# Special edition paper

## Broadband Radio Transmission in Railways




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Radio systems are widely used in railways, carrying on the communications between onboard and wayside equipment. In recent years, higher transmission speed is being demanded for the radio system. In this research, we carried out a survey on the current situation to see application of radio transmission in railways. The results of our survey including comparisons showed that a broadband environment using WiMAX is being put in place around conventional lines in the greater Tokyo area. We also conducted transmission tests using broadband radios to clarify the technical issues of and possibilities for broadband radio transmission services on Shinkansen trains. The tests confirmed that transmission at a rate of 4.4 Mbps is possible.

●Keywords: Broadband radio transmission, Train radio, Internet, LCX, Throughput

## 1 Introduction

With the recent arrival of a full-fledged ubiquitous age, a variety of broadband radio transmission services are coming to be available. It is said that the new radio application fields are going in two directions; one is “a shift to broadband”, and the other is “diversification”[1)].

Progress is being demanded in broadband radio transmission services for railway systems, particularly those that can be used in communications between onboard and wayside equipment. In addition to general passenger services such as connection to the Internet, radio systems that are directly related to railway operation also need higher functionality and use of broadband.

The Advanced Railway System Development Center is now researching a next-generation railway system for the greater Tokyo. In this system, broadband radio transmission enables coupling of optimally allocated wayside and onboard system functions. The aim of that is to improve safety, stability and convenience and to reduce costs. For the purpose of identifying how broadband radio transmission can be used in railways, we conducted a survey on radio transmission systems currently in use, centering on systems of JR East.

We also conducted transmission tests using broadband radios to identify technical issues and possibilities for broadband radio transmission services on Shinkansen trains. This article reports on those two issues.

## 2 Current Situation of Radio Data Transmission in Railways

### 2.1 Conventional Lines

JR East currently utilizes many kinds of radio technologies. Most of those are applied to railway operation-related jobs in frequencies used exclusively for railway business. A typical example is train radio. Train radio had been gradually put into use since 1985 in the pre-privatization Japan National Railways era, but only for voice calls over analog radio. As equipment was more than 20 years old, we planned to switch train radio to digital communications for higher transmission quality and functionality. Starting with the Yamanote line in 2007, all of conventional lines in the greater Tokyo area were equipped with digital train radio by 2010.

Thanks to the introduction of a digital radio system, data transmission became possible in addition to voice calls. Instructions from train dispatchers (operational notices) can be shown on the monitor display in the driver’s cab by text transmission. And train operation status can also be notified to passengers using displays in passenger cabins.

Moreover, on lines under the control of the Autonomous decentralized Transport Operation control System (ATOS), information such as line occupation by trains and delay time can be transmitted from the wayside. And in case of a vehicle failure, information about the failure can be transmitted from onboard to terminals in the dispatcher’s office and the depot and displayed on those terminals, allowing support for recovery by the dispatcher’s office and the depot.

As the transmission speed of digital train radio is only 9.6 kbps, it is hard to call it broadband radio transmission. By efficiently applying technologies such as those for voice encoding and transmission error correction, however, we can effectively use and transmit information at that small capacity of 9.6 kbps.

We are also making efforts to put into practical use the Advanced Train Administration And Communications System (ATACS) radio train control system that utilizes the same radio technologies as those of digital train radio. Japan’s Radio Law specifies that those systems use narrow band digital transmission methods, so the systems transmit in a very narrow radio bandwidth of 4.8 kHz.

Generally, high-speed and large-capacity radio system is called “broadband radio transmission” because transmission of large volumes of data needs a broad radio bandwidth. Typical examples of broadband transmission include general-purpose radio systems such as Wi-Fi and Worldwide Interoperability for Microwave Access (WiMAX).

Those radio systems are used to transmit train operation information to large LCD displays above the doors of commuter



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trains (Visual Information System, VIS) and to provide Internet access services on limited express trains. Wi-Fi enables transmission to and from onboard equipment using access points set up on locations such as platforms. Wi-Fi signals only have a range of up to 100 m, so required information is transmitted mainly when stopped at stations. WiMAX, on the other hand, has a greater signal range. It can thus make data transmission while running between stations too, sending the newest information in real time.

The new Narita Express (series E259) trains started Internet access service as part of efforts to improve on-train services in October 2009. This system communicates with WiMAX base stations using antennas on the train roof and converts data into that for Wi-Fi at onboard repeaters to communicate with passengers' terminals. In this way, the system provides onboard Internet access.

The other broadband radio transmission system on conventional lines utilizes millimeter waves. This system is used for the aforementioned transmission to VIS and makes high-speed transmission at 100 Mbps when stopped at terminal stations. While millimeter waves allow very fast transmission, the system requires special attention to the coupling of onboard and wayside antennas due to their extremely high directionality. Other usages of millimeter waves include image transmission for platform monitoring and detection of obstacles on crossings as is used with other railway operators. Millimeter wave systems are currently mainly analog systems. However, systems will be shifted to digital in the future.

### 2.2 Shinkansen

In November 2002, train radio of the Tohoku and Joetsu Shinkansen was upgraded with the newest digital radio technologies, enabling many data transmission services that could not be offered with the previous analog system. The switch to digital improved transmission quality to increase data transmission speed. The major outcomes include a Shinkansen dispatch transmission system, a vehicle technology support system, communication device monitoring and an onboard information system. The signaling system of the Shinkansen, also partially uses data transmission via digital radio.

The transmission speed of current digital Shinkansen train radio is much higher than with the 9.6 kbps transmission speeds of conventional lines, providing transmission at up to 384 kbps. The current radio system is used for voice calls and operational purposes, however, and it has no leeway in terms of capacity. As many passengers are increasingly demanding onboard Internet access in recent years, a higher-speed radio transmission system is needed.

## 3 Need for Broadband Radio Transmission

### 3.1 Comparison between Transmission Methods

Broadband radio transmission needs broad bandwidth and a stable radio reception level. The broadband radio transmission methods include Wi-Fi, WiMAX and millimeter wave systems as introduced in section 2. Table 1 shows a comparison between those methods. The necessary frequency bandwidth for Wi-Fi, WiMAX and millimeter wave systems has been secured.

Of the three methods, millimeter wave systems allow the highest-speed transmission at 100 Mbps. But, to ensure continuous transmission service, many technical issues in securing a stable radio reception level while running currently need to be overcome. Those issues include setting up of base stations and attenuation by rain. Furthermore, passengers' terminals cannot receive millimeter wave signals, so we have to use a system like that for WiMAX Internet access service where trains receive millimeter waves and transmit data via Wi-Fi or other access points set up in cabin.

The millimeter wave systems shown in Table 1 are of the 60 GHz frequency used for VIS transmission, but this frequency suffers particularly large transmission loss. Currently, the National Institute of Information and Communications Technology (NICT) is carrying out R&D on high-speed mobile transmission technology by airplanes in the 40 GHz frequency that has less transmission loss. It is reported that broadband radio transmission in railways can be a major application of the airline millimeter wave system[2)].

WiMAX already has many base stations in operation along railway lines in the greater Tokyo area. Small base stations and relay stations are installed in railway stations to supplement weak electric fields. In this context, we can say that a broadband radio transmission environment by WiMAX is in place, as stable radio reception level can be achieved relatively easily on conventional lines in the greater Tokyo area.

At the same time, use of WiMAX on Shinkansen trains faces the issues of transmission in tunnels and the number of base stations required along the lines. Many base stations secure communications along Shinkansen lines in the greater Tokyo area. In other areas, however, WiMAX can be used only in and around railway stations. Since WiMAX uses a different frequency from that of train radio, it is difficult to use leaky coaxial cables (LCX) for transmission in tunnels.

Table 1 Comparison between Transmission Methods

| Transmission method | Space wave, conventional line | LCX, Shinkansen | Wi-Fi | WiMAX | Millimeter wave |
|---|---|---|---|---|---|
| Frequency | 400 MHz | 400 MHz | 2.4/5 GHz | 2.5 GHz | 60 GHz |
| Transmission speed | 9.6 kbps | 384 kbps | 11/54 Mbps | 40 Mbps | 100 Mbps - |
| Bandwidth | 4.8 kHz | 288 kHz | 22/20 MHz | 10 MHz | Approx. 200 MHz |
| Transmission range | 3 km | 1.5 km (relayed) | 100 m - 2 km | 1 km | 50 m |

### 3.2 Trends in Internet Environments

Fig. 1 shows the trends in Internet environments. First of all, broadband has spread to offices and homes. Next, Internet access from mobile phones has become possible, making them broadband-enabled instead of just voice call-connected. Mobile phone broadband capabilities enabled broadband transmission anywhere, anytime. But, in railways with tunnels, mobile phones need special measures to communicate with base stations along the line. Measures were taken in tunnels from Tokyo to Sendai on the Tohoku Shinkansen, but those are still not sufficient.

As described in 3.1, broadband radio transmission requires broad bandwidth and stable radio reception level. The LCX cable laid along all Shinkansen lines secures this level to realize 384 kbps transmission with almost no error. On the Tokaido Shinkansen, Internet access service is offered at 2 Mbps using LCX radio lines[3].

As a switch to digital was accomplished on the Tohoku and Joetsu Shinkansen in 2002, immediate replacement with a new system is almost impossible. However, we need to develop an environment for future broadband radio transmission on the Shinkansen. To deal with such trends in Internet environments, the Advanced Railway System Development Center carried out tests by new radio transmission methods.

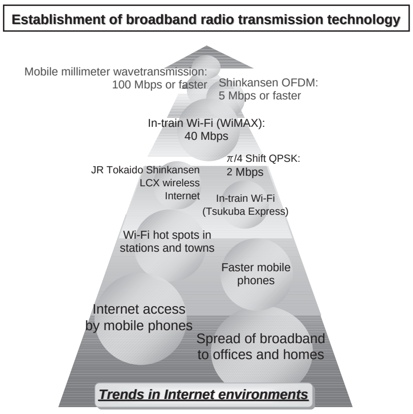


Fig. 1 Trends in Internet Environments

## 4 Shinkansen Broadband Radio Transmission Test System

In order to achieve stable and economical broadband radio transmission in running Shinkansen cars, we developed a system that combines an optical fiber repeater method and existing LCX cables (hereinafter, "the System"). In this chapter, we introduce the overview of the System.

### 4.1 Optical Fiber Repeater System Configuration

While high-frequency signals such as radio waves are usually transmitted via coaxial cables, transmission via optical fiber has also recently become possible. This technology is called "Radio on Fiber (RoF)". Using optical fiber allows long distance transmission with higher capacity and smaller loss than transmission via coaxials, so we adopted the optical fiber repeater method for the System. Fig. 2 illustrates the configuration of the System.

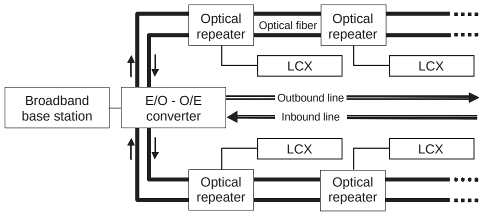


Fig. 2 Configuration of Broadband Transmission System

### 4.2 Optical Repeater

Optical repeaters in Fig. 2 have a function of optical/electric (O/E) conversion in the direction from the base station to the train (Down Link, DL) and electric/optical (E/O) conversion in the direction from the train to the base station (Up Link, UL). Those also transmit signals to the next optical repeater. Fig. 3 shows the internal composition and Fig. 4 shows the exterior of the optical repeater we developed this time.

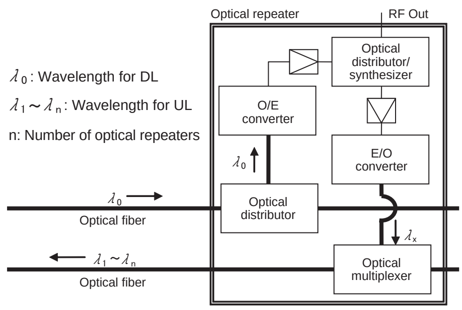


Fig. 3 Internal Configuration of Optical Repeater

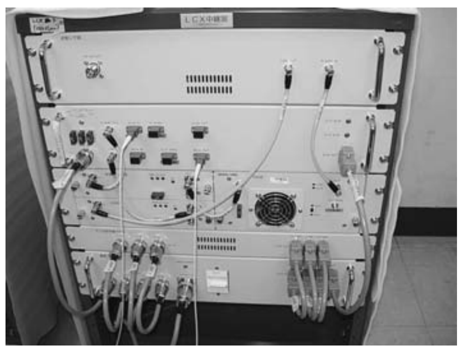

Fig. 4 Exterior of Optical Repeater

As shown in Fig. 3, different signals are transmitted from each optical repeater in UL, while a single wave is used exclusively by the core of the optical fiber in DL. Thus, by allocating light of different wavelengths to each optical repeater as Wavelength Division Multiplexing (WDM), we made it possible to send signals via one core in UL too.

### 4.3 E/O - O/E Converter

(a) Base station that does not apply diversity

The E/O - O/E converter in Fig. 2 converts high-frequency electric signals from the base station into optical signals and sends them, and it receives optical signals and converts into high-frequency electric signals. Fig. 5 shows the internal configuration when a base station uses diversity technology neither in transmission nor in reception.

The DL signal received from the transmitter (TX) of the base station is branched with the distributor into the inbound line and the outbound line, and each of those then modulated into optical signals at the E/O converter.

For the UL signal, the optical signal is separated per wavelength with the optical distributor, and each of those is converted into high-frequency electric signal with the O/E converter. Inbound and outbound signals are then combined and sent to the receiver (RX) of the base station. The E/O and O/E converters are used in pairs. Because all of the items between those converters are passive elements, high-quality optical transmission is achieved without superimposed thermal noise.

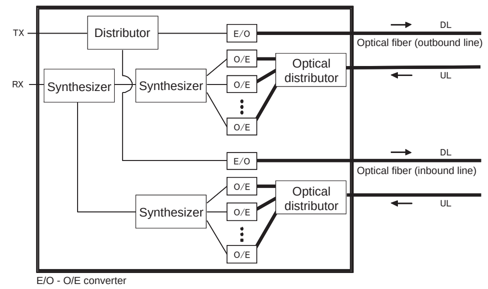


Fig. 5 Internal Configuration of E/O - O/E Converter (base station without reception diversity technology)

(b) Base station that applies reception diversity

Diversity technology is being applied more often these days to improve reception sensitivity. In the Shinkansen, reception diversity can be applied at base stations because LCX cables are laid on each side of the track. In this research, we produced an E/O - O/E converter that allows reception diversity to be applied. To prevent interference by the UL signal of the train radio, the converter has a built-in Band Elimination Filter (BEF). Its internal configuration is shown in Fig. 6 below.

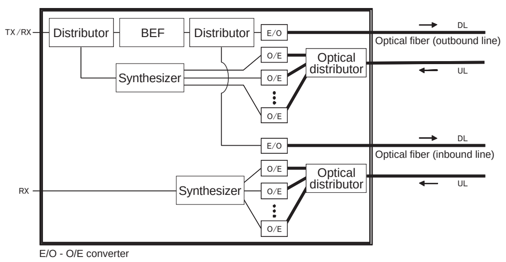


Fig. 6 Internal Configuration of E/O - O/E Converter (base station with reception diversity technology)

### *4.4 Overview of Broadband Radio*

The broadband radio system we used for the tests is based on a general-purpose radio system in actual use by European railways in a space-waved 400 MHz band[4]. We modified the frequency of the radio system for the Shinkansen. Since the purposes of this test system were the development of an optical repeater and evaluation of the possibility of broadband radio in the Shinkansen, we used a general-purpose broadband radio. Tests of this transmission method using LCX cables for a high-speed railway were the first of their kind worldwide as well as in Japan, so they had great technical significance. The specifications of the general-purpose broadband radio used this time are as shown in Table 2.

Technical features are its multiplex and modulation methods shown in Table 2. OFDM for the multiplex method is an abbreviation of Orthogonal Frequency-Division Multiplexing. It has 113 subcarriers of a bandwidth of 11.25 kHz each in the whole 1.28 MHz bandwidth. Those subcarriers are transmitted in a modulation method that prevents interference to each other at such a dense frequency interval. That brings about a maximum transmission speed of 5.3 Mbps.

Table 2 Specifications of Broadband Radio

| | |
|---|---|
| Radio frequency | $f_C$: 416.25 MHz (UL)<br>$f_C$: 460.75 MHz (DL) |
| Radio transmission output | 2 W (base station)<br>0.2 W (mobile station) |
| Dedicated frequency | 1.28 MHz (UL)<br>1.28 MHz (DL) |
| Multiplex method | OFDM |
| Modulation method | Adaptive modulation<br>(BPSK - 256 QAM) |
| Diversity | Nil (DL)<br>Space diversity (UL) |
| Transmission speed (radio link) | UL: 1.8 Mbps (effective 1.6 Mbps)<br>DL: 5.3 Mbps (effective 4.4 Mbps) |

Fig. 7 illustrates a comparison of the frequency bandwidth. To transmit 384 kbps data in the conventional manner, a bandwidth of 288 kHz is needed. Thus, in a 1.28 MHz bandwidth, only up to four waves can be sent for a total approx. 1.5 Mbps at the maximum. The advantage of OFDM is obvious.

The next feature is adaptive modulation. Adaptive modulation is technology that selects the optimal transmission speed by switching the modulation method according to the wave strength and noise volume. Those two technologies were tested for the first time in the Shinkansen LCX radio system.

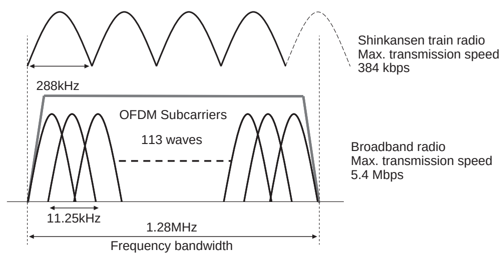


Fig. 7 Comparison between Frequency Bandwidths

### *4.5 Common Use of Existing LCX Cables*

In 4.1, we covered the configuration of the optical transmission system, provided that the System can exclusively use the LCX cables. However, train radio actually uses the existing LCX cables, so we have to design the optical transmission system in a manner that introduction of the System does not affect train radio. Now we explain the current system of train radio and the configuration required to commonly use LCX cables.

*4.5.1 Configuration of Train Radio*

Train radio of the Tohoku and Joetsu Shinkansen consists of communication zones that divide the line approx. every 30 km. In a communication zone, LCX cables of an approx. 1.5 km-long span are connected in multistage in line. Repeaters at 1.5 km intervals compensate and amplify transmission losses that occur per span. To make the electric field more uniform, LCX cables are made with different radiation characteristics in the direction from the base station to the end.

In a zone, signals are relayed and transmitted the LCX cables from the base station unit installed in the station signal house etc. to the end of the zone. The configuration is as shown in Fig. 8.

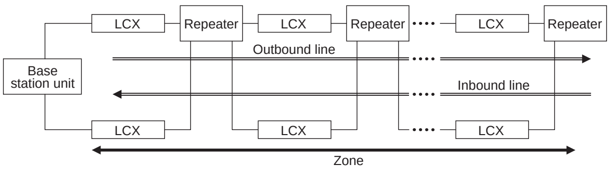


Fig. 8 Configuration of Train Radio

*4.5.2 Configuration of Connection to Broadband Radio*

The frequency of the System approaches the train radio frequency by approx. 2 MHz in UL and approx. 8 MHz in DL, as shown in Table 2. The System commonly uses LCX cables with train radio in this test, so high-frequency signals need to be superimposed without any effect on the train radio.

In light of that, we connected the System to LCX cables using two types of interfaces (I/F). Fig. 9 shows the details.

Attaching a directional coupler to interface A prevents DL signal of the System from flowing in the train radio base station and causing transmission intermodulation. That brings about common use of LCX cables between different systems without interfering with each other. To maintain transmission quality of train radio, we gave the System a coupling loss of -10 dB in the connection to the directional coupler.

For interface B, we applied a band path filter that allows only the frequency of train radio to pass through. In this way, the filter prevents the UL signal of the System from flowing in the base station side of the System via the LCX and causing interference to the UL signal via the optical fiber due to multipath.

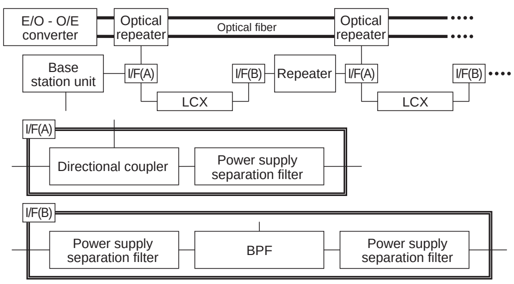


Fig. 9 Connection between the System and LCX Cable with Interfaces

## 5 System Performance Test

*5.1 Throughput Speed*

We carried out performance evaluation of the System at different speeds by changing the running speed of the Shinkansen between 60 km/h and 240 km/h. The mobile stations were installed in the driver's cab and in the passenger cabin. Fig. 10 shows the mobile station in the driver's cab. At this installation point, objects such as the window frame interrupt the direct view of the LCX.

Fig. 11 shows the speed characteristics of the DL throughput. In the figure, the horizontal axis is the running speed of the Shinkansen vehicles and the vertical axis is the DL throughput. The figure indicates a tendency where throughput decreased as running speed increased. As an installation point for the mobile station, the passenger cabin showed better throughput than the driver's cab.

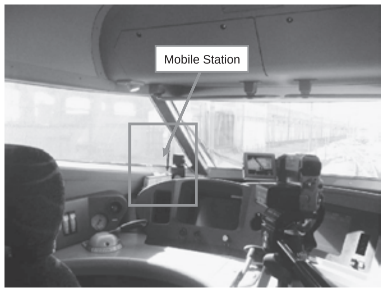


Fig. 10 Mobile Station in Driver's Cab

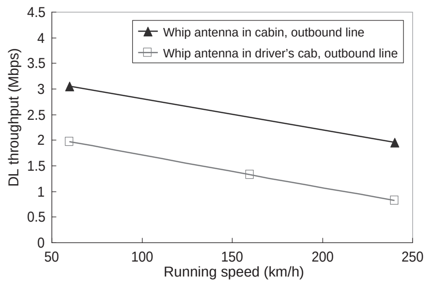


Fig. 11 DL Throughput in Line with Running Speed

*5.2 Throughput Level*

For further improvement of throughput, we carried out evaluation tests using a flat antenna of the Shinkansen train radio by installing that to the cabin window. Fig. 12 shows installation of the mobile station in the cabin. In Fig. 13, the horizontal axis is time, the left vertical axis is DL throughput and the right vertical axis is DL reception level. Fig. 13 proved that throughput of up to 4.2 Mbps could be achieved at points with good reception, even during running at 240 km/h.

(1) Flat antenna (2) Whip antenna

Fig. 12 Mobile Stations in Passenger Cabin

Fig. 14 shows the relationship between signal noise ratio (SNR) and DL throughput in the test section. Fig. 14 indicates that throughput increased as SNR increased. At points with good SNR, results were similar to the actual values of the train radio. This confirmed that the 256 QAM modulation method, the most efficient method for the adaptive modulation at base stations, worked well.

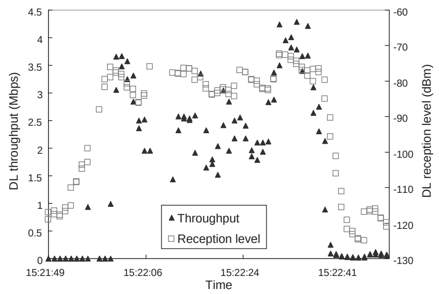


Fig. 13 DL Throughput and Reception Level while Running at 240 km/h

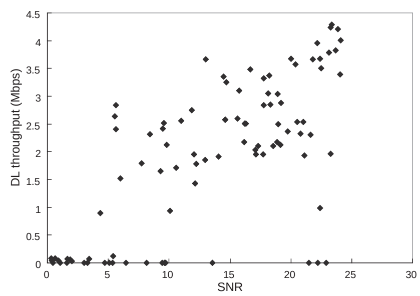


Fig. 14 DL Throughput in Line With SNR while Running at 240 km/h

### *5.3 Throughput Evaluation with Two Mobile Stations*

We evaluated the change of UL and DL throughput with two onboard mobile stations. Fig. 15 shows DL throughput with two mobile stations and Fig. 16 shows UL throughput. Both diagrams demonstrate that throughput of a mobile station was roughly half of the total throughput of two mobile stations. Therefore, when using more than one mobile station in the System, the throughput per mobile station will be the total of maximum throughput of each mobile station divided by the number of the mobile stations.

Comparing Fig. 15 and Fig. 16, we can see that the throughput in Fig. 16 was more stable. This is the effect of the space diversity function implemented in UL. The diversity function is the reception method where two receivers receive data with two separate antennas to supplement the received data by each other. While this function is implemented both in UL and DL of a digital train radio, it was implemented only in UL of the radio used this time. With the diversity function in DL too, higher-quality transmission will be achieved.

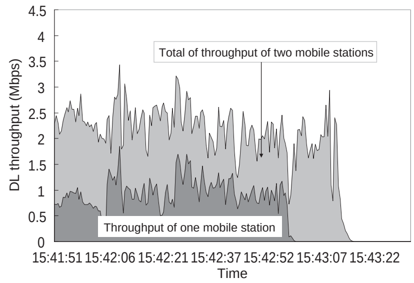


Fig. 15 DL Throughput with Two Mobile Stations

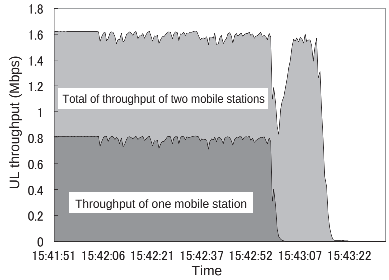


Fig. 16 UL Throughput with Two Mobile Stations

## 6 Conclusion

We conducted a survey on the current situation of radio transmission in railways and compared transmission methods to assess application of radio transmission in railways.

As described above, WiMAX transmission in Shinkansen trains has some issues such as transmission in tunnels, while broadband radio transmission with WiMAX is possible on conventional lines. We thus studied a radio system that allows faster transmission than with the existing system and developed a relay system that commonly uses existing LCX cables. In running tests for a broadband radio using the latest technology using actual vehicles, we confirmed that transmission at 4.4 Mbps, the maximum capacity of the radio used in the test, is possible.

In the future, we will proceed with studies on elemental technologies to achieve higher-speed transmission than in this test and design of a service model more in detail based on the results of this research. From those, we hope to achieve a system update for Shinkansen train radio.

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