Broadband Telecommunication System for Railways Using Laser Technology

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A high-speed internet connection system applicable to railways was developed to improve customer service and efficiency in railway operation by establishing broadband telecommunication between ground facilities and trains in operation. A mobile communication system was built for use on railways and capable of transmitting data at a transmission rate of nearly 1Gbps by applying laser beam communication technology. Field tests were performed using commercial trains, and results demonstrated a transmission rate of approximately 700Mbps on the TCP layer between the ground and a train running at a speed of approximately 130km/h.

Keywords: mobile broadband communication, handover, laser beam communication

1. Introduction

In recent years, remarkable progress has been seen in mobile communication technologies, for example the standardization of Mobile WiMAX [1] as IEEE802.16e in 2005. Japanese railways have also seen the introduction in many areas of onboard internet connection services. One pioneering example is the wireless LAN service on the Tsukuba Express Line introduced in 2006 [2]. Similar services are now available on some Shinkansen lines, for example the Central Japan Railway Company (JR-Central) launched such a service onboard N700 coaches running on the Tokaido Shinkansen, in Mar. 2009 [3]. This service utilizes leaky coaxial cables laid along railway lines, and has received much attention as a specialized service for railways. Onboard internet connection services also exist on foreign railways, such as THALYS in Europe and KTX in South Korea.

At the same time high capacity telecommunication technologies have been developed using laser beams. It enables long distance and secure communication by taking advantage of the high directionality of laser beams. Its effectiveness has already been demonstrated in the field of fixed section-to-section communications, but it has not yet been applied to mobile communication systems composed of elements which vibrate irregularly, like running trains.

Given the above research and development work has focused on creating a high capacity communication system which uses laser beam communication technology for ground-to-train communication. It is believed that such system can offer practical improvements to railways not only in terms of customer service but also for railway operators themselves. This paper describes the telecommunication system developed and the field tests carried out to investigate the feasibility of applying such a system, which uses laser communication technology, to the railway field.

2. How to Apply the Laser Communication Technology to Railways

2.1 Examination of the Transmission Method

It was thought initially that various transmission methods might exist in applying laser communication to railways. Three prototype systems were built for experimental purposes, each adopting a different transmission method, described below:

(1) Leaky optical fiber method (see Fig. 1)

In this method, the optical fiber cable is laid along a railway line, and laser lights are purposely leaked out from the cable to establish communication. This method allows continuous communication.

(2) Fan-shaped laser beam method (see Fig. 2)

This method uses a laser beam spread by a concave lens for communication. The lens radiates the laser beam only in a horizontal direction. The light receiving ele-
(3) Laser beam tracking method (see Fig. 3)

The transmitter contains a laser emission device and a movable mirror. It emits the laser beam to the receiver, aiming at the beacon infrared light which the receiver emits. By dynamically controlling the movable tracking mirror, the transmitter can track the receiver and establish continuous communication.

Performance evaluation tests were carried out on each of these three prototype systems. Table 1 shows the results. This led to the adoption of the laser beam tracking method to develop the broadband ground-to-train communication system, in order to ensure long communication distances and high feasibility in terms of ground facilities which would have to be installed.

### Table 1  Performance comparison of the three communication methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Leaky optical fiber</th>
<th>Fan-shaped laser beam</th>
<th>Laser beam tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principle</td>
<td>Reduce the laser beam evenly from the optical fiber</td>
<td>Reduce the laser beam covering a certain area by the diffusing lens</td>
<td>Control the mirror to radiate the laser beam toward beacon light</td>
</tr>
<tr>
<td>Transmission distance</td>
<td>several – 10 m</td>
<td>20m–</td>
<td>300m–</td>
</tr>
<tr>
<td>Reliability, Maintainability</td>
<td>Laying cable all along the line</td>
<td>Many base stations are required</td>
<td>Flexible parts exist</td>
</tr>
</tbody>
</table>

2.2 Outline of Ground-to-Train Communication based on the Laser Beam Tracking Method

Figure 4 shows the concept underlying the proposed laser beam tracking communication system. The onboard communication device (mobile station) and its ground counterparts (base stations) send out a signal beam to each other to establish bidirectional communication. Both of them also emit beacon infrared lights as their identification signal, which differ in wavelength to the signal beam.

To apply the laser beam tracking method to the railways, many base stations are required, in order to get good coverage over the whole area through which a train runs. Consequently the system requires a function which allows switching from one base station to another in accordance with the moving train. This function is called ‘handover.’

Based on these facts the obstacles to be overcome before applying laser beam tracking technology to railways, and which have been taken into account during development, are as follows:

1. The communications connection must be maintained between base stations through rapid adjustment of their internal mirrors, even in a situation where the relative positions of the mobile and base stations change rapidly because of the high speed of the trains and their irregular vibration.

2. The handover should be executed quickly and dynamically in response to the running speed of the train, because the connection is temporarily disrupted during the handover.

3 Communication System Prototype

3.1 Constitution and Features of the Communication Device

The system which has been developed is capable of transmitting data with a theoretical transfer rate of 1Gbps. Figure 5 shows the external view of the communication device, and details of its features are shown in Table 2. The devices are designed so that they can be easily installed on the train and along the track. The transmission distance is based on examinations which were carried out (details are described in 4.1.) The light intensity of the signal beam is at the level of class 1M specified in JIS C 6802, which means it is safe for hu-
The flow of processes executed within the device to establish communication is as follows:

1. The communication device receives the beacon infrared light radiated from the counterpart by using two quartering photodiodes, as shown in Fig. 6. The surface of the photodiodes is divided into four and can measure the amount of light received on each of the surfaces.
2. The measured result of the amount of light through the wide-angle lens is sent from the photodiode to the control unit. Note that the photodiode can receive the beacon light coming from a broad area, due to the wide-angle lens.
3. The control unit calculates the direction of another communication device, and sends the mirror actuator the signal to control the mirror so as to receive the beacon light axis at the center of the quartering photodiode (see Fig. 7.)
4. The actuator controls the mirror subject to the signal.
5. The same process (2)-(4) is repeated, by using the measured result of the amount of light through the telescopic lens.

Through these ongoing processes, the communication devices can keep rapid and precise track of each other, and even when they lose sight of the beacon light, they can quickly restart the searching and tracking process.

### 3.2 Fast Handover Mechanism

When constructing a network on the ground along the side of a track, it is necessary to divide the network into a number of subnetworks, in order to limit the length of the overall network and reduce the quantity of internal traffic to an appropriate volume. Two kinds of handover are therefore necessary: one where two base stations executing handover are in the same subnetwork and the other where each of them is in a different subnetwork. The handover mechanism also has to be compatible with the IPv6 network mobility protocol – NEMO Basic Support Protocol [4] - which was adopted for our system out of consideration for future needs. Based on these elements, the fast handover mechanism was developed by improving the standard protocol [5].

(1) Handover within a subnetwork (see Fig. 8)

This is handover on the data link layer (L2-handover), and consists of the following two processes: (a) The mobile station gives the mobile router (the router connected with the mobile station; hereafter abbreviated to MR) a notice of having captured the base station (b) The communication route is constructed. To speed up process (a), the mobile station and the MR are connected via a dedicated cable for this notice. The MR then receives this notice and requests the access router (the router connected to the base stations; hereafter abbreviated to AR) to construct the communication route. Reception of a response to this request indicates that handover is complete.
4. Examination and Preliminary Experiments for Application of the Proposed System to the Railway Field

4.1 Transmission Distance and Number of Base Stations

Although base stations are designed to be able to transmit over long distances, long-distance communication may be hindered due to track alignment or trackside shielding. On the other hand, designing communication devices to have a short transmission distance offers the advantage of reducing the size and weight of the devices, because of the lower output power of the beacon light and the size and performance of the components. Pursuant to this, in order to determine the appropriate standard transmission distance, simulations were carried out for various case scenarios to examine how many base stations would be required along the Tokaido Shinkansen line (from Tokyo to Shin-Osaka, 515.4 km.)

The track was assumed to have no gradient and no visibility outside the construction gauge along the track. The number of necessary base stations was calculated to enable a mobile station to keep continuous communication with any of the base stations anywhere between Tokyo and Shin-Osaka. The result is shown in Fig. 10. Even if the transmission distance exceeds 300 or 400 meters, the required number of base stations only decreases slightly, therefore the distance of 300-400 meters was deemed appropriate as the standard for this design.

4.2 Evaluation of the Effects of Rain

In general, laser beams are attenuated by rain, fog and snow. It is known that the level of this attenuation is closely related to the visibility range [6]. Since railways are mostly outdoors, our system may be affected by such attenuation. A communication test was therefore performed in a rain simulation laboratory to examine the effects of rain.

A communication device was placed in the laboratory, with another device on the other side of the “Rainfall Area”. The rainfall area was about 12.5m long, within which rainfall of up to a maximum of 200mm/h could be simulated (see Fig. 11.) Packet loss rate, transmission rate and distance of vision were measured under these conditions.
conditions. Results demonstrated that as rainfall increased, the visibility range became shorter, and attenuation of the beacon light and signal beam were also observed. Furthermore, in the case of small rain drops in a type of mist, the visibility range became shorter and the beacon light was attenuated even with low rainfall. This test illustrated that the level of attenuation is closely related to the visibility range. However, neither packet loss nor decline in transmission rate were observed except in the case of small raindrops forming a kind of mist.

When installing optical communication system under open sky, some influence from weather is inevitable. Setting margins to take attenuation of optical energy in account and to maintain the availability ratio above a certain level is therefore standard procedure. Simulations were therefore performed for the intervals between base stations considering the visibility range. However, neither packet loss nor decline in transmission rate were observed except in the case of small raindrops forming a kind of mist.

To evaluate the static properties of the system and its applicability to mobile communications, communication tests were carried out on a test route. First tests were performed between two fixed communication devices, set at various distances apart. A data transmission rate of 923Mbps was measured using TCP at a transmission distance of 320m using the benchmark software, Netperf. Communication was established even when the transmission distance was extended to 360m. This confirmed that the system can still transmit over this type of distance as described in section 4.1.

Second, other similar tests were carried out with a heat-absorbing glass set between the devices, to simulate the effects of the glass windows on trains. As a result, the distance over which transmission was still possible fell to 200m when the glass was perpendicular to the optical path. Nonetheless, within the transmission range the transmission rate was the same as without the glass.

Mobile communication tests were then performed by placing one communication device on an automobile and another one on the ground. Even at a running speed of 100km/h, a maximum transmission rate of 656Mbps was obtained. These tests demonstrated the applicability of the system to mobile communications in railways.

5. Field Tests

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5.2 Field Tests on Conventional Line

To investigate the feasibility of applying laser communication technology to railways, the system which was developed was tested on a commercial train running on conventional line with the co-operation of JR-West (West Japan Railway Company) in Jan. and Feb. 2010.

The area for the field test was selected along the section between Tachibana and Koshienguchi stations (they are located between Osaka and Kobe) on the Tokaido-line. In this area, the alignment of the railway is straight with good visibility.

The configuration and a picture of the field test are shown in Fig. 13 and Fig. 14 respectively. Three base stations were installed at 100m intervals, and each was placed in a chassis fixed to the side of a pole beside the tracks, facing towards Kobe. They were connected with the home agent of a control center near the base station, by optical fiber. The mobile station was placed facing backwards in the crew cabin in the tail onboard the “new rapid service train” operated from Osaka towards Kobe. The speed of passing trains was 120-130km/h, which means that handover was executed about every three seconds.

Twenty tests were performed over a total of five days (four tests per day.) Packet loss rate, transmission rate and handover time were measured during the tests. Results showed that in 19 out of 20 tests, communication was established and data transmission was successful (the only failure was due to a PC fault). The transmission rate ranged from 500Mbps to 700Mbps, as shown in Fig. 15. Two big falls which appear on this graph were...
caused by the handover. Results also revealed a probability of 20-30% of packet loss, a phenomenon which will have to be improved in future.

Handover latency (time duration from the last data transmission before the brake to the first transmission after the brake) was approximately 400 milliseconds (see Fig. 16). Even in the best case, this time was 232 milliseconds and the L3-handover time was 124 milliseconds, exceeding the theoretical value of 30 milliseconds. The main reason why the handover time exceeded the theoretical value is the vibration of the train and the mobile station, which causes a fall in infrared link stability. Although this may be of little importance for some applications, it may become an issue, especially for communication on board high-speed trains. Based on our analysis, packet loss often occurs just after the handover and signaling messages which are required for re-establishing the communication have often been lost. This means that the system must be more resistant to vibration and the communication protocol must be upgraded so as not to be affected by packet loss, for practical use.

Bidirectional transmission tests were also carried out with high-definition video data. Tests revealed only minor disruption to the picture and the received video could be seen smoothly both onboard the train and on the ground. In the TCP tests in particular, no effects caused by the handover were observed by virtue of buffering, retransmission or the short handover time.

Consequently, the mobile and base stations were both able to capture the beacon light in all six tests, and were able to track each other, for a maximum 0.7 second. In one test, the base station received the signal beam from mobile station with precision and succeeded in establishing communication on the physical layer for 0.006 second. However data packet transmission was not achieved.

Analysis of the results confirmed that attenuation due to the glass windows of the Shinkansen trains shortened the effective transmission distance so much that there was not enough time to transmit the data packet. In addition the presence of a pole along the track located at about 50m from the base station momentarily blocked the signal beam between the base station and the mobile station breaking the communication. Even after the obstruction disappeared between both stations capturing of the beacon light and tracking did not start again. These results point to the following important elements to be taken into account: the installation environment of the base station, countermeasures against window glass, and the high-speed of the train.

5.3 Field Tests on the Shinkansen Line

Since some positive results were obtained in tests on the conventional line, similar field tests were carried out on the Shinkansen line to evaluate the applicability of the system to higher-speed trains, again with the cooperation of JR-West. The test field was selected from a section between Shin-Osaka and Shin-Kobe stations on the San-yo Shinkansen line. These tests only used one base station due to installation constraints; as such only one-to-one communication tests were performed which did not include handover. Tests were performed over three days in Mar. 2010, twice a day (a total of six times.) The speed of passing trains was 240-270km/h.

Consequently, the mobile and base stations were both able to capture the beacon light in all six tests, and were able to track each other, for a maximum 0.7 second. In one test, the base station received the signal beam from mobile station with precision and succeeded in establishing communication on the physical layer for 0.006 second. However data packet transmission was not achieved.

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6. Conclusion

With a view to developing the basic technology for a high capacity ground-to-train communication system, research and development work was carried out on a laser beam tracking communication system for railways. The experiments carried out on this system included bi-
directional communication tests which achieved a transmission rate of about 500-700Mbps between the ground and the running train on a conventional line. Mutual tracking between the base station and mobile station was also achieved in similar tests on a Shinkansen line. These tests demonstrate the applicability of laser beam tracking communication technology to railways. Investigations were also made to determine the appropriate number of base stations required for the system and the effects of rain.

Based on the results obtained, it appears that further research will be required to improve the performance of the system, and in particular to promote its application in practice.

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References