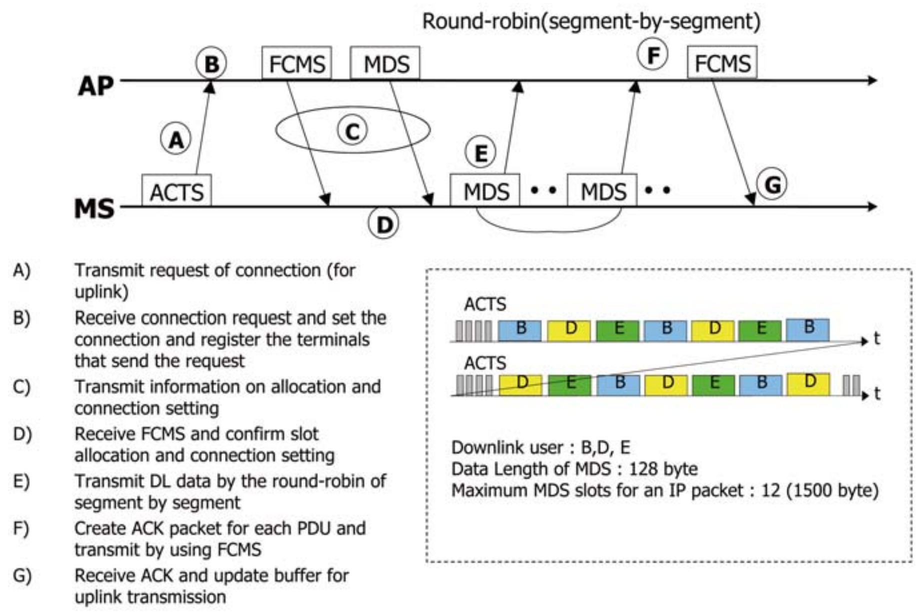

Fig.6 *Slot allocation method for uplink*

4.5 Re-transmission control method

In PR-DSMA, re-transmission control using Go-back-N may be used, as shown in reference[11]. Note that re-transmissions are not made for broadcast data for transmission performed by MDS in the downlink or for MDS data that contain only ACK/NACK data in the uplink.

5 Evaluation using computer simulations and prototype testing

To evaluate the transmission characteristics of the proposed communication system, we have carried out computer simulations and have also constructed a prototype.

5.1 Example of frame configuration

In the proposed DPC-OF/TDMA, the basic frame configuration for transmissions at carrier rates exceeding 100 Mbps were investigated using the parameters in Fig. 1. Table 1 shows an example of the results. For the parameters in this table, the temporal lengths of MDS and FCMS are the same, and the length of the ACTS is half of that for MDS and FCMS. When a single FCMS and eight MDS are sent in the downlink and four ACTS and seven MDS are sent in the uplink, the temporal length of a single TDMA frame was the same for uplink and downlink.

5.2 Example of basic transmission characteristics of MDS

An evaluation was made of transmission properties, with special emphasis on slot error rate, when performing MDS transmission using all subchannels using the parameters in Table 1. The frequency band was 5 GHz, and the Doppler frequency was assumed to be 500 Hz (corresponding to 100 km/h). The channel model used was a 24-wave exponentially attenuating independent Rayleigh fading model (delay spread of 350 ns). The basic scheme of the MDS frame is shown in Fig. 7, and the results are presented in Fig. 8. With these parameters, it was assumed that the OFDM signals (having a total carrier number of 768 and subcarrier number of 64) divided into 12 subchannels were all used for the transmission. Two OFDM symbols for radio propagation characteristics estimation were prepared in addition to those for MAC data

Table 1

Common items	
Length of 1 OFDM symbol (us)	8
Length of guard interval (us)	2
Total length of 1 OFDM symbol (us)	10
FFT length (point)	1024
Guard interval (point)	256
Sampling clock (Msps)	128
Total number of subcarriers	768
Number of subcarriers in a subchannel	64
Number of subchannles	12
Downlink transmission time (us)	2250+250(inc. frame guard)
Uplink transmission time (us)	2250+250(inc. frame guard)

FCMS	
Length of header Length of payload	16byte 64 byte+2byte CRC
Modulation scheme	BPSK
FEC	Convolutional code (rate=1/2,K=7) Viterbi decoding
Number of OFDM data symbols	21
Number of OFDM preamble symbols	3 (Channel estimation 2)
FCMS transmission time (us)	240
Slot guard for FCMS (us)	10
Total transmission time for FCMS	250

MDS	
Length of header Length of payload	12 byte 128/256/384 +2byte CRC
Modulation scheme	QPSK/16QAM/64QAM
FEC	Convolutional code (rate=1/2,K=7) Viterbi decoding
Number of OFDM data symbols	19
Number of OFDM preamble symbols	5 (Channel estimation 2)
MDS transmission time (us)	240
Slot guard for MDS (us)	10
Total transmission time for MDS	250
Number of MDS	8(uplink),7 (downlink)

ACTS	
Length of header Length of payload	6 byte 32 byte+2byte CRC
Modulation scheme	BPSK
FEC	Convolutional code (rate=1/2,K=7) Viterbi decoding
Number of OFDM data symbols	10
Number of OFDM preamble symbols	2 (Channel estimation 2)
ACTS transmission time (us)	120
Slot guard for ACTS (us)	2.5
Total transmission time for ACTS	122.5
Number of ACTS	4
Transmission time of 4ACTS (us)	490
Guard time for 4ACTS (us)	10
Total transmission time for 4ACTS (us)	500

transmission, and the symbols were used to acquire radio propagation characteristics and to alleviate the effects of distortion of the transmission signals caused by fading. The QPSK modulation method was employed. The MDS error rate shown in Fig. 8 may be defined as the ratio of erroneous MDS (i.e., those that contain even a single error in data) when information is transmitted via MDS as shown in Fig. 7. From this figure, it can be seen that the MDS error rate obtained for the case when QPSK modulation is used as the primary modulation method at a speed of 100 km/h for the proposed method is on the

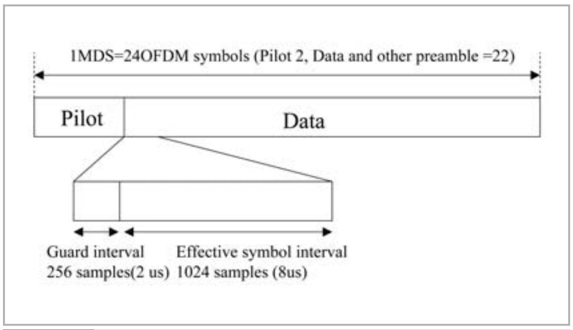

Fig.7 General scheme of the MDS frame

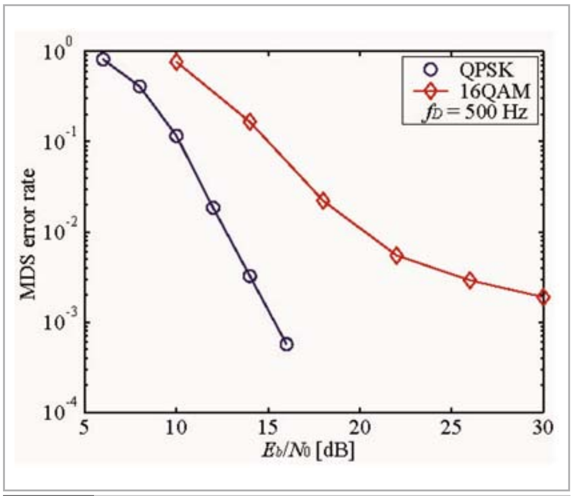

Fig.8 MDS error rate

order of 10e-2 at Eb/N0 greater than 10 dB. In the case of QPSK, the volume that can be transmitted by one MDS is 128 kbytes. Therefore, an IP packet having maximum length can be sent using 12 MDS. In other words, when the MDS error rate is on the order of 10e-2, then the error rate for a maximum-length IP packet is at most 10e-1, and so information transmission is thus possible through re-transmission of packets.

5.3 Evaluation of the prototype

To investigate the feasibility of the proposed DPC-OF/TDMA hardware, we have developed the prototype shown in Fig. 9 using the parameters in Table 1. The specifications of the prototype are presented in Table 2. The frequency used was 4 GHz on the base station side, and 3 GHz on the mobile terminal side. The transmission powers were 5.5 W and 5 W for the base station and mobile terminals, respectively. The present prototype used a

768-carrier OFDM and the 99 % occupied bandwidth was approximately 96 MHz, as shown in Fig. 10. The transmission characteristics of this prototype were measured for fading conditions similar to those used in the computer simulation in Section **5.2**, by increasing the speed generated by the hardware fading simulator. QPSK was used as the primary modulation method, and when a code having a coding length of 1/2 was used (corresponding to a maximum carrier bit rate of 76.8 Mbps), the IP data throughput was 34.026 Mbps for downlink when the transmission and receiver units were directly connected, and the maximum throughput was 21.467 Mbps when 24-wave exponential-attenuating multi-path fading was applied. For the uplink, the IP data throughput was 30.02 Mbps when the transmission and receiver units were directly connected, and the maximum throughput was 16.59 Mbps when 24-wave exponential-attenuating multi-path fading was applied. Thus, it was proven that a maximum IP data throughput of at least 10 Mbps could be secured even at high mobility of 100 km/h, for both downlink and uplink.

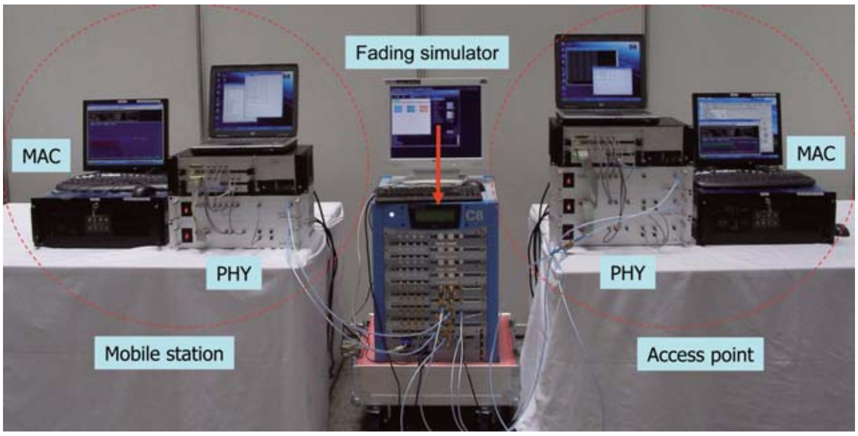

Fig.9 General scheme of prototype

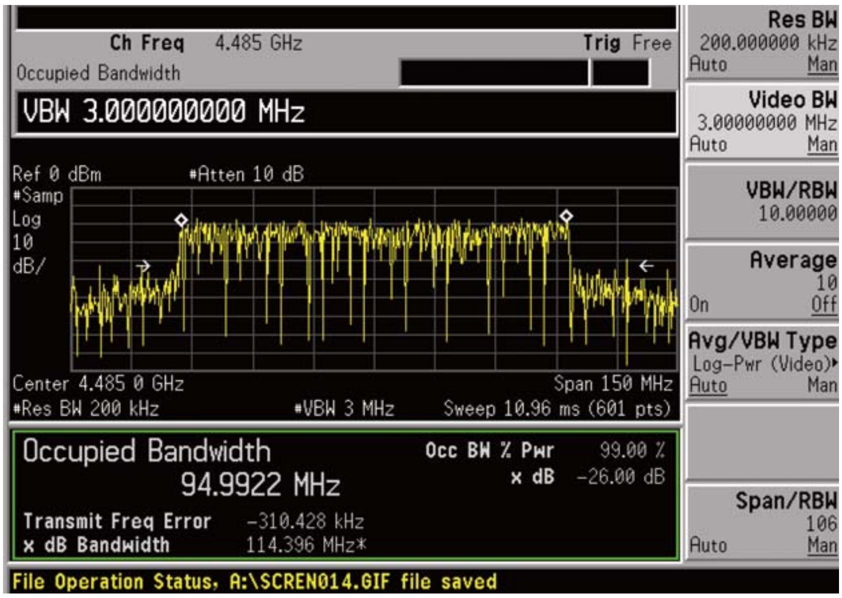

Fig.10 Occupied bandwidth

Table 2 Prototype specifications

Common items	
Length of 1 OFDM symbol (us)	8
Length of guard interval (us)	2(FCMS/MDS),4(ACTS)
Length of 1 OFDM symbol (us)	10
FFT length (point)	1024
Guard interval (point)	256(FCMS/MDS),512(ACTS)
Sampling clock (Msps)	128
Total number of subcarriers	768
Number of subcarriers in a subchannel	64
Number of subchannles	12
Downlink transmission time (us)	2250+250(inc. frame guard)
Uplink transmission time (us)	2250+250(inc. frame guard)
FEC	Convolutional code
Transmission rate	QPSK rate=1/2 76.8 Mbps QPSK rate=2/3 102.4 Mbps 16QAM rate=1/2 153.6 Mbps 16QAM rate=2/3 204.8Mbps

6 Conclusions

This article proposed a new-generation mobile communication system DPC-OF/TDMA based on OFDM and provided summaries of the system's physical layer and the MAC layer. We evaluated the transmission characteristics of the system by computer simulations and prototype testing, thus proving that the present system is capable of providing a minimum carrier bit rate of several tens of Mbps even in a multi-path environment with high mobility exceeding 100 km/h. This evaluation also demonstrated the possibility of offering a carrier bit rate of up to several hundred Mbps. The present prototype was the first in the world to succeed as a mobile communication system employing OFDMA and TDMA at carrier bit rates greater than 100 MHz, has proven itself capable of becoming the fourth-generation mobile communication system for the future, and will no doubt form one of the touchstones of future research. In the future, our group hopes to pursue the standardization of various technologies that have been gained in the course of obtaining these results, and to conduct further and more detailed transmission tests using the system in outdoor environments.

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***HARADA Hiroshi**, Ph.D.*

Research Manager, Ubiquitous Mobile Communication Group, New Generation Wireless Communications Research Center

Cognitive Radio, Software Defined Radio, Broadband Wireless Access System

***FUNADA Ryuhei**, Ph.D.*

Expert Researcher, Ubiquitous Mobile Communication Group, New Generation Wireless Communications Research Center

Cognitive Radio, Software Defined Radio, Broadband Wireless Access System