3-1-2 156 Mbps Ultrahigh-Speed Wireless LAN Prototype in the 38GHz Band

Gang WU, Masugi INOUE, Homare MURAKAMI, and Yoshihiro HASE

This paper describes a 156 Mbps ultrahigh-speed wireless LAN operating in the 38 GHz millimeter (mm)-wave band. The system is a third prototype developed at the Communications Research Laboratory since 1998. Compared with the previous prototypes, the system is faster (156 Mbps) and smaller (volume of radio transceiver < 1000 cc), it has a larger service area (two overlapping basic service sets), and a longer transmission distance (the protocol can support a distance of more than two hundred meters). The development is focused on the physical layer and the data link control layer, and thus a GMSK-based mm-wave transceiver and an enhanced RS-ISMA (reservation-based slotted idle signal multiple access) protocol are key development components. This paper describes the prototype system's design, configuration, and implementation.

1 Introduction

The millimeter (mm)-wave band (from 30 to 300 GHz) is the focus of considerable academic and industrial interest because it can support high-speed and large-capacity information transmission. New applications, such as ultrahigh-speed wireless local area networks (WLAN), wireless home-links, and indoor multiplex television broadcasting for indoor environments, as well as fixed wireless access, broadband mobile access, and ITS (intelligent transportation systems)-based inter-vehicle communications for outdoor environments will become available through the use of mm-wave communications. In Japan, the 38 GHz band has been made available for fixed wireless access and the 60 GHz band with a bandwidth of over 10 GHz will be made available for licensed and unlicensed use very soon[1].

The development of the mm-wave band for communications began at the Communications Research Laboratory in the early 1990s[2]. As a result of early research on the mm-wave propagation characteristics and the development of devices and equipment for mm-wave communications, several indoor high-speed WLAN prototypes were developed[2]~[7]. An ATM- (asynchronous transfer mode) based WLAN prototype was developed to support multimedia transmission in 1998[4][5][6]. It is a centralized system consisting of an access point (AP) connected to a backbone network and six stations (STA) connected to multimedia terminals. The system is operating in the 60 GHz band and has an FDD (frequency division duplex) channel configuration providing high-speed transmission (51.84 Mbps) on each channel. A novel MAC (medium access control) protocol, called RS-ISMA (Reservation-based Slotted Idle Signal Multiple Access), was proposed and developed to support integrated multimedia transmission in the system[4][8].

The second prototype system developed in 1999, which also operates in the 60 GHz band, is an IP-based WLAN with an AP and three STAs[7][9]. Compared with the first prototype, the second one has a higher radio transmission rate (64 Mbps) on each channel. Modified RS-ISMA is used as a MAC protocol in the system. The system can support TCP (UDP)/IP-based applications and multicast services.

Currently, products for 2.4 GHz WLANs have a maximum transmission rate of 11 Mbps under the specification of IEEE 802.11b[10]. In the 5 GHz band, chipsets based on IEEE 802.11a are already available and more products will be available by the end of 2001. The Association of Radio Industries and Businesses (ARIB) of Japan has standardized ultrahigh-speed WLANs operating in the 60GHz band (STD-T74) on the basis of the system described in this paper[11].

In this paper, we describe a recently developed 156 Mbps WLAN prototype operating in the 38 GHz band. Compared with the previous prototypes, this system was developed to have a higher data rate (i.e., 156 Mbps), have a smaller hardware size (i.e., the volume of the transceiver < 1000cc), and have a larger service area (i.e., multi-cell configuration). The rest of this paper is organized as follows. Section 2 describes the system design for the 156 Mbps system based on the technologies developed in previous prototype systems. The implementation is explained in Section 3 and the experimental results are shown in Section 4.

2 System design

A. System Configuration

A WLAN in a single basic service set (BSS) consists of an AP and a number of STAs. Different from the 2.4 GHz band and 5 GHz band WLANs designed as distributed systems, a WLAN in the mm-wave band should have a centralized system configuration. The main reason for this is that a directional antenna with circular polarization is required in mm-wave communications to obtain a high gain and reduce the multipath effect, and thus the functions required for communication between stations without a relay, such as carrier-sense, are not available. Another reason is that centralized control is generally preferred for multimedia transmissions. In such a system, all the traffic generated from, or arriving at, a BSS should pass through an AP, and the AP connected to a backbone network controls the transmission on mm-wave channels.

Since the radius of a BSS of an mm-wave WLAN is around ten meters, providing services in a larger area (i.e., ESS: extended service set) requires several BSSs in the same WLAN. In an ESS, all BSSs may use the same frequency bands because a directional antenna is used in an STA. To offer seamless transmission for user STAs moving between two BSSs, the AP should support handoff between neighboring BSSs.

B. Transceiver

The objective of the physical layer design is generally to implement high-speed and high-quality transmission. Since the utilization of mm-wave bands for communications is so new a system concept that devices are still in the development phase and are thus very expensive, small-scale and low-cost technologies are also important. Compared with devices in the 60 GHz band, those in the 38 GHz band are less expensive because the 76 GHz band has been developed for radar-based automobile collision avoidance, and 76 GHz devices are developed based on 38 GHz ones with double the frequency.

Our target radio transmission rate is 156 Mbps. To meet the requirements for MPEG 2-based video transmission, the bit error rate (BER) should be less than 10-7. Since FDD is chosen and the uplink channel is shared by multiple users, burst transmission in the uplink channel should be supported. A very short receive-transmit switching delay is required. In contrast to the first and second prototypes using ASK (amplitude shift keying) and FSK (frequency shift keying), the new prototype is based on GMSK (Gaussian filtered minimum shift keying) modulation to provide better power-spectrum performance.

C. Enhanced RS-ISMA

The MAC protocol RS-ISMA was developed to support multimedia transmission in mm-wave WLANs and it was used in the first and second WLAN prototypes. RS-ISMA was developed based on the MAC protocols of R-

ISMA (Reserved ISMA)[12] and S-ISMA (Slotted ISMA)[13]. Functionally, it is a combination of random access protocol and a polling scheme. It consists of two steps: reservation and information transmission. In the first step, an STA transmits a short frame to make a reservation under a random access scheme. In the second step, either an isochronous or an asynchronous polling scheme is used for information transmission depending on the QoS requirement.

RS-ISMA was developed in the first prototype to support integrated multimedia transmission based on wireless ATM. In the second prototype, RS-ISMA was modified to carry IP datagrams most efficiently and to support wireless multicast services. Because RS-ISMA requires STAs to respond to the control signal sent by the AP immediately, there will be a round-trip propagation delay in each slot. The delay, though in the order of 100 ns over a few meters, results in a 16-bit loss when the transmission rate is 156 Mbps. The RS-ISMA was therefore modified and enhanced for ultrahigh-speed transmission.

The first modification was to introduce a time offset for STAs to transmit after receiving the control signal. Fig.1 shows the time chart of the enhanced RS-ISMA. After receiving a POLL, for example, the STA waits time offset ΔT before sending a data frame. ΔT is automatically adjusted to have the frame arrive at the AP at the beginning of the next time slot. ΔT depends on the distance between the AP and a specified STA. The second modification was to adaptively adjust the polling period for asynchronous polling depending on the traffic variations. The polling period is increased when the AP detects that the traffic generation rate of an STA has become low and is shortened when the AP detects a high rate. The third modification was to shorten the ACK (acknowledgement) period in the uplink transmission to improve the efficiency. As shown in Fig.1, the ACK field becomes part of the time slot. Because an immediate ACK is used, we simplified the ACK from a control frame to a specially defined data block with a length much shorter than that of a frame. At the AP, the carrier sense of the ACK field is used to detect if there is an ACK.

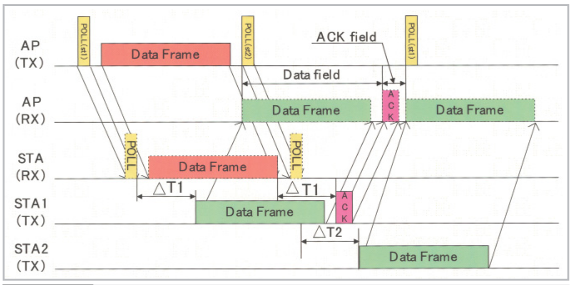


Fig.1 A time chart of the enhanced RS-ISMA

D. Handoff Control

A WLAN with a single BSS was used in both the first and second prototypes. If an ESS includes several BSSs, however, the handoff control should keep the connection in the upper layers when an STA is moving from one BSS to another. In contrast to the handoff control in a cellular system where adjacent cells use different frequency bands (when the frequency reuse factor is larger than 1) and handoff detection is based on the received power strength at the base station, the same frequency band is used in an ESS (the factor is equal to 1). The handoff control in mm-wave WLAN is based on the following procedure.

The first step is to detect if there is a handoff. An STA always compares the subscribing AP's address with the address in the control signal being received. If the addresses are different, it means that the STA gets into a new BSS. The second step is to subscribe to the new BSS. The STA is trying to subscribe to the new BSS by sending a subscribing request to the AP. The third step takes place after the STA's request is admitted by the new AP. The address of the STA is registered at the new AP and deleted from the old AP's table.

E. QoS Control

QoS control is a hot topic being widely studied today in attempts to enable multimedia transmission over the Internet. There are generally two basic services in the Internet QoS, Intserv and Diffserv. Though their implementation is based on two different methods, the basic idea is to divide the traffic into different classes and then give higher priority to the class of traffic that needs to be transmitted as soon as possible. Several methods have been proposed and standardized to define and implement different classes. The ToS (type of service) field of the IP header is used to announce information on classes. In IEEE 802.1Q frame format, a 3-bit user priority filed is defined to map the QoS in layer 3 (IP) into that in layer 2 (Ethernet). Since RS-ISMA is designed to support multimedia transmission using isochronous and asynchronous polling, it is necessary to map the QoS in layer 3 into these two polling schemes.

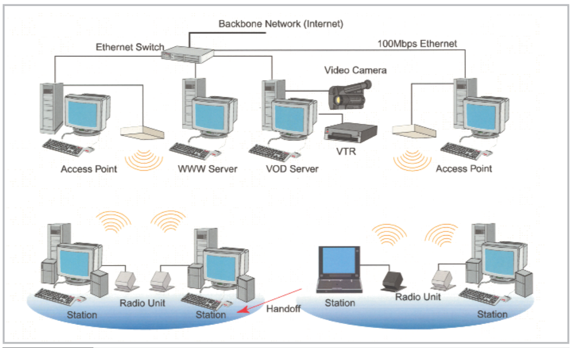


Fig.2 System Construction

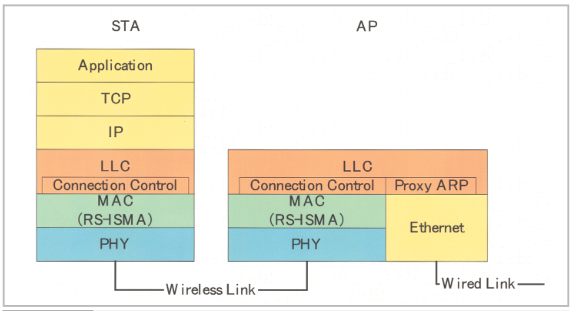


Fig.3 Protocol stack

3 Implementation

A. System Construction

As shown in Fig.2, the prototype is composed of two APs, four STAs, two media servers, and an Ethernet switch. The system is setup in a large office with desks and chairs, which is sectioned into small areas by partitions. The transceivers of the APs are set on top of a 2.2-m-high partition on one side, and the other equipment is set on 1.2-m-high desks on the opposite side. The APs and servers are connected to the Ethernet switch via twisted-pair cables and the switch is linked to the backbone network (intra-/Internet). The two APs construct two BSSs that can be either overlapped partly to form a continuous ESS or isolated from each other. If the APs are within the same subnet, the STAs can travel freely between the two BSSs without any change.

Table 1 lists the system parameters. Two frequency bands in the 38 GHz band are used for uplink (from STA to AP) and downlink (from AP to STA) transmission (FDD). The radio transmission rate is as high as 156 Mbps. The antennas at AP and STA have different characteristics: a broad beamwidth but a low gain at the AP and a narrow beamwidth but a high gain at the STA.

Fig.3 shows the protocol stack of the WLAN prototype. Our development focuses on the lower two layers, physical and DLC (data link control). The DLC layer consists of a MAC and an LLC (link logic control) sub-layer. The enhanced RS-ISMA protocol for access control and a stop-and- wait ARQ (automatic repeat request) scheme based on RS-ISMA for error control are involved in the MAC sub-layer. The LLC sub-layer mainly functions as an interface between the DLC and upper layers, fragmenting and assembling PDUs (protocol data unit) at the LLC. Also, the LLC has a special connection control function to enable the WLAN to manage connection requests generated by the STAs. A proxy ARP (address resolution protocol) is used in the APs to eliminate the problem of handoff.

B. Transceiver

A photo of the transceivers of an AP and an STA is shown in Fig.4. The less-than-1000cc transceiver is made up of two plane antennas for transmitting and receiving respectively, several MMICs (monolithic microwave integrated circuits), and a waveguide interfacing the antennas and circuits. The transceiver is connected to the baseband signal processing module, which is developed on the DLC board inserted in the PCI Bus extension slots at the personal computer, via

Table 1 System parameters		
Tx frequencies	AP:37.75GHz	STA:38.75GHz
Tx power	AP:10mW	STA:10mW
Ant. gain	AP:5dBi	STA:20dBi
Half-power beamwidth	AP $\geq 60^{\circ}$	STA $\geq 10^{\circ}$
Modulation	GMSK	
Radio trans. rate	Up:156Mbps	Down:156Mbps
Volume of transceiver		$<$ 1000cc
MAC		Enhanced RS-ISMA
Multiplex		FDD
System configuration	AP: 2	STA:4
MAC frame	header(4B) + payload(64 to 256B) + CRC(2B)	

an LVDS (low voltage differential signaling) cable.

The block diagram of the transceiver is shown in Fig.5. At the transmitter, the signal is directly modulated and thus the circuit becomes very simple. At the receiver, the circuit is simplified by using a waveguide filter and a single conversion method. In addition, an analog detector is used to support 156 Mbps transmission. The isolation between the transmitter and receiver is guaranteed by using separate antennas. Since the uplink channel is shared by multiple users, an ON/OFF switch is used at the transmitter of the STA to reduce the power leakage when the transmitter is not transmitting anything.

C. DLC Board

The functions of the DLC and baseband signal processing in PHY are implemented in a half-size PCI board inserted in one of the PCI Bus extension slots of a personal computer. Fig.6 and 7 show a photo of the DLC board and its block diagram, respectively. Devices used to implement the DLC layer functions and PCI Bus Control mainly include a large (400,000 Gates for the STA and 800,000 Gates for the AP) FPGA (field programmable gate array) chip and a dual-port SRAM. Another high-speed FPGA with 30,000 Gates is used for implementing the functions of PHY baseband signal processing. The board has both a PCI Bus interface between the board and the PC, and an LVDS interface between the board and the transceiver. The board is capable of processing transmission at 156 Mbps.

The main function of the baseband signal-processing unit is assembly and reassembly of physical-layer frames. The assembly process in each STA can be described as follows. After receiving a 70-octet MAC frame from the DLC processing unit, the baseband signal-processing unit scrambles it by using a 4 to 5-bit scrambling code and adds a 20-bit frame start (FS) code to the scrambled 700-bit MAC frame. The resultant frame is optionally encoded by using a BCH (14, 10) code, and then a 20-bit preamble (PA) code is added to it. Finally, a frame is handed over to the transceiver. Thus, the physical-layer frame for MAC data frame transmission from the STA is composed of a 20-bit PA field, a 20-bit FS field, and a 700-bit MAC PDU field. Several physical layer frame structures are used in the AP depending on the objectives. For MAC data transmission, a frame composed of a 20-bit FS field and a 700-bit MAC PDU field is used. To control the uplink transmission, a frame composed of a 20-bit control start (CS) field and a 20-bit control data field is used. For the other cases, i.e., when the AP has nothing to transmit, the PA stream is continuously broadcast.

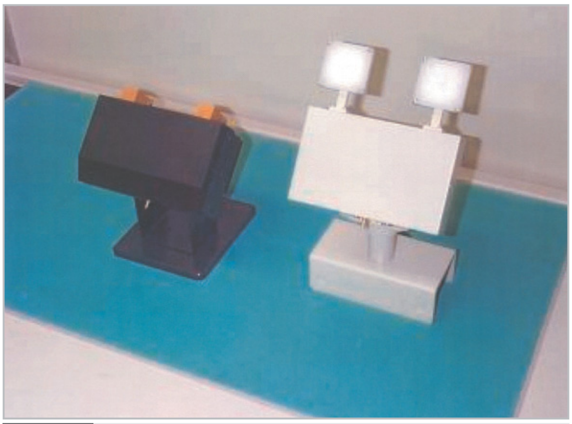


Fig.4 Photo of transceivers (left: STA; right: AP)

The DLC processing unit has two functions: access control according to the enhanced RS-ISMA and fragmentation of an IP datagram into MAC PDUs and assembly of MAC PDUs into an IP datagram. In the fragmentation process, the unit first receives an IP

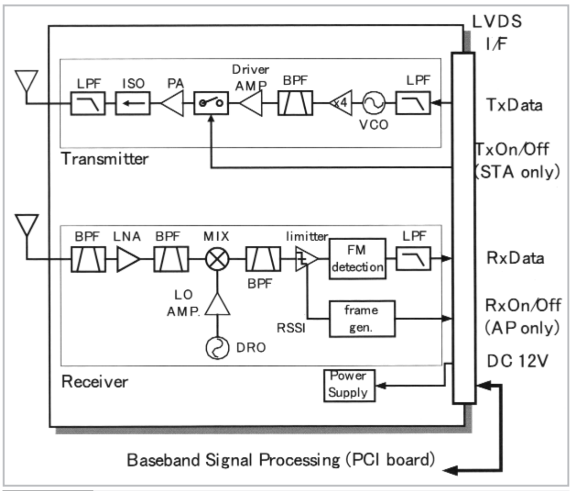


Fig.5 *Diagram of transceiver*

datagram through an internal PCI-bus interface. Then, it adds to the IP datagram a trailer that includes a source LLC address, a destination LLC address, a CRC code, and padding bits to produce an LLC-PDU. Then the LLC-PDU is divided into 64-, 128-, or 256-octet segments. Finally, a MAC PDU is made by adding a 4-octet header, which includes the frame type, the source and destination MAC addresses, the sequence number, and the trailer of a 2-octet CRC code to each segment.

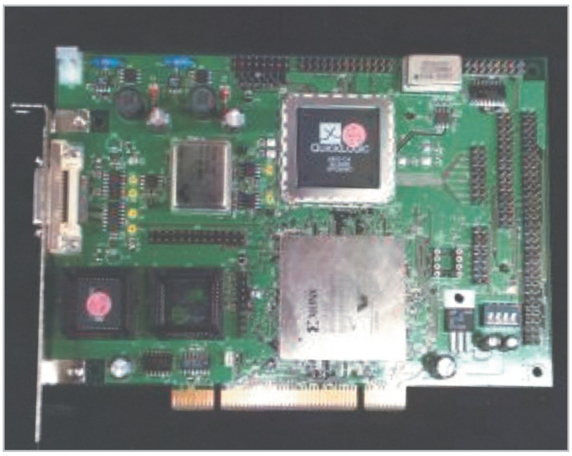


Fig.6 *Photo of DLC board*

The function of the connection control in the LLC sub-layer is to match a packet flow of an application to either the isochronous or the asynchronous polling mode. When a connection is requested, a suitable polling mode is chosen based on the TOS field of the header of the IP packet, and the header information is

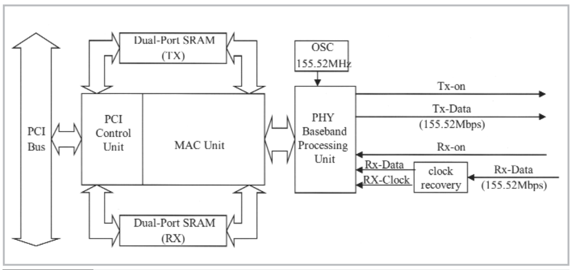


Fig.7 *Block diagram of DLC board*

recorded in a connection table. Once the information is recorded, the following IP packet stream is routed according to the table.

D. Handoff Control

A handoff control function was developed in the prototype. Fig.8 describes the handoff procedure of an STA moving from BSS_0 to BSS_1. The detailed sequence is described in Fig.9. When STA_0 is going to subscribe to an AP, say AP_0, it first checks the AP address ("01h" in the example) in the IDLEs broadcast in the downlink channel (step a). Then, it sends a Subscribe Request to AP_0 (step b). If the request is approved, AP_0 registers STA_0's address in the table of the proxy ARP and sends back a Subscribe Response (step c). STA0 sets AP_0's address to the local AP_Reg register.

When STA_0 moves into BSS_1 and receives the IDLEs broadcast from AP_1, it compares the AP address in the IDLEs with that in AP_Reg (step d). STA_0 sends a Subscribe Request to AP_1 because a different AP address is detected (step e). Since the address of AP_0 is includeed in the new request, AP_1 sends a proxy ARP table update request to AP_0 via the Ethernet (step f). AP_0 deletes the address in the local ARP table and sends back a response to AP1 (step g). AP_1 registers STA_0's address in the local ARP table and sends a subscribe response to STA_0 (step h). The handoff procedure ends after STA0 updates the contents of AP_Reg from 01h to 02h. Since the handoff procedure is implemented in layer 2, the connection of the upper layers is kept during the handoff.

E. QoS Control

MPEG 2-based video transmission is one of the main applications in this prototype to

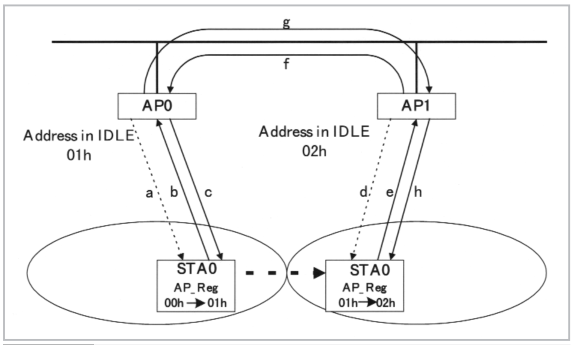


Fig.8 *Handoff procedure*

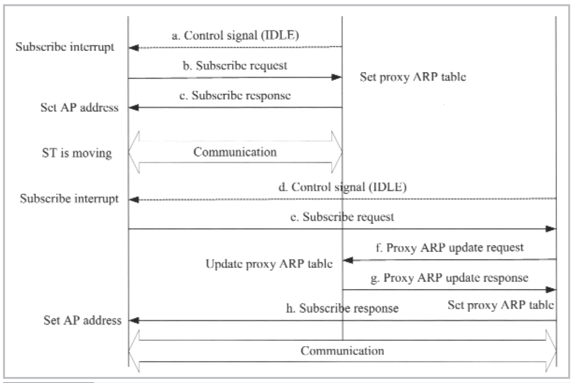


Fig.9 *Handoff procedure sequence chart*

demonstrate the importance of ultrahigh speed. To guarantee QoS in this case, the mapping of IP classes and the two polling modes is implemented. In RS-ISMA, either the isochronous or the asynchronous polling mode can be used for information transmission according to the QoS requirement from applications. The TOS field of the IP header is used here to relate an IP datagram flow to a suitable polling mode. For example, the TOS field of an IP datagram generated from non-real-time applications has a low-priority value and the IP datagram is sent in the asynchronous mode. In the case of real-time applications, a high-priority value is set and the isochronous mode is used to transmit corresponding IP datagrams.

4 Experimental results

The prototype system was tested in various experiments. Here we show the results obtained in two experiments as follows. In the first experiment, we measured the BER performance of the system in a chamber room (without the multipath effect). An AP and an STA were set in the chamber room at a distance of 5 m as shown in Fig.10(a). We fixed the AP and changed the angle of the STA in both the vertical and horizontal directions.

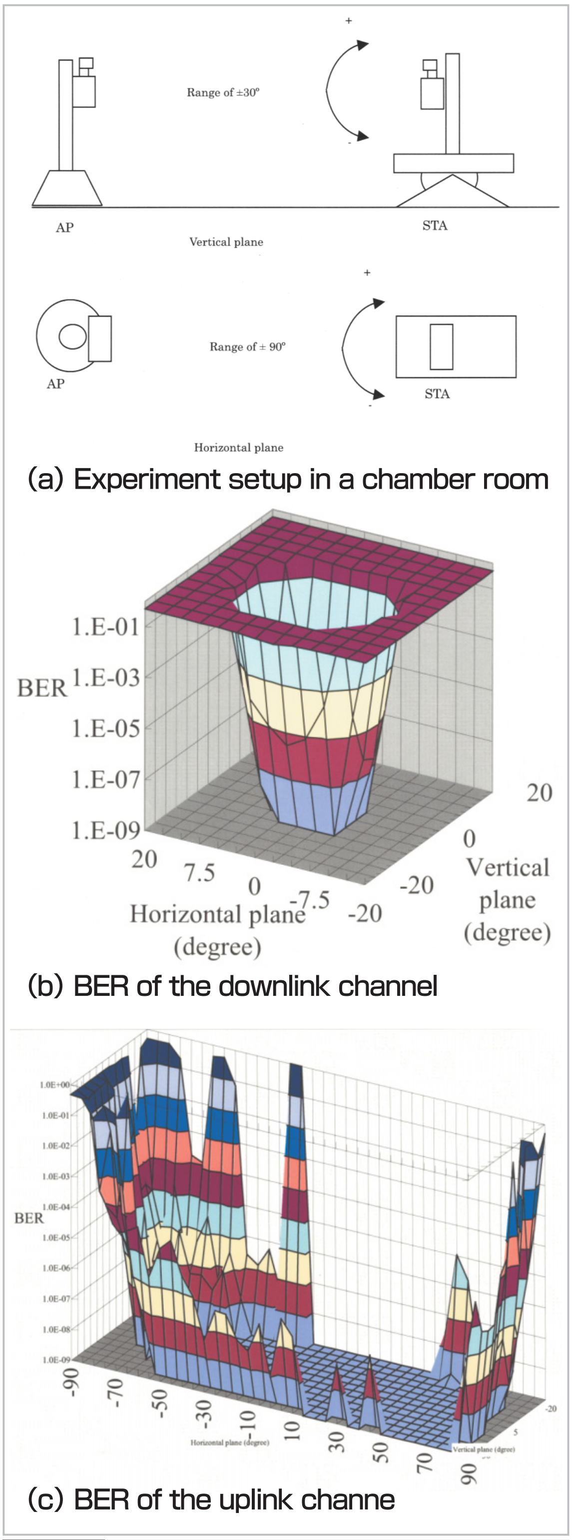


Fig.10 *Experiment in a chamber room*

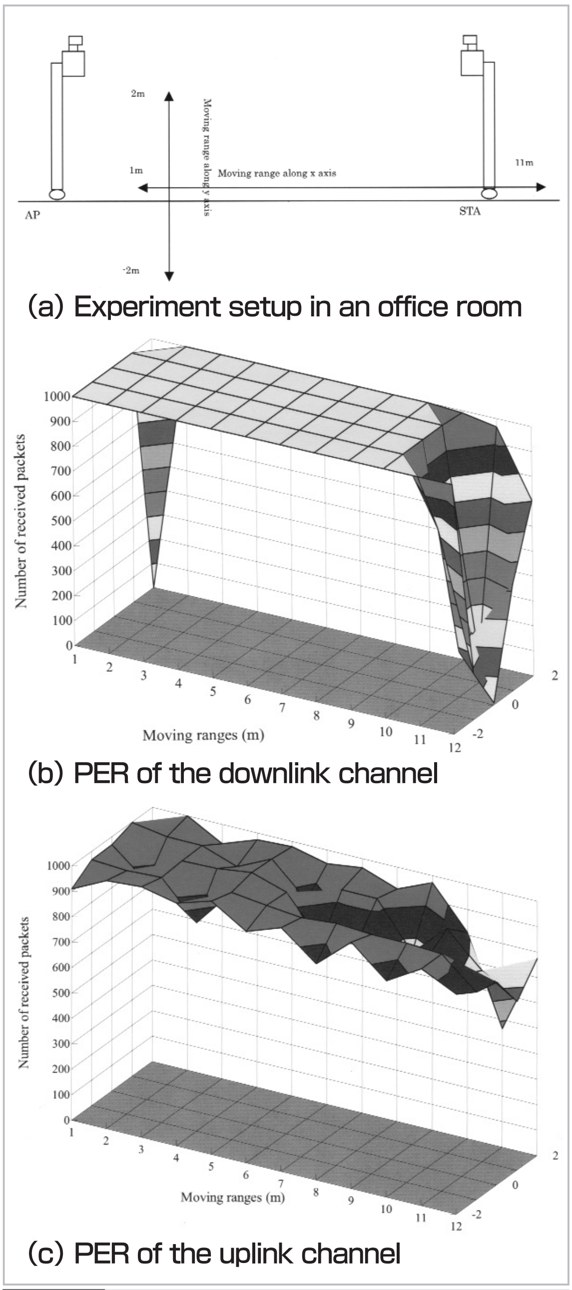
Thus, the BER performance reflects the position of the antennas in this case.

Fig.11 shows a general experimental setup in an office. The second experiment was done in the same office. The AP and STA were set on top of a 2-meter-high partition panel and a 1-meter-high desk, respectively, as shown in Fig.12 (a). The AP was fixed and the STA was moved in a 4*11-m area. The PER (packet error rate) was measured by counting the number of packets received when sending 1,000 packets. From the results shown in Figs.12 (b) and (c), we conclude that: (a) the downlink transmission has a better PER performance because burst transmission was required in the uplink channel and, (b) there was a multipath effect.

Fig.11 Experimental setup

5 Conclusion

We described a recently developed 156 Mbps ultrahigh-speed WLAN operating in the 38GHz band. The WLAN is a third prototype developed at the CRL since 1998. Similar to the second prototype, the system was developed to fully support the Internet access but at a higher speed with a smaller hardware, and with more functions. It contributes to the Japanese industry standard of ultrahigh-speed WLANs operating in the 60 GHz band (ARIB STD-T74). Experiments to evaluate the physical layer performance have been conducted and an experimental environment to accurately measure the performance of the upper layers is under development. The WLAN technologies are expected to be commercialized in the near future.



(a) Experiment setup in an office room

(b) PER of the downlink channel

(c) PER of the uplink channel

Fig.12 Experiment in a chamber room

References

1 News released by Ministry of Posts & Telecommunications, Japan, http://www.soumu.go.jp/joho-tsusin/pressrelease/japanese/denki/000228j601.html, Feb. 2000.

2 T. Ihara, T. Manabe, M. Fujita, T. Matsui, and Y. Sugimoto, "Research activities on millimeter-wave indoor wireless communications systems at CRL," ICUPC'95, Japan, pp. 197-200, Nov. 1995.

3 Kato, T. Manabe, T. Ihara, and M. Fujise, "Development and Evaluation on the Millimeter-wave Indoor Wireless LAN Demonstrators," PIMRC'98, Boston, USA, Sept. 1998.

4 G. Wu, Y. Hase, and M. Inoue, "Broadband radio access integrated network (BRAIN) in mm-wave band: indoor wireless LAN prototype," PIMRC'98, pp. 23-27, Boston, USA, Sept. 1998.

5 G. Wu, Y. Hase, and M. Inoue, "An ATM-based indoor millimeter-wave wireless LAN for multimedia transmission," IEICE Trans. Commun., Vol.E83B, No.8, Aug. 2000.

6 M. Inoue, G. Wu, and Y. Hase, "Development of a prototype of the broadband radio access integrated network (BRAIN)," Int. J. Commun. Sys., Vol.13, No.3, pp.255-269, May 2000.

7 M. Inoue, G. Wu, and Y. Hase, "IP-based high-speed multimedia wireless LAN prototype for broadband radio access integrated network (BRAIN)," VTC'99 Autumn, Amsterdam, The Netherlands, pp. 357-361, Oct. 1999.

8 G. Wu, Y. Hase, K. Taira, and K. Iwasaki, "A wireless ATM oriented MAC protocol for high-speed wireless LAN," PIMRC'97, pp. 199-203, Helsinki, Finland, Sept. 1997.

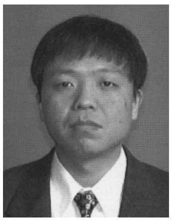
9 M. Inoue, G. Wu, Y. Hase, T. Sugitani, E. Kawakami, S. Shimizu, and K. Tokuda, "An IP-over-Ethernet-based ultrahigh-speed wireless LAN prototype operating in the 60-GHz band," IEICE Trans. Commun., Vol.E83B, No.8, Aug. 2000.

10 IEEE P802.11, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications," 1999.

11 Ultrahigh-speed wireless LAN in the 60-GHz band, ARIB STD-T74, Japan, May 2001.

12 G. Wu, K. Mukumoto, and A. Fukuda, "Performance evaluation of reserved idle signal multiple-access scheme for wireless communication networks," IEEE Trans. VT, Vol.43, No.3, pp.653-8, Aug. 1994.

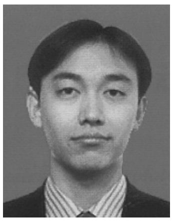
13 G. Wu, K. Mukumoto, and A. Fukuda, "Slotted idle signal multiple access scheme for two-way centralized wireless communication networks," IEEE Trans. VT, Vol.43, No.2, pp.345-352, May 1994.



***Gang WU**, Ph. D.*

Senior Researcher, Wireless Networks Integration Group, Yokosuka Radio Communications Research Center

Wireless Internet



***Masugi INOUE**, Ph. D.*

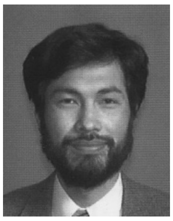
Researcher, Wireless Networks Integration Group, Yokosuka Radio Communications Research Center

Wireless Internet

Homare MURAKAMI

Wireless Networks Integration Group, Yokosuka Radio Communications Research Center

Wireless Internet



***Yoshihiro HASE**, Ph. D.*

Head, Research Planning Office, Strategic Planning Division

Wireless Internet