3-4 ITS Wireless Transmission Technology

3-4-1 Technologies of Millimeter-Wave Inter-vehicle Communications
– Propagation Characteristics –

Akihito KATO, Katsuyoshi SATO, and Masayuki FUJISE

In this paper, we introduce developed technologies for millimeter-wave inter-vehicle communication (IVC) system in intelligent transport systems (ITS), especially propagation characteristics of 60 GHz band for the system design of IVC. First we introduce the outline of an IVC system using millimeter wave and its research subjects. Next we show experimental results of propagation characteristics of radio wave at 60 GHz between running vehicles. The propagation model and mechanism of fading propagation are argued. The joint research activity of IVC system in Yokosuka Research Park (YRP) is also introduced.

Keywords
Inter-vehicle communication, Millimeter wave, Propagation, ITS

1 Introduction

The number of cell-phone service subscribers reached 60 million at the end of March 2001 and has continued to increase, exceeding the number of fixed-phone subscribers. In addition to the growth in wireless mobile communications systems, the range of their applications is further expanding into new fields such as Intelligent Transport Systems (ITS), while moving toward the microwave and even millimeter wavelength regions. With such technological innovations in its scope, the Mobile Communication Group of the Yokosuka Radio Communications Research Center has been investigating radio communications technologies in the untapped millimeter wave band since FY1998, in anticipation of new developments in the info-communications area of ITS. In Yokosuka Research Park (YRP) where this research center is located, the world's top mobile-device manufacturers and research institutes have gathered to push ahead with leading-edge mobile communications research on mobile multimedia systems represented by the next-generation cell-phone and ITS radio communications system, in cooperation with industry, academia, and government[1].

This paper describes our research on on-road radio propagation during millimeter-wave Inter-Vehicle communications, a subject that is among the research activities conducted at YRP. We first explain the features of the millimeter-wave inter-vehicle communication and its applications, clarifying the relevant technological issues that remain to be resolved. Research on ITS millimeter-wave inter-vehicle communication conducted in YRP is also introduced. Next, we consider propagation models and fading mechanisms based on the experimental results of our field propagation tests. The paper concludes with a discussion of future research activities.

2 Features of Millimeter-Wave Inter-Vehicle Communications and Problems to Resolved

The millimeter-wave inter-vehicle com-

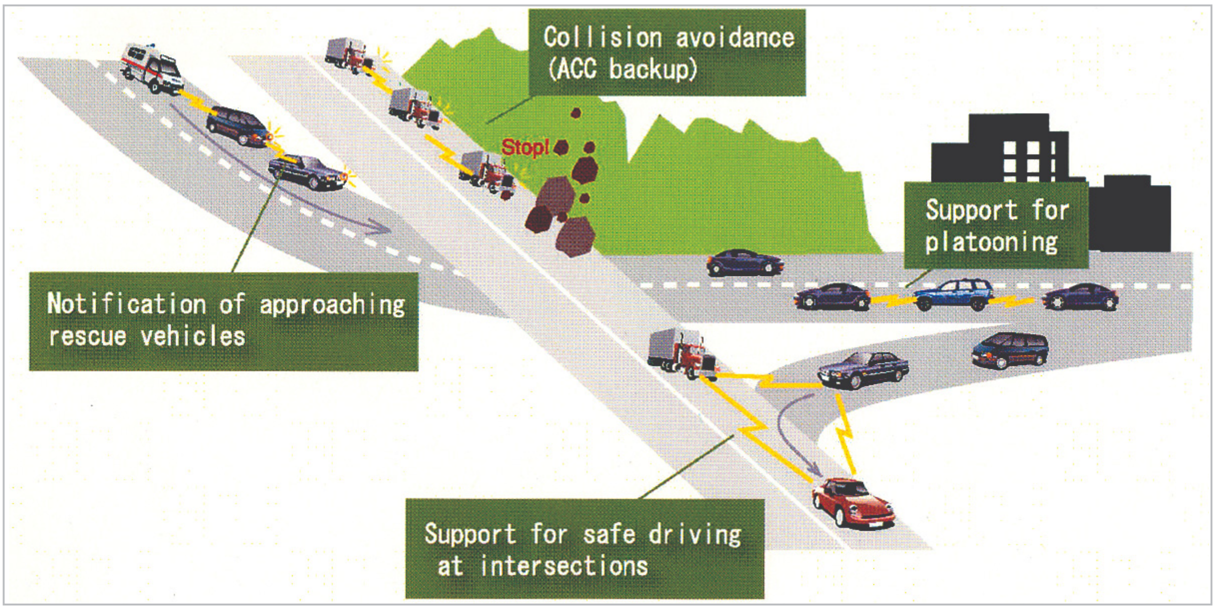


Fig.1 *Application examples of millimeter-wave inter-vehicle communications*

munications system is a wireless communications system that can improve safety and convenience during driving by enabling direct communications between vehicles, without relying on roadside infrastructure, by using a millimeter-wave band such as the 60-GHz band. Fig.1 shows some example applications of the millimeter-wave inter-vehicle communications system.

When the millimeter-wave band is employed for such inter-vehicle communications, the signal is less attenuated by fog and snow than communications systems based on infrared light, and is less affected by interference from sunlight. In particular, the inter-vehicle communications system, as a dedicated short-range communications system (DSRC) using the 60-GHz band in the millimeter-wave region, provides a number of advantages. For example, the reuse efficiency of channels is high due to the large atmospheric absorption, capacity for high-speed broadband communication, and the ability to provide linkage operations and share circuits with onboard radar, which has already been commercialized.

As with communications for transmitting control signals for unmanned operations such as platooning, an inter-vehicle communications system using millimeter waves basically assumes communication among vehicles moving in the same direction within line of radio sight. Although the vehicles move quickly on the ground, the relative speed between the communicating vehicles is low. Thus, direct communications between such mobile stations is similar to that of conventional fixed stations. In contrast, millimeter-wave-based communication may be seriously affected by even small amounts of relative movement between vehicles, due to the short wavelength of the millimeter wave. The influence of the multipath effect from the surrounding terrestrial features near the road may be relatively small, as the antenna will have a relatively narrow beam width. However, the signal reflection from the road surface is not negligible, and very strong fading occurs due to interference between the direct waves and the reflected waves from the road surface. In this way, the radio-wave propagation phenomenon observed during millimeter-wave inter-vehicle communication will differ significantly from that of conventional mobile communications. Thus, it is very important to clarify the propagation mechanism and establish a propagation model[2][3] for practical use of this system.

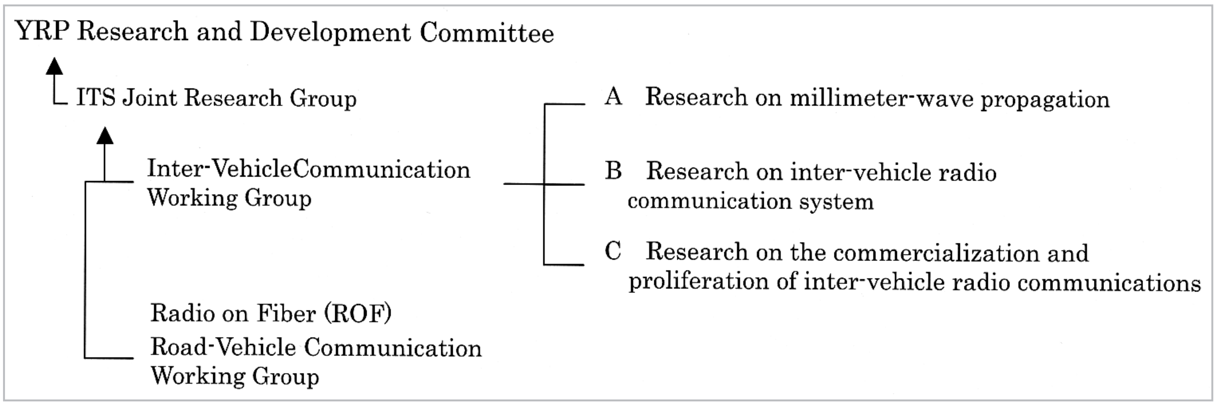


Fig.2 *Joint research organizations in YRP (for FY 2000)*

3 ITS Joint Research in Yokosuka Research Park[1]

Yokosuka Research Park (YRP) was established in October 1998 to contribute to the development of domestic and international info-communications technologies and to help establish an affluent society with a high quality of life for the 21st century by strengthening the research base for info-communications technologies and by proceeding with research on both basic and new technologies. Activities in this area are currently developing on a globally unprecedented scale, as a research park dedicated to mobile-communications technology. Indeed, research institutes and the world's top manufacturers of mobile communications devices have gathered at YRP, and are resolutely forging ahead with research on cutting-edge mobile-communications technologies, such as mobile systems represented by next-generation cell phones. A wide range of research is underway involving industry, academia, and government to realize the multimedia information society of the 21st century. As part of such research activities, ITS communications technology has been under study since FY1998 by private companies (joined by 19 additional companies in FY2000), led by the Communications Research Laboratory. They have been jointly conducting research on ITS wireless-communications technologies (for inter-vehicle communication, road-vehicle communication) using millimeter waves. Fig.2 illustrates the cooperative research organization for FY2000.

The Inter-Vehicle Communications Working Group launched its activities in 1998 to create the ITS inter-vehicle wireless-communications system based on millimeter waves, and to provide insight into its technological basis and standardization issues. In FY 2000, joined by some 12 organizations, it conducted research and development of specific applications and worked toward the widespread distribution of useful systems. Currently emphasizing activities that target commercialization, it is divided into three sub-working groups for the undertaking of specific studies.

4 60-GHz-Band Outdoor Radio Propagation Measurement System

We have been investigating a 60-GHz-band outdoor radio propagation measurement system since 1998 to determine its on-road radio propagation characteristics during millimeter-wave inter-vehicle communication and have conducted a variety of measurements. The system configuration and its specifications are shown in Fig.3 and Table 1, respectively. Fig.4 shows an external view of the RF unit of the system, along with views showing installation in test vehicles. This system configuration is such that the RF units and measurement devices are aboard two test vehicles. The configuration assumes a situation in which the experiment is conducted using a pair of vehicles traveling on roads and

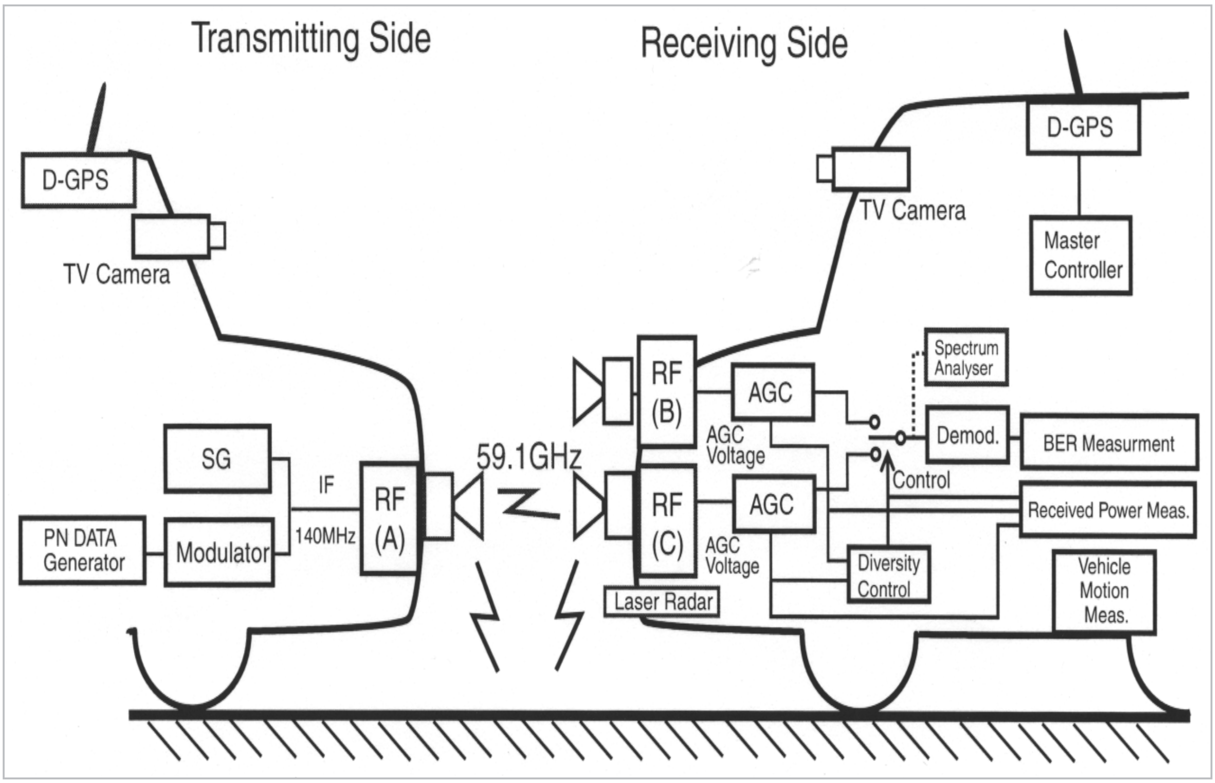


Fig.3 Configuration of the 60-GHz outdoor radio-wave propagation measurement system

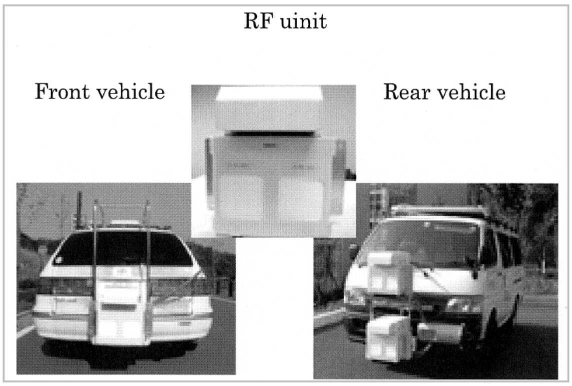


Fig.4 External view of the RF unit and installation in the test vehicle

Table 1 Specifications of the 60-GHz outdoor radio-wave propagation measurement system

Center frequency	59.1GHz
Maximum transmission power	10dBm
Data transmission rate	1Mbps～10Mbps
Modulation-demodulation method	DFSK(Manchester code)
Detection mode	Delay detection
Measurement of received power	Use of AGC voltage
Diversity	Selective synthesis based on condition fulfillment

expressways. In principle, the RF unit is capable of two-way communication based on frequency division duplex. During our propagation experiments, however, the experiment was performed on a single-direction basis, with the front vehicle serving as the transmitting side and the rear vehicle serving as the receiving side. The rear vehicle is equipped with two series of wireless systems to examine the effects of space diversity by changing the heights of the systems. This diversity is based on selective signal synthesis in which signal-receiving paths are switched with time lag determined at the moment conditions are met, such that the receiving powers and threshold values are compared and matched in the two receiving systems. Thus, the timing of switching is not synchronized with the demodulation symbols. The data on received power is obtained from the control voltage of AGC in the IF unit, and data acquisition is possible in the 150-kHz band at maximum in both systems. Our system temporarily includes a DFSK-type modem that can provide BER at intervals of 1 s or 10 ms during data transmission at transmission rates of 1 Mbps, 5 Mbps, and 10 Mbps. To precisely monitor the ever-changing measurement conditions, the measurement system also features a distance between vehicles measurement system using laser radar, a three-axial measurement system using optical gyroscopes, and a recording system using a video camera that records the surrounding views. All data provided by these systems is synchronized with the GPS signal, and off-line analysis can be performed based on the synchronized data after measurements have been taken.

5 Two-Ray Model for On-Road Radio Propagation

It has been pointed out[2]~[5] that millimeter-wave propagation on a road is multipath propagation combining the direct wave and other waves reflected by the road surface and surrounding structures. In the current experiment, we conducted measurements in an open area with relatively few surrounding structures, such as buildings. Thus, we considered a two-ray model that limited the waves incoming to the receiver to direct waves and waves reflected from the road surface, and then compared the measurement results with the calculations for received power provided by the model. As shown in Fig.5, received power P_r is given by the following equation[6], considering only the direct wave and the reflected wave when a transmitter held at a height h_t and a receiver at a height h_r, with each r_d apart from one another in the horizontal direction:

$$P_r = \frac{P_t G_t G_r}{L(r_d)} \left[D_d \left(\frac{\lambda}{4\pi r_d} \right) + D_r \left(\frac{\lambda}{4\pi r_r} \right) \Gamma \cdot e^{-j\{k(r_d - r_r) + \Phi\}} \right]^2 \tag{1}$$

where G_t and G_r are the gains of the boresight of the transmitter and receiver, respectively, r_d and r_r are the optical path lengths of the direct wave and the wave reflected from the road surface, $L(r_d)$ is the absorption factor[7] in the 60-GHz band, λ is the wavelength of the carrier wave, $2\pi/\lambda$, ϕ is the phase rotation during road reflection (assuming π in this study), D_d and D_r are the coefficients of antenna directivity for the direct wave and the reflective wave in the arrival direction, and Γ is the reflection coefficient of the road surface.

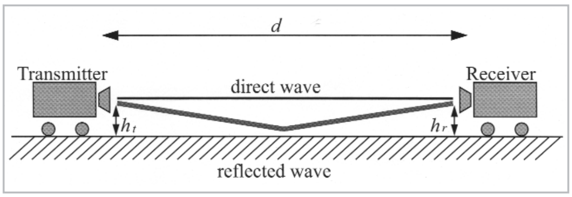


Fig.5 Two-ray model for on-road propagation

Next, considering the current experimental conditions, if antenna heights h_t and h_r are 50cm when the distance between vehicles r_d is 50-100 m, the incident angle of the reflected wave onto the road surface falls in the range of 88.8-89.4 degrees. Assuming that the refractive index of asphalt is 2.0-j 0.05[8], the absolute value of the reflection coefficient of asphalt is estimated to be 0.90-0.99 at 60 GHz within the above incident angle range. Although various polarization antennas may be used in actual measurements, the reflection coefficient is expected to fall in the above range. Thus, in the present study, we have assumed the absolute value of the on-road reflection coefficient to be 1. In addition, the two test vehicles travel in the same lane nearly throughout the experiment. Thus, both direct and reflected waves strike the antenna at incident angles much smaller than the antenna half-width, making it unnecessary to consider antenna directivity. Therefore, Equation 1 can be approximated using a simpler equation that does not account for antenna directivity, as follows[9]:

$$P_r = \frac{P_t G_t G_r}{L(r_d)} \left(\frac{\lambda}{2\pi r_d} \right)^2 \sin^2 \left(\frac{2\pi h_t h_r}{\lambda r_d} \right) \tag{2}$$

We have conducted a theoretical investigation using the above equation for the two-ray model of the on-road propagation phenomenon.

6 On-Road Millimeter-Wave Propagation Characteristics

With respect to radio-wave propagation between moving vehicles, a number of factors influence radio-wave propagation characteristics, such as vehicle motions and changes in surrounding conditions. However, we have conducted measurement under conditions that may be affected as little as possible by the motion of vehicles and the surrounding conditions, so as to gain an understanding of the fundamental characteristics of on-road radio-wave propagation. In the experiment, two vehicles nearly at a standstill transceived millimeter-wave signals on a straight road with clear sight, and measured the received power and bit error rate (BER) at each distance (distance characteristics), gradually changing the distance between the transmitter and receiver in the 10-200 m range.

(1) Distance characteristics with antenna height as a parameter[10]

Fig.6(a) and (b) show examples of the measurement results for received power and the bit error rate plotted for two antenna heights. The solid line represents the measurement, while the dotted line represents the model calculation provided by the propagation model considering both direct waves and road-surface reflected waves. In both graphs, the measurement and calculation approximately agree, implying that the two-ray model considering both direct waves and road-surface reflected waves can be used under open measurement conditions such as those employed in the experiment. In addition, we can expect effects of space diversity in the vertical direction, as the distance that provides the null point resulting from the interference of the two waves changes with antenna height. Fig.7 shows the measurement results obtained when space diversity was utilized. In comparison with the previous figures, this figure indicates that vertical space diversity eliminates the deep null point and improves BER.

(2) Distance characteristics with antenna-beam width as a parameter[7][11]

Fig.8 shows the measurement results for received power in relation to the transmitter-receiver distance when the beam width of the transceiver antenna was set at 4 or 10 degrees. The solid line represents the measurement, while the broken line represents the simulation results provided by a two-ray model considering the directivity of the rectangular aperture antenna. This figure indicates that the influence of reflected waves is reduced as directivi-

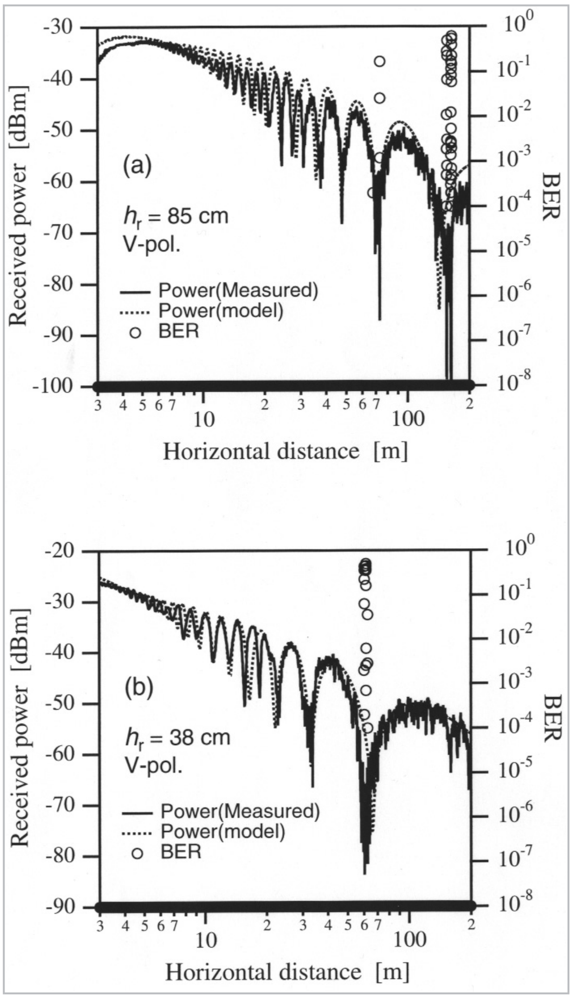


Fig.6 Distance characteristics with antenna height as a parameter

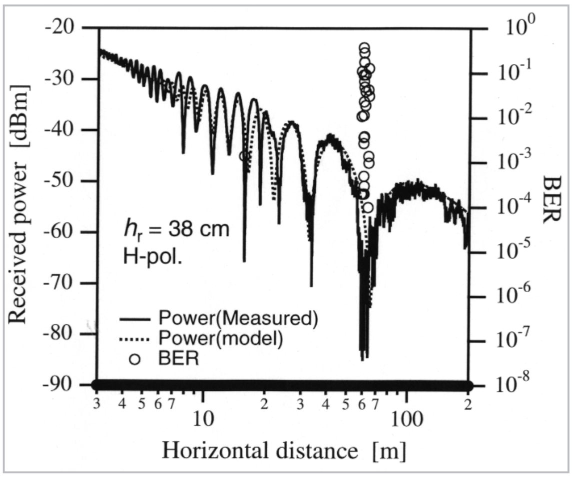
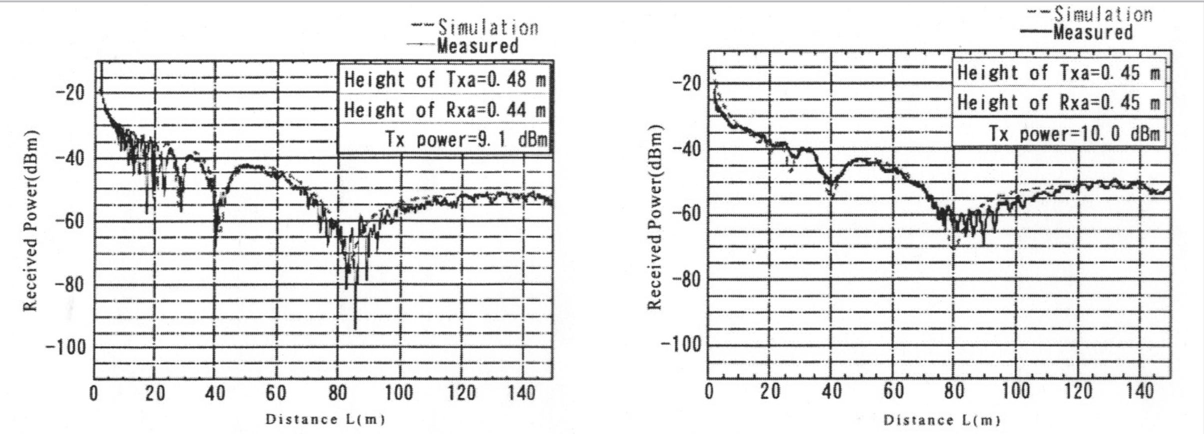


Fig.7 Distance characteristics with diversity



Beam width of 10 degrees

Beam width of 4 degrees

Fig.8 Distance characteristics with antenna-beam width as a parameter

ty is augmented, and that the decrease at the null point then becomes small. Thus, the fading caused by road-surface reflected waves will be reduced by narrowing antenna directivity.

(3) Signal blocking by intermediate vehicles[12][13]

We measured the change in received power by employing two vehicles equipped with transceivers on a straight road 46 m apart from each other, and slowly moving an intermediate vehicle (sedan) from the receiver side to transmitter side so that it intervened in the propagation path between the transmitter and receiver. Fig.9 shows the measurement results, with the horizontal axis representing the distance from the receiver to the intermediate vehicle. The received power with no intermediate vehicle was −46 dBm. The graph indicates that the received power peaked when the intermediate vehicle reached the midpoint between the transmitter and the receiver. This is probably due to the fact that the direct waves were blocked by the sedan, but that signals reached the receiver by passing under the intermediate vehicle, being reflected off the road surface. The region between the two vertical lines in the figure represents the distance when the reflected wave enters the line of sight by passing the vehicle, based on the calculation of clearance. The figure indicates that the signal decay becomes relatively small when the propagation path enters the line of sight. Indeed, there are cases in which the decay due to blocking is merely a few dB. In other words, even if there exists an intermediate vehicle, blocking loss may be relatively small, depending on specific conditions. Communications may then be continued with no shadowing. On the other hand, this implies that interference will become a serious problem in a system that uses a co-channel among several platooning vehicles in anticipation of a large blocking loss.

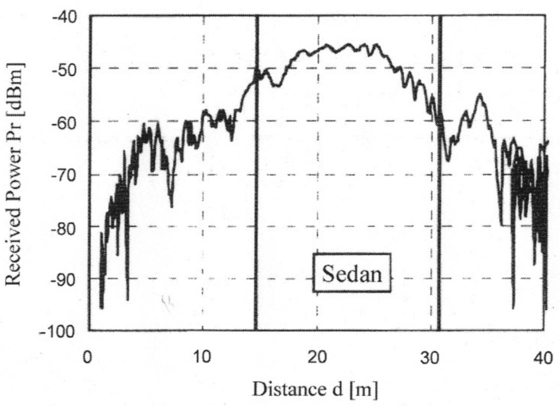


Fig.9 Shadowing characteristics of intermediate vehicle

7 Received-Power Fading during High-Speed Travel[10]

The preceding section examined the validity of adopting the two-ray model of the inter-vehicle radio propagation phenomenon for periods sufficiently short to disregard the vehicle motion and the dependence of received power upon the antenna-to-antenna distance and antenna height. However, the height of a traveling vehicle and the distance between vehicles change from time to time, as do the surrounding terrestrial features. Therefore, the simple two-ray model may not accurately simulate the propagation phenomenon of actual travel under complex conditions. We therefore operated two vehicles on a common expressway to measure the inter-vehicle propagation characteristics and data-transmission characteristics under such realistic conditions.

In the experiment, we operated two vehicles in the same lane, maintaining a distance of approximately 80 m at a speed of 80 km/h on the Yokohama-Yokosuka Expressway (between Sawara and Namiki), and measured the instantaneous received power and bit error rate. Table 2 lists the measurement conditions, while Fig.10 shows a view of the measurement site.

Fig.10 View of the experimental site on an expressway

Table 2 Measurement conditions

Transmission power	10dBm
Modulation-demodulation method	DFSK
Data transmission rate	1Mbps
Antenna	Patch array
Antenna gain	20dBi
Beam width (horizontal)	30degrees
Beam width (vertical)	7.2degrees
Polarized wave	45degrees tilt
Height of transmitter	47cm
Diversity threshold (level)	−80dBm
Diversity threshold (difference in level)	20dB
Diversity timing delay	10ns

7.1 Received power and BER fluctuations over time

Fig.11 shows the median value of the short-term median values of received power measured at intervals of 10 ms in each receiver, the bit error rate (BER), and the distance between the vehicles over time. The measurement was begun immediately before the Sawara Interchange and ended immediately

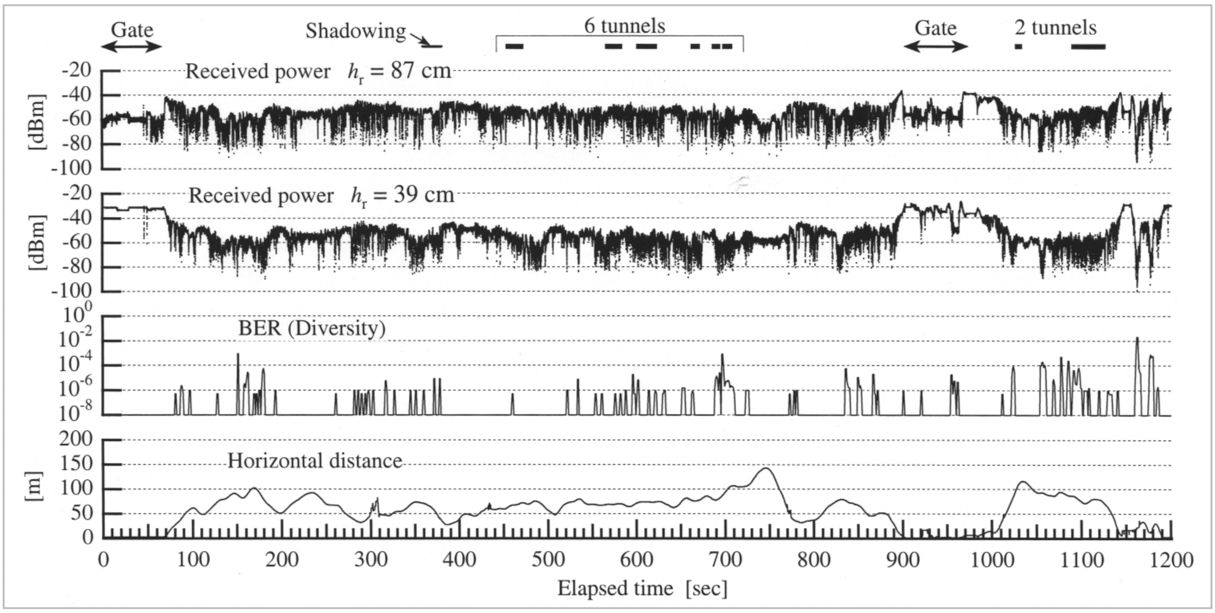


Fig.11 Short-term median value of received power, bit error rate, and horizontal distance over time

after the Namiki Exit. This figure indicates that there was serious fading of more than 20 dB in received power over the entire measurement period, and that BER degraded as the received power declined. Fig.12(a) and (b) demonstrate the relationship between the short-term median value of received power and the distance between vehicles. The curve in each figure represents the received power predicted by a model using Equation (2) for the individual inter-vehicle distances. The calculated curve implies that the level of received power changes along with the distance between vehicles due to interference between the direct waves and reflected waves. The measurement results also indicate that the level of received power fluctuates significantly, even when the distance between vehicles remains constant. This is probably due to the fact that the actual height of the vehicle changes as it traveled on the road, although the theoretical study assumed a constant height for each transceiver. Under actual conditions, the received power fluctuates even if the distance between vehicles remains unchanged.

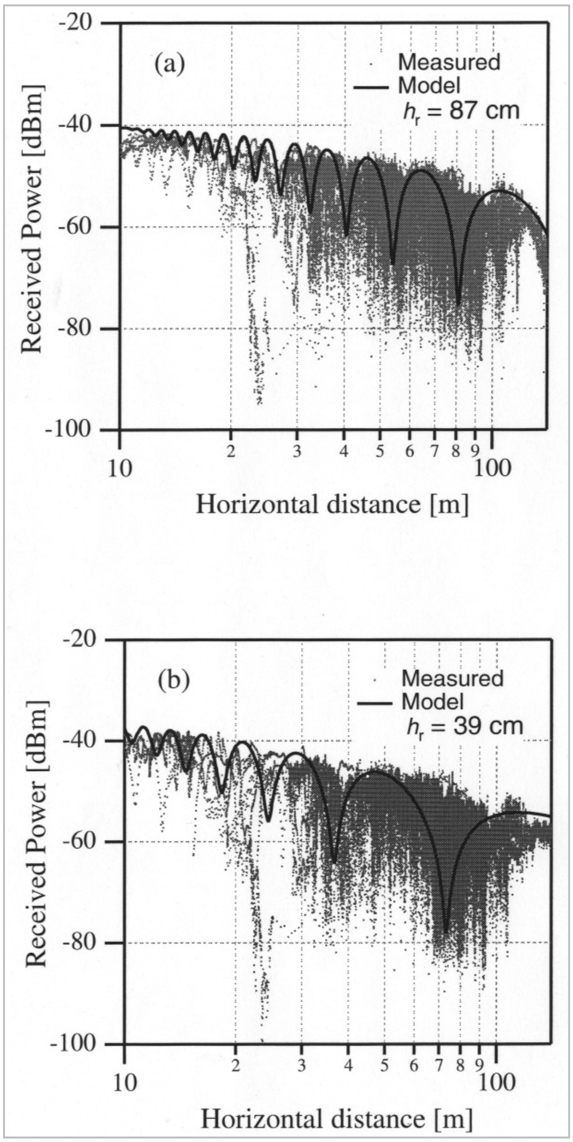


Fig.12 Measurement results for the short-term median value of received power in relation to the horizontal distance for each receiver height

7.2 Cumulative distribution

Fig.13 shows the cumulative distribution of the short-term median value of received power at each receiver. This figure includes the theoretical predictions of the Rayleigh distribution and the log-normal distribution (assuming a standard deviation of 1). The cumulative distribution obtained through measurement is not dependent on the height of the receiver, which is located halfway between the Rayleigh distribution and the log-normal distribution in the figure. Specifically, the height of the transceiver is not constant, but changes over time in actual driving on a road. Measurement using the optical gyroscope has shown that the distribution of the vertical fluctuations of a transceiver is close to the normal distribution. In addition, calculations using the two-ray model based on Equation (2) pre-

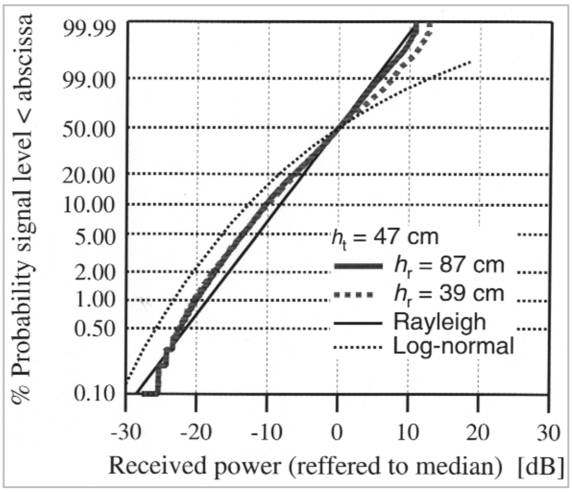


Fig.13 Cumulative distribution of the short-term median value of received power

dict that the distance characteristics will change considerably if the height of the transceiver changes by even a few centimeters[10]. Specifically, the vertical movement of the vehicle is among the crucial factors affecting the fading mechanism for millimeter-wave inter-vehicle communication.

We then estimated the vehicle height at each moment based on the pitch of the vehicle measured during a drive on an expressway. Referring to the obtained results and the measurement results for distance between vehicles, we estimated the instantaneous value of received power based on a theoretical study using Equation(2). We then calculated the cumulative distribution for these fluctuations over time. Fig.14(a) and (b) show the cumulative distribution obtained from the previous measurement of received power and the theoretical prediction based on the current analysis, respectively. As they show good agreement overall, we can assume that the vertical motion of the vehicle is an important factor in determining the fading mechanism.

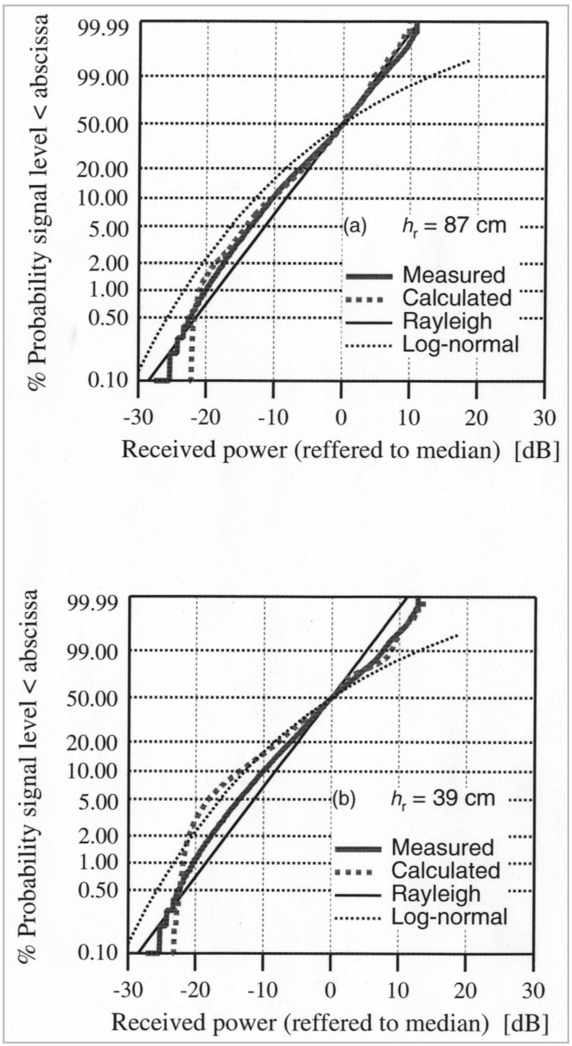


Fig.14 Comparison between measurement and calculation of the cumulative distribution of received power

Fig.15 shows the cumulative distribution of BER during 1 Mbps data transmission and selective-synthetic space diversity. In this figure, the horizontal axis represents the exponent of BER (log10), while the vertical axis represents the time ratio as a percentage indicating the length of time for which BER is equal to or smaller than the corresponding value on the horizontal axis. Note that the position denoted -8 indicates that there is no error. The figure indicates that there were no errors for 70% of the entire span of time, and that the figure rose to 87% when diversity was employed. The results of this study imply that vertical space diversity will be effective in millimeter-wave inter-vehicle communication.

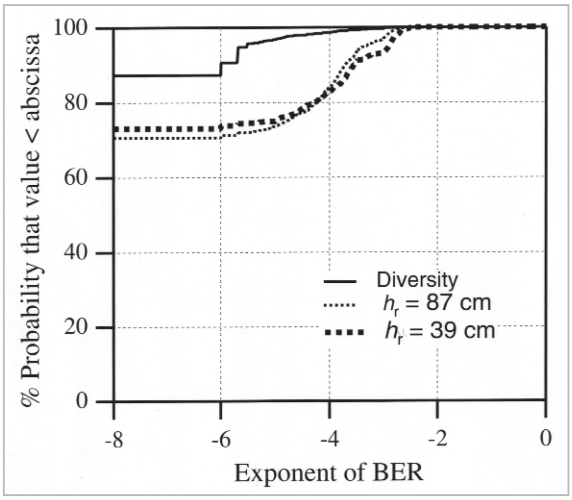


Fig.15 BER cumulative distribution for each receiver height for diversity reception

8 Conclusions

We have reported on the on-road radio propagation characteristics that must be understood in the design of inter-vehicle communications systems using millimeter waves. Our research activities entered a new phase in FY 2001, in anticipation of the implementation of the millimeter-wave inter-vehicle communications system in around FY 2003. Targeting a few applications that are expected to be readily accepted in our society, we have directed our efforts toward commercialization, focusing on individual system designs and field tests. In addition, we are concentrating our efforts on realizing this service by carrying out field tests to verify its effectiveness, and on realizing technical standardization as quickly as possible by providing standardization organizations with a YRP draft that can serve as the basis of official technological standards.

We would like to express our deep appreciation to the members of the Inter-Vehicle Communication Working Group for numerous exciting discussions concerning the experiment and analysis.

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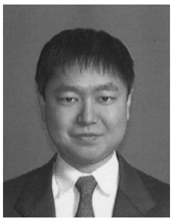


Akihito KATO, *Ph. D.*

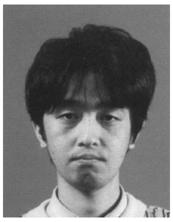
Senior Researcher, Mobile Communications Group, Yokosuka Radio Communications Research Center

Propagation, Mobile Wireless Communication

Masayuki FUJISE, *Dr. Eng.*

Leader, Mobile Communications Group, Yokosuka Radio Communications Research Center

Optical Fiber Communication, Wireless Communication



Katsuyoshi SATO

Senior Researcher, Mobile Communications Group, Yokosuka Radio Communications Research Center

Propagation