3-4-2 Technologies of millimeter-wave road-vehicle communications

Katsuyoshi SATO, Hiroshi HARADA, Fumihide KOJIMA, and Masayuki FUJISE

In recent years interest in ITS (Intelligent Transport Systems) technology has been growing, because it is thought that ITS can solve problems such as traffic jams and traffic accidents. Communication between roadside base stations and vehicles is a critical element of an ITS. In this paper, we describe the road-vehicle communication (RVC) system using ROF technology and software radio. These systems can realize multimode service and high speed data transmission. We developed RVC system using ROF technology which can transmit three kind of services (ETC, PHS, BS) simultaneously. The software radio with small size for mobile terminal is also developed. The overview of these systems is shown. In addition, activities of YRP (Yokosuka Research Park) ITS Joint Research Group are shown.

Keywords
road-vehicle communications, millimeter wave, Radio on Fiber, software radio, propagation

1 Introduction

Intelligent Transport Systems (ITS) are expected to increase the availability of current transportation systems and help solve the complex problems they involve. The advantages of ITS are recognized in a wide range of areas, including safety, efficiency, and environmental friendliness. For example, a typical advantage of ITS is lighter traffic, resulting in an increase in the efficiency of transportation systems, higher fuel efficiency, and a reduction in problems related to the supply of energy. Wireless communications technologies form the basis of the implementation of ITS; among the related technologies, road-vehicle communications technology, which serves as a link between the street-side infrastructure and drivers, plays an important role in this implementation. Applications of the road-vehicle communications technology have already been commercialized, with examples including ETS (Electric Toll Collection) and VICS (Vehicle Information and Communications Systems). With a view toward further diversifying services and expanding DSRC (Dedicated Short-Range Communications), we should strive to develop technologies for high bit rate data transmission and multiservices. Under such circumstances, the Communications Research Laboratory has continued to conduct research on the implementation of road-vehicle communications technology using the ROF (Radio on Fiber) technique[1][2]. This paper describes our investigation of millimeter-wave ROF road-vehicle communications technology.

2 ROF Road-Vehicle Communications

2.1 ROF communications system[3][4][5]

Road-vehicle communications and inter-vehicle communications play an essential role in ITS. A variety of services are currently available in road-vehicle communications; as these services are provided using different frequencies and methods, additional infrastructure such as base stations are required if a new service is to be offered. The vehicle station also requires the installation of antennas and other devices for individual services — it would look like a hedgehog with all of its antennas, placing an under burden on users in terms of service ability (Fig.1).

We have proposed the ROF (Radio on Fiber) road-vehicle communications system as a solution to the above problems and a tool that will be capable of properly handling future services. This communications system can transmit different services by integrating them into one; Fig.2 demonstrates its basic concept. The ROF road-vehicle communications system consists of a central base station, local base stations, and optical fibers to link them. The central base station converts a number of frequencies for different services into a common frequency band. The integrated signal after conversion is further converted from an electric signal to a light signal, and then transmitted through optical fibers to local base stations installed at roadsides. The use of optical fibers makes it possible to transmit a massive amount of data at a satisfactory speed. Electric/optical signal conversion is carried out at a local base station, and the converted signals are emitted from a common antenna. As these RF signals contain a considerable amount of data for numerous services, the employed frequency should be such that a broad bandwidth can be secured. The mobile station receives the integrated signals using a common antenna, and the signals are distributed to individual service terminals. If software radio technology (to be explained later) is employed, the structure of the vehicle station can be greatly simplified. The system configuration is inverted between uplink and downlink.

2.2 Software radio technology[6]

A wide range of systems are available for use in current road-vehicle communications, and more will be developed in the future. Users will have to deal with the burden of installing new hardware each time to have access to a new service. It is therefore urgently necessary to establish a system that can handle different communications services using a single terminal. A typical example of such systems is software radio communications technology that realizes a desired communications function by customizing the software program saved in the terminal hardware

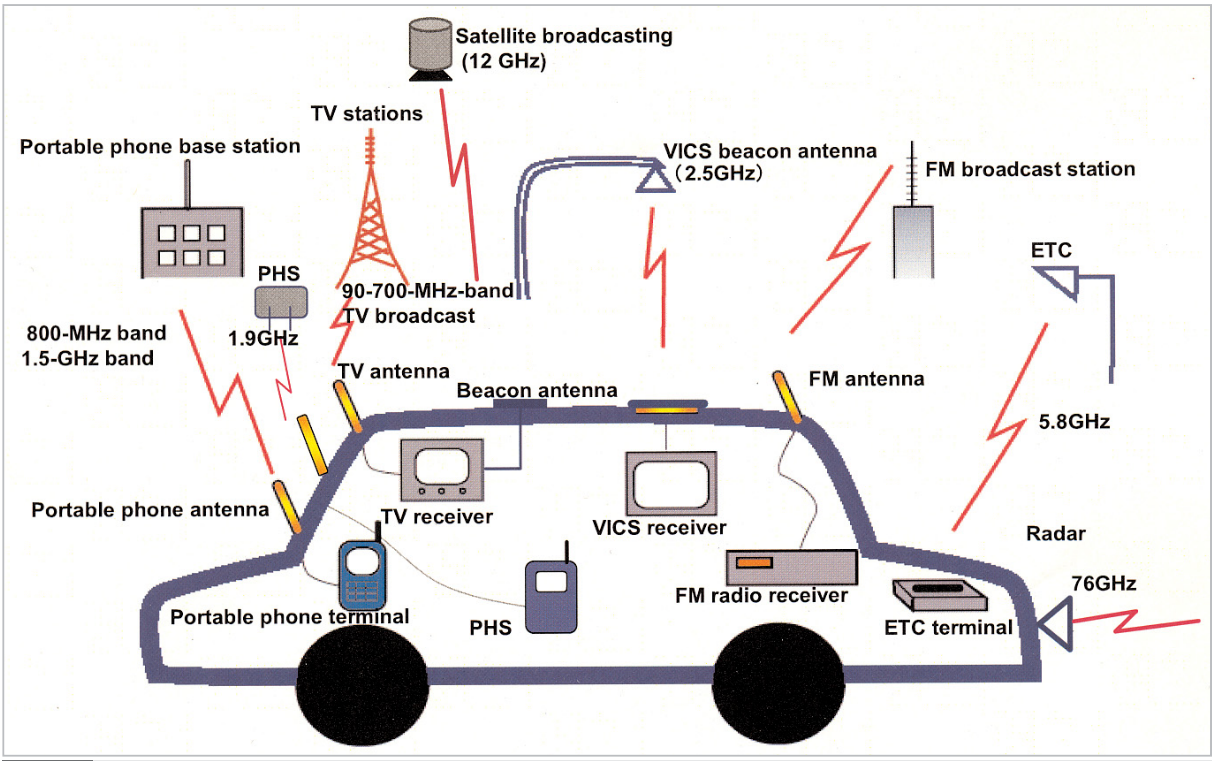

Fig.1 *Current situation of communications and broadcasts provided for cars*

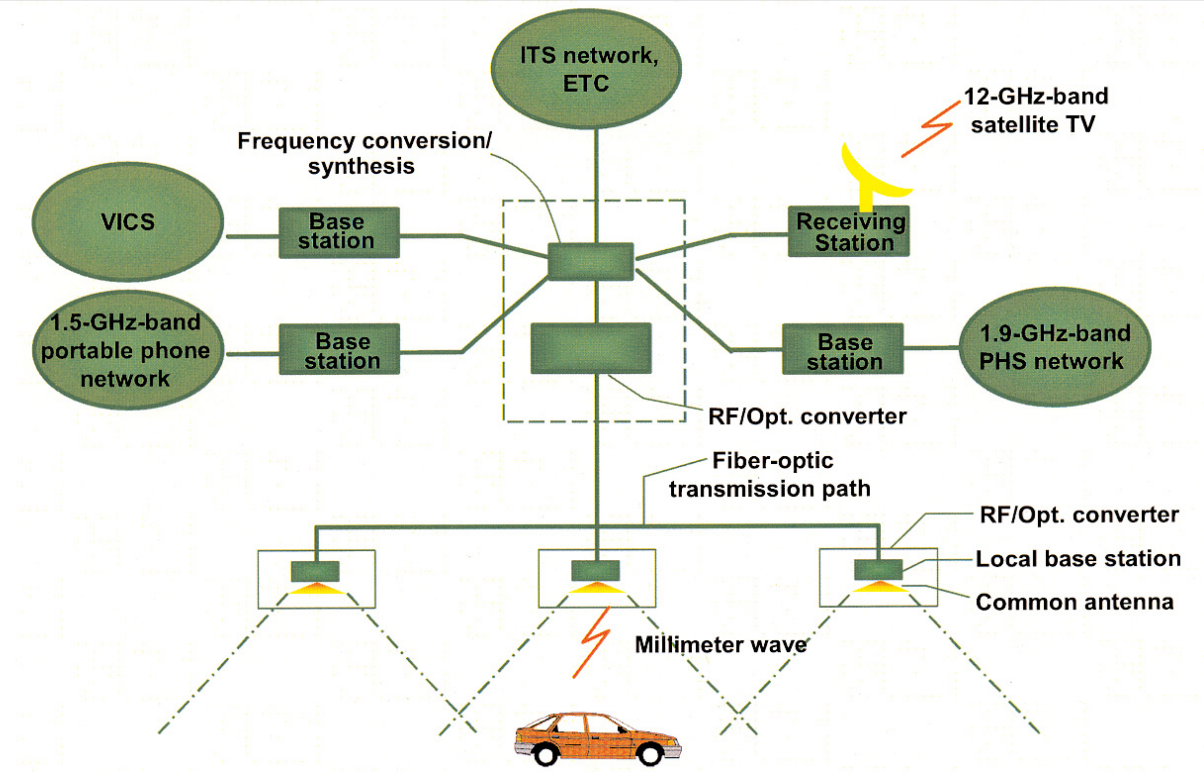

Fig.2 *ROF-based multiservice road-vehicle communications*

and the base station by using an external controller. The target hardware of main interest is the digital signal-proceeding unit, and the elemental techniques required for carrying out a specific function are described in this program.

When this software radio communications technology becomes available, different mobile communications systems can be operated using a single terminal, making it easy to employ a wide range of modulation methods, transmission speeds, bandwidths, and connection modes. In addition, as the system can flexibly adapt to changes in propagation conditions, the wireless terminal will be capable of handling multimode and multimedia. This will make wireless base stations economically efficient, and eventually the frequency resource will be used more efficiently as a result. Additionally, in the development and operation of a new communications system, it will only be necessary to prepare the software; new hardware will not be required. This will allow a new system to be brought to operational status quickly. In addition, it involves the environmental advantage that industrial waste is reduced upon system changeover. This technology is ecologically friendly in such respect. The Communications Research Laboratory has been working intensively toward the smooth realization of this flexible system since 1997.

3 36-GHz-Band ROF Road-Vehicle Communications System

3.1 36-GHz-Band ROF Road-Vehicle Communications System

The millimeter-wave band, which can provide a broad band, will be a good choice for taking advantage of the high capacity for data transmission provided by ROF road-vehicle communications. We have developed an ROF road-vehicle communications system utilizing the millimeter-wave band that provides a large bandwidth. Fig.3 shows part of its basic structure. As illustrated in the figure, the facilities are configured so as to provide functions for ETC (Electronic Toll Collection) as an ITS service, PHS (Personal Handy-Phone Systems) as a wireless communications service, and BS (Broadcasting Satellite) service as a broadcasting service. Our experimental facilities are composed of an integrated control base station, an optical-cable region, local base stations, a wireless region, and mobile station. The integrated control base station is installed in a laboratory of YRP (Yokohama Research Park), and the local base stations are installed along an experimental course extending along approximately 240 m of a public road. The interval between the local base stations is 20 m, and as many as 10 local base stations have been built thus far. Fig.4 shows external views of the local base station and mobile station. In our experimental system, frequency bands of the RF signals for conventional wireless services are converted into common millimeter-wave bands, enabling the local base stations and vehicles to share the same frequency band and unify the wireless sections. The antenna for the mobile station and RF unit can then be shared among several services, and the system configuration is considerably simplified. Fig.5 shows the frequency allocation for wireless services sharing a common frequency band. As common frequency bands for our experiment, a 500-MHz band has been assigned to each of the 36.00 to 36.50-GHz uplink channel and the 36.75 to 37.25-GHz downlink channel. As previously described, our experimental system is capable of offering ETC, PHS, and BS services simultaneously. The control base station converts the frequencies used for these services into the integrated 36-GHz-band radio signals that are used for analog-based light intensity modulation. In providing radio signals for services converged in a common frequency band in the wireless region, there is a method of transmitting signals via optical fiber by converting them into millimeter-wave signals in the control base station. Another method is to send signals in the optical-fiber region by converting service signals into integrated RF or intermediate frequencies, and then further converting them into millimeter-wave signals at each local base station. The configuration of our experimental system allows both methods to be used. The mobile station converts the received RF signals into those of the respective original frequencies, making it possible to use pre-existing terminals.

3.2 Influence of third-order intermodulation distortion (IM3)

Third-order intermodulation distortion (IM3) will be a great challenge in the implementation of our system[7]. In the integrated central base station, the service signals for PHS, ETC, and BS are combined in the 5.8-GHz band and then used in the modulation of light signals. The converted signals are sent to local base stations through optical cables. Noise may therefore occur in the service-signal band due to, for example, distortion caused by amplifiers inserted along the transmission path. Figure 6 shows the frequency allocation

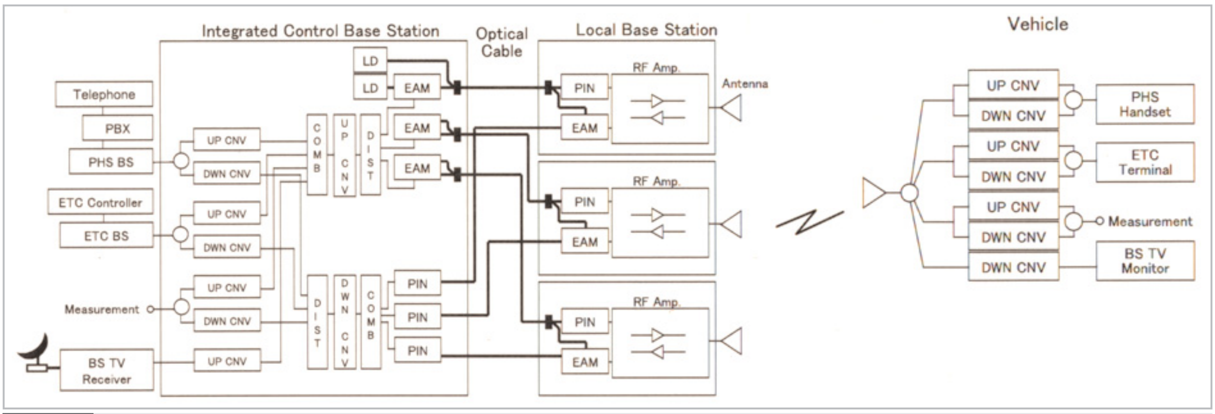

Fig.3 *Structure of the 36-37-GHz-band ROF multiservice experimental system*

Fig.4 *Views of the central base station, local base station, and mobile station*

for service signals in the downlink channel, along with possible locations at which IM3 may occur. The IM3 can be divided into the three-tone-type distortion (A in Fig.6) caused by three signals, and the two-tone-type distortion (B, C, D) caused by two signals. Either type of IM3 may occur in the currently allocated band for service signals, as shown in Fig.2. Affected by the signal distortion, the quality of each service signal will decline due to a fall in the D/U ratio.

Fig.7 shows the spectra of service signals and IM3 in the downlink channel. In the figure, part of the IM3 (IM3) caused by ETC and BS signals is recognized in the band of the PHS signal, and the quality of PHS service is predicted to degrade. However, a study examining decay and other factors in the radio-wave propagation path of integrated service signals has shown that the extent of such a quality decline due to IM3 is sufficiently small.

3.3 Millimeter-wave propagation in ROF road-vehicle communications[8]

As described above, our system employs the 37-GHz band for signal transmission in the air. While the millimeter-wave band makes it possible to realize high-capacity communication, numerous propagation-related problems remain to be solved due to its extremely high frequency. For example, the millimeter wave is not suitable for use in long-distance communications, as the propagation loss becomes too large. This may actually serve as an advantage in terms of the frequency efficiency but, in cases in which an antenna with a relatively wide directivity is used, the available

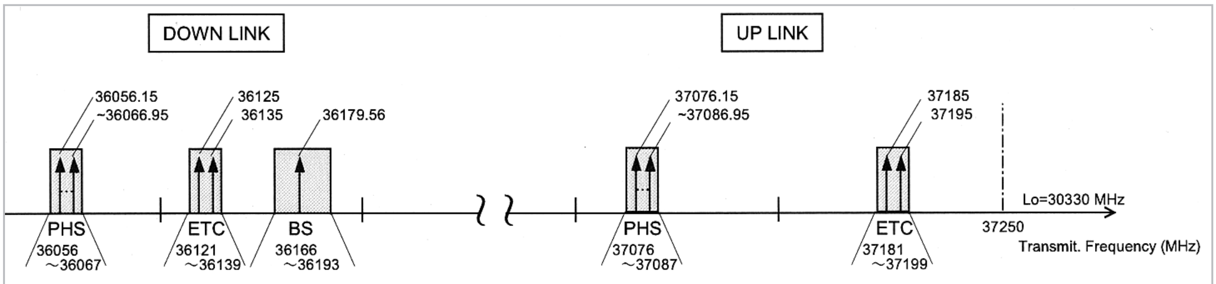

Fig.5 *Frequency allocation in the common frequency band*

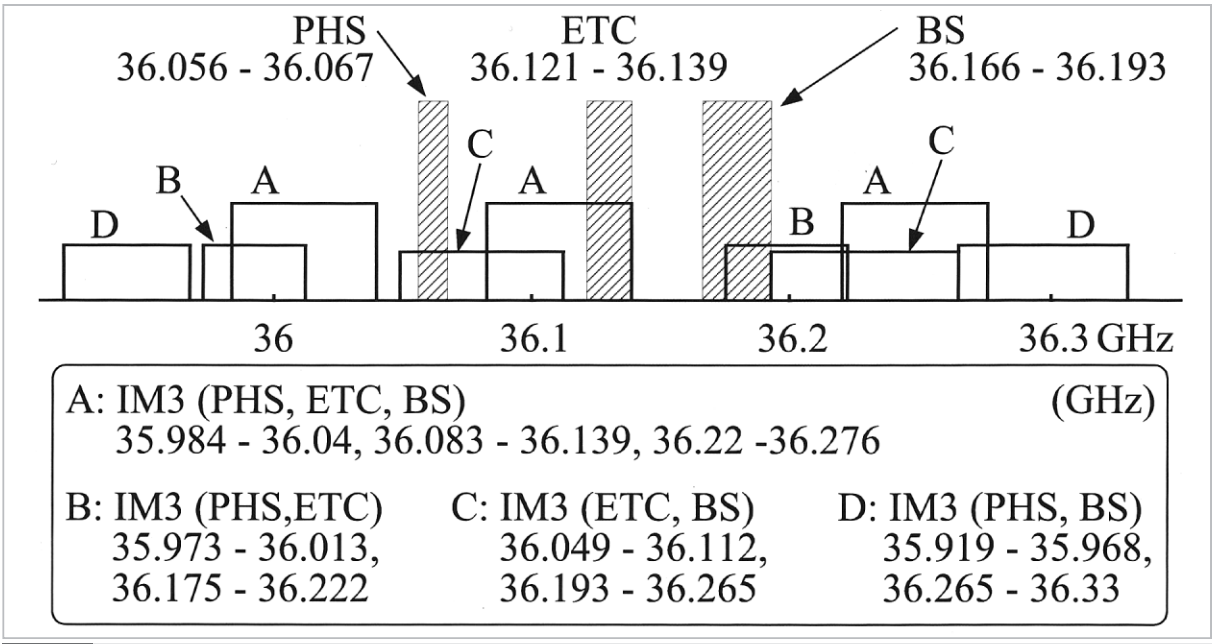

Fig.6 *Locations of third-order intermodulation distortion (IM3)*

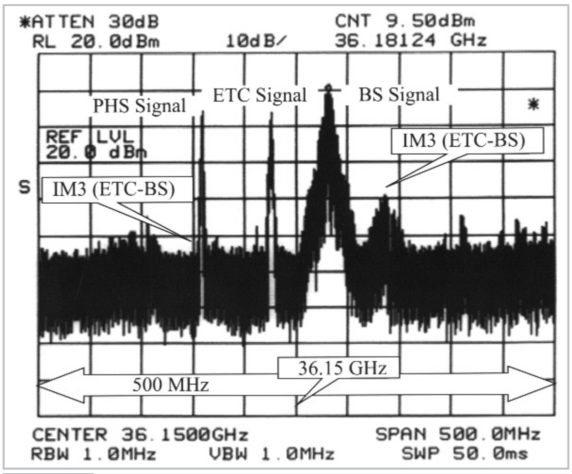

Fig.7 *Spectra of the signal and third-order intermodulation distortion (IM3)*

service area will be limited to a few tens of meters, depending on the employed communications methodology. In addition, millimeter waves are easily blocked by obstacles; for example, if a large car cuts into the millimeter-wave propagation path, communication becomes very difficult to continue. Similarly, communication using millimeter waves is easily affected by rain. During road-vehicle communication, the Doppler shift will be extremely noticeable, as the relative velocity between the base station and mobile terminal station is large.

Nevertheless, the broad bandwidth of the millimeter waves is a great advantage. High-capacity data transmission is an essential element of ROF road-vehicle communications. Thus, the problems with the propagation of millimeter waves must be solved to realize our system. Interference is a crucial issue, particularly for the millimeter-wave system using ROF technology. If, in the ROF system, two or more local base stations linked to a single central base station are allowed to emit millimeter waves of the same frequency, the system structure will be greatly simplified. At the same time, the adjacent service areas of local base stations linked to the common central base station may be regarded as a virtually continuous single service area, even if the service area of each local base station is small. However, in such a case, there will inevitably be strong interference at the boundaries of service areas formed by local base stations.

Fig.8 illustrates an example of the measurement of received power. In this figure, the antenna of the base station uses the cosecant squared-beam pattern, and thus the dynamic range within the service area is relatively small compared with that provided by a standard horn antenna. Large-level fluctuations are recognized near the boundaries of service areas formed by local base stations. A close

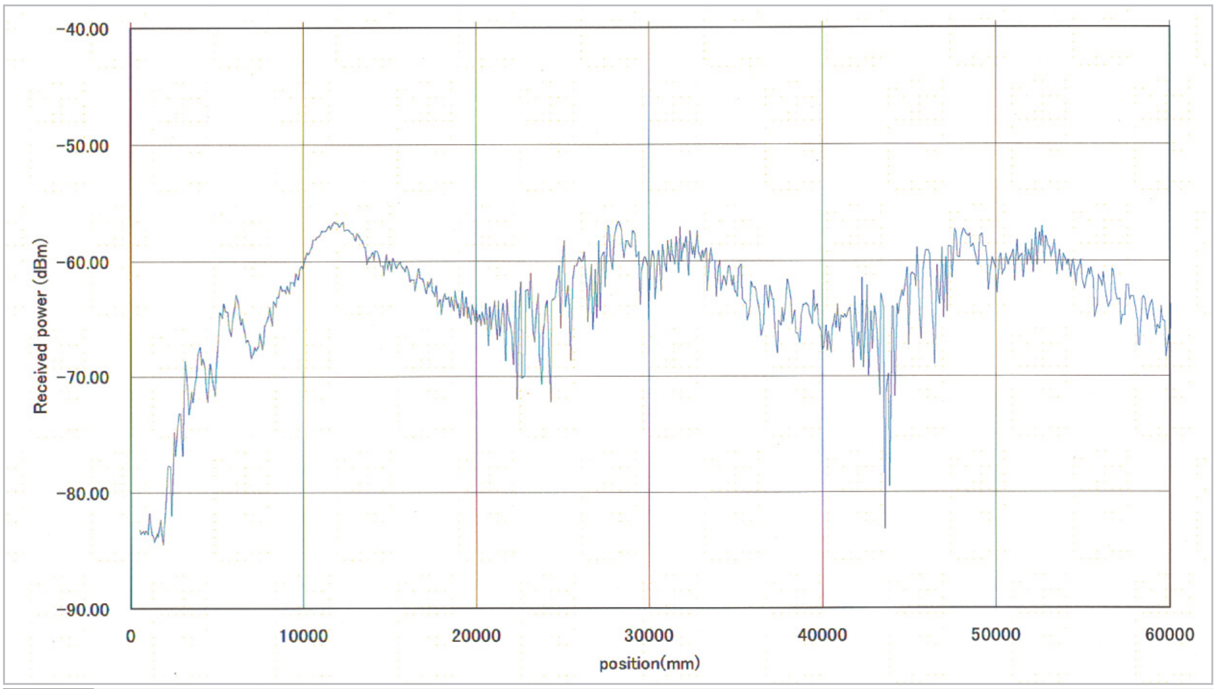

Fig.8 Measurement of received power (base stations located at the 0-m, 20-m, and 40-m positions)

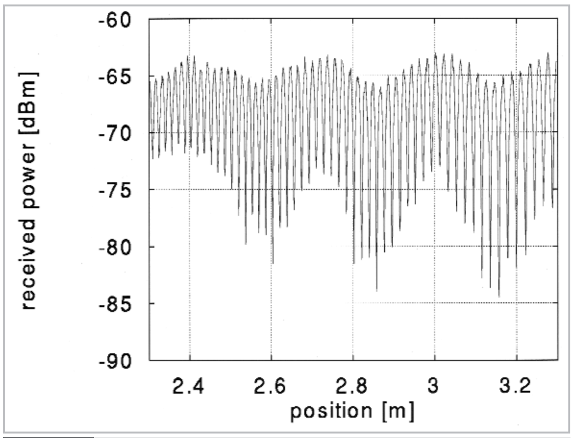

Fig.9 Received power near the boundaries of service areas (when polarization of adjacent base stations was used as circular polarization with the same rotational direction)

examination of the received power fluctuations at the boundaries (Fig.9) reveals a micro-interference pattern having a cycle of several times the wavelength. Fluctuations of as great as 20 dB are seen in some areas. This problem must be solved if the independent service areas are to be regarded collectively as a virtually continuous single area.

We adopt a technique using diversity as a means of solving the problem. We have been investigating a diversity technique using polarization to provide flat frequency characteristics over a broad band, and to make fluctuation cycle affected by interference very short. Fig.10 shows the fluctuations in received power observed near the boundaries of service areas for the case using right-handed circular polarization and left-handed circular polarization in adjacent stations. As demonstrated in Fig.10, the amplitude of fluctuations decreases in the case of diversity, compared with the case in which the same polarization is employed in adjacent stations. Although further improvements in the axis

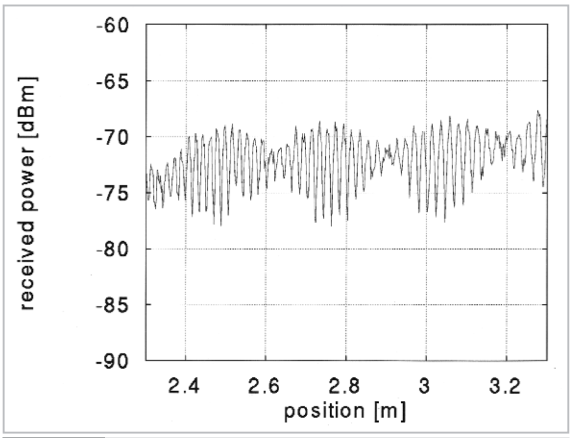

Fig.10 Received power near the boundaries of service areas (when polarization of adjacent base stations was used as circular polarization with opposite rotational directions)

ratio, for example, are required, we feel that diversity is a promising technique.

4 Multimode Vehicle Terminal by using Software Radio Technology

Before the software radio technology is adopted in ITS, we must gain an understanding of the situation specific to ITS. Specifically, there will be demand for the simultaneous reception of two or more services depending on the time slot. In other words, we should develop a multi-process wireless communications system that will enable multi-mode communications as well as simultaneous services. For this purpose, the Communications Research Laboratory has proposed Multi-Mode and Multi-Process Software Radio (MMSR) technology and has periodically examined its utility. As part of this investigation, we have created a prototype compact vehicle-borne terminal device using MMSR communications technology with enhanced efficiency. Fig.11 shows the external view of the prototype terminal device. Table 1 contains a summary of its system specifications.

Fig.11 External view of the on-vehicle software radio terminal

This compact software radio terminal can provide services such as GPS, VICS, ETC, AM radio, FM radio, FM text broadcasting service, and modulation/demodulation such as BPSK, QPSK, GMSK, ASK, and π/4QPSK, using only compact (17.5 cm in width, 19 cm in depth, 5 cm in height) hardware. These services will be available simultaneously within the framework of the Intelligent Transportation Systems. The signal-processing unit of this software radio system is composed of only two FPGAs of two million gates each, and the terminal can be driven by a power supply of 12 V and 2-3 A. The software to be installed will be downloaded via wires as well as wireless channels.

Fig.12 shows the system configuration of the compact software radio terminal. In principle, its digital signal-processing unit is composed of two FPGAs and one CPU serving as a controller. The software for FPGAs is saved in a PC connected using Ethernet cables, allowing it to be downloaded as desired. The RF and IF units for ETC and GPS are not included in the terminal and can be added upon request. The RF and IF units are pre-installed only for VICS and FM and AM radio.

The software to serve as a modem unit is downloaded to one of the two FPGAs. This modem unit can provide modem functions for BPSK, QPSK, GMSK, ASK, and π/4QPSK, simply by changing the parameters that are

Table 1 System specifications

Service	GPS, VICS, ETC, Broadcasting (AM, FM), FM Multiple service, User mode (BPSK, QPSK, GMSK, ASK, π/4QPSK)
RF frequency band	5.8 GHz, 1.5 GHz, 76-100 MHz, 0.5-1.6 MHz
IF frequency band	70 kHz-5 MHz
Configuration	2FPGAs (2 million gates x2) + PCSR and MMSR technologies
Maximum number of simultaneous services	5 (variable)
AD Conversion	IF over-sampling 20 Msps, 10 bit
Software download	Ethernet VICS radio channel (broadcasting-type) ETC radio channel (communication-type)

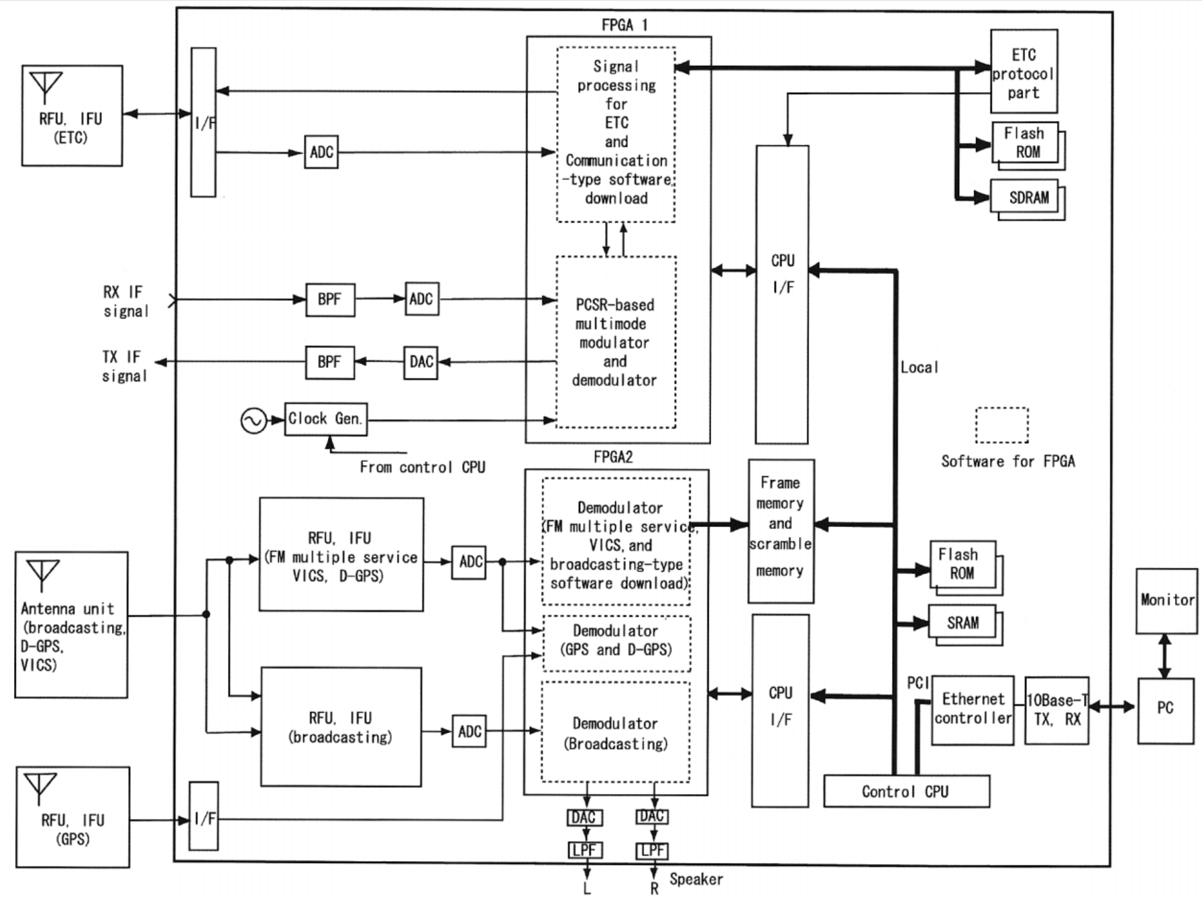

Fig. 12 *System configuration*

differences among modulation and demodulation schemes. The parameters to be input in this software are the system clock frequency, the employed modulation mode, the coefficients of the waveform configuration filter for the transmitter and receiver, the local oscillation frequencies of the orthogonal modulator and demodulator, the data clock frequencies of the transmitter and receiver, the coefficient of the loop filter used for clock recovery, and the threshold level used for data demodulation.

As performance indices of the prototype system, the size and download time of software constituting this system are shown in Tables 2 and 3, respectively. The prototype system uses FPGA-1 for the ETC and USER modes, while FPGA-2 is used for all other purposes, as illustrated in Fig.11. Regardless of the number of downloaded communication services or used FPGAs, software of 1241 KB must be downloaded when either FPGA-1 or FPGA-2 is used. As the required time for downloading to an FPGA is approximately 8 seconds, as indicated in Table 3, all software

Table 2 *Software size*

Service	Time (byte)	Service	Time (byte)
ETC	1241 k	GPS	1241 k
FM Multiple	1241 k	Broadcasting	1241 k
VICS	1241 k	Download	1241 k
USER mode (full download)	1241 k	π/4QPSK (parameter)	1.73 k
ASK (parameter)	1.73 k	BPSK (parameter)	1.73 k
QPSK (parameter)	1.73 k	GMSK (parameter)	1.73 k

Table 3 *Software downloading time*

Service	time	Service	Time
1.ETC	8380 ms	4.VICS	8260 ms
2.FM Multiple	8260 ms	5.GPS	8750 ms
3.Broadcasting	8260 ms	6.Download	16650 ms
1+2	16620 ms	1+2+3	16620 ms
1+2+3+4	16640 ms	1+2+3+4+5	16650 ms
USER mode (full download)	8380 ms	π/4QPSK (parameter)	less than 1 ms
ASK (parameter)	less than 1 ms	BPSK (parameter)	
QPSK (parameter)		GMSK (parameter)	

changes can be completed within 16 seconds.

We compared the software volume and download time between full downloading and parameter information downloading for system changeover, under the same conditions as used for the prototype system. The results are shown in Tables 2 and 3. These tables indicate that the software to be downloaded is reduced to approximately 1/1000 of its original size, and that its configuration time is shortened to approximately 1/8000 of its original length through the use of the parameter-information downloading software radio communications technology, which requires only differential information for activation. When the differential parameter-driven software radio communications technology (PDSR) is used, the time required for downloading changes little among different modulation-demodulation schemes. As a conclusion, the MMSR and PDSR technologies are important key technologies for realizing future software-radio-based intelligent transport systems.

5 Multimedia Lane and Multimedia Station[9]

It takes time to introduce facilities such as base stations, and to build up the infrastructure necessary for implementation of the ROF road-vehicle communications system. Thus, in the early stages, the availability of the infrastructure will be limited to major roads and a few other areas, and related service will be available only in such limited areas. It is therefore unlikely that a moving vehicle will receive the RVC service over an extended period on a continuous basis. The actual service areas will be limited to only parts of roadways or to discontinuous sections of roadways. These limitations will restrict the range of service contents, and the early-stage services will consist of large-capacity simultaneous downloading through media where real-time characteristics are not of great importance.

We propose the concept of a multimedia lane and multimedia station serving as ITS road-vehicle communications infrastructure capable of providing a large-capacity, simultaneous data transmission service. The multimedia lane and multimedia station are local facilities intended to provide large-capacity, simultaneous data transmission services and to download information from the installed ROF local base stations to the vehicle. A multimedia station is defined as that using a single local base station for the broad band package transmission, while a multimedia lane is that using two or more local base stations to download information. Their system specifications are shown in Table 4. In our definitions, the multimedia lane assumes a situation in which the vehicle is operating during information download. It will typically be employed in main lanes and side lanes. In contrast, with the multimedia station, there are no limitations on the speed of the moving vehicle. However, the amount of information a vehicle can download from a local base station decreases as the speed of the vehicle increases. Thus, when a user downloads information with a large data size, static downloading will be dominant under actual conditions, such as when information is downloaded from a local base station installed in a parking lot.

Table 4 *System features*

	Multimedia lane
Definition	Download information through multiple connected local base stations
Vehicle	Should be moving during information download
Major sites of application	Main lanes, side lanes

	Multimedia station
Definition	Download information through a single local base station
Vehicle	No vehicle speed requirements during information download (In principle, vehicle, should be at a standstill.)
Major sites of application	Parking lots

Fig.13 shows a system model of the multimedia lane. The multimedia lane is composed of two or more local base stations installed by the roadside, and an entrance gate. The entrance gate senses the arrival of a vehicle that will download service data, and the local base stations transmit the service data to the vehicle. The vehicle downloads the data, passing by more than one local base station. In this case, the continuous cells used in data downloading by a vehicle share a co-channel in order to reduce the load of handover on the terminal mounted in the vehicle.

Fig.13 shows a system model of the multimedia station. The configuration of the multimedia station is almost the same as that of the multimedia lane, except that only one local base station is used each time data is downloaded. Each local base station has equipment for sensing the arrival of a vehicle.

6 YRP ITS Joint Research Group

Yokosuka Research Park (YRP) conducts research and development on ITS communications, having established a research group composed of the Communications Research Laboratory and various private companies in FY1998. The ITS joint research group are doing separate activities in the inter-vehicle

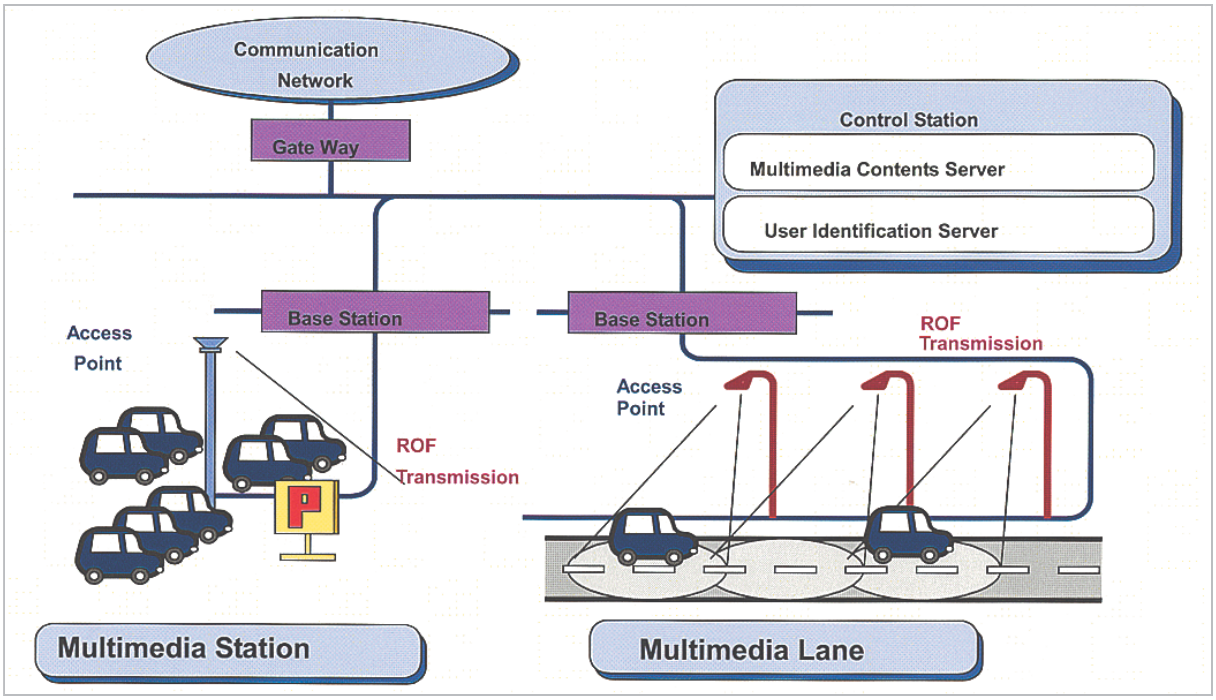

Fig. 13 *System models of the multimedia lane and multimedia station*

communications and road-vehicle communications working groups.

The road-vehicle communications joint working group has provided a base for the standardization of road-vehicle communications technology using ROF technology. This working group comprises three sub-working groups (SWG) — propagation SWG, high-speed transmission SWG, and multi-service SWG. The sub-working groups have been actively conducting their own experiments and discussions.

7 Conclusions

This paper has described the technological requirements for the implementation of ROF road-vehicle communications using millimeter waves, and the facilities we have developed for field tests on the ROF technology. The millimeter-wave ROF road-vehicle communications system incorporates a wide range of related technologies. Currently, we are working to enable the transmission of more diverse applications, and are investigating the technical items that will serve as a base for standardization of the multimedia station. As a variety of leading-edge technologies are incorporated into the millimeter-wave ROF road-vehicle communications system, many technological problems remain to be solved before it can be implemented. One of our challenges is to develop a technique (such as IM3) that will bring together a number of applications on the same frequency band, and another is to solve the problems associated with the use of millimeter waves (in terms of propagation and devices, for example). We will tackle such technological issues on an individual basis. We plan to expand the range of available services and combine road-vehicle communications technology with inter-vehicle communications technology in order to provide an integrated road-vehicle, inter-vehicle communications service in the near future.

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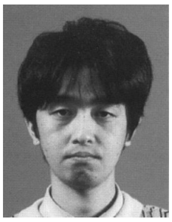

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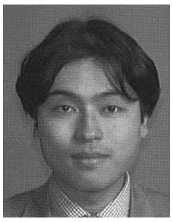
Propagation



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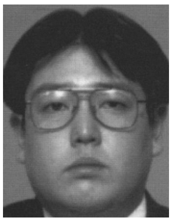
Transmission



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