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Study of a Millimeter Wave Communications System for Railway Trains




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In recent years, aiming to achieve large-capacity radio communications between wayside equipment and onboard equipment in the field of railways, development of millimeter band radio communications based on the 40 GHz band has been proceeding. The millimeter band radio communications system is expected to realize faster communications. Especially in tunnel sections, it has the possibility to realize longer intervals between base stations than those along open sections because reflection waves to the wall are combined. In this paper, we report the test results and future feasibilities through propagation tests conducted using actual rolling stock and maintenance cars on Shinkansen tracks, aiming to obtain fundamental data for the radio system design.

●Keywords: Millimeter wave, Shinkansen train radio, Large-capacity communications, Directivity, Propagation test

1 Introduction

With the recent spread of smartphones and Wi-Fi, demand for transmission of video and other large-volume content is increasing. As frequency resources are becoming strained due to such large-volume data transmission, effective use of limited frequency resources and technical research on frequency domains not yet exploited are being promoted. In the course of those efforts, communications using millimeter waves, which is expected to bring about large-capacity transmission by widely securing frequency bandwidth, is attracting attention.

In the field of railways too, demand for large-capacity transmission is increasing so as to further improve safety, stability, and passenger service. As the communications method to be adopted to the future Shinkansen train radio system, millimeter wave communications can be regarded as one of the most feasible methods.

In this paper, we will explain the current state of the Shinkansen train radio system as well as characteristics of millimeter wave communications and a proposal for Shinkansen train radio system configuration utilizing millimeter wave communications. Finally, we will report on the results of basic field tests using an actual Shinkansen train and maintenance cars.

2 Current Shinkansen Train Radio System

The Shinkansen train radio system plays a very important role as a means of exchanging information between dispatchers and crew to ensure safe and stable operation of Shinkansen trains. With the change from analog to digital in 2002, the Tohoku and Joetsu Shinkansen train radio systems were provided with many new functions such as the Shinkansen operational notice transmission system, in-train passenger information service system, rolling stock technical support system, and communications equipment monitoring system.[1] Outlines of each of those new functions achieved by the switch to digital are as follows.

(1) Shinkansen operational notice transmission system
The system displays dispatchers' notices to crew, slowdown information, and the like on the Shinkansen cab monitor.
(2) In-train passenger information service system
The system displays operation information of Shinkansen trains and conventional trains with Shinkansen connections, news, weather forecasts, and the like on LED displays in the cabin of Shinkansen trains.
(3) Rolling stock technical support system
The system enables real-time check of operational status of Shinkansen rolling stock equipment on the monitors in the dispatcher's office and the rolling stock depots
(4) Communications equipment monitoring system
In failure of train radio onboard devices and the like, the system issues alerts on a terminal in the dispatcher's office using a communications equipment monitoring line.

In order to build those systems, it is necessary to secure stable radio communications between onboard devices installed to high-speed trains and wayside units. The current system is thus using the leaky coaxial cable (LCX) method, where information is transmitted between LCX cables laid along Shinkansen lines and onboard antennas, instead of the space wave method that is widely used for mobile communications. The transmission speed of the current Tohoku and Joetsu Shinkansen train radio system is 384 kbps.

3 Future Shinkansen Train Radio System

Classifying the future Shinkansen train radio system by type of communications into operational communications and passenger service communications, characteristics and requirements for each are considered as follows.

(1) Operational communications
Here, operational communications means voice and data communications related to train operation. From a perspective of safe and stable transport, radio transmission needs to be highly reliable on the entire line. In order to extend applications for operational communications in the future, further increase of

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transmission capacity will be needed.
(2) Passenger service communications
Here, passenger service communications means information service communications such as in-train Internet service for passengers. With the recent rapid spread of mobile terminals such as smartphones and tablets, large-capacity transmission will need to be achieved to improve Shinkansen passenger service.

As seen above, the future Shinkansen train radio system will need to achieve sufficient large-capacity transmission both for operational communications and passenger service communications. In this paper, we thus focus and discuss on millimeter wave communications as one of the communication methods applicable to future Shinkansen train radio communication systems because of its broadband performance that allows large-capacity transmission.

4 Examples of Actual Application of Millimeter Wave Communications in Railways

Examples of actual application of millimeter wave communications in railways (conventional lines) include platform video transmission and information transmission such as news and weather forecasts. In this chapter, we introduce some of those.
(1) Platform video transmission
As a means of confirming safety on the platform by only one crew member at train departure, we use a system where video of the platform recorded by cameras on the platform is transmitted to driver's cab and/or conductor's cabin. Millimeter wave communications has been applied to that system in recent years. By installing cameras and millimeter wave transmitters to the platform and millimeter wave receivers onboard, video transmission via millimeter wave communications is performed to confirm safety on platforms when opening/closing of doors and at train departure.
(2) Information transmission such as news and weather forecasts
By utilizing millimeter wave communications, large volumes of information can be transmitted in a short time while a train is stopped at a station. Millimeter wave communications is utilized to distribute information such as news and weather forecasts on the "Train Channel" broadcast in trains on the Yamanote and Chuo lines.

5 Proposed Configurations of Train Radio Systems Using Millimeter Wave Communications

There are concerns about attenuation of received power in rain with millimeter waves, but they enable large-capacity transmission because a wide frequency bandwidth is secured, and they enable beams with strong directivity due to their nature. Therefore, it will be possible to make full use of their advantages in a transmission environment that is relatively linear without obstructions as radio waves can easily reach destinations far away. As Shinkansen lines include many linear sections, communications using millimeter waves, which have strong directivity, can be regarded as relatively suitable to a Shinkansen train radio system.

Now we introduce a proposed system configuration that uses millimeter wave communications in all sections—both open sections and tunnels (the "all-section millimeter wave system configuration proposal")—and a proposed system configuration that uses a public network in open sections and millimeter wave communications in tunnels and other sections (the "combined public network/millimeter wave configuration proposal") for the future Shinkansen train radio system.[3)]

5.1 All-section Millimeter Wave System Configuration Proposal

In this proposal, base stations will be installed at approx. 1 to 3 km intervals, the transmission distance assumed to be appropriate for millimeter wave communications. Since transmission distance is expected to become shorter in an environment that includes changes in slope and curves due to the strong directivity of millimeter waves, we think we will need additional measures such as installing local low power base stations in the areas where radio waves cannot reach base stations. Furthermore, transmitting high-frequency signals like millimeter waves via coaxial cable could cause very large transmission loss, so using radio on fiber (RoF) for wired backbone facilities such as between base stations is a possible option.

This proposed configuration has an advantage that one communications method alone can cover the entire line. However, it will probably need many base stations in an environment with changes of slope and curves. The effect of attenuation due to rain in open sections will also need to be considered.

5.2 Combined Public Network/Millimeter Wave Configuration Proposal

LTE, WiMAX and other public networks have spread in recent years, particularly in urban areas. Here we explain an example combination proposal where public networks are used in open sections where radio waves of such public networks likely can easily reach and millimeter wave communications is used in tunnels and mountainous areas where public network radio waves have difficulties reaching.

Fig. 1 shows the public network/millimeter wave combination proposal. In this combination, data is assumed to be received by users via public networks and millimeter wave communications after being converted to Wi-Fi data using an onboard mobile router. By automatically switching between public networks and millimeter wave communications using an onboard mobile unit, users will be able to use the communication system without noticing switchover of outside communication media (switching between public network and millimeter wave communications).

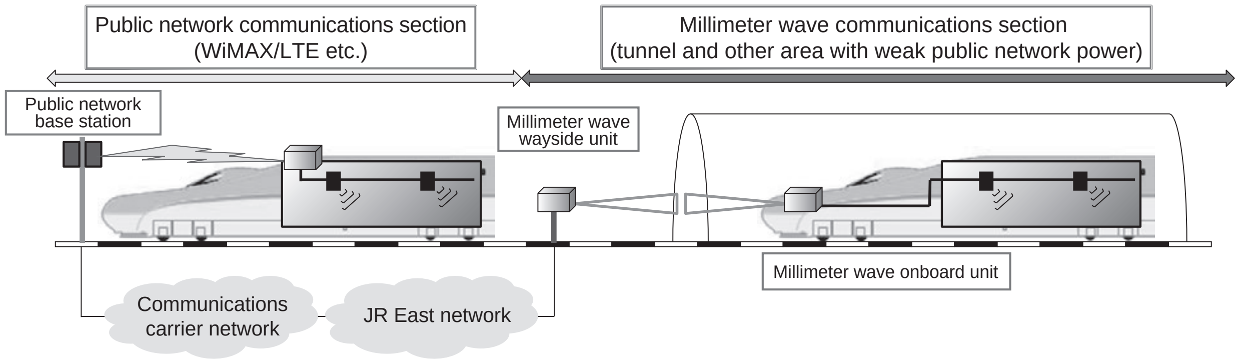


Fig. 1 Combined Public Network/Millimeter Wave Configuration Proposal

6 Basic Field Tests of Millimeter Wave Communications

With an aim of obtaining basic data for designing a wireless communications line and system for the train radio network using millimeter wave communications along Shinkansen lines, we carried out a large-capacity transmission tests using an actual Shinkansen train and in-tunnel transmission tests using maintenance cars.

6.1 Large-Capacity Transmission Tests Using Shinkansen Rolling Stock

6.1.1 Test Objectives

Results of field tests of 100 Mbps radio communications using 40 GHz millimeter waves have been reported in the past.[4] The report states that 100 Mbps communications was achieved in a distance of approx. 3 km from a base station in a tunnel section and approx. 1.5 km in an open section. However, the running speed of the mobile unit in that report was less than 15 km/h and 100 km/h, and we can find no report of large-capacity transmission tests at around 100 Mbps using Shinkansen rolling stock running at high speed.

In order to evaluate the possibility of building a future Shinkansen train radio system, we first carried out large-capacity transmission tests with 100 Mbps millimeter waves using a Shinkansen train running at high speed.

6.1.2 Test Conditions

(1) Transmission environment

We installed a wayside unit in an open section near Ninohe Station on the Tohoku Shinkansen line. The Shinkansen track near that wayside unit is a curved section of 4,000 m radius.

(2) Communications specifications

Table 1 shows the specifications of the millimeter wave large-capacity communications tests. Setting the wayside unit as a transmitter and the onboard unit as a receiver, we conducted radio transmission tests at a maximum transmission speed 100 Mbps from the wayside unit to the onboard unit. The transmission diversity configuration of the wayside unit included two transmitter antennas and the reception diversity configuration of the onboard unit included two receiver antennas. The antennas were Cassegrain antennas.

Table 1 Specifications of Test Using Shinkansen Rolling Stock

Item	Specification
Carrier wave frequency	40 GHz band
Number of antennas	2 for wayside unit (transmitter) 2 for onboard unit (receiver)
Modulation method	64 QAM-OFDM
Transmission speed	100 Mbps
Transmission power	10 mW
Rolling stock used	Shinkansen rolling stock
Transmission environment	Open section

6.1.3 Test Results

Fig. 2 shows the test results for reception power and frame error rate. "E.F." on the vertical axis of the diagram of frame error rate means "error free". It was found that, in the "error free" section with a distance between wayside unit and onboard unit of 0 km to 1.2 km where a certain level of power could be received, good communications performance is gained even in high-speed running.

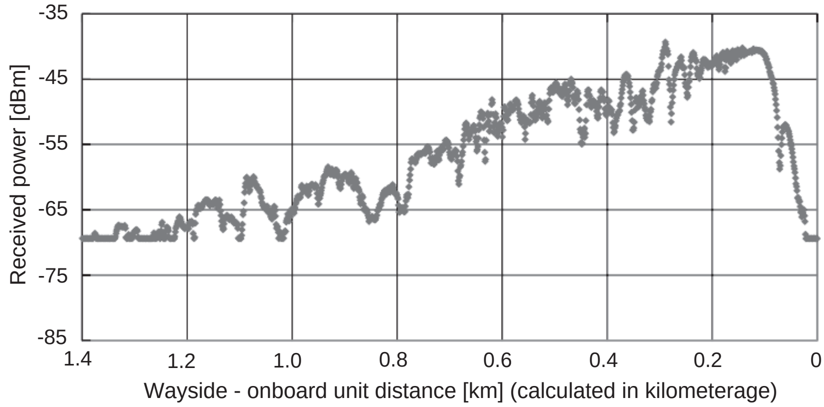
Due to restraints of test conditions, we installed the wayside unit antennas outside of noise barriers, so we could not carry out tests with the main lobe of the wayside antenna facing that of the onboard antenna for a long time. Moreover, radio waves were attenuated when coming through the window of the driver's cab because the onboard unit antenna was installed in the driver's cab of the Shinkansen rolling stock. The reason the section where communications was possible was relatively short is assumed to be that the tests were conducted in less than ideal conditions in terms of radio wave transmission due to the restraints.

In actual use, wayside unit antennas are assumed to be installed inside the noise barriers. In that case, the main lobe of the wayside unit can be set almost parallel to the track direction and face the onboard antenna for longer time. That will enlarge the section where communications is possible.

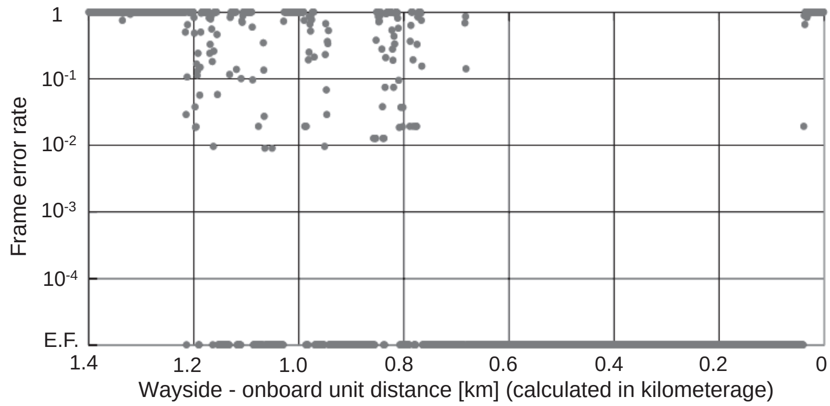
6.2 In-tunnel Communications Tests Using Maintenance Cars

6.2.1 Test Objectives

With the evaluation results described in the previous paragraph in mind, we carried out as the next step tests and evaluation in an actual Shinkansen tunnel to check communications quality in tunnels, where long-distance communications is assumed to be possible. With an objective of obtaining basic data in a



(a) Received power



(b) Frame error rate

Fig. 2 Results of Millimeter Wave Communications Tests Using Shinkansen Rolling Stock

tunnel section, we conducted millimeter wave communications tests using maintenance cars in a tunnel that had a relatively long straight section and no changes of slope.[5)]

6.2.2 Test Conditions

(1) Communications environment

This test was conducted in a section in the 25,808 m long Iwate-Ichinohe Tunnel between Iwate-Numakunai and Ninohe Stations on the Tohoku Shinkansen line. From the point where a wayside unit is installed, the track extends in a straight line and then a curve of radius 8,000 m and its transition curve in the section between 7.2 and 9.8 km kilometerage. The track has a downward slope of 10‰.

(2) Communications specifications

Table 2 shows the specifications of the tests. The transmitter and receiver diversity configuration includes two transmitter antennas of an onboard unit and two receiver antennas of a wayside unit. Taking into account practical use with clearance in mind, we installed two antennas of the wayside unit vertically near the tunnel wall. Two antennas of the onboard unit were installed horizontally on a transport carriage of the maintenance car.

Table 2 Specifications of In-Tunnel Communications Tests Using Maintenance Cars

Item	Specifications
Carrier wave frequency	40 GHz band
Number of antennas	2 for onboard unit (transmitter) 2 for wayside unit (receiver)
Modulation method	64 QAM-OFDM
Transmission speed	100 Mbps
Transmission power	10 mW
Rolling stock used	Maintenance car
Transmission environment	Tunnel section

6.2.3 Test Results

Fig. 3 shows the test results of frame error rate. "E.F." on the vertical axis of the diagram of frame error rate means "error free". It was confirmed that radio waves were received with no error in the area where power greater than the sensitivity point was received and that communications was stable until the curve section starting point (at 7.2 km point). The reason stability was lost could be that the onboard unit entered an environment where diffracted waves were dominant and direct waves were blocked when the maintenance car moved into the curve.

For practical use, it will be important to examine installation of wayside antennas taking into account location of curves and directivity.

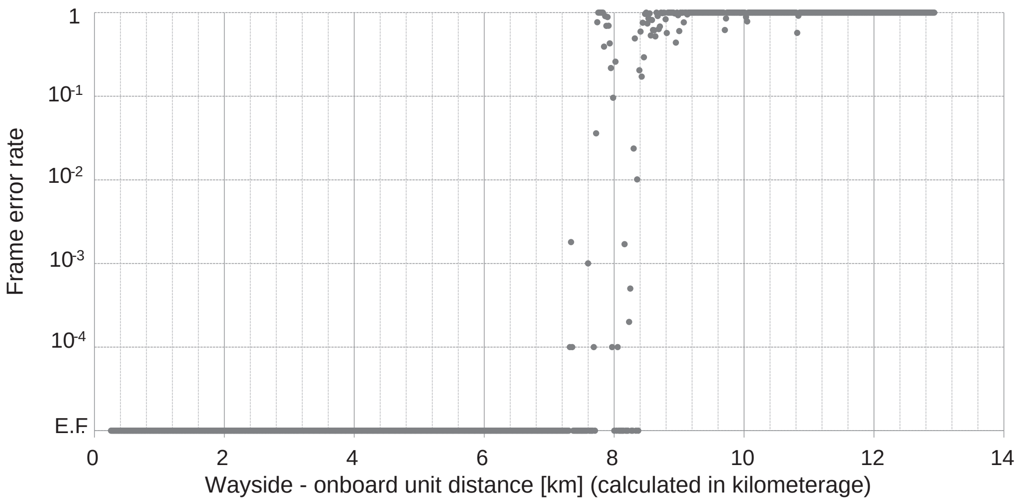


Fig. 3 Results of Millimeter Wave Communications Tests Using Maintenance Cars (1)

6.2.4 Consideration of Test Results

(1) Inclination of transmission attenuation

In the frame error rate tests mentioned in the previous paragraph, received power greatly decreased beyond the 7.2 km point where track linearity changes from straight section to curved section. Thus, in order to check transmission characteristics of millimeter waves after passing through the curved section in the tunnel, we made measurements with transmission power increased. As a test condition, we transmitted from one antenna of the wayside unit as the transmitter to one antenna of the onboard unit as the receiver using non-modulated waves. Fig. 4 shows the results.

The diagram indicates that inclination of transmission attenuation was improved after leaving the curved section. From this, it can be assumed that direct waves were blocked in the curved section and diffracted waves became dominant, but then diffracted waves gradually weakened and transmission environment changed into one where waves reflected on the tunnel wall were dominant around the end of the curved section.

(2) Sharp drop in received power

Next, we investigated the sharp drop in received power observed at around the 7.9 km point in the curved section as shown in Fig. 4, the in-tunnel test results. More specifically, we investigated that drop based on the assumption that directivity of the antenna affected that drop.

Fig. 5 shows the relation between relative power gain of the antenna and transmission/reception distance. The diagram indicates how antenna pattern affected that drop at locations in the tunnel based on directivity of the antenna.

Taking the environment of the tunnel and directivity of the antenna into account, the relative power gain dropped at around the 7.9 km point due to the effect of the first null point (the point where received power locally drops) of the antenna pattern. As this is equal to the drop in received power at the same location shown in Fig. 4, we can assume that the sharp drop in received power was due to the effect of the null point.

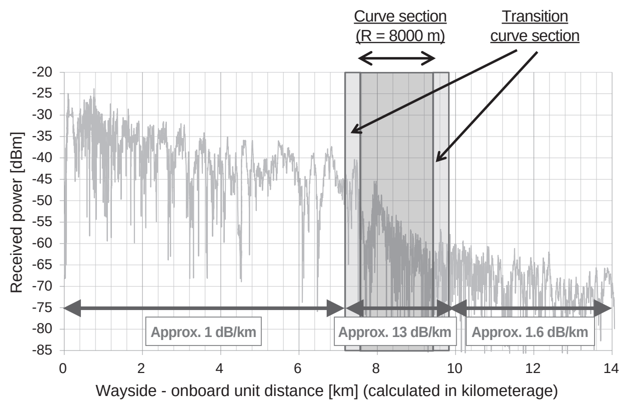


Fig. 4 Results of Millimeter Wave Communications Tests Using Maintenance Cars (2)

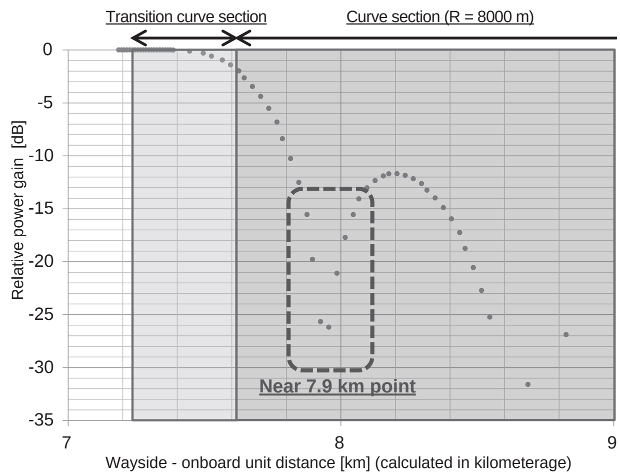


Fig. 5 Relation between Transmitter/Receiver Distance and Relative Power Gain of Antennas

7 Issues to Overcome in Building a Millimeter Wave Communications System

Some issues still remain in building a millimeter wave communications system for the Shinkansen. Here we explain those issues.

7.1 Issue of Directivity of Antennas

By making the half-power angle smaller as directivity of an antenna of an appropriately selected type, transmission distance in the radiation direction can be extended. However, the half-power angle needs to be appropriately set according to the environment because directivity of receiver antennas becomes unfit in environments such as curves sections.

7.2 Issue of Device Installation Method

When installing wayside and onboard millimeter wave antennas and communications devices, we have to take into account the following.

(1) Installation method of wayside devices

To avoid interference with other equipment, height and angle of antennas have to be appropriately set. Particularly in tunnels, strict clearance conditions restrict locations at which devices can be installed.

(2) Installation method of onboard devices

To install devices to existing rolling stock, antennas have to be installed inside the rolling stock. In this case, radio circuits need to be designed with sufficient consideration of power loss when radio waves pass through the window. In addition, when installing an antenna in the driver's cab, it must not obstruct the view of the driver. According to the in-train location at which an antenna is installed, type of antennas such as Cassergrain, horn, and planar has to be studied and selected. When installing antennas to newly built rolling stock, it would be desirable to install antennas not only inside but also to the outside of the car body. In this case, however, we have to overcome the issues of shielding of radio waves by surface material of car body and pressure-resistance performance in high-speed running.

7.3 Interval of Base Stations

In order to install millimeter wave base stations along a Shinkansen line, we have to take into account conditions such as open and tunnel sections to appropriately set intervals of base stations according to the transmission test results.

8 Conclusion

In this article, we introduced system configuration proposals for a Shinkansen train radio system using millimeter waves and reported on the results of basic field tests of millimeter wave communications in high-speed running of Shinkansen trains. We were able to obtain good communications performance results in the section where power greater than the sensitivity point could be received. We also reported on the results of in-tunnel millimeter wave transmission tests. In actually introducing the system, it will be important to examine installation and directivity of antennas taking into account different installation environments. We will further work on studying and refining the designs and proposals.

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