A High Speed Mobile Communication System implementing Bicasting Architecture on the IP Layer

（IP レイヤにおけるバイキャスティング
アーキテクチャを実装した高速移動通信システム）

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Abstract

Having a broadband connection on high speed rails is something that business travelers want most. Increasing number of passengers is requesting even higher access speeds. We are proposing the Media Convergence System as an ideal communication system for future high speed mobile entities. The Media Convergence System recognizes plural wireless communication media between the ground network and each train, and then traffic is load-balanced over active media which varies according to circumstances. The Media Convergence System must have a pivot wireless communication media. We are focusing on IEEE 802.11g as a pivot medium of the Media Convergence System, because it is expected to have a high performance in communication with high financial efficiency. In order to realize a high speed mobile communication system based on IEEE 802.11g (referred to as IEEE 802.11g Communication System), this paper designs the IEEE 802.11g Communication System, constructs an experimental IEEE 802.11g Communication System on a commercial high speed rail system, and evaluates performances of the system through trials.

The organization of this paper is as follows. Chapter 1 describes a background of this research and overviews this paper. Chapter 2 discusses ideal high speed communication systems in the future based on surveys of train communication technologies so far. The consideration leads a result where a Media Convergence System will be the desired high speed mobile communication system for the future. Chapter 3 through Chapter 7 is divided into two parts. Part 1 consists of Chapter 3 and Chapter 4, in which they stress a necessity of a pivot wireless communication medium of the Media Convergence System and explains that IEEE 802.11g satisfies all the requirements to be the medium. The IEEE 802.11g Communication System is proposed, designed and constructed on a commercial high speed rail system, and then performances of that system are evaluated in this part. Trial results have proven that the IEEE 802.11g Communication System realizes the maximum application throughput of around 20(*Mbps*). On the other side, the results have also clarified that the IEEE 802.11g Communication System suffers from very frequent Layer 2 Handovers (L2HO) which degrade the communication quality. Part 2 consists of Chapter 5 through Chapter 7. In order to solve problems caused by L2HOs, Part 2 proposes the Bicasting-Multipath Mobile IPv4 and it is verified through trials. Trial results have proven that the Bicasting-Multipath Mobile IPv4 improves the communication quality over L2HOs and also stabilizes communication.

Detailed discussions in each chapter are as follows. Chapter 1 describes a background of this research and overviews this paper. The Internet using TCP/IP is not only for immobile computers in rooms but also for any devices under any situation for anyone who wants to use it. It is not an exception when people are on a high speed train traveling at around 300(*km/h*). Although we have demands for connectivity to the Internet from cabins, a supply of communication bandwidth is not enough for the demands in high speed mobile environments. Chapter 1 explains a necessity of making communication bandwidth broader for high speed mobile systems.

Chapter 2 surveys various train communication systems with their history and discusses present

systems. The focus of this paper is communication on high speed rail systems. High speed trains generally travel through various geographical areas such as cities, suburbs, mountains, tunnels and so on. With these geographical conditions taken into account, there seems to be no perfect wireless communication medium which suits best to all places. Communication media which have different characteristics from each other should be deployed in accordance with geographical conditions. Plural communication media may become available in the same place at the same time. A wireless communication system for high speed trains in the future must recognize these plural wireless communication media and traffic must be load-balanced over active media which varies according to circumstances. It is referred to as "Media Convergence System" that all the communication media available at local places are logically bundled up into a single path. This chapter proposes a Media Convergence System which will be desired in future high speed trains.

Chapter 3 discusses a pivot communication media of the Media Convergence System. The pivot wireless communication medium for the Media Convergence System has to satisfy four following requirements.

(1) To have enough communication bandwidth
(2) To be feasible and affordable in the near future
(3) To be easy to procure devices for the system
(4) To be easy to operate

After a careful consideration of these requirements, IEEE 802.11g was employed as a pivot wireless communication medium in the Media Convergence System. This research is aiming at developing a broadband communication system based on IEEE 802.11g under high speed mobile environments.

Chapter 3 also designs the IEEE 802.11g Communication System for each layer. Major design policies for each layer are as follows. For a radio transmission channel on Layer 1, a radio propagation line was established on the train track by a high gain directional antenna. The Fresnel Zone was kept as clear as possible to make the quality of the radio transmission channel higher. As for Layer 2, the IEEE 802.11g Communication System leverages IEEE 802.11g as the name indicates. One of the requirements for the system is to construct a system in which it is affordable with the use of IEEE 802.11g. Our policy does not permit any customizations on IEEE 802.11g. Product dependences were accepted on Layer 2. As for Layer 3, design policies are as follows. The IEEE 802.11g Communication System assumes trains as its mobile stations. Since trains move on their tracks, a migration path for each train can be identified unless the train suddenly leaves its intended route. This peculiar characteristic allowed us to design a network topology which minimizes damages to communications caused by L3HOs.

Chapter 4 verifies that the IEEE 802.11g Communication System performs in accordance with the designing intentions and proves that the system works in real situations. The trials were done on a commercial high speed rail system. The speed of the test train was kept at 270(*km/h*). Experimental results have revealed communication performances on the IEEE 802.11g Communication System as shown in Table. 1. Results showed that the IEEE 802.11g Communication System working in Mode

2 had a TCP bandwidth of 13.7(*Mbps*) even while a mobile node was moving at 270(*km/h*). On the other side, however, Table. 1 also clarified a problem of high communication stall duration rate caused by downtimes over L2HOs and wireless link failures. Here, a ratio of communication stall duration to the whole communication period is referred to as Communication Stall Duration Rate.

Table. 1 Communication Performance on the IEEE Communication System

Examined Contents	Results	
IEEE802.11g Link (Wireless Link Failure)	Failed in 5.2%	
Round Trip Time	Average: 9.95(*ms*), Standard Deviation: 5.79(*ms*)	
UDP	Mode 1	Average: 16.3(*Mbps*) Max: 25(*Mbps*) or higher
	Mode 2	Average: 17.7(*Mbps*) Max: 25(*Mbps*) or higher
TCP	Mode 1	Average: 9.86(*Mbps*) Max: Around 20(*Mbps*)
	Mode 2	Average: 13.7 (*Mbps*) Max: Around 22(*Mbps*)
Communication Stability (Communication Stall Duration Rate)	Mode 1	9.9%
	Mode 2	18.1%

In order to reduce Communication Stall Duration Rate, requirements to improve the IEEE 802.11g Communication System were considered. Our policy does not permit any customizations on the IEEE 802.11g. Instabilities on Layer 1 and Layer 2 must be compensated for by Layer 3. These discussions brought three Requirements to be satisfied as follows.

(1) To enable traffic forwarding while a Layer 2 link is down

(2) To eradicate TCP Time Out caused by L2HOs

(3) To be applicable to all transport protocols

In order to improve the IEEE 802.11g Communication System with satisfying these three Requirements, Chapter 5 proposes “Multiplexing of wireless links between the ground network and each train network” and “Bicasting traffic between the redundant paths.” Two wireless links between the ground and a train were redundantly established. Each link was recognized as different IP routes (Paths) by MP-MIPv4. This is a bicasting architecture of traffic over two MIPv4 tunnels. The architecture was named “Bicasting-Multipath Mobile IPv4.”

Chapter 5 describes our proposal of the Bicasting-Multipath Mobile IPv4. A MP-MIPv4 network for its platform was also designed and the characteristics were considered with experimental results. The results have shown that IPLB (IP-based Load-Balancing) is the best load-balancing algorithm for the IEEE 802.11g Communication System.

Chapter 6 describes a design and an implementation of a bicasting architecture between paths in the Bicasting-Multipath Mobile IPv4. The bicasting architecture works over redundant paths established by MP-MIPv4. In order to satisfy three Requirements of the IEEE 802.11g Communication System held up in Chapter 4, the Bicasting-Multipath Mobile IPv4 bicasts traffic while either a L2HO or a Wireless Link Failure is taking place. Here, bicasting has to be started before the occurrence of either of them. Even if bicasting is started after a detection of a link being down, target traffic is no longer there and thus TCP has to wait for a RTO expiration. Therefore the Bicasting-Multipath Mobile IPv4 has to predict both a L2HO and a Wireless Link Failure before the start of its process.

The IEEE 802.11g Communication System predicted the events by RSSI (Received Signal Strength Indication) which each TBR received from one of the GBRs. RSSI on both TBRs were observed every 125(*ms*) by SNMP get-requests. For the Front BR which was set up at the front edge of the test train, a L2HO was predicted by an occurrence of a RSSI peak. This method successfully predicted L2HOs on the Front BR with the rate of 88.2%. For the Rear BR which was set up at the rear edge of the test train, on the other side, we introduced a threshold to judge a L2HO. The threshold is referred to as "L2HO threshold." When a RSSI fell under this L2HO threshold, a L2HO was predicted. Accuracy on the Rear BR depends on a configurable L2HO threshold.

Chapter 7 reports experimental results of the Bicasting-Multipath Mobile IPv4. Communication performances on the Bicasting-Multipath Mobile IPv4 are shown in Table. 2. The results have proven that the Bicasting-Multipath Mobile IPv4 is able to reduce Communication Stall Duration Rate to 0.67% and realizes TCP Rate of 16.4(*Mbps*) at the same time. Our proposed method improved the Communication Stall Duration Rate which was a serious problem of the Singlepath Configuration. The Bicasting-Multipath Mobile IPv4 realized both high communication speed and low Communication Stall Duration Rate at the same time. We have successfully configured a practical communication system for high speed rail systems.

Table. 2 Communication Performance on Bicasting-Multipath Mobile IP

L2HO Threshold (*dBm*)	TCP Rate (*Mbps*)	Communication Stall Duration Rate	
		Measured (%)	Estimated (%)
-71	16.4	0.67	1.89

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Chapter 1. Introduction

1.1. Background

Having a broadband connection on high speed rails is something that business travelers want most. Increasing number of passengers is requesting even higher access speeds. We are proposing the Media Convergence System as an ideal communication system for future high speed mobile entities. The Media Convergence System recognizes plural wireless communication media between the ground network and each train, and then traffic is load-balanced over active media which varies according to circumstances. The Media Convergence System must have a pivot wireless communication media. We are focusing on IEEE 802.11g as a pivot medium of the Media Convergence System, because it is expected to have a high performance in communication with high financial efficiency. In order to realize a high speed mobile communication system based on IEEE 802.11g (referred to as **IEEE 802.11g Communication System**), this paper designs the IEEE 802.11g Communication System, constructs an experimental IEEE 802.11g Communication System on a commercial high speed rail system, and evaluates performances of the system through trials.

This paper shows a methodology to exploit IEEE 802.11g for high speed mobile communications. IEEE 802.11g radio stations were deployed on a trackside of a high speed rail system with the approximate interval of 500(*m*). Communication performances of IEEE 802.11g were verified under the environment. The largest issue of the system is a handover. Mobile stations have to stay connected over handovers from one ground station to another. The average handover interval is 6.7 seconds, when a mobile station moves at 270(*km/h*) which is the maximum speed in our experiments, because the average geographical interval is 500(*m*) long. The average handover interval is quite short in comparison with cellular systems. Therefore, degradation of the communication quality over each handover seriously affects the communication performance of the whole system. The deterioration must be minimized. This paper analyzes IP (Internet Protocol) communication behaviors under an environment where a mobile station experiences very frequent handovers. Especially, it focuses on TCP (Transmission Control Protocol) implementing Retransmission and Congestion Control for reliability. Also this paper proposes a method to stabilize TCP performances over handovers. The background of this research is described below.

In 1960s, the United States government demanded a strong availability on a computer network even when some parts of the system went down. Packet Switching was born to meet this requirement with the study of the RAND Corporation (a government agency). ARPANET (the Advanced Research Projects Agency NETwork) improved the way of switching. ARPANET is the prototype of the Internet. Research results evolved into major protocols in the TCP/IP architecture. They include IP[1], TCP[2], UDP[3] and so on. TCP/IP was designed to be adaptable for communication over computers without any consideration about the difference of hardware or operating systems. By around 1990, many computers in the US were connected, the Internet was expanded and TCP/IP became a de facto standard protocol among computer networks. After the invention of WWW (World Wide Web), many documents in computers became open to the public as a "Home Page." It brought quite a large number of people to the Internet. From the year 2000, TCP/IP was applied to cellular communication, cross connection among home appliances, voice communication over VoIP (Voice over IP), broadcast using multicast technology and etc. Today, the Internet based on TCP/IP is one of the important infrastructures to support our daily life. Japanese government set up "e-Japan Strategy" [4] in 2001 and it was followed by "New IT Reform Strategy" [5] in 2006. Ministry of Internal Affairs and Communications of Japan kicked off "u-Japan Policy" [6] which aimed at realizing the "Ubiquitous Network Society." The fundamental concept of "Ubiquitous" is to be able to connect to networks at anytime, anywhere by anyone and anything including items we would have never considered communication devices. As the principles show, the Internet using TCP/IP is not only for immobile computers in rooms but also for any devices under any situation for anyone who wants to use the Internet.

It is not an exception when people are on a high speed train traveling at around 300(km/h). We have demands for connectivity to the Internet from cabins. In a case of the Tokaido-Shinkansen, a high speed train system in Japan, large portion of the passengers are business people. It is not difficult to guess their appetites for Internet connections for business purposes. An Internet connection service was started on the Tokaido-Shinkansen in March 2009 [7].

Smart phones until recently which have been used exclusively by business people have now become more main stream due to the explosive popularity of iPhone and Android terminals. Some applications working on these devices frequently communicate with servers without owners' requests. Movies and games run on many web sites. Unintended large sized content is sometimes downloaded when a user simply sends HTTP (Hypertext Transfer Protocol) [8] get requests to these kinds of sites.

As described above, we see requests of Internet connections from smart phones as well as conventional PCs (Personal Computer). The supply of communication bandwidth is not enough for the demands of the communication volume in high speed mobile environments. This paper describes a methodology to obtain a broader bandwidth for high speed mobile systems.

1.2. Current Situations and Approach of Research

1.2.1. Current Situation

A Leaky Co-aXial (referred to as LCX) technology [9] was employed for an Internet connection service on the Tokaido-Shinkansen as a communication medium. TGV took advantage of satellite communication and Wi-Fi [10]. We see a cellular system and WiMAX (Worldwide Interoperability for Microwave Access) [11] being used in other systems. A satellite system is also applied to aircraft communication. There are various communication media which are adaptable to high speed mobility. Each medium has different characteristics. The rough outline of a LCX Communication System and a satellite communication system are described below as examples of communication media. Details of those and other communication media are in Chapter 2.

LCX Communication System: The LCX cable itself plays the role of the radio antenna. The communication effective distance from the LCX cable is not long in the perpendicular direction. A LCX cable covers the rail track and trackside for communication. In LCX communication systems, the distance between the antennas of base stations (LCX cables) and those on mobile stations is always constant and close during movements of mobile stations. Therefore communication is always very stable and thus is a great advantage of LCX communication systems. On the other side, the transmission characteristics of standard LCX cables show the lowest propagation loss on several hundred MHz band. This frequency band is quite crowded with various wireless systems and available bandwidth is constrained. It is difficult to develop a mobile communication system with speed of 10(*Mbps*) or higher.

Satellite Communication System: In satellite communications, coverage of each space station is quite large, in some cases it is nationwide. It does not have a handover problem which lies on mobile communications. Portable receivers are able to catch a downlink signal which is transmitted from a Space station to an Earth station. On the other side, an uplink signal departing an Earth station for a Space station has to be emitted with strong power enough to reach a satellite floating 36,000km above the ground. It is not so easy to be implemented just like a simple receiver. When an Earth station moves, the direction of an antenna on the Earth station has to be adjusted in real time in order to track the counterpart Space station. It is impossible to keep connectivity when an Earth station goes under tunnels or moves behind buildings. A satellite communication is mainly expected as a downlink connection under a Line-Of-Sight (LOS) communication condition.

1.2.2. Train Communication System in the Future

As described in Section 1.2.1, each communication medium has advantages and disadvantages. It is unreasonable to establish an ideal communication system with a single medium. Plural communication media which have different characteristics to each other should be deployed in accordance with geographical conditions. Those media must be bundled up on the network and provided as one single logical path between a mobile entity and the ground network. They must be adequately controlled to perform together at the same time. The word “perform together at the same time” means that traffic is load balanced on active wireless communication media, which makes the communication speed faster up to the total of all the active media. We named this kind of system “Media Convergence System.” It is the Media Convergence System that is the desired train communication system we would like to design for the future.

A configuration example of the Media Convergence System is illustrated in Fig. 1-1. Fig. 1-1 contains communication media such as LCX, IEEE 802.11g, satellite and WiMAX as an example. All the communication media other than these are also able to be mounted on the Media Convergence System.

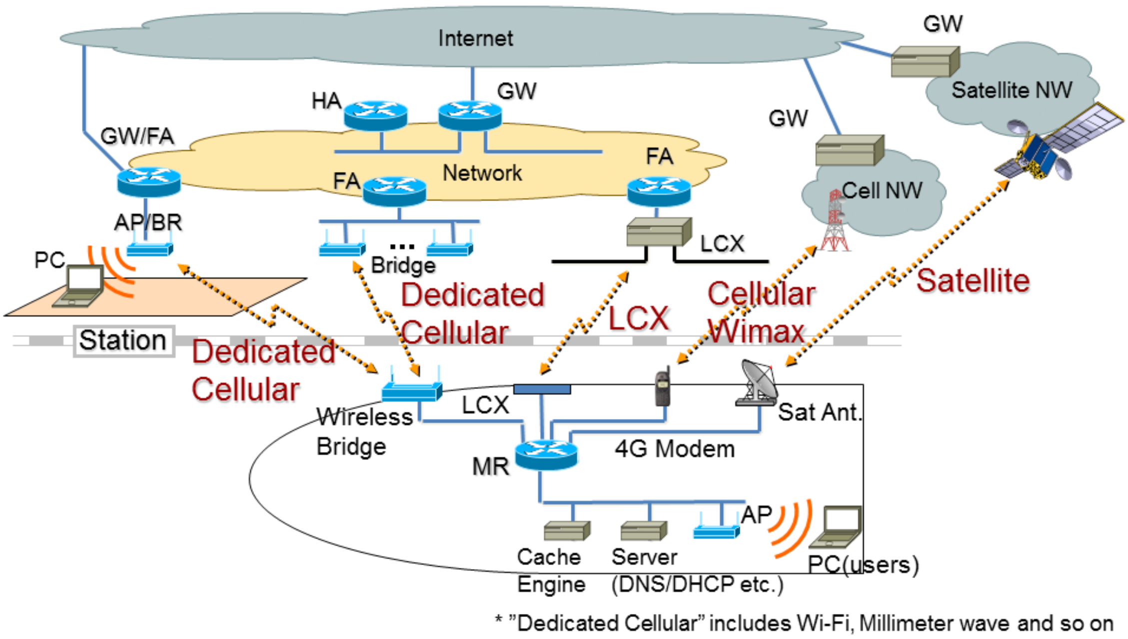


Fig. 1-1 Media Convergence System

1.2.3. Mobile Communication System using IEEE 802.11g

This research aims at consolidating a methodology to realize a broadband communication for entities moving at high speed around 300(*km/h*) and showing its practicality. Although the Media Convergence System shown in Fig. 1-1 is one of the ideal configurations for the future, it is ineffective when the system consists of communication media with low performances. The Media Convergence System needs a pivot communication medium. IEEE 802.11g is a promising technology due to its maturity as a media and superior cost performance per communication speed. A program was launched in order to develop a high speed mobile communication system using IEEE 802.11g, stated as the IEEE 802.11g Communication System below.

IEEE 802.11g devices are traded in quite a large market of consumers in the world. This fact enables us to obtain high performance devices for lower costs. While running at peak performance, the maximum communication speed is 54Mbps. The cost and the communication performance make it attractive for us. IEEE 802.11b was proved to have an UDP throughput of 1.2(*Mbps*) under a travelling speed of 300(*km/h*) [12]. This result evoked that IEEE 802.11g as a successor of IEEE 802.11b was also available under high speed mobile environments with an appropriate system configuration, though it originally assumed walking speed as mobility. This research first verified the adaptability of IEEE 802.11g to high speed mobile communication.

1.2.4. Handovers on IEEE 802.11g Communication System

In general, a handover is one of the difficult problems for mobile communications. The IEEE 802.11g Communication System is not an exception. As a matter of fact, the handover issue on the IEEE 802.11g Communication System is much larger than that of cellular systems. The coverage of each antenna is not larger than 500(*m*) under Japanese Radio Law for the exploitation of the IEEE 802.11g Communication System on the trackside of rail systems. The handover interval is 6(*sec*) when a mobile station (train) moves at 300(*km/h*). The key to a success of the system is an appropriate control of frequent handovers. This is the core issue of this research.

A handover mechanism is as follows.

(1) Physical radio switching from one wireless connection to another
(2) Update of MAC address tables on the Data Link Layer (Layer 2, referred to as L2). The process of (1) and (2) is referred to as L2HO (Layer 2 HandOver) in this paper.
(3) Update of Routing tables on the Network Layer (Layer 3, referred to as L3). This process is referred to as L3HO (Layer 3 HandOver) in this paper.
(4) Various controls by TCP due to packet losses caused by (1)-(3), in case that TCP is used on the Transport Layer (Layer 4, referred to as L4)

Occurrences of process (1) – (3) are unavoidable for mobile communications. Each of those takes time. Process (1) is completely dependent on the performance of radio stations. This process is put away from the focus of this research. In our system, a radio station having a short switching time was selected and short disruptions of communication due to the process were regarded as a precondition of the system.

Process (2) takes shorter time than Process (3), because each device locally updates its MAC Address Table. On the other side, an interval of L2HOs is short because they always occur when a mobile station switches over from one ground station to another. The handover interval of 6(*sec*) as described above is for the L2HO interval. Damages to communication by L2HOs are severe because of their short interval. Therefore this research focused on an improvement of communication performances during L2HOs. At first, damages to communication by L2HOs were analyzed through communication experiments on the IEEE 802.11g Communication System. As for a transport protocol, TCP was chosen because it was widely used for web browsing, mail transmissions and so on. Results have shown that TCP stalls in 10 to 20% of the whole communication duration and it is caused by not only L2HOs but also TCP timeouts triggered by a L2HO.

In order to reduce communication stall duration, a system was designed to make traffic forwarding possible even during a L2HO. It is natural that traffic forwarding is disrupted when the exclusive wireless path between the ground and a train is disconnected due to a L2HO. Therefore, we propose "multiplexing of wireless links between the ground network and each train network" and "a methodology of an implementation of traffic bicasting between the redundant paths." Two wireless links between the ground and a train were redundantly established and unified on Layer 3 by Multipath Mobile IPv4 (MP-MIPv4) [13]. When a L2HO occurred on one of the paths, packets were bicasted to both paths and sessions were maintained through the other active path. Results have shown that our proposal can reduce the TCP communication stall duration rate to around 1%.

A L3HO in Process (3) has to update Routing Tables of related devices. This process is not able to be localized as Process (2). Although Process (3) generally takes the longest time of all three processes, the occurrence is rare. This paper describes a design of a network topology which can separate a L3HO from a L2HO in order to reduce damages to communication by a L3HO.

1.3. Organization of This Paper

The goal of this research is to consolidate a configuration methodology of a broadband communication system for high speed mobile systems traveling at around 300(*km/h*). Although the Media Convergence System is the desired communication system, there is no communication media which has a sufficient bandwidth with a high financial performance. With a careful consideration, we focused on IEEE 802.11g as a pivot communication media on the Media Convergence System. This research aims at developing a broadband communication system based on IEEE 802.11g under high speed mobile environments. The organization of this paper is shown in Fig. 1-2. In part 1, the IEEE 802.11g Communication System was designed and deployed on a commercial high speed rail system. Results of field trials have shown that the IEEE 802.11g Communication System has a TCP bandwidth of 13.7(*Mbps*) even while a mobile node is moving at 270(*km/h*), though it suffers from frequent L2HOs. TCP did not recover from a freeze until its timeout expired after a L2HO and thus TCP stalled 10 to 20% of the whole communication duration. In order to reduce these communication disruptions, part 2 proposes a way to implement a bicasting solution over paths established by MP-MIPv4. MP-MIPv4 is used to make multiple connections between the ground network and mobile entities. Traffic was bi-casted over the paths during L2HOs. A field trial on a high speed train has proven that our proposal achieves a TCP bandwidth of 16.4(*Mbps*) and the TCP communication stall duration rate of around 1% at the same time.

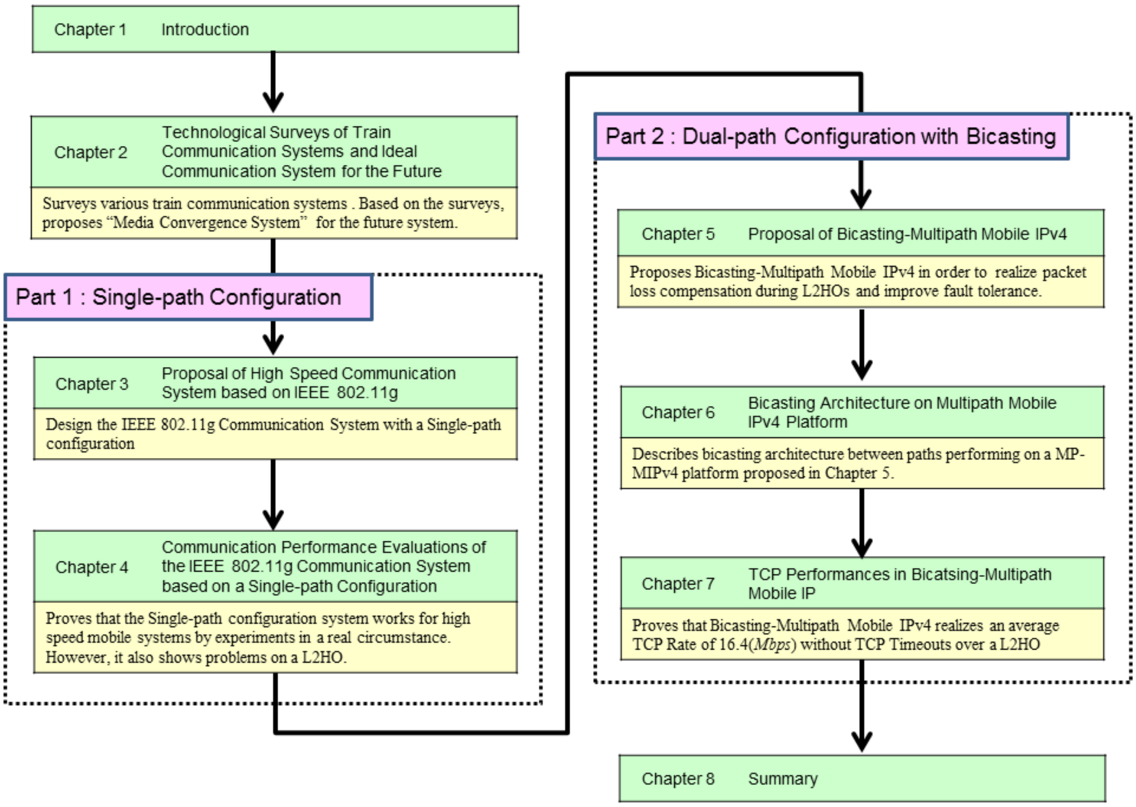


Fig. 1-2 Organization of This Paper

[Chapter 2]

Chapter 2 surveys various train communication systems with their history and discusses present systems. The focus of this paper is communication on high speed rail systems. High speed trains generally travel through various geographical areas such as cities, suburbs, mountains, tunnels and so on. With these geographical conditions taken into account, there seems to be no perfect wireless communication medium which suits best to all places. Communication media which have different characteristics to each other should be deployed in accordance with geographical conditions. Plural communication media may become available in the same place at the same time. A wireless communication system for high speed trains in the future must recognize these plural wireless communication media and traffic must be load-balanced over active media which varies according to circumstances. It is referred to as "Media Convergence System" that all the communication media available at local places are logically bundled up into a single path. This chapter proposes a Media Convergence System which will be desired in future high speed trains.

[Part 1]

A high speed mobile communication system based on IEEE 802.11g is proposed, designed and constructed. Its performances are evaluated in real situations. Part 1 deals with a system configuration with a single IEEE 802.11g link between the ground network and the test train. Results have shown that the IEEE 802.11g Communication System has a TCP bandwidth of 13.7(*Mbps*) even while a mobile node is moving at 270(*km/h*). On the other side, TCP suffered from a long communication stall due to instability on the wireless link and the communication stall duration rate was 10 to 20%. Content of each chapter in Part 1 is as follows.

[Chapter 3]

Chapter 3 considers a pivot communication medium for the Media Convergence System. Requirements for the medium are; having enough communication speed, feasible in the near future, available in the market for a moderate price and so on. Wi-Fi was positioned in the center of our consideration for media, which satisfies these requirements. A project was started to develop a high speed mobile communication system based on IEEE 802.11g (IEEE 802.11g Communication System).

Chapter 3 designs the IEEE 802.11g Communication System. The IEEE 802.11g Communication System is one of the cellular communication systems. Although a basic system configuration does not have a big difference from other cellular systems, system designs require careful consideration for mobility of high speed trains because mobile stations in the IEEE 802.11g Communication System experience frequent L2HOs. This chapter describes how to apply IEEE 802.11g for high speed trains. The system is designed for each Layer. The IEEE 802.11g Communication system is one of the access networks to the Internet from cabins on high speed trains. Subjects of design lie on Layer 3 and lower. For Layer 4 and higher, all protocols, applications and services perform on this platform.

[Chapter 4]

Chapter 4 verifies that the IEEE 802.11g Communication System performs in accordance with the designing intentions and proves that the system works for high speed mobile systems by experiments in real circumstances. The speed of the test train was kept at 270(*km/h*).

The results have revealed that the IEEE 802.11g Communication System realizes an average UDP throughput of 16.3(*Mbps*) in Mode 1 and 17.7(*Mbps*) in Mode 2, and an average TCP throughput of 9.86(*Mbps*) in Mode 1 and 13.7(*Mbps*) in Mode 2. On other side, an analysis of TCP performances over a L2HO has shown that TCP does not recover from a freeze until its timeout expires after a L2HO. Thus TCP has a high communication stall duration rate of 9.9% in Mode 1 and 18.1% in Mode 2. This result has clarified a necessity of the reduction of this rate.

In order to reduce the communication stall duration rate, Chapter 4 discusses requirements to improve the IEEE 802.11g Communication System. Our policy does not permit any customizations on IEEE 802.11g. The IEEE 802.11g Communication System compensates for instabilities on Layer 1 and Layer 2 by Layer 3. Requirements to be satisfied are as follows.

(1) To enable traffic forwarding while a Layer 2 link is down

(2) To eradicate TCP Time Out caused by L2HOs

(3) To be applicable to all transport protocols

[Part 2]

In order to satisfy three Requirements set up in part 1 and reduce the communication stall duration rate, Part 2 proposes "multiplexing of wireless links between the ground network and each train network" and "Bicasting traffic between the redundant paths during a L2HO." This proposal was implemented and tested on the IEEE 802.11g Communication System. Results have revealed that our proposal is able to reduce the communication stall duration rate to around 1% and realize an average TCP throughput of 16.4(*Mbps*) at the same time. Content of each chapter in Part 2 is as follows.

[Chapter 5]

Chapter 5 discusses improvements of the IEEE 802.11g Communication System. In order to realize "packet loss compensation during L2HOs" and "improvement of fault tolerance during Wireless Link Failures" at the same time, we propose "multiplexing of wireless links between the ground network and each train network" and "Bicasting traffic between the redundant paths." Two wireless links between the ground and a train were redundantly established. Each link was recognized as different IP routes (Paths) by MP-MIPv4. This is a bicasting architecture of traffic over two MIPv4 tunnels. The architecture was named "Bicasting-Multipath Mobile IPv4."

Chapter 5 describes our bicasting architecture and builds a basic design of the Bicasting-Multipath Mobile IPv4. Its network platform based on Multipath Mobile IPv4 was considered and also tested in real situations. The experimental result has revealed that IP-based Load Balancing (IPLB) is the most appropriate load-balancing algorithm for our system.

[Chapter 6]

Chapter 6 designs a bicasting architecture on the Multipath Mobile IPv4 platform and explains behaviors of both the Ground Duplicator and the Train Duplicator. The Bicasting-Multipath Mobile IPv4 has to control the start and the stop of bicasting and it is based on the status of IEEE 802.11g links. This chapter proposes a method to predict both L2HOs and Wireless Link Failures using RSSI (Received Signal Strength Indication) received on wireless bridges on a train and describes our algorithm of L2HO prediction and its accuracy.

[Chapter 7]

This chapter reports experimental results of the Bicasting-Multipath Mobile IPv4. The results have revealed that the Bicasting-Multipath Mobile IPv4 realizes an average TCP Rate of 16.4(*Mbps*) and reduces Communication Stall Duration Rate to 0.67%, which was originally 9.9% in Mode 1 and 18.1% in Mode 2. Finally, we have established a mobile communication system which has a stable communication bandwidth of 10(*Mbps*) or more during high speed movements.

[Chapter 8]

Chapter 8 summarizes this paper.

1.4. Terminology

This paper frequently uses the following terms.

Table 1-1 Terminologies in this Paper

Terminology	Definition
Mobile IPv4 (MIPv4)	Standardized in RFC3344 [14].
Mobile IPv6 (MIPv6)	Standardized in RFC 6275[15]
Mobile IP (MIP)	Indicates both MIPv4 and MIPv6 in this paper
MIPv4 Tunnel	Virtual tunnel established by MIP
Path	Used in the same definition as MIPv4 Tunnel in this paper
Home Agent (HA)	Used in the same definition as in RFC3344
Foreign Agent (FA)	Used in the same definition as in RFC3344
Mobile Node (MN)	Used in the same definition as in RFC3344
Mobile Router (MR)	Used in the same definition as in RFC3344
Mobile Network(s)	Network(s) deployed under MR
Home Address	Used in the same definition as in RFC3344
Home Network	Used in the same definition as in RFC3344
Care-of Address	Used in the same definition as in RFC3344
Bridge (BR)	IEEE 802.11g Wireless Bridge
Ground Bridge (GBR)	a BR set up as a ground radio station.
Train Bridge (TBR)	a BR set up as a mobile radio station on a train.
Local Acknowledgements (Local ACK)	Used in the same definition as in RFC3135 [16]

Chapter 2. Technological Surveys of Train Communication Systems and the Ideal Communication System for the Future

This chapter surveys various train communication systems with their history and summarizes their characteristics. Detailed study is done on present systems. Results of surveys and studies point out a difficulty to construct a high speed mobile communication system with a single wireless communication medium. This chapter also discusses high speed communication systems which will be desired in the future. High speed trains generally travel through various geographical areas such as cities, suburbs, mountains, tunnels and so on. With these geographical conditions taken into account, there seems to be no perfect wireless communication medium which suits best to all places. Communication media which have different characteristics to each other should be deployed in accordance with geographical conditions. Plural communication media may become available in the same place at the same time. A wireless communication system for high speed trains in the future must recognize plural wireless communication media between the ground network and each train. Traffic must be load-balanced over active media which varies according to circumstances. It is referred to as “Media Convergence System” that all the communication media available at local places are logically bundled up into a single path. This chapter proposes a Media Convergence System which will be desired in future high speed trains.

2.1. Introduction

The Internet became popular in offices and at homes. It has been an indispensable infrastructure equivalent to electricity or water. Today, an internet connection is available through cellular phones under mobile environments. However, cellular phone systems do not provide stable broadband connections to users on high speed trains. Therefore communication technologies for high speed mobile systems are being developed. An internet connection service was started on the Tokaido-Shinkansen in Japan in these circumstances.

This chapter surveys various train communication systems with their history and summarizes their characteristics. Detailed discussions with experiments are also given on contemporary systems. High speed trains generally travel through various geographical areas such as cities, suburbs, mountains, tunnels and so on. With these geographical conditions taken into account, there seems to be no perfect wireless communication medium which suits best to all places. Communication media which have different characteristics to each other should be deployed in accordance with geographical conditions. Plural communication media may become available in the same place at the same time. A wireless communication system for high speed trains in the future must recognize plural wireless communication media between the ground network and each train. Traffic must be load-balanced over active media which varies according to circumstances. It is referred to as "Media Convergence System" that all the communication media available at local places are logically bundled up into a single path. This chapter proposes a Media Convergence System which will be desired in future high speed trains.

The organization of this chapter is as follows. Section 2.2 overviews various train communication systems in the past and also focuses on communication technologies for high speed trains in the present day. Section 2.3 discusses a train communication system which will be desired in the future in accordance with surveys in Section 2.2. As a result, the section proposes a "Media Convergence System." Section 2.4 summarizes this chapter.

2.2. Various Train Radio Communication Systems

This section surveys various train communication systems in the past and also especially focuses on communication technologies for high speed trains in the present day.

2.2.1. Inductive Radio Communication System

It was 1920s when the development of the first communication system for trains was started by Ministry of Railways in Japan. The system was based on Inductive Radio Communication with the LF (Low Frequency) band and tested between Oimachi and Odawara. When alternative current travels on a bare wire on a trackside, alternating magnetic field is generated around the derivation wire as shown in Fig. 2-1. The magnetic field is a wireless communication medium between an onboard loop antenna and the derivation wire. Inductive Radio Communication had the disadvantage that noise on the LF band was worse than that on the VHF (Very High Frequency) band or the UHF (Ultra High Frequency) band. Its communication capacity was limited.

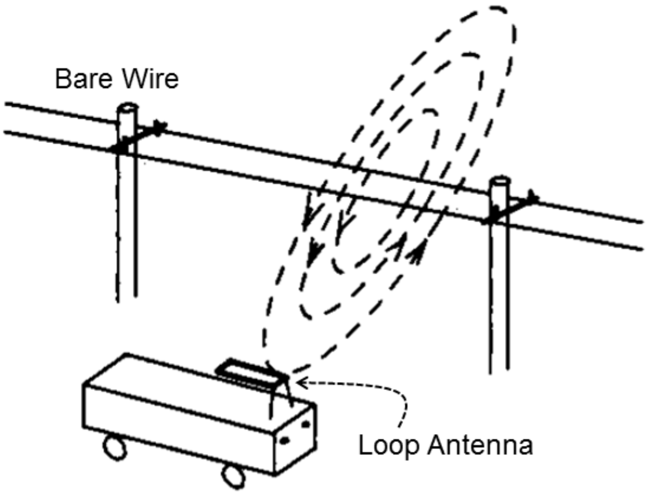


Fig. 2-1 Inductive Radio Communication System

2.2.2. Cellular Communication System

In order to overcome deficits of Inductive Radio Communication, a research for Cellular Communication based on the VHF band or the UHF band was started around 1956. A Cellular Communication System as shown in Fig. 2-2 uses electro-magnetic waves propagating in the air as a communication medium. It is the same as Cellular Phone Systems. In 1958, this system came into practical use for a train radio system on the Tokaido line (not the Tokaido-Shinkansen) between Tokyo and Osaka. The Cellular System of the day covered even inside tunnels. It realized a continuous communication for trains without disruptions.

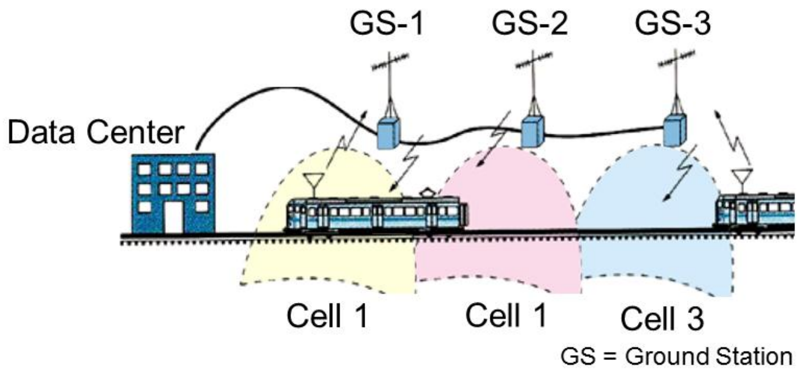


Fig. 2-2 Cellular Communication System

The Tokaido-Shinkansen which was started in 1964 also equipped a Cellular Communication System. The system was designed; frequency was 400MHz band, S/N (Signal / Noise) ratio was 35dB or larger for 90% or more of the track and communication was available for 99.9% or more of the path.

A train’s movement is limited by its track, although coverage by each antenna of a Cellular Communication System is not limited to only the track. A Cellular Communication System is appropriate, when it is applied to Metropolitan transport systems in which multiple lines are accessed through a single antenna. On the other side, high speed rail systems link big cities. Since a Cellular Communication System has a round communication area, it is likely to have ineffective areas when it is applied for high speed trains.

2.2.3. Leaky Co-axial (LCX) Communication System

A development of a LCX Communication System was started around 1960 to overcome problems of a Cellular Communication System. The LCX cable itself plays the role of the radio antenna. The effective communication distance from the LCX cable is not long in the perpendicular direction. A LCX cable effectively covers the rail track and trackside for communication as shown in Fig. 2-3. In a LCX Communication System, the distance between the antenna of base stations (LCX cable) and that on mobile stations is always constant and close during movements of mobile stations. Therefore communication is always very stable. It is the large advantage of a LCX Communication System.

A LCX cable is a co-axial cable with holes (called as “Slot”) on the outer conductor. Electro-magnetic wave leaks through the slots. The structure of LCX cable is shown in Fig. 2-4. The center conductor is made by a hollow copper pipe. A polyethylene insulator is spirally winded over the center conductor and again a polyethylene pipe covers the twisted structure. A thin outer conductor is fixed on the polyethylene pipe. It is vulnerable to tensions generated by curves or cross section distortions of a cable. Therefore it is laid to reduce undesired forces.

Electric currents go on center and outer conductors when power voltage is energized between them. Slots on the outer conductor change a current density. This phenomenon makes leakages of electro-magnetic waves from the slots. In accordance with the principle above, the LCX cable itself plays the role of the radio antenna. The transmission characteristics of standard LCX cables show the lowest propagation loss on several hundred MHz band. An optimized system can be configured with LCX cables working on this frequency.

It is called “Coupling Loss” for the ratio of the power received on an antenna on a mobile station to that transmitted from a LCX cable. Considering a system configuration where signal power is supplied at an edge of a LCX cable and a mobile station moves while keeping a constant distance to the LCX cable, the received power on the mobile station decreases as it goes farther from the power supply point. In order to compensate for this loss, the LCX transmission line is configured with the use of lower coupling loss LCX cables (leakage of electro-magnetic wave is larger) for farther distance from the energy source as shown in Fig. 2-5. This enables intervals between repeaters longer than ones for a system with the same kind of LCX cable. It also contributes for a system to reduce a variance of a received power level. This method of configuring a transmission line is called “Grading.”

A LCX Communication System was employed for the Tokaido-Shinkansen in 1989. The Sanyo-Shinkansen installed it from Shin-Osaka to Okayama in 2000 and from Okayama to Hakata in 2004. Also the other Shinkansen routes in Japan equipped the system at the beginning of their services. Today, a LCX Communication System is a de facto standard of radio communication systems for all bullet trains in Japan.

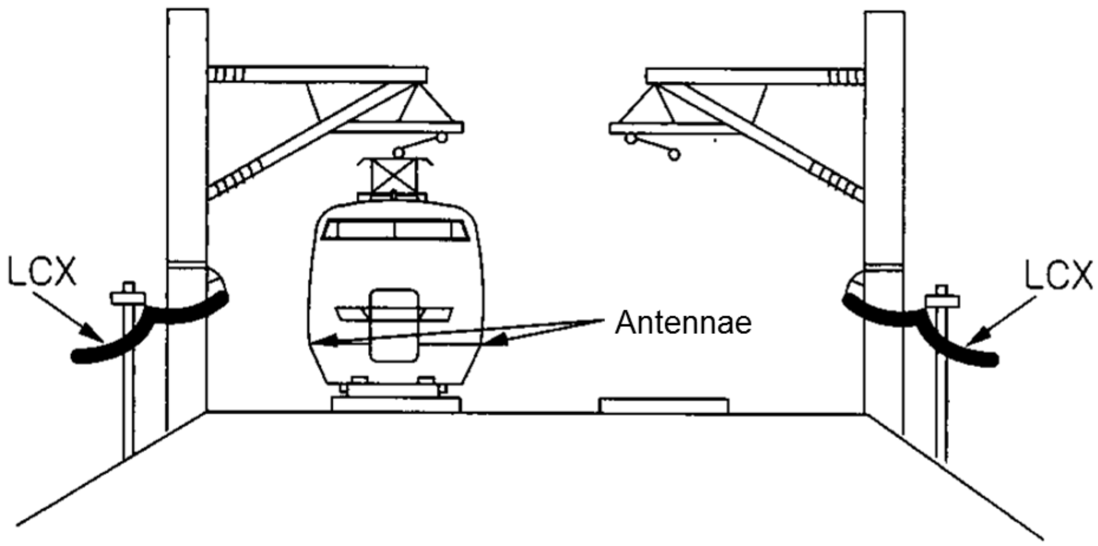


Fig. 2-3 LCX Communication System

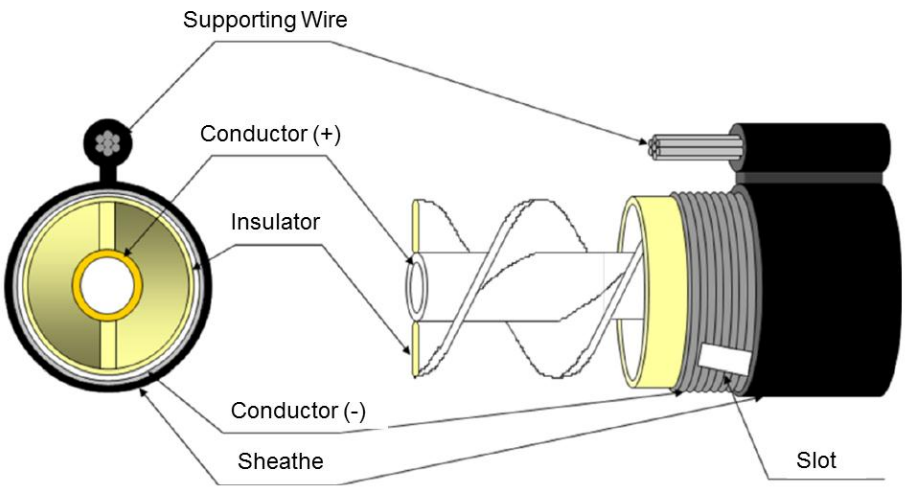


Fig. 2-4 Structure of LCX cable

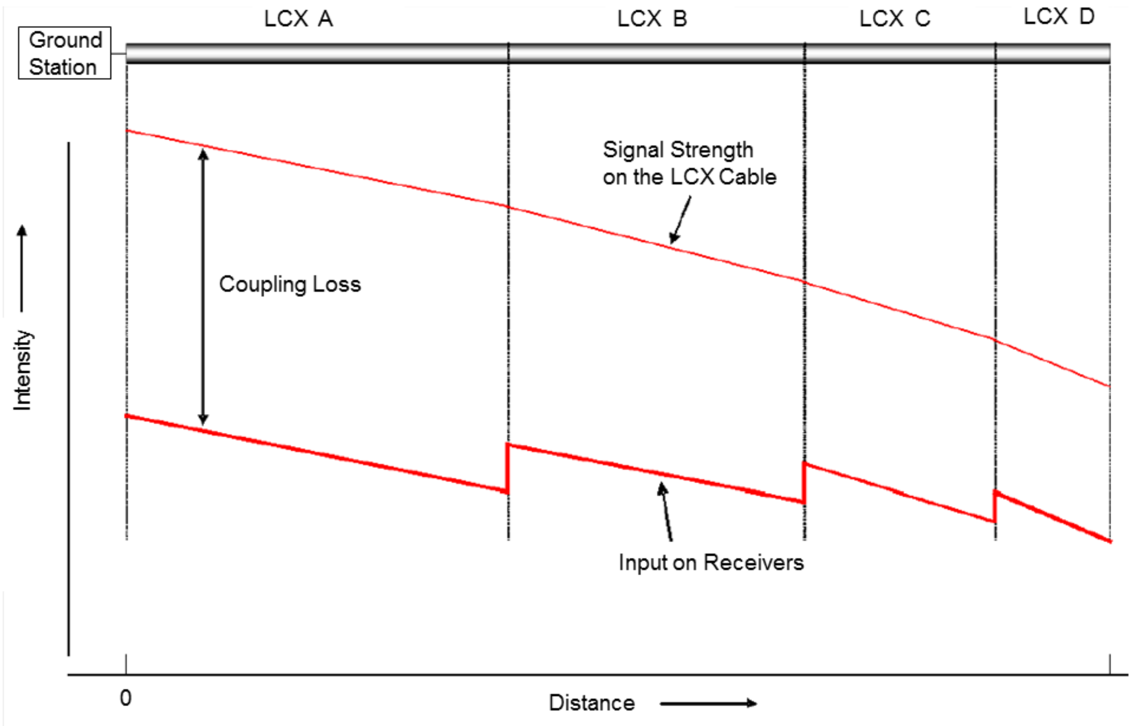


Fig. 2-5 LCX Cable Deployment by Different Coupling Loss Cables

2.2.4. Digitalized Leaky Co-axial (LCX) Communication System

Communication technologies have been evolving with the times. Although the original LCX Communication System had run only on an analogue system, digital transmission became available for LCX Communication Systems.

A digital phase encoding is used for transmissions on a Digitalized LCX (referred to as D-LCX) Communication System. A D-LCX Communication System was employed for the Tohoku&Joetsu-Shinkansen, the Kyushu-Shinkansen and the Tokaido-Shinkansen in 2002, 2004 and 2009, respectively. Especially, an Internet connection service for passengers was started on the Tokaido-Shinkansen trains with the D-LCX technology.

The Internet connection service on the Tokaido-Shinkansen is available all the way between Tokyo and Osaka. It is approximately 500km long. A gateway to the Internet was set up in Tokyo on top of the system. The service area was divided into cells each of which covers about 10km long. The configuration of the system is shown in Fig. 2-6.

Different frequency bands for D-LCX transmissions were allocated to the uplink and the downlink. Each cell has a communication capacity of 1Mbps and 2Mbps for the uplink and the downlink, respectively. When there are plural trains in a cell, all the accesses are on the same band. The bandwidth is shared by all the users. The expected number of train sets is two in a cell.

The communication line quality for the system is defined by Bit Error Rate (BER) [7]. It is as follows.

- ✓ BER = 1.0×10^{-5} or lower with Forward Error Correction (FEC)
- ✓ BER = 1.0×10^{-4} or lower without FEC

IEEE 802.11b/g Wireless LAN is provided for the users' accesses onboard. Wireless LAN Access Points (WLAN-AP) supports multi-SSID (Service Set Identifier). It is a MVNO (Mobile Virtual Network Operator) system. Each SSID works for a Wireless LAN business operator. Two WLAN-APs are set up in each car, which offers the accessibility to the Internet from anywhere on the trains.

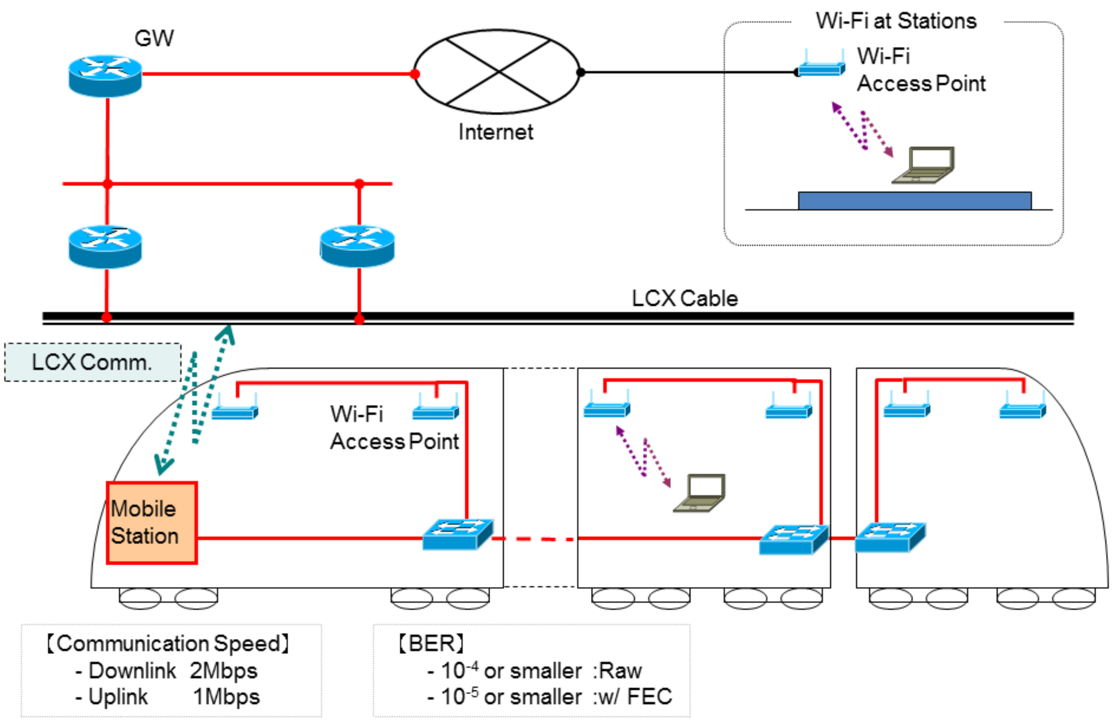


Fig. 2-6 System Configuration by LCX Communication System for the Tokaido-Shinkansen [7]

BER was measured for the D-LCX system. A packet loss rate of ICMP (Internet Control Message Protocol) Echo Requests was measured and then BER was calculated. A topology for the measurement is shown in Fig. 2-7. The Operation System (OS) for the PCs was Ubuntu 9.04 [17]. A payload size of the requests was 1,000Bytes and a sending interval was 1.0 second. Measurements were done between Tokyo and Nagoya. It is about 340km long and a one hour 40 minutes ride. The number of measurements was eight for uplink and one for downlink. They were done on Shinkansen trains in service. Not only the test traffic but also passengers' traffic was on the line at the same time.

Table 2-1 shows the results. The packet loss rate was 0.34%. No information is available for the D-LCX transmission protocols. Here we assume 100Bytes for additional data for each packet. It includes some IP headers for MIP (See Table 1-1). So the total packet size is 1,100 Bytes to be transmitted. BER is calculated by the following.

$$L = 1 - (1 - E)^{8\times 1100} \tag{2-1}$$

Let packet loss rate be L and BER be E. Formula (2-1) gives $E \sim 3.9 \times 10^{-7}$. The actual performance is one digit better than the specification (BER = 1.0×10^{-5}). The quality of the D-LCX communication line is quite high when we take into account the fact that this is a high speed mobile communication system.

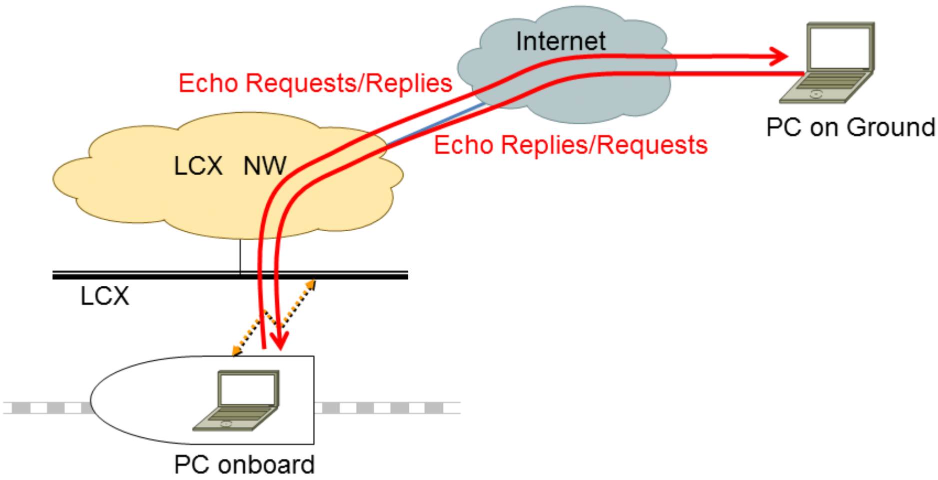


Fig. 2-7 Configuration for BER Measurements of the D-LCX System

Table 2-1 Ping Packet Loss

Direction	Number of Echo Requests	Number of Lost Packets	Packet Loss Rate: L (%)
Uplink	33,560	117	0.35
Downlink	5,717	17	0.30
Total	39,277	134	0.34

2.2.5. Satellite Communication System

Satellite Communication Systems are being used in not only fixed communications but also mobile communications, because it has advantages of wide area coverage, easiness of broadcasting, disaster tolerances and so on. Coverage by a satellite often is as large as the size of some nations. Handover problems do not tend to take place unlike some mobile communication systems. On the other side, in case that an earth station moves, the direction of antennas must be controlled in order to acquire the satellite station. A connection is disrupted when an earth station goes into tunnels or behind buildings.

Portable receivers on the ground easily catch signals from a satellite station. On the other side, for an uplink transmission (from an earth station to a satellite station), electro-magnetic waves emitted from an earth station must be strong enough to reach the counterpart satellite station floating about 36,000km above the earth. The size of transmitters is likely to be large. An implementation of a transmitter is not as easy as that of a receiver. A large parabola antenna on the roof of a high speed train causes a large noise, which makes peripheral environments worse. It is required to develop a small and high performance antenna in order to apply this solution for a high speed rail system.

TCP is the most popular protocol in internet communication. As for TCP, an efficiency of operations on a communication line is given by an occupancy ratio of a congestion window to a Bandwidth * Delay Product (BDP) which is a product of bandwidth and delay. A long communication line such as a satellite communication and a transpacific communication causes latency of several hundred milli-seconds and thus has a large BDP. These lines are called “Long Fat Pipe.” In order to obtain a sufficient throughput in a Long Fat Pipe network, TCP must have a large congestion window to occupy a large BDP. From the discussions above, satellite communication systems show their superiorities when it is adapted to downlink communications under a Line-Of-Sight (LOS) condition between a satellite transmitter and ground receivers.

Satellite Communication System is in use on the TGV-Est Line in France. The service was started on June 10th in 2007. The maximum speed for services is 320km/h. The TGV-Est Line installed IT service [18] in December 7th in 2007. The service includes internet accesses and portal services by a portal server on trains. Contents of the portal site on a train are enriched in order to minimize data traffic to the Internet. The contents are news, travel information, movies, games, net magazines, a position of train and so on.

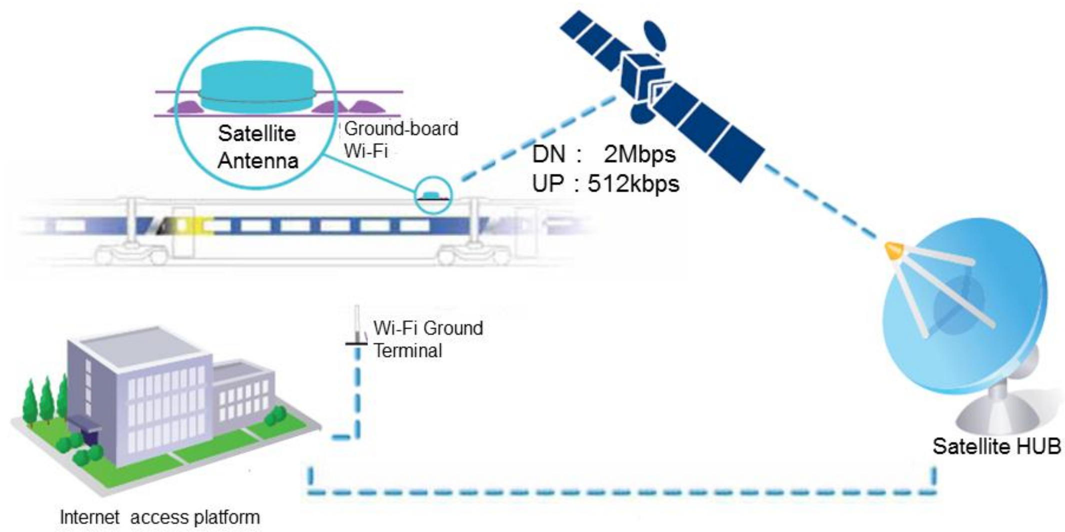


Fig. 2-8 System Configuration by Satellite Communication System for TGV-Est

2.2.6. Wi-Fi Communication System

Wireless cells are deployed on the ground for Wi-Fi communication systems. Mobile stations move with handovers from one ground station to another. This is the same as cellular communication systems described in section 2.2.2. A difference from cellular communication systems is a cell size generated by each ground station. Although a cell covers a couple of kilometers in conventional cellular communication systems, a Wi-Fi cell is much smaller due to regulations in each country. Therefore mobile stations have to experience frequent handovers in Wi-Fi communication systems. One of the issues is the optimization of handovers.

We can see this type of system on the Tsukuba-Express. It launched an internet connection service on its trains on August 24, 2006. They worked with Intel and NTT-BP. The system configuration is shown in Fig. 2-9. Ground stations with directional antennas were set up at the edges of each platform at stations. In cases where there is a white space in the middle of stations due to geographical conditions such as curves, a relay station wirelessly extends a network segment using 25GHz band. This system is based on MIP to support network mobility. Each SSID of Wi-Fi for user accesses represents Wi-Fi service operators. It is a MVNO system.

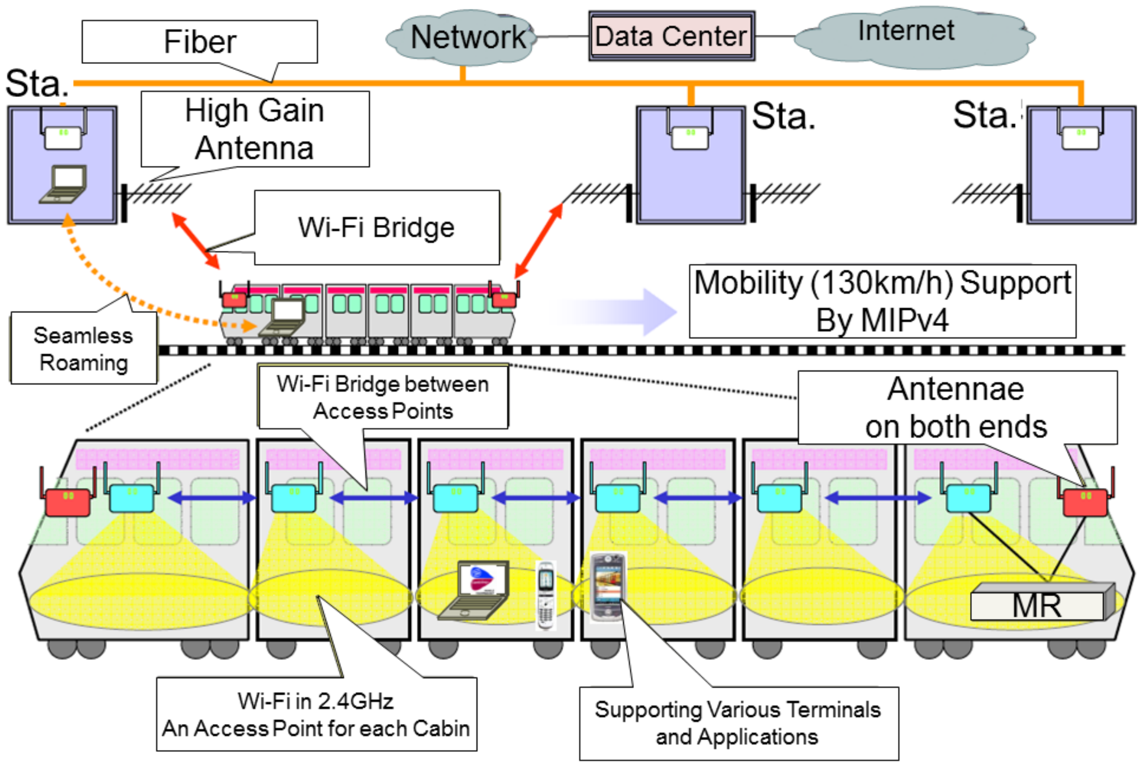


Fig. 2-9 System Configuration by Wi-Fi Bridge for Tsukuba Express

2.2.7. Systems using Communication Carriers Services

In communication systems using carrier services, communication carrier networks are access lines to the Internet from mobile entities. Current major services are cellular phone networks as a WAN (Wide Area Network) service and WiMAX as a MAN (Metropolitan Area Network) service. These solutions are under a worldwide competition. Evolutions are taking over on these technologies in order to deploy high performance networks to wide areas.

We can see an example of system configurations in the Heathrow Express. The line links city of London and Heathrow Airport. The 30km-journey with maximum speed of 160km/h takes 15 minutes. An internet connection service was launched for onboard passengers in 2007. In London, the Internet is accessible through Wi-Fi services in many places such as airports, train stations, hotels, cafes and so on. Cabins on trains are not an exception for places with an internet accessibility. Passengers are likely to read e-mail and send documents for business purposes, and tend to download music and destination information for private use.

WiMAX is an access line on the underground section (7km long) of the line. On the other areas, cellular networks of HSPA (High Speed Packet Access) are in use. The underground section has a large curve. Five WiMAX ground stations covers 7km. WiMAX is on an unlicensed 5.4GHz band. CCU (Communication Control Unit) controls the ground-train link. A train equips 3 antennas in total, two for WiMAX and one for HSPA. Passenger accesses are provided through IEEE 802.11g. Wi-Fi access points are set up on the ceiling of each cabin. Links between cabins are on IEEE 802.11a. The system configuration is shown in Fig. 2-10.

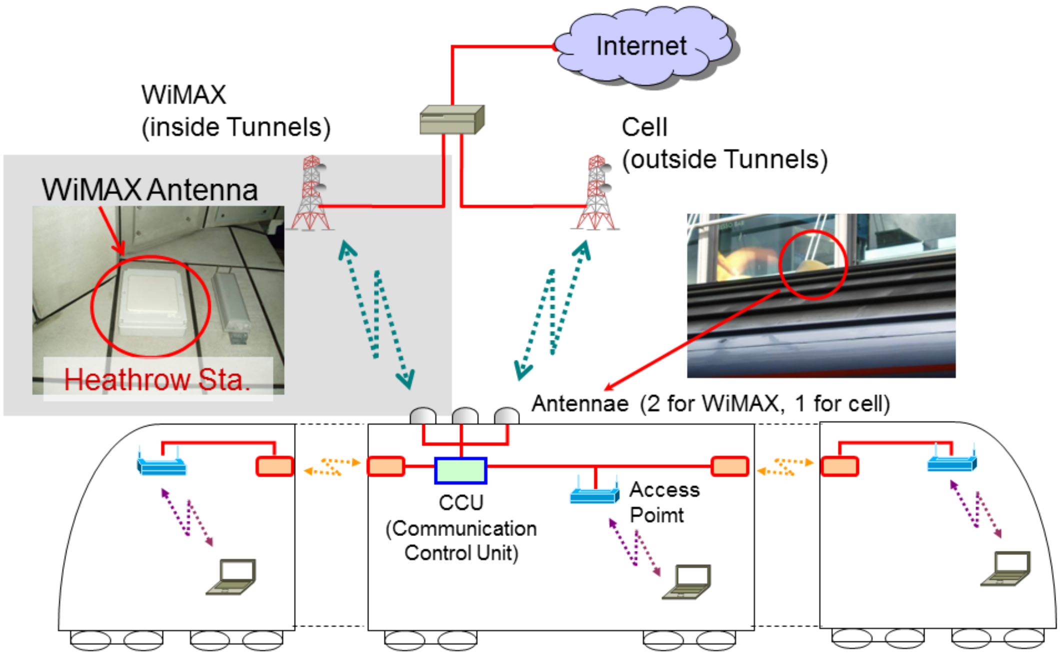


Fig. 2-10 System Configuration by Communication Carrier System for Heathrow Express

2.3. Ideal Train Communication System in the Future

Various mobile communication technologies are applied to high speed rail systems in the world as described in section 2.2. Some of them switches communication media while traveling, however, no system has a load balancing solution which simultaneously uses multiple communication media.

High speed mobile entities go through various places such as cities, rural areas, mountainous areas and tunnels. No communication technologies fit for all of the situations from a view point of geographical condition. Each media has to be employed to match their advantages with background conditions. A communication system should equip multiple wireless communication media and they should be adequately controlled to perform together at the same time. The word "perform together at the same time" means that traffic is load balanced on active wireless communication media, which makes the communication speed faster up to the total of all the active media. We named this kind of system "Media Convergence System." It is the Media Convergence System that is the desired train communication system we would like to design for the future.

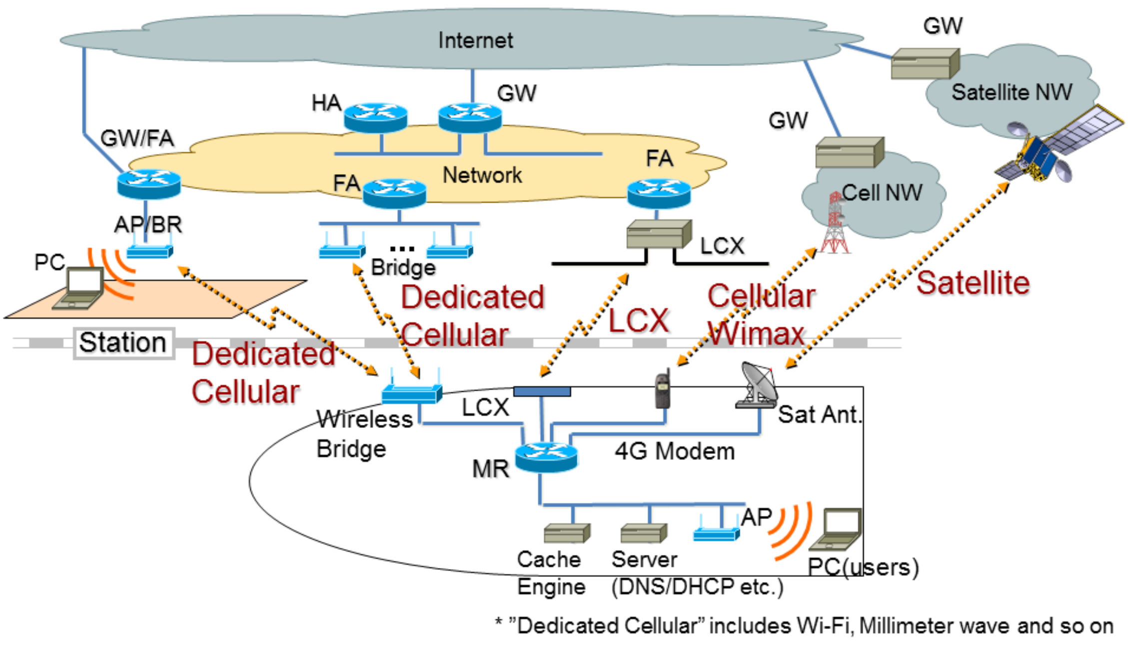


Fig. 2-11 Media Convergence System (Re-drawn of Fig. 1-1)

A certain protocol is required in order to interconnect plural wireless communication media on the Media Convergence System. The best matched protocol to do it is IP. One or more subnet(s) are deployed for each wireless communication medium and consolidated on the Network Layer using IP. In other words, the Media Convergence System is able to support any wireless communication media which support IP.

A configuration example of the Media Convergence System is illustrated in Fig. 2-11. Fig. 2-11 contains communication media such as LCX, IEEE 802.11g, satellite and WiMAX as an example. All the communication media other than these are also able to be mounted on the Media Convergence System.

2.4. Summary

This chapter surveyed various train communication systems with their history and summarized their characteristics. As for communication media for present high speed rail systems, a Digitalized LCX Communication System, a Satellite Communication System and a Wi-Fi Communication System were reported. The reported maximum speed for all of them is around 2(*Mbps*) in commercial services. It is required to increase communication speed in current circumstances where high speed accesses with the use of optical fibers have already prevailed in offices and at homes. Three communication media have advantages and disadvantages to each other. For instance, Digitalized LCX Communication Systems have a constraint on a radio frequency resource and thus a substantial increase in the communication speed is out of expectation. Satellite Communication Systems are unavailable in tunnels. High speed trains generally travel through various geographical areas such as cities, suburbs, mountains, tunnels and so on. Required communication speed varies in each section because the number of trains (train density) differs from place to place. It is unrealistic to cover all the tracks with a single wireless communication medium.

We need flexibility on a system configuration with a freedom of choice of communication media. Adequate communication media should be installed in adequate areas. The Media Convergence System which is proposed in this chapter is a solution. The Media Convergence System is the one we should design for the future.

Chapter 3. Proposal of a High Speed Communication System based on IEEE 802.11g

Chapter 2 proposed the Media Convergence System as a desired communication system in the future. The Media Convergence System logically bundles up all the wireless communication media available at local places into a single path. Traffic is load balanced on active communication media, which makes the communication speed faster up to the total of all the active media. However, it is ineffective when the Media Convergence System consists of communication media with low performances. The Media Convergence System needs a pivot wireless communication medium. After a careful consideration, this chapter proposes IEEE 802.11g which has a high performance in communication with high financial efficiency as a pivot communication medium.

The major objective of this chapter is a system design of the IEEE 802.11g Communication System. This chapter describes how to apply IEEE 802.11g for high speed trains. The system was designed for each Layer. Since the IEEE 802.11g Communication System assumed IEEE 802.11g on Layer 2, no customization was allowed to be implemented on IEEE 802.11g itself. On the other side, Layer 1 and Layer 3 were developed to support high speed movements. This chapter focuses on "a radio transmission channel design" on Layer 1 and "a network design" on Layer 3.

3.1. Introduction

Functions of mobile terminals have been advancing. Network accessing devices have been increasing. Cloud Computing which requires to be always on line has been spreading. A manner of computer usage is changing to one where it is assumed that high speed networks are always available. Therefore an environment where we can get a broadband connection anywhere anytime is required.

Having a broadband connection on high speed rails is something that business travelers want most. An internet connection service has started on the Tokaido-Shinkansen (Japan) since March 2009. The system provided a very stable downlink speed of 2Mbps (for the link from the ground to a train) with the use of a LCX technology.

We proposed the Media Convergence System to bundle plural communication media in Chapter 2. It is the desired system for train communications in the future. The Media Convergence System load-balances traffic over all the active wireless communication media. Communication bandwidth between the ground network and each train becomes the total bandwidths. The idea is productive, but ineffective when the Media Convergence System consists of communication media with low performances. As surveyed in Section 2.2, any current communication medium does not show a performance higher than a few Mbps. The Media Convergence System needs a pivot wireless communication medium.

At first, this chapter considers a pivot communication medium for the Media Convergence System. Requirements for the medium are; having enough communication speed, feasible in the near future, available in the market for a moderate price and so on. Wi-Fi was positioned in the center of our consideration for media, which satisfies the requirements. We propose IEEE 802.11g which has a high performance in communication with high financial efficiency.

The major objective of this chapter is a system design of the IEEE 802.11g Communication System. The IEEE 802.11g Communication System is one of the cellular communication systems as described in Section 2.2.6. Although a basic system configuration does not have a big difference from other cellular systems, system designs require careful considerations for mobility of high speed trains, because mobile stations in the IEEE 802.11g Communication System experience frequent L2HOs. This chapter describes how to apply IEEE 802.11g for high speed trains. The system is designed for each Layer. The IEEE 802.11g Communication system is one of the access networks to the Internet from cabins on high speed trains. Subjects of design lie on Layer 3 and lower. For Layer 4 and higher, all protocols, applications and services perform on this platform.

Major design policies for each layer are as follows. For a radio transmission channel on Layer 1, a radio propagation line is established on train tracks by a high gain directional antenna. The Fresnel Zone is kept as clear as possible to make the quality of the radio transmission channel higher. The IEEE 802.11g Communication System leverages IEEE 802.11g on its Layer 2 links as the name indicates. One of the requirements for the system is to construct a system in which it is affordable with the use of IEEE 802.11g. Our policy does not permit any customizations on IEEE 802.11g. Product dependences are accepted on Layer 2. At last, design policies on Layer 3 are as follows. The IEEE 802.11g Communication System assumes trains as its mobile stations. Since trains move on their tracks, a migration path for each train can be identified unless the train suddenly leaves its intended route. This peculiar characteristic allows us to design a network topology which minimizes damages to communications caused by L3HOs.

The organization of this chapter is as follows. Section 3.3 points out the nonexistence of a candidate for a pivot communication medium in the Media Convergence System in the current situation. In order to tackle this problem, IEEE 802.11g is proposed for the pivot communication medium. It is expected to achieve high communication performances with high economic efficiency. Section 3.4 mentions the basic configuration of the IEEE 802.1g Communication System. Section 3.5 describes designs for a radio transmission channel on Layer 1. Section 3.6 verifies required functions on Layer 2 and chooses an IEEE 802.11g product for the system. Section 3.7 discusses network designs to support high speed mobility. MIPv4 is employed for the platform to make the IEEE 802.11g Communication System compatible with the current LCX Communication System. Section 3.8 summarizes this chapter.

3.2. Related Works

The IEEE 802.11g Communication System must support network mobility. Mobility support for IP networks has been defined by MIP. However, L3HOs on the default MIP architecture take a long time. This is a well-known problem. Various countermeasures to make L3HO process time shorter have been proposed.

3.2.1. L3HOs in MIPv4

RFC3344[14] describes MIPv4 as follows.

> *Each mobile node is always identified by its home address, regardless of its current point of attachment to the Internet. While situated away from its home, a mobile node is also associated with a care-of address, which provides information about its current point of attachment to the Internet. The protocol provides for registering the care-of address with a home agent. The home agent sends datagrams destined for the mobile node through a tunnel to the care-of address. After arriving at the end of the tunnel, each datagram is then delivered to the mobile node.*
>
> (Citation : RFC3344 abstract)

A L3HO in MIPv4 is a process where MR updates a care-of-address and registers it on HA. Now consider about a movement of MR from pFA to nFA in Fig. 3-1. After the TBR completed a L2HO from pBR to nBR, A L3HO by MIPv4 is required to keep IP reachability. In order to start the L3HO by MR, MR needs to listen to an IRDP Advertisement [19] from nFA and detect self-movement. This L3HO process is depicted in Fig. 3-2. A problem of this default L3HO in MIPv4 is a delay. As shown in Fig. 3-2, MR is not able to start a L3HO process until it receives an IRDP Advertisement from nFA. In general, a FA periodically broadcasts IRDP Advertisements. In the worst case, this default L3HO procedure makes a delay of the IRDP Advertisement sending interval from nFA.

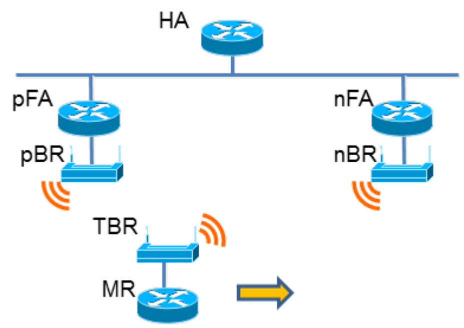
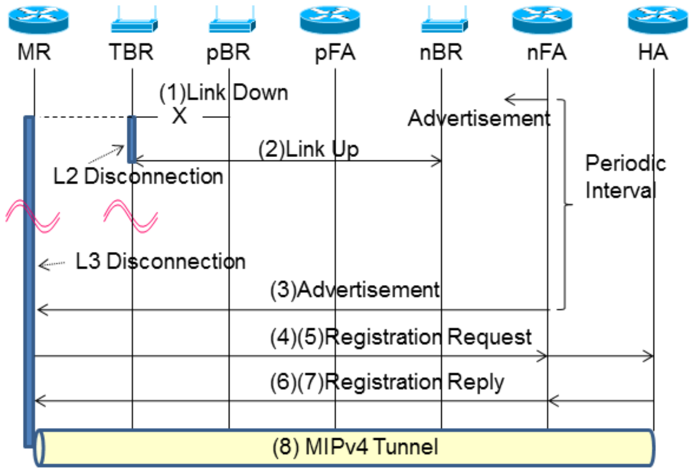


Fig. 3-1 L3HO by MIPv4



(1) IEEE 802.11g Link Down with pBR
(2) IEEE 802.11g Link Up with nBR
(3) An IRDP Advertisement reaches MR from nFA
(4) MR sends a Registration Request (RRQ)
(5) nFA relays the RRQ to HA
(6) HA replies with Registration Reply (RRP)
(7) nFA relays the RRP to MR
(8) A MIPv4 Tunnel is established

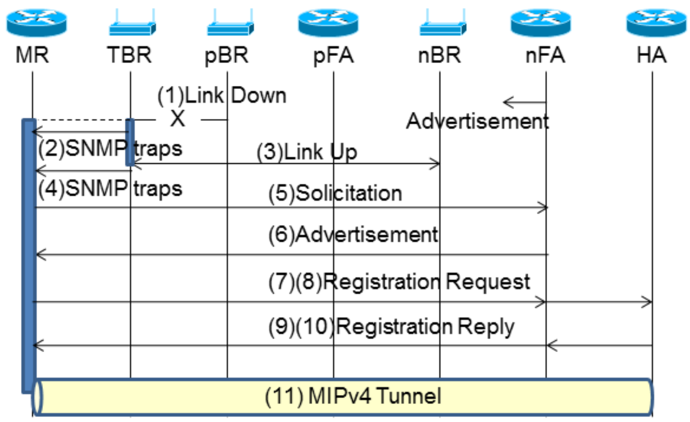
Fig. 3-2 MIPv4 Handover (Default)

3.2.2. Fast L3HOs

A simple MIPv4 network topology without consideration causes high latency in L3HOs. This fatal problem is a well-known fact. There are many research papers for making MIPv4 handovers faster. Major characteristics of these papers are described as follows.

(1) L2 Triggered L3HOs

This method reduces latency between a L2HO completion and a L3HO activation. Layer 2 (wireless link interface) status information is used in many cases [20][21][22][23][24][25]. For example, a status of an IEEE 802.11g interface is informed MR through SNMP traps, when it changes [20]. The notification triggers MR to broadcast an IRDP Solicitation. After a receipt of the solicitation, a FA replies with an IRDP Advertisement, which lets MR start a L3HO process. With this method, MR is able to begin a L3HO procedure just after the L2HO completion. Fig. 3-3 shows the L2 triggered L3HO process in a topology depicted in Fig. 3-1.



(1) IEEE 802.11g Link Down with pBR
(2) TBR informs MR of the event
(3) IEEE 802.11g Link Up with nBR
(4) TBR informs MR of the event
(5) MR broadcasts an IRDP Solicitation for an IRDP Advertisement
(6) nFA replies with an IRDP Advertisement to MR
(7) MR sends a Registration Request (RRQ)
(8) FA relays the RRQ to HA
(9) HA replies with Registration Reply (RRP)
(10)FA relays the RRP to MR
(11)A MIPv4 Tunnel is established

Fig. 3-3 MIPv4 Handover with SNMP traps

(2) Reducing process time of each L3HO

There are methods to reduce process time of each L3HO. In Hierarchical Mobile IPv6

(HMIPv6) [26], the ground network is configured in a hierarchical topology. Mobile nodes are locally managed for their location and thus latency for Binding Updates is reduced. A similar approach was also proposed in [27].

(3) Separation of a L3HO from a L2HO

When a L3HO occurs just after a L2HO, higher layer protocols lose reachability during the total time of a L2HO and a L3HO. This method detaches a L3HO from a L2HO. And further, if a L3HO is processed while data traffic is being transmitted, transmission latency of a Registration Request and a Registration Reply (which are exchanged between HA and MR) can be eliminated from a L3HO procedure time. This method can reduce damages to the communication performance, though it still results in some packet drops when a L3HO process changes active FAs on a MIPv4 Tunnel.

In this method, a FA to which MR is going to be connected must be identified without failure, because MR logically moves to the future FA by the time the physical link is changed from the current FA to the future FA. Mobile IPv6 Fast Handovers (FMIPv6)[28] describes a method to do a L3HO prior to a L2HO with an identification of a New Access Router (NAR) based on link layer information. Packets are forwarded from the Previous Access Router (PAR) to the NAR during the L2HO.

3.3. Proposal of the IEEE 802.11g Communication System

Traffic is load balanced on active wireless communication media in the Media Convergence System. The communication bandwidth between the Ground network and each Mobile Station is the total bandwidths of all the active media. It contributes to make the communication speed faster, but it is ineffective when the Media Convergence System consists of communication media with low performances. Section 2.2 reports various train communication media. However any medium has a bandwidth up to a few Mbps and it is obviously not enough. The Media Convergence System needs a pivot wireless communication medium. The pivot wireless communication medium for the Media Convergence System has to satisfy four following requirements.

(1) To have enough communication bandwidth

The system is operated under a high speed mobile environment of around 300(*km/h*). It is impossible to obtain the same Giga-bits communication as in offices or homes. The maximum TCP throughput for current systems is around 1(*Mbps*). We decided to require one digit larger throughput for a pivot wireless communication medium for the Media Convergence System. So

the target throughput of the pivot medium was set to 10(*Mbps*) for applications.

(2) To be feasible and affordable in the near future

This requirement is frequently demanded in many systems. A pivot wireless communication media we are seeking is not an exception. It must be feasible and affordable in the near future. In order to satisfy this requirement, **commercially available wireless devices** must be employed instead of developing a new one.

(3) To be easy to procure devices for the system

An easiness of device procurement is directly connected to cost and maintainability. It is demanded to use as many commercially available wireless devices as possible. In order to satisfy this requirement, **widely distributed wireless communication media in the market** must be employed. Especially, an international standard device is desirable.

(4) To be easy to operate

Operational difficulties may cause failures, human errors and troubles in real operations. Wireless communication media to be operated easily must be employed. **Widely distributed wireless communication media in the market** may satisfy this requirement.

With the consideration of these four requirements, a pivot wireless communication medium in the Media Convergence System was chosen as follows. A desired communication medium must have a communication bandwidth of 10(*Mbps*) or more. It also must be commercially available and widely distributed in the market. There are only a few wireless communication media which are widely distributed in the market. Candidates are Wi-Fi, Wimax and cellular phone systems. Wimax and cellular phone systems are communication carriers' services and they are operated under their managements. It is only Wi-Fi in which all parts are available in the market. Wi-Fi was internationally standardized as IEEE 802.11.

Although IEEE 802.11 has some varieties under itself, there are only four types which have a large market. They are IEEE 802.11a, IEEE 802.11b, IEEE 802.11g and IEEE 802.11n. A required wireless communication medium must have a communication bandwidth of around 10(*Mbps*), which is 10 times faster than current media. Even though the maximum speed of IEEE 802.11b is 11(*Mbps*), the expected average throughput is around 5(*Mbps*). It does not meet the requirement. IEEE 802.11n is able to communicate in 300(*Mbps*) by MIMO (Mulitple-Input Mutiple-Output) technology which multiplexes communication channels. Although the communication speed of IEEE 802.11n is quite attractive, it is a large risk to choose it before verifying IEEE 802.11g, the ancestor of IEEE 802.11n. Both IEEE 802.11a and IEEE 802.11g supports the maximum speed of 54(*Mbps*) in the specification by OFDM (Orthogonal Frequency Division Multiplexing) technology. As for frequency, IEEE 802.11a works on the 5.2GHz band. IEEE 802.11g performs on the 2.4GHz band. IEEE 802.11a has three channel groups, W52, W53 and W56. Since W52 and W53 are restricted for outside use in Japan, thus they are not eligible as candidates of a pivot wireless communication medium. W56 is allowed to be deployed outside, though it uses the same bandwidth of a meteorological radar. Japanese regulations oblige W56 devices to avoid interferences with the radar by DFS (Dynamic Frequency Selection). When a W56 device detects a radar signal, it must stop its emission and change channels. This process results in a communication disruption. Therefore we decided not to take IEEE 802.11a for a pivot communication medium. IEEE 802.11g is the most popular Wi-Fi technology in the current market. IEEE 802.11g device prices are relatively lower than other radio stations. It has no restrictions for outside use. We can deploy IEEE 802.11g devices anywhere with our discretion. As a result of the discussion above, IEEE 802.11g was employed as a pivot wireless communication medium in the Media Convergence System. This research is aiming at **developing a broadband communication system based on IEEE 802.11g under high speed mobile environments.**

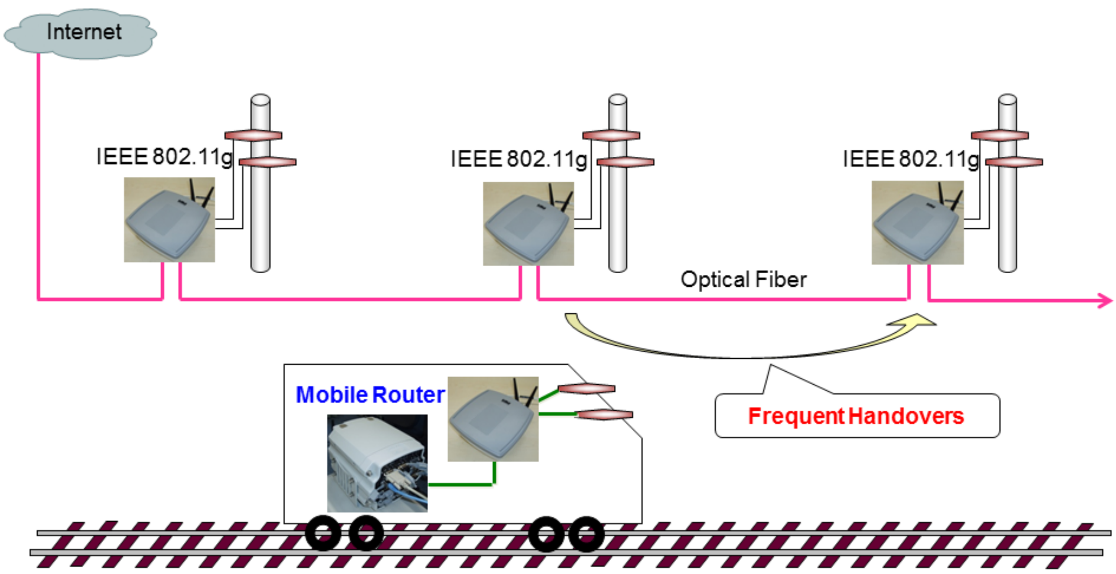


Fig. 3-4 Basic Configuration of IEEE 802.11g Communication System

3.4. Basic Configuration of the IEEE 802.11g Communication System

The IEEE 802.11g Communication System is a small-sized cellular system. A basic configuration is almost the same as other cellular systems. As is the case with cellular phone systems, wireless cells are deployed on the ground. Wireless cells for a cellular phone system have to be two-dimensionally deployed in cities. On the other side, for the IEEE 802.11g Communication System, IEEE 802.11g cells were one-dimensionally deployed on a rail track. A basic configuration of the IEEE 802.11g Communication System is depicted in Fig. 3-4. Mobile stations hop ground stations from one to another as they move.

3.5. Design of a Radio Transmission Channel

This section describes a design of the Physical Layer, or a radio transmission channel if stated differently, of the IEEE 802.11g Communication System.

3.5.1. Overview of Radio Transmission Channel

The output power of IEEE 802.11g is limited by regulations in each country. Since trains equipping a mobile station run on rail tracks in the IEEE 802.11g Communication System, the coverage must be focused on the tracks rather than relying on circular coverage. Ground stations were set up and the signal was emitted in the direction parallel to the tracks. It is able to extend the coverage farther for each ground station.

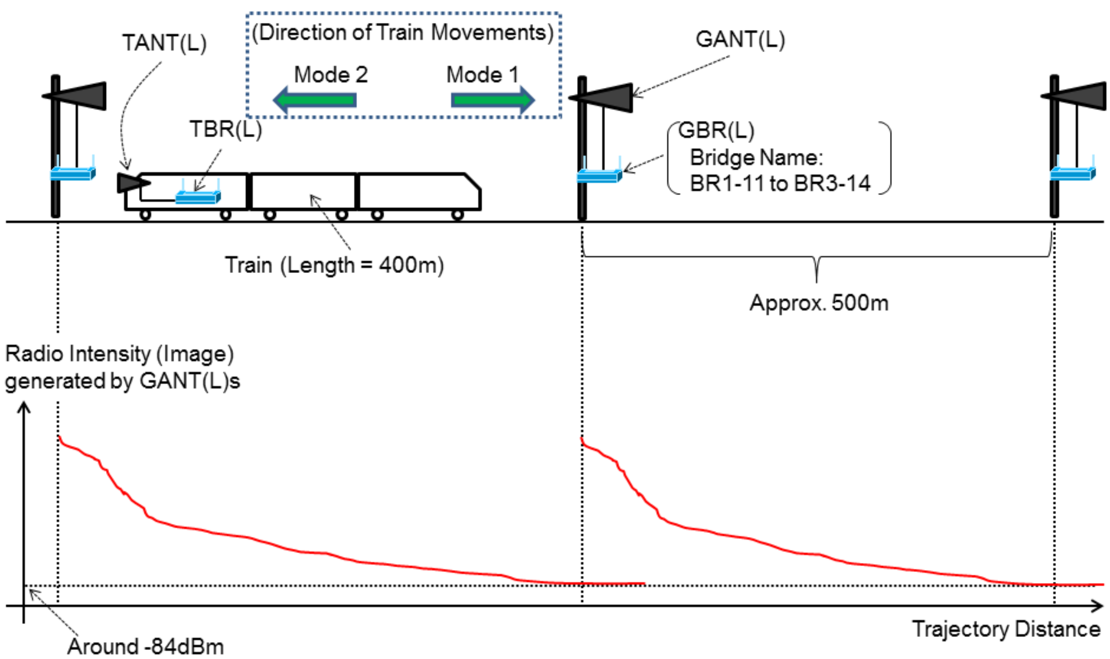
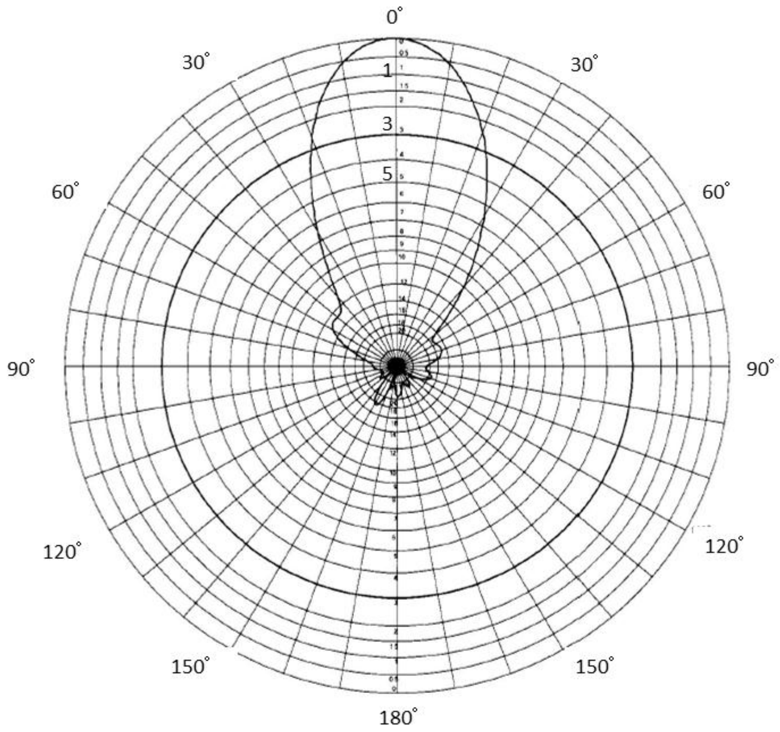
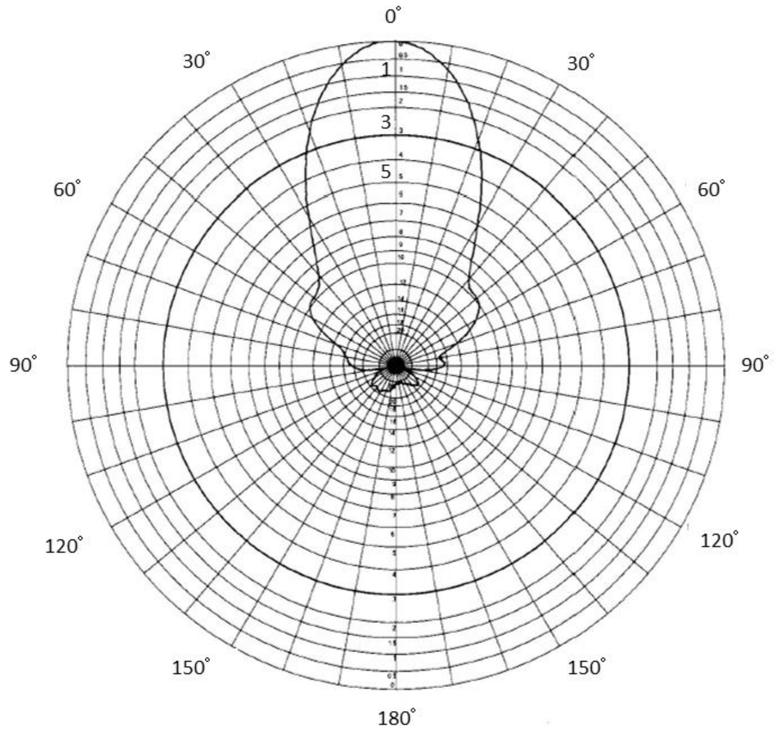


Fig. 3-5 Configuration of Wireless Links (Single-path)



E-Plate



H-Plate

Fig. 3-6 Antenna Pattern

Counterpart antennas on mobile stations must have the same beam spread that ground stations have. It is apparent that antennas of mobile stations should be mounted at the front or the rear edge. For our IEEE 802.11g experimental system, they were set up in a drivers' cabin. As a result, ground and train antennas were deployed as shown in Fig. 3-5 for radio transmission channels of the IEEE 802.11g Communication System. GBR(L) stands for "Ground Bridge (Left path)" and it is an IEEE 802.11g station device. GANT(L) shows "Ground Antenna (Left path)" and it is an external antenna connected with GBR(L) through a co-axial cable. The word "Ground station" includes GBR(L), GANT(L) and the other devices to maintain a connection of each GBR(L) with the backbone network. TBR(L) and TANT(L) respectively stands for "Train Bridge (Left path)" and "Train Antenna (Left path)." The word "Mobile station" contains all the devices and networks on each train. A reason why these abbreviations have "(L)" is a distinction from the same type of additional devices for the Dualpath Configuration described in Chapter 5. Each additional device has a suffix of "(R)" for Right path.

3.5.2. Radio Antennas

A trajectory of each part on a train is the same over a rail track whenever the train moves. Therefore when antennas on a train are installed at a point from which they are able to see counterpart antennas on the ground, an exceptional wireless communication condition can be established apart from the Doppler shift whenever the train passes through. Also directional antennas can cover one-dimensional rail tracks effectively. With these characteristics taken into account, an antenna was developed with 11.5(*dBi*) gain and the half-value angle of 40 degrees. The antenna pattern on 2,450(*MHz*) is shown in Fig. 3-6.

3.5.3. Design of Radio Transmission Line

An IEEE 802.11g radio transmission channel was designed with an assumption where a propagation loss of electro-magnetic waves obeys the free space loss model. The track on which the Mobile Station moves is assumed to be straight. A geometrical deployment of communicating antennas is depicted in Fig. 3-7. The intersection point of the track (the trajectory of the Mobile Station) and the perpendicular line dropped onto the trajectory from the Ground Station is set to 0. Let the distance between the intersection and the Mobile Station (referred to as Trajectory Distance) be d. And let the distance between antennas be l. The Ground Station was located on a perpendicular direction 3.0(m) from the center of two rails. The signal from the Ground Station was directed parallel to the rail track. The angle to see the Mobile Station from the emitted signal direction is referred to as Directional Angle and let it be θ.

For both the Ground Station and the Mobile Station, the output power of IEEE 802.11g is 10(*dBm*) and the pattern of antennas gain is shown in Fig. 3-6 with the maximum of 11.5(*dBi*).

Coaxial cables between antennas and radio stations are AIR-CAB020LL-R [29] manufactured by Cisco which has a signal power loss of 1.3(dB). Two antennas were connected to the GBR and the TBR for a diversity transmission and reception. TANTs were set up in a drivers' cabin. A windshield is placed on the radio propagation line and causes a penetration loss of signal. Although a penetration loss on normal glass is small enough to neglect, a windshield on high speed trains is especially robust and causes a significant propagation loss. The measured penetration loss was 8.3(dB) on 2.45(GHz) for IEEE 802.11g. As a result, the transmission line of IEEE 802.11g Communication System is as shown in Fig. 3-8. Characteristics of the communication line for IEEE 802.11g Communication Systems are symmetric. When signal is transmitted from the GBR, the input power on the TBR, $P_{rcv}(dBm)$, is formulated as follows.

$$P_{rcv} = 22.1 - L_{ant} - L_{air} \tag{3-1}$$

Where, $L_{ant}\ (dB)$ is a loss shown as in Fig. 3-6. The amount of loss depends on the Directional Angle. Let $L_{air}\ (dB)$ be a propagation loss in air. The free space propagation loss model shown in the next formula is employed for $L_{ant}\ (dB)$.

$$L_{air} = 10\log(\frac{4\pi l}{\lambda})^2 \tag{3-2}$$

Where, λ is a wave length of the electro-magnetic waves. IEEE 802.11g has 13 channels. The 1ch is allocated on 2.412(GHz) for its center frequency with a wave length, $\lambda = 1.244 \times 10^{-1}\ (m)$, while the 13ch is on 2.472(GHz) with $\lambda = 1.214 \times 10^{-1}(m)$. Since the frequency differences among channels are small, the channel difference does not have a significant effect on L_{air}. However, in order to make assurances, the worst scenario was taken into account. A radio transmission line was designed on 13ch with the largest L_{air} of all the IEEE 802.11g channels.

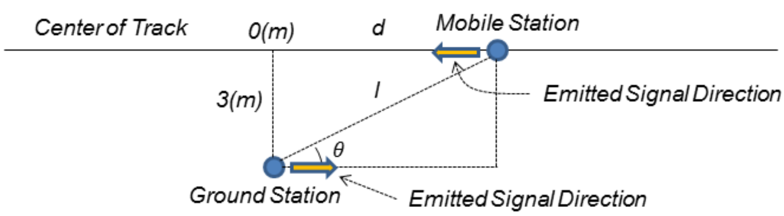


Fig. 3-7 Geometrical Deployment of Radio Stations

Assuming that the Mobile Station does not pass by the Ground Station while communicating, the Trajectory Distance d, must be a positive number. This is because the Mobile Station associates with an adjacent Ground Station (which must be set up on the left side of the Ground Station in Fig. 3-7), when it moves in the left direction and passes by the communicating Ground Station. When the position of the Mobile Station is given, the Directional Angle and the distance between antennas are uniquely fixed. $L_{ant}\ (dB)$ and $L_{air}\ (dB)$ depend only on the Trajectory Distance d. The input power on the TBR, $P_{rcv}(dBm)$, is shown in Fig. 3-9 as a function of the Trajectory Distance d.

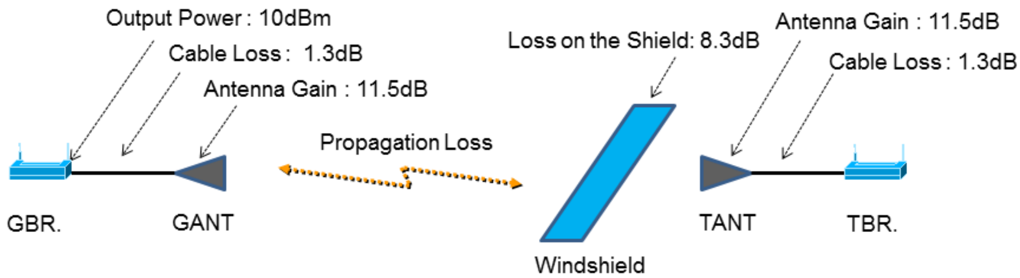


Fig. 3-8 Communication Line for IEEE 802.11g Communication System

It is required to keep the Fresnel Zone as clear as possible in order to reduce the propagation loss in real situations. The Fresnel Radius takes the largest value r_F , in the middle of two communicating points. r_F is formulated as follows.

$$\begin{aligned} r_F &= \frac{\sqrt{\lambda l}}{2} \\ &= \frac{1}{2}\lambda^{\frac{1}{2}}(d^2 + 3^2)^{\frac{1}{4}} \end{aligned} \tag{3-3}$$

Although differences of a wave length among IEEE 802.11g channels do not have a significant effect on r_F, in order to make assurances, we employed the wave length which maximizes r_F. The wave length is $1.244 \times 10^{-1}\ (m)$ for 1ch of IEEE 802.11g with the center frequency of 2.412(GHz).

Consider the height where antennas should be set up to keep the Fresnel Zone. When the Trajectory Distance d, is 500(m), the maximum Fresnel Radius r_F, becomes 3.94(m). Here 500(m) for d was chosen just for estimation. The IEEE 802.11g Communication System is dedicated to high speed trains. Locations for devices to be installed have various physical restraints. For example, a train body does not have a height of 3.94(m). Therefore it is obvious that keeping the Fresnel zone clear is impossible. Antennas on both communicating sides were set up at around 2.4(m) high from the ground. The antennas with that height keep about 60% of the maximum Fresnel Radius clear at Trajectory Distance of 500(m).

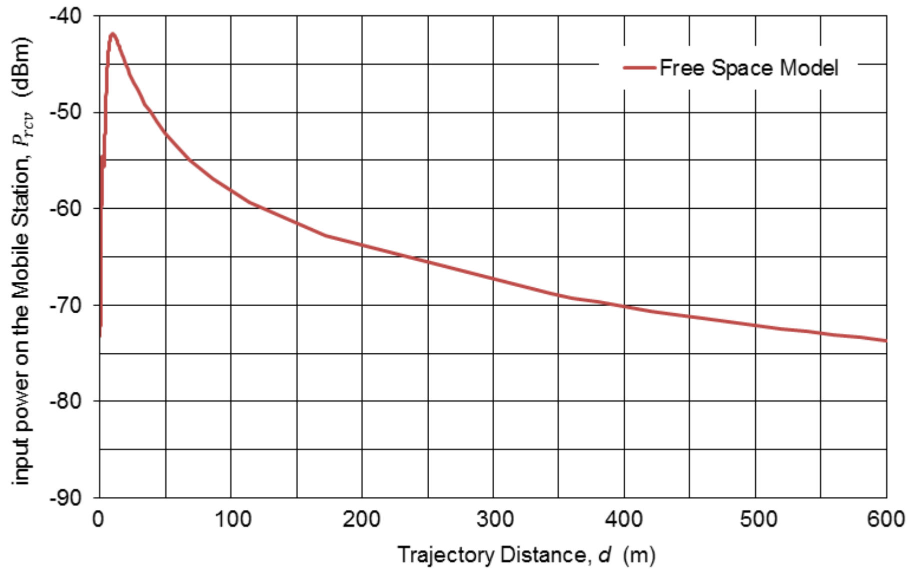


Fig. 3-9 Communication Line Design

3.5.4. Observations of signal propagation during high speed movement

RSSI which a mobile station received was measured while the train was moving at 270km/h. Cisco-manufactured AIR-BR1310G-J-K9-R IEEE 802.11g bridge (BR1310) [30] was used for both GBR and TBR. A BR1310 was the one we employed for all GBRs and TBRs for the IEEE 802.11g Communication System. Both GANTs and TANTs were set up at a height of 2.4(*m*). Both sides have two antennas for diversity transmission and reception. A system for this observation is shown in Fig. 3-10.

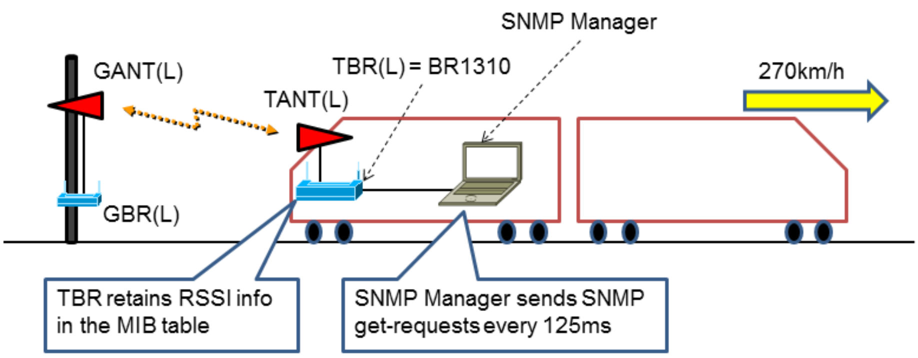


Fig. 3-10 RSSI Measurement Configuration

A BR1310 has a real-time RSSI value from the counterpart BR1310 in its MIB (Management Information Base) table. A RSSI value in the MIB table of the TBR was periodically checked by

SNMP (Simple Network Management Protocol) get-requests every 125(*ms*). The train moved away from the ground station at speed of 270(*km/h*). Fig. 3-11 shows the result. The solid line on the graph is borrowed from Fig. 3-9 and shows the calculated input power on the TBR, $P_{rcv}(dBm)$. It is referred to as the theoretical value.

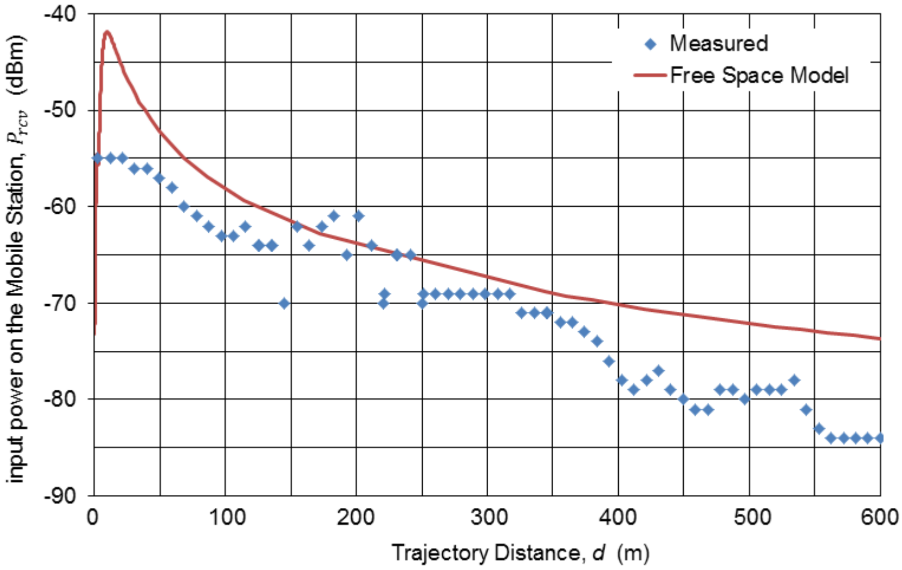


Fig. 3-11 Received RSSI on Mobile Station

Theoretically, RSSI which is received on the TBR has a peak at $d = 9.8(m)$ due to the directional pattern of the antenna. It takes only 131(*ms*) for the train to move the distance. On the other side, the TBR is not able to associate with a GBR just after it enters the GBR coverage in real situations, because the pair of BR1310s on the ground and the train has to detect beacon signals from their counterpart BR1310s, synchronize the radio, and authenticate each other by AES (Advanced Encryption Standard). RSSI does not have a peak, when the train goes farther than 9.8(*m*) in this processing time.

A difference between measured and the theoretical values was larger in a shorter Trajectory Distance of $d < 100(m)$, and a longer Trajectory Distance of $d > 400(m)$. Although the free space loss model was employed for the theoretical value calculation, the real environment has differences from the theory as follows.

(1) Observations under a high speed (270(*km/h*)) movement

(2) Not a free space

(3) Unclear and changeable Fresnel Zone due to movements

(4) Multipath transmission and multipath fading

(5) The Doppler shift due to a high speed movement

When the Trajectory Distance *d*, is 100(*m*) or shorter, the observation and the theory differ from each other. In that range, however, the measured RSSIs have -65(*dBm*) or larger. According to Table 3-1 showing the required RSSI for a BR1310 [30], it is -72(*dBm*) to communicate at the maximum speed of 54(*Mbps*) for IEEE 802.11g. The observed values exceeded this threshold. Thus the condition of the communication channel where *d* is 100(*m*) or shorter is quite good. It is clear that IEEE 802.11g is able to perform proficiently.

The larger the Trajectory Distance becomes, the more severely (3) and (4) affects the difference between the observed and the theoretical value. The Fresnel Radius is in proportion to the $\frac{1}{2}$ power of the Trajectory Distance. On the other side, the cleared radius is equivalent to the height of the antennas, which is 2.4(*m*) high. The maximum value of the Trajectory Distance with the completely cleared Fresnel Radius is 185.2(*m*). When the onboard BR1310 goes farther than that distance, the Fresnel Zone loses some of the outer area. This may be a significant cause for the gap around 8(*dB*) between the measured and the theory. The design of communication line was based on the observed values.

The observation result shows another meaningful fact. The measured RSSI is the received RSSI on the TBR. It is not a radio field intensity obtained by a spectrum analyzer. The fact that the measured RSSI is a finite number indicates IEEE 802.11g works as a communication line while the TBR is traveling at 270(*km/h*).

Table 3-1 Requested RSSI for Each Communication Speed [30]

Communication Speed	Modulation	Code Rate	Required RSSI (dBm)
1 Mbps	DBPSK	Barker	-94
2 Mbps	DQPSK	Barker	-91
5.5 Mbps	DQPSK	CCK	-89
11 Mbps	DQPSK	CCK	-85
6 Mbps	BPSK	1/2	-90
9 Mbps	BPSK	3/4	-89
11 Mbps	QPSK	1/2	-86
18 Mbps	QPSK	3/4	-84
24 Mbps	16QAM	1/2	-81
36 Mbps	16QAM	3/4	-77
48 Mbps	64QAM	2/3	-73
54 Mbps	64QAM	3/4	-72

3.5.5. Deployment of Ground Stations

The IEEE 802.11g Communication System is targeting at an average application throughput of 10(*Mbps*) or more during high speed movements. IEEE 802.11g works with an Adaptive Modulation.

When a radio field intensity is large enough, the maximum speed of 54($Mbps$) is expected. On the other side, modulation speed gets slower near edges of wireless cells and communication throughput is changeable during movement. When 18($Mbps$), one of the IEEE 802.11g modulation speeds, is available near each edge of coverage, an average application throughput during high speed movements should achieve 10($Mbps$). A modulation speed of 18($Mbps$) is based on a QPSK (Quadrature Phase Shift Keying) modulation with a code rate of 3/4. The radio transmission channel of the IEEE 802.11g Communication System was designed to obtain this modulation speed.

According to Table 3-1, the required RSSI is -84(dBm) for BR1310 to achieve a modulation speed of 18($Mbps$). We decided to keep a design margin of 3(dB) for the radio transmission channel of the IEEE 802.11g Communication System. Therefore an adjacent ground station should be set up not farther than where P_{rcv} drops under -81(dBm). Fig. 3-11 shows that this distance is around 500(m). This value is the target distance between adjacent ground stations of the IEEE 802.11g Communication System under the ideal condition without any constraint. The IEEE 802.11g Communication System was installed on a commercial high speed rail system. There were some physical constraints due to existing facilities in deploying ground stations on the trackside. Lower P_{rcv} than -81(dBm) had to be accepted in some places. Although the throughput deteriorates in such rare cases, we expected that an average application throughput during high speed movements could exceed 10($Mbps$).

3.5.6. Channel Allocation for IEEE 802.11g

IEEE 802.11g has 13 channels. Three channels are able to work at the same time without any radio interference with each other. Our experimental IEEE 802.11g Communication System has 11 ground stations. One of each channel, 3ch, 8ch, and 13ch, were repeatedly allocated in this order to each GBR of the ground stations. This channel set has no radio interference. In the IEEE 802.11g Communication System, a TBR of mobile stations working as client bridges periodically searches for GBRs performing as parent bridges. IEEE 802.11g channels which the TBR scans were also limited to 3ch, 8ch and 13ch.

3.5.7. Mode 1 and Mode 2

Since a TBR was set up at an edge of a high speed train, communication performances depend on the running direction of the train [31]. As the train travels with the TBR at the rear edge of the train, in this case the train moves in the right direction in Fig. 3-5, the distance between the two communicating antennas gets larger. This mode is defined as Mode 1, or named “Departing Scenario.” On the other side, as the train travels with the TBR at the front edge of the train, in this case the train moves in the left direction in Fig. 3-5, the distance between the two communicating antennas gets smaller. This mode is defined as Mode 2, or named “Approaching Scenario.”

3.6. Required Layer 2 Functions and a Selected Device

The IEEE 802.11g Communication System uses IEEE 802.11g for Layer 2, as its name suggests. One of the objectives is to construct the system for an affordable price with the use of commercially available IEEE 802.11g devices. When devices are modified, they become special ordered devices and the cost for them increases dramatically. Therefore customizations on IEEE 802.11g commercial devices are not allowed at all. Layer 2 performances differ from product to product. An IEEE 802.11g device which suits a high speed mobile communication was selected.

3.6.1. Required Functions on the IEEE 802.11g Device

Required functions on IEEE 802.11g devices are considered as follows. Section 3.5 describes a design of a radio transmission channel for the IEEE 802.11g Communication System. A radio propagation path was established in open areas above train tracks. The Fresnel Zone was kept as clear as possible. Consequently, IEEE 802.11g properly linked up while the mobile station was traveling at 270(*km/h*) and acquired enough RSSI to obtain throughput of 10(*Mbps*) or more as shown in Fig. 3-11. Since it is a mobile communication by radio, especially under a high speed mobile environment, packet losses are unavoidable on IEEE 802.11g links. A Retransmission Control of TCP is able to compensate for packet losses for End-to-End communication. Furthermore, a Congestion Control also works as well as a Retransmission Control in TCP. A Congestion Control decreases the Congestion Window size and an application throughput deteriorates. TCP is not able to diagnose a cause of packet loss if it is a true congestion due to overflows somewhere on a communication path or a packet loss which sometimes randomly happens on a wireless link. As discussed above, when TCP works on a communication path which is likely to drop packets on the way, TCP throughput deteriorates. In order to avoid this occurrence, in case of random packet losses on a low reliable wireless link, dropped packets should be retransmitted between radio stations. A retransmission architecture on Layer 2 provides a packet loss free communication link for higher layers. The first requirement for an IEEE 802.11g device is "**Communicating radio stations are bilaterally able to retransmit packets which were lost on a wireless link**."

The TBR(L) physically switches over from one GBR(L) to another during L2HO processes. These processes must cause a temporal link down and packets to be dropped. The IEEE 802.11g Communication System experiences frequent L2HOs. It is a key to success to control these frequent L2HOs. From a discussion in Section 3.5.5, with assumptions that the distance between adjacent ground stations is 500(*m*) and train speed is 270(*km/h*), the L2HO interval is 6.7(*sec*). A L2HO process generally includes: (1) An event which triggers a L2HO occurrence, (2) TBR(L)'s physical switch over from one GBR(L) to another and (3) A MAC Address Table update on relevant layer 2 devices. The second requirement for an IEEE 802.11g device is “**These L2HO processes are appropriately done in a short duration**.”

Cisco-manufactured AIR-BR1310G-J-K9-R IEEE 802.11g bridge (BR1310) satisfies these two requirements above and thus was selected for the IEEE 802.11g device. The IEEE 802.11g device is used as a RB (Root Bridge), a Non-RB (Non-Root Bridge) or a WGB (Work Group Bridge). A RB is what is called a parent station in IEEE 802.11g systems. Ground stations in the IEEE 802.11g Communication System work as RBs. WGB is a working mode defined for mobile stations. Train stations in the IEEE 802.11g Communication System performs as WGBs. As for the first requirement, BR1310 meets it and thus packets which were lost between two communicating BR1310s are able to be retransmitted. For the second requirement, the functions which are described in the next section are implemented on BR1310.

3.6.2. L2HO processes on BR1310

L2HO features on a BR1310 are as follows.

(1) Events to trigger L2HOs

BR1310s in the IEEE 802.11g Communication System support L2HOs as follows. A L2HO is always initiated by a WGB, mobile station. There are some triggers as described below for WGBs to start a L2HO process. When one of the events happens, the WGB initiates a L2HO.

i. Max Data Retry Count Exceeded the specified value. (MaxRetries)

Two communicating BR1310s bilaterally retransmit packets which were lost on the wireless link. When a WGB retries a packet more than the specified value, the station initiates a L2HO. The threshold was set to 16 for our trials. The wireless link had been active until the moment the event caused a physical disconnection. In this case, the WGB starts to search for new available RBs after the disconnection of the wireless link. This incurs a longer L2HO time.

ii. The receiving RSSI has fallen below the specified value. (LowRSSI)

A WGB acquires RSSI by detecting beacon signal intensities from RBs. When the RSSI has fallen below the specified value, the station initiates a L2HO. The threshold was set to either -75dBm or -80dBm. The wireless link is still functioning when the event causes a L2HO trigger. The WGB searches for new available RBs before the link goes down and starts a L2HO process if it finds a stronger RB. In this case, A L2HO seems to take a shorter time.

iii. Other less common events

A L2HO is triggered by other less common events such as when a WGB has missed many consecutive beacons which are periodically sent from RBs.

(2) L2HO Processes

Whichever trigger occurs, the L2HO process follows the sequence below. The following example shows a scenario where the WGB roams from pRB (previous RB) to nRB (new RB) in Fig. 3-12.

i. The WGB scans for available RBs.

ii. The WGB checks Service Set Identifier (SSID) and encryption settings. The station discards candidates unless keys match.

iii. The WGB associates with the best RB (nRB in this scenario) from above.

iv. The WGB sends a SNAP (Subnetwork Access Protocol) multicast packet on the new wireless link. This multicast frame is immediately flooded to the whole broadcast domain.

v. The above frame makes nRB, pRB and L2SW change their MAC address tables.

vi. nRB informs pRB that nRB has accepted the WGB.

vii. pRB deletes the WGB from its association table of IEEE 802.11g

viii. Finally, traffic from the ground network to the mobile network can be accurately switched on all devices.

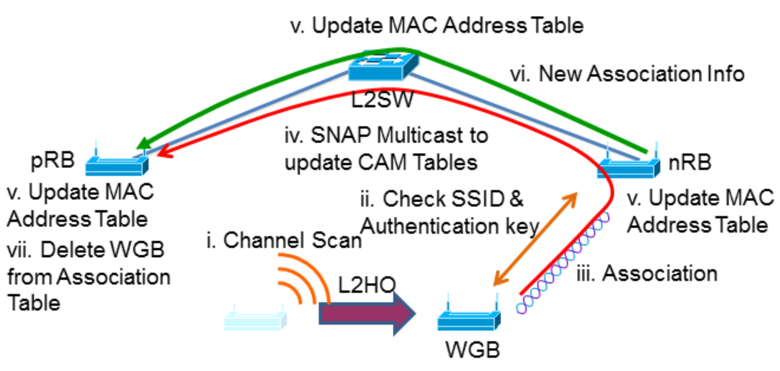


Fig. 3-12 L2HO from pRB to nRB

3.6.3. L2HO Characteristics in Mode 1 and Mode 2

In mode 1, the TBR(L) communicates with the active GBR(L) as it moves away from the station. It is a movement in the right direction as in Fig. 3-5. When the TBR(L) reaches near an edge of the communicating GBR(L)'s coverage, RSSI deteriorates to around -84(*dBm*). This causes one of the events that triggers a L2HO occurrence on the TBR(L). The type and the position of the events depends on a radio field intensity and also are affected by weather and speed at that time. It is not reproducible. When the event happens, if the TBR(L) has already entered the next wireless cell generated by the adjacent GBR(L), a L2HO takes place. On the other side, if the TBR(L) has not yet entered the next wireless cell, a L2HO does not occur and the TBR(L) makes its best effort to keep the active association. The TBR(L) also starts periodical scans for any new available wireless links. When it finds a new GBR(L) with a scan after it enters the GBR(L)'s cell, a L2HO takes place. Since the distance between the TBR(L) and the new GBR(L) is close just after each L2HO, RSSI from the counterpart BR1310 is large.

In Mode 2, the TBR(L) communicates with the active GBR(L) as it approaches the station. It is a movement in the left direction as in Fig. 3-5. Since RSSI gets better as the TBR(L) approaches the active GBR(L), no event triggering a L2HO occurs. Once the TBR(L) passes by the active GBR(L), RSSI from the GBR(L) observed on the TBR(L) dramatically decreases. This causes one of the events to trigger a L2HO occurrence. The TBR(L) searches for next available GBR(L)s. The expecting candidate is then located 500(*m*) ahead of the TBR(L). Therefore RSSI from the GBR(L) is quite low at around -84(*dBm*).

3.7. Network Design

This section describes a network design of the IEEE 802.11g Communication System. The IEEE 802.11g Communication System must support a mobility of Mobile Networks (See Table 1-1). The IEEE 802.11g Communication System is one of the components of the Media Convergence System. The LCX Communication System is another medium and is now in service. The IEEE 802.11g Communication System and the LCX Communication System must be converged. The current LCX Communication System works on a MIPv4 platform [32]. Therefore networks for the IEEE 802.11g Communication System was also designed on the same platform.

3.7.1. Network Topology

The IEEE 802.11g Communication System is being developed to support high speed rail systems. Wireless cells on the ground are one-dimensionally deployed on the train track as depicted in Fig. 3-5. Therefore an FA to which MR on a train visits next can be perfectly identified unless the train suddenly leaves its intended route. With this peculiarity taken into account, forwarding disruption time due to a L3HO is able to be decreased by an appropriate implementation of "(3) Separation of a L3HO from a L2HO" as described in Section 3.2.2

In order to separate a L3HO from a L2HO, a network as shown in Fig. 3-13 was designed and constructed for an experimental IEEE 802.11g Communication System. HA and three FAs were installed in the same segment. Three to four GBR(L)s were deployed under each FA. Networks under each FA belong to different subnets. Shortcuts were established between subnets under geographically adjacent FAs as shown in Fig. 3-13. Cisco Catalyst 2960 switches were employed as endpoints of the bypasses. On the L2SWs, Protected Ports [33] were configured on physical ports indicated with arrows in Fig. 3-13. The L2SWs forward all packets between a normal port and a protected port, while discard all packets between protected ports. This makes two broadcast domains under physically adjacent FAs overlap each other. For example, BR2-11, BR2-12 and BR2-13 are able to receive packets from both FA2 and FA3. Consequently, MR is able to listen to MIPv4 advertisements from two adjacent FAs at the same time. MR can carry out a MIPv4 binding update process through the next visiting FA and finish the L3HO while it is forwarding and receiving data traffic from the current FA. This solution does not need to modify MIPv4 at all. The implementation is simple.

A L3HO process is explained with an example case. Consider a case where the test train runs in the right direction as in Fig. 3-13. After an association of the TBR(L) and BR1-11 (one of the GBR(L)s) MR receives MIP advertisements from FA1 and establishes a MIPv4 Tunnel to HA through FA1. The train moves to the right. Once the TBR(L) makes a wireless connection with BR1-13, MIP advertisements from FA2 can also reach MR. After the reception, MR starts a MIPv4 binding update process via FA2 as it forwards data traffic into a path via FA1. As soon as the L3HO process is completed, MR changes the traffic forwarding path from FA1 to FA2. This method handles L3HOs while data traffic is being forwarded.

As for the links drawn in Fig. 3-13, Ethernet cables of 100Base-TX Full-Duplex were used for the links drawn by blue single lines and the other links drawn by red double lines were connected by optical fibers with the use of media converters. It worked on 100Base-FX Full-Duplex. Therefore the bottleneck of communication is on the IEEE 802.11g link between a GBR(L) and the TBR(L). All the devices composing the IEEE 802.11g Communication System are commercially available and they are shown in Table 3-2.

Table 3-2 Devices composing the IEEE 802.11g Communication System

Role	Device(s)
HA, FAs	Cisco 2811 Integrated Service Router [34]
MR	Cisco 3250 Mobile Access Router [35]
L2SW	Cisco Catalyst 2960 [36]
GBR(L), TBR(L)	Cisco Air-BR1310G-J-K9 [30]

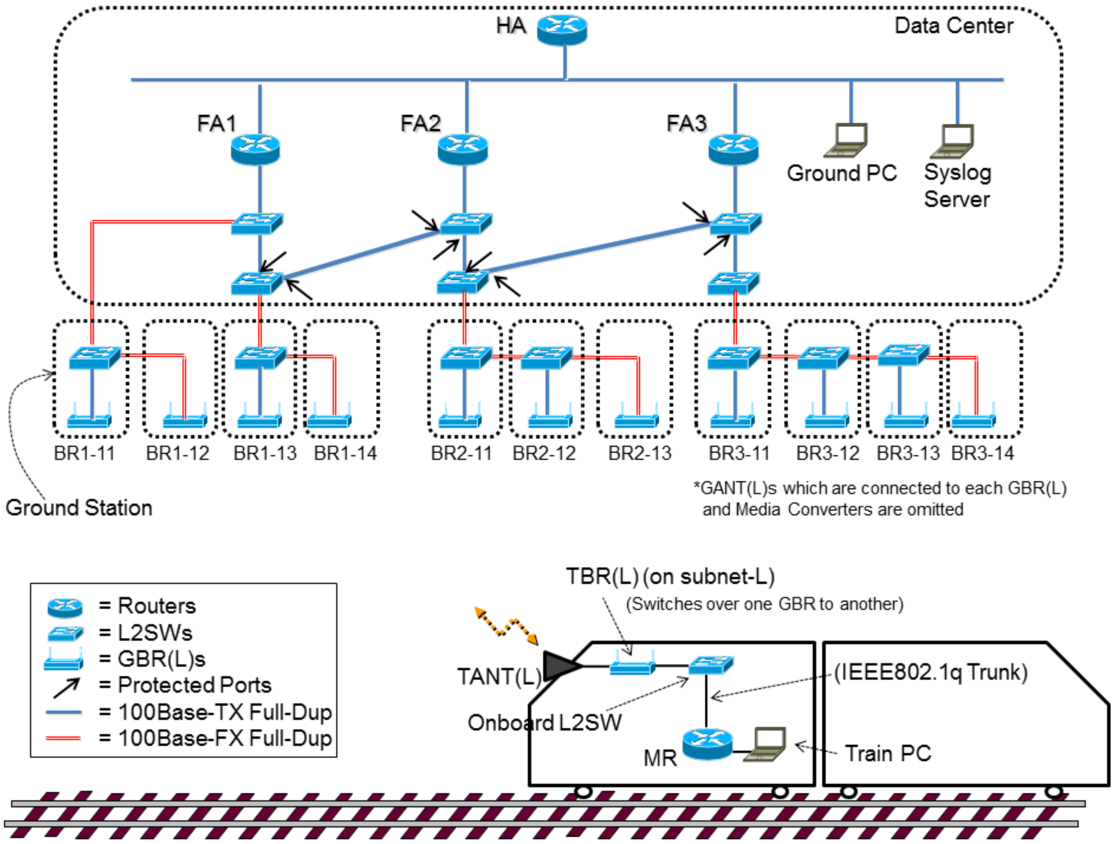


Fig. 3-13　IEEE 802.11g Communication System (Experimental)

The experimental IEEE 802.11g Communication System was divided into three subnets by FAs and each FA has three to four GBR(L)s as depicted in Fig. 3-13. This network topology is for tests of a L3HO performance. It is not optimized for practical use. Here, consider an appropriate network topology. The number of GBR(L)s which can be placed under a FA is unlimited. It works well as far as the broadcast domain size is adequate. There is one more constraint, which is that any wired link must not be a bottleneck of communication. We have only one test train in our experiments. However, when plural trains move under a FA and are connected to it at the same time in practical situations, a wired link in the subnet might be a bottleneck. When estimated that throughput on each GBR(L) is 25(*Mbps*) as reported in [31], the number of active GBR(L)s must be four or fewer with the use of Ethernet of 100(*Mbps*) for wired links under the FA. This calculation did not take packet overheads into account, because it is for a rough estimation. Where, "active GBR(L)" means a GBR(L) which is being accessed by a TBR(L) and the wireless link of which is active. In other words, the expected number of trains which are connected to GBR(L)s under a FA at the same time should be four. Trains may run on either set of tracks of the same line. The average in a single direction becomes two trains. Under a condition that an average distance between trains traveling in the same direction is 10(*km*), an appropriate coverage of each FA is 20(*km*). Each FA is able to support 40 GBR(L)s (= 20km/500m). Assume that there is neither bottleneck between HA and FAs nor outer networks of HA.

3.7.2.Frame Structure of MIPv4

A frame structure of MIPv4 is shown in Fig. 3-14. For Mobile Nodes, the IEEE 802.11g Communication System employed Routers instead of Hosts as single terminals. These routers are referred to as Mobile Routers (MR) which support mobility for all terminals under the router. When a MR is used, in accordance with RFC3344, double MIPv4 tunnels are established between HA and FA and between HA and MR. Packets are double-capsuled on the section between HA and FA. RFC3344 assumes IPinIP [37] and GRE (Generic Routing Encapsulation) [38] for capsuling protocols of the tunnels. Our experimental IEEE 802.11g Communication System employed GRE.

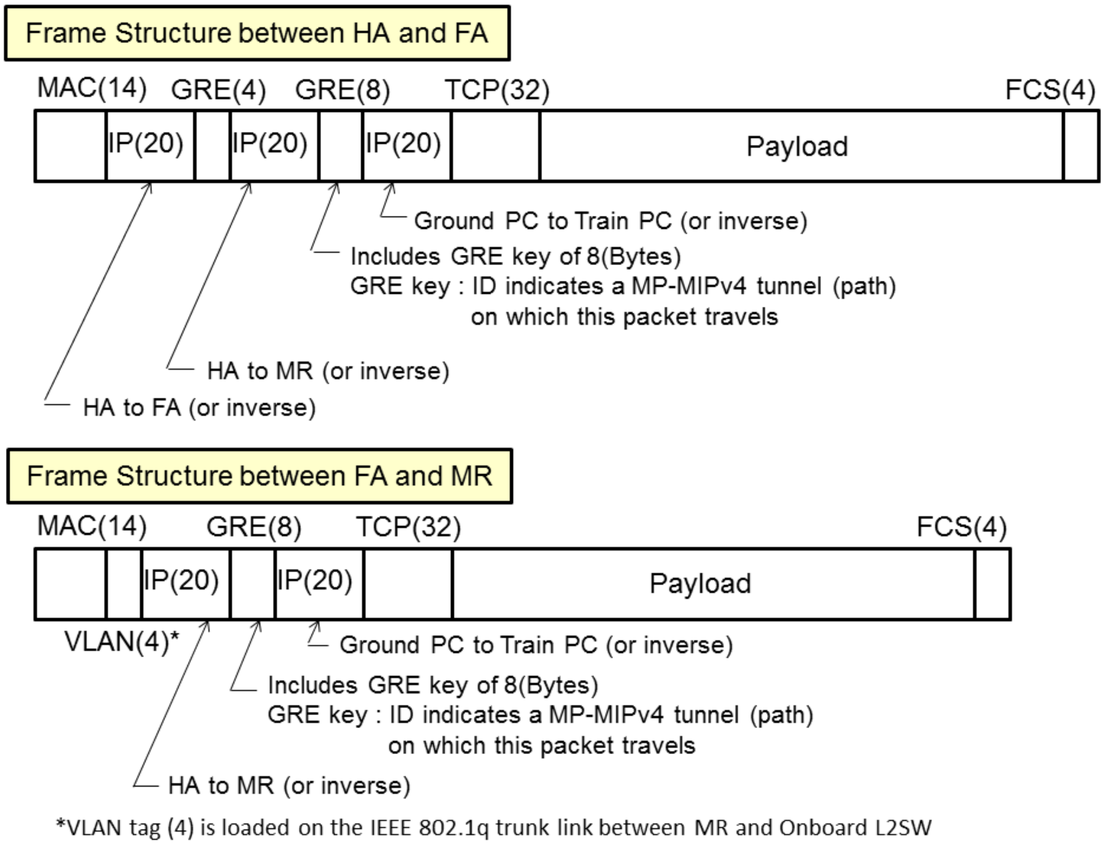


Fig. 3-14 Frame structure of Mobile IPv4

An IP packet which is destined to the Train PC from the Ground PC in Fig. 3-13 is considered for an example. At first the IP packet is routed to the Home Address (defined in [RFC3344]) of the Train PC. The Home Network (defined in [RFC3344]) to which the Home Address belongs is under a management of HA. The IP packet is physically forwarded to HA. HA encapsulates the IP packet by GRE and adds an IP header destined to MR from HA. Again HA encapsulates the capsuled IP packet by GRE and puts another IP header destined to a FA from HA. The FA must be the one which has leased a Care-of Address (defined in [RFC3344]) to MR. Consequently, the IP packet is double-capsuled by GRE between HA and FA as depicted in the top half of Fig. 3-14. When the IP packet reaches FA, FA picks up the IP packet from the MIPv4 tunnel between HA and FA. This motion means to take out both the IP header destined to FA from HA and the following GRE header. After that, FA forwards the single-capsuled IP packet to MR. The frame structure between FA and MR is shown in the bottom half of Fig. 3-14. Note that the structure includes a VLAN tag mounted in the section between Onboard L2SW and MR. An IEEE 802.1q Trunk configuration using VLAN tags was required to be implemented for a Multipath Mobile IPv4 platform proposed in Chapter 5. Therefore it was installed here in advance. GRE headers between HA and MR contain an ID named "GRE key." It indicates a MIPv4 tunnel where the IP packet travels.

3.8. Summary

This chapter proposed IEEE 802.11g as a pivot communication medium in the Media Convergence System. The Media Convergence System unifies various communication media into a single system. However, it is ineffective when the system consists of communication media with low performances. The Media Convergence System needs a pivot wireless communication medium. The major requirement for the pivot medium is high communication performances with high financial efficiency. Using IEEE 802.11g became our main focus. The major goal of our research was set to achieve an average application throughput of 10(*Mbps*) with the use of IEEE 802.11g while a mobile station is traveling at around 300(*km/h*).

This chapter also reported system designs to apply IEEE 802.11g to high speed mobile communications. The IEEE 802.11g Communication system is one of the access networks to the Internet from cabins on high speed trains. Therefore designs for the IEEE 802.11g Communication System were done on Layer 3 and lower. For Layer 4 and higher, all protocols, applications and services perform on this platform.

A radio transmission channel on Layer 1 was designed first. A radio propagation line was established on train tracks by a high gain directional antenna. This contributed to make most part of the Fresnel Zone clear. The farther the distance between the two communicating antennas becomes, the larger the Fresnel Radius. The Fresnel Zone loses some of the outer area, when the trajectory distance d, exceeds 185.2(m). However, the observation result of the radio field intensity showed that we could obtain enough RSSI to achieve an average application throughput of 10(*Mbps*) in case of the maximum distance between adjacent ground stations of 500(m).

As for a design for Layer 3, an FA to which MR on a train visits next can be perfectly identified unless the train suddenly leaves its intended route. With this peculiarity taken into account in network designs, a L3HO was separated from a L2HO. This method is expected to reduce packet losses due to a L3HO.

In accordance with the designs discussed in this chapter, an IEEE 802.11g Communication System for trials was constructed on a commercial high speed rail system. The subsequent chapters report communication performance evaluations of the IEEE 802.11g Communication System under a high speed mobile environment.

Chapter 4. Communication Performance Evaluations of the IEEE 802.11g Communication System based on a Singlepath Configuration

Chapter 3 revealed that the IEEE 802.11g Communication System satisfies requirements to be a mobile communication system by designing a radio transmission channel and a MIPv4 platform. This chapter verifies that the IEEE 802.11g Communication System performs in accordance with the designing intentions and proves that the system works for high speed mobile systems by experiments in real situations.

4.1. Introduction

Increasing number of passengers are requesting even higher access speeds. In order to meet these requests, we are developing the IEEE 802.11g Communication System. This chapter reports performance evaluations of the system. The IEEE 802.11g Communication System described in this chapter has a single transmission line between ground stations and the mobile station as designed in Chapter 3. This system is particularly referred to as "the IEEE 802.11g Communication System with Singlepath Configuration." This is because it has to be distinguished from "the IEEE 802.11g Communication System with Dualpath Configuration." The IEEE 802.11g Communication System with Dualpath Configuration has two IEEE 802.11g transmission channels between ground stations and the mobile station as its name implies.

The organization of this chapter and reporting contents are as follows. Section 4.3 reports that Wireless Link Failures occur in the IEEE 802.11g Communication System. The TBR(L) has sometimes failed to establish an IEEE 802.11g link with a GBR(L) due to its high speed movement. A Wireless Link Failure occurs at arbitrary GBR(L) with the probability of 5.2%. This section points out that **the occurrence of Wireless Link Failures is not unavoidable** in the IEEE 802.11g Communication System. Section 4.4 describes L3HO performances in the IEEE 802.11g Communication System. Section 4.5 reports a RTT observation. **An average RTT was 9.95(*ms*)** and a standard deviation was 5.70(*ms*). Section 4.6 reports UDP performances. The results have proven that the IEEE 802.11g Communication System realizes **a maximum UDP throughput of 25(*Mbps*)**. Although it suffered from Wireless Link Failures, **communication became stable once an IEEE 802.11g link made an association**. Section 4.7 reveals TCP behaviors over a L2HO. The results have clarified that TCP does not recover from a freeze until its timeout expires after each L2HO. Section 4.8 makes a TCP Rate Model based on statistical data from our experiments. The model has shown a saw-shaped TCP Rate with a train movement and also revealed that **an average expected TCP Rate is 9.86(Mbps) for Mode 1 and 13.7(Mbps) for Mode 2**. Section 4.9 evaluates communication stall duration rate for TCP. The results have shown that **TCP wastes 9.9% and 18.1% of the whole communication period in Mode 1 and Mode 2, respectively**. This section also discusses requirements to improve the performances of the IEEE 802.1g Communication System. Section 4.10 summarizes this chapter.

4.2. Trial System Configuration

A trial system configuration is shown in Fig. 3-13. All the links but IEEE 802.11g links between ground stations and the train station were connected by Ethernet cables of 100Mbps or Optical fibers. Therefore the bottle neck of communications is on the IEEE 802.11g links between ground stations and the train station. Two PCs depicted in Fig. 3-13 were used as the end nodes of communication tests. The PC on the ground is referred to as the Ground PC. The PC on the test train is referred to as the Train PC. Major hardware configurations for the PCs are shown in Table 4-1. Ubuntu10.04LTS (Kernel 2.6.32 with web100[39] patch) was employed for the Operating System for both PCs.

Table 4-1 Hardware Configuration for PCs

	Ground PC	**Train PC**
PC	Lenovo ThnikCentre M57 Tower 9174A28	Lenovo ThinkPad X301
Processor (speed, L2 cache, FSB)	Intel® Core™ 2 Quad Q6600 (2.4 GHz, 8 MB, 1066 MHz)	Intel® Core™ 2 Duo processor SU9400 (1.4 GHz, 3 MB, 800 MHz)
Memory	2GB PC2-5300 DDR2 SDRAM	4 GB PC3-8500 DDR3 SDRAM (3 GB addressable with 32-bit OS)
Ethernet	10BASE-T/100BASE-TX/1000BASE-T	10BASE-T/100BASE-TX/1000BASE-T

The focus of our research is on communication characteristics in a high speed mobile environment. Travelling speed of the test train was kept at 270km/h for all the experiments. Measurements were done on train reciprocate movements (left and right bound motions in Fig. 3-13).

Physical relationship between GANT(L) and TANT(L) is shown in Fig. 3-5. One of the objectives was to obtain communication characteristics in two cases: (1) a train runs away from the active ground antenna, and (2) a train approaches that antenna. As described in section 3.5.7, the former case is called Mode 1, and the latter case is called Mode 2.

4.3. Wireless Link Failures of IEEE 802.11g

Before observations on the high speed train, IEEE 802.11g connections were checked between GBR(L)s and the TBR(L) under an immobile environment in order to make sure soundness of the links. Instead of TBR(L) mounted on the test train, another BR1310, referred to as a Fake TBR(L), was used for the experiment. The Fake TBR(L) was brought by hands on the track and connectivity was verified between GBR(L)s and the Fake TBR(L). This was quite a simple link test of IEEE 802.11g. The Fake TBR(L) associated with all the GBR(L)s without any troubles at all.

Measurements under a high speed mobile environment are reported below. The test train equipping the TBR(L) ran at 270km/h and the speed was kept during the test. Establishments of IEEE 802.11g links between GBR(L)s and the TBR(L) were validated. Results showed that wireless link failures accidentally occurred between the TBR(L) and arbitrary GBR(L)s. The event is referred to as a Wireless Link Failure. These Wireless Link Failures happened at random. It might depend on weather, temperature, train speed and so on. Although the speed of the test train was tried to be kept at 270km/h, it had a small fluctuation around the speed. Statistics of results showed that a Wireless Link Failure has occurred on arbitrary GBR(L)s with the probability of 5.2%. Since all trials were done in the high speed mobile environment of 270km/h, the relationship between train speed and Wireless Link Failures is unclear. However, it is sure that the cause of Wireless Link Failure is the high speed movement of the TBR(L), because it never occurred during the static situation.

Although it was reported that the probability of Wireless Link Failure was 5.2%, the figure must depend on IEEE 802.11g devices. Wireless devices must be commercially available and widely distributed in the market for the IEEE 802.11g Communication System. Our trial system employed Cisco-manufactured Air-BR1310G-J-K9 wireless LAN Bridge (BR1310). The Wireless Link Failure rate of 5.2% was an experimental result based on this device. A replacement of the wireless device would change the rate. However, what we have to keep in our minds is that any IEEE 802.11g devices would not completely eradicate Wireless Link Failures in high speed mobile environments because they have been originally developed for fixed or slow speed usages. Therefore we must recognize the existence of wireless link instability that **wireless LAN bridges in the IEEE 802.11g Communication System sometimes fail to associate with their counterpart device**.

4.4. L3HO process time

As described in Section 3.7.1, data traffic can be transferred all the time except for a short duration while routers are overwriting their routing table. The duration relies on the router performance. The devices in our experiment were Cisco ISR2811 for HA and FAs, Cisco MAR3250 for MR. The duration for each router to update its routing table was measured by router logs. It was an average of 21.7(*ms*) for ISR2811 and 28.4(*ms*) for MAR3250.

4.5. Round Trip Time (RTT)

RTT of ICMP (Internet Control Message Protocol) ping was measured while traveling at 270(*km/h*). ICMP Echo Requests were sent from the Ground PC to the Train PC depicted in Fig. 3-13. Payload size was 1,200(*Bytes*) and the Sending interval was 200(*ms*). The result is shown in Fig. 4-1. In this trial, Wireless Link Failures happened on BR1-11 and BR1-14. **An average RTT was 9.95(*ms*)** and a standard deviation was 5.70(*ms*). Dots on the RTT = 0 in Fig. 4-1 indicate packet losses.

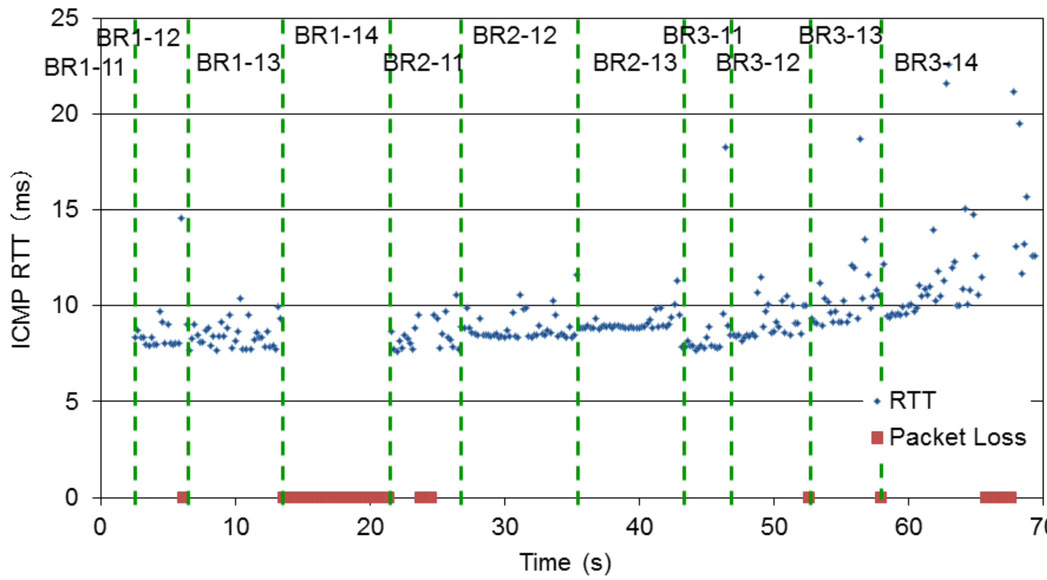


Fig. 4-1 Ping Round Trip Time

As the TBR(L) moved in the order of BR2-11, BR2-12 and BR2-13, RTT showed a stair-like increase on each L2HO. In the experimental IEEE 802.11g Communication System, L2SWs on the ground were tandem-connected as depicted in Fig. 3-13. Therefore the number of L2SWs which traffic goes through increases by two for the round trip after each L2HO. RTT jumps at each L2HO due to the increase of switching delay on L2SWs. A similar phenomenon was observed from BR3-11 through BR3-14.

RTT seriously deteriorated in the BR3-14 cell, which is the last GBR(L) in the experiment. There is no more cells to which the TBR(L) roams from BR3-14. Therefore the TBR(L) made its best effort to keep a connection with BR3-14 as long as it could. A communication was carried out after the distance between the TBR(L) and BR3-14 got larger than 500(*m*). The area must be in a coverage of the adjacent GBR(L) under normal circumstances. Since RSSI was quite low in the section, the worse RTT was observed there.

4.6. UDP Performance Evaluation

The UDP throughput was measured in order to evaluate the communication bandwidth of the IEEE 802.11g Communication System. UDP traffic was sent at a constant rate from the Ground PC to the Train PC depicted in Fig. 3-13. The Reception rate on the Train PC was thus observed. Iperf[40] was used to generate UDP traffic and the sending rate was always kept at 25(*Mbps*). The payload size of each packet was 1,200(*Bytes*) (MAC frame size was 1,242(*Bytes*)). All packets were captured on the Train PC by Wireshark[41]. The UDP throughput was calculated every 0.1 second by accumulating all the payloads of the packets which arrived at the PC. Here the word “UDP Downtime” is defined as follows. Assume that the last packet before a L2HO arrived at the Trian PC at time A. In the same fashion, the time when the first packet after the L2HO arrived at the PC was time B. The interval, time B – time A, is referred to as UDP Downtime. Both time A and time B were obtained by Wireshark logs.

4.6.1. Departing Scenario (Mode 1)

The measured UDP throughput was shown in Fig. 4-2. The first packet was received at the Train PC at relative time 0. Captions on top of the figure indicate GBR(L)s matching with ones in Fig. 3-13. Broken lines show L2HOs. In this trial, the TBR(L) did not associate with BR1-11 due to a Wireless Link Failure.

Just after a L2HO in each wireless cell, almost all of the data sent from the Ground PC was received by the Train PC. This proved that **the IEEE 802.11g Communication System is capable of communicating with a maximum UDP throughput of 25(*Mbps*) or more**. Also **the average UDP throughput was 16.3(*Mbps*)**.

The UDP throughput deteriorated in each wireless cell. The chain of deteriorating events in a cell is as follows.

(1) The distance between the active antennas increases.

(2) The RSSI decreases.

(3) Both the GBR(L) and the TBR(L) slow down the modulation speed for the wireless link.

(4) Unsent packets are discarded on the GBR(L).

However, no instable event such as a sudden disconnection happened while communicating. This indicates one of the very important natures of the IEEE 802.11g Communication System. **Once an IEEE 802.11g wireless link was established, the communication became stable in the cell.**

The UDP throughput dropped to 0 at all the L2HOs. The TBR(L) physically switches over from one communicating GBR(L) to another at each L2HO. A L2HO has a certain time duration where packet forwarding is impossible. The trial had a Wireless Link Failure at BR1-11 and thus experienced nine L2HOs in total. UDP Downtime for six of these L2HOs was less than 160(*ms*). For the other three cases, they were 261.110(*ms*) (from BR2-13 to BR3-11), 382.771(*ms*) (from BR1-12 to BR1-13) and 751.222(*ms*) (from BR1-14 to BR2-11). Although the number of samples is small, the result shows a probability of an occurrence of L2HOs with longer UDP Downtime of several hundred milli-seconds.

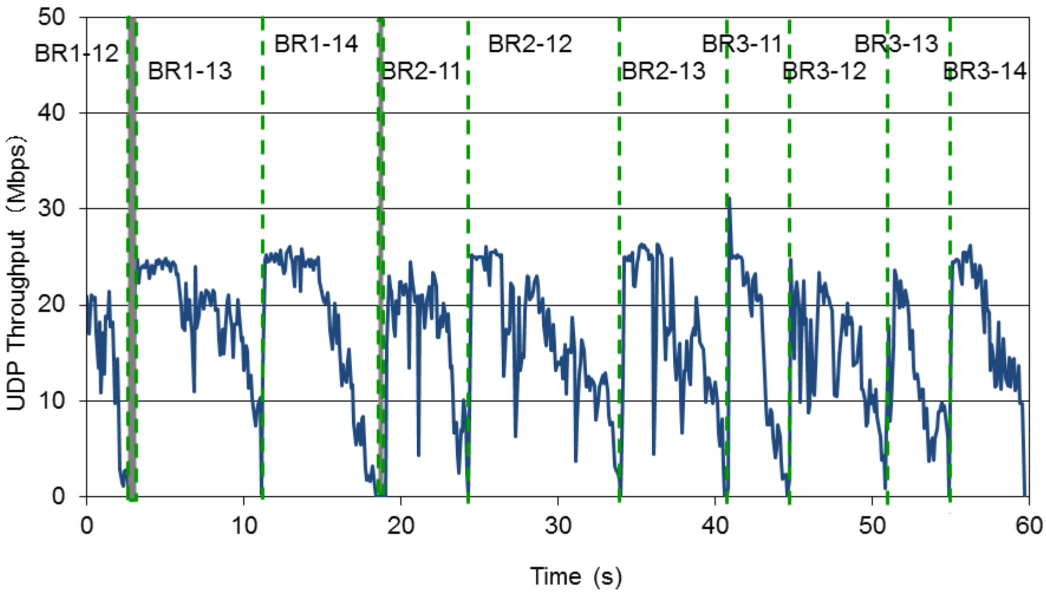


Fig. 4-2 UDP Throughput in Mode 1 (Departing Senario)

Larger UDP Downtime was caused by lower layers. The fact of larger UDP downtime means a longer L2HO duration. RSSI from a new GBR(L) is always sufficiently large when the TBR(L) tries to process a L2HO to the GBR(L) in Mode 1. These two facts mean that a L2HO takes longer time even under large RSSI in some cases. Mode 1 also suffered from Wireless Link Failures, which meant that IEEE 802.11g wireless bridges sometimes failed to make a connection even under large RSSI. These results revealed that the IEEE 802.11g bridges have a difficulty in making an association to each other, whereas the communication is stable in cells after an establishment of the

IEEE 802.11g link. Instability is unavoidable in making an IEEE 802.11g link as long as IEEE 802.11g is used in high speed mobile situations. Therefore **we must recognize the existence of cases where a L2HO takes longer time than usual in the IEEE 802.11g Communication System.**

4.6.2. Approaching Scenario (Mode 2)

The UDP throughput is drawn in Fig. 4-3 in the same manner as Fig. 4-2. The first packet was received at the Train PC at relative time 0. This trial did not experience any Wireless Link Failure.

The average throughput was 17.7(*Mbps*). In Mode 1, a gradual RSSI deterioration dragged down the UDP throughput in Fig. 4-2. In Fig. 4-3 for Mode 2, however, the UDP throughput did not go up little by little. What was even better, it showed a steep advance just after each L2HO and then held the top speed.

The UDP throughput also descended to 0 at all the L2HOs in Mode 2. The trial had 10 L2HOs in total. The UDP Downtime for six L2HOs was distributed from 200(*ms*) to 400(*ms*) with the minimum value of 208.317(*ms*). On the other side, the TBR(L) experienced extraordinarily long UDP Downtime. They were 1.8(*sec*) from BR2-11 to BR1-14, and 2.0(*sec*) from BR1-13 to BR1-12. Section 4.6.1 pointed out a difficulty of an IEEE 802.11g association over a L2HO. In Mode 2, when the TBR(L) ran a L2HO process, the RSSI which it received from a candidate GBR(L) was around -84(*dBm*), very weak. It was much more difficult in Mode 2 to make a wireless link association than in Mode 1. This caused longer UDP Downtime in Mode 2.

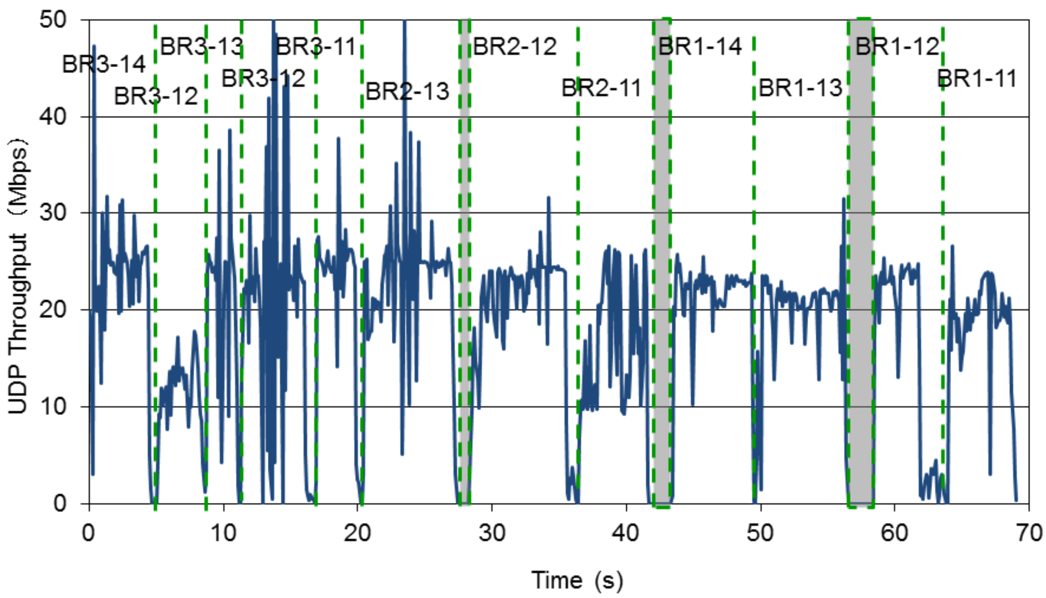


Fig. 4-3 The UDP Throughput in Mode 2 (Approaching Scenario)

An association order in Fig. 4-3 did not match with the physical order of BR3-12 and BR3-13. The TBR(L) searched for new available GBR(L)s by channel scans after a disassociation with BR3-14. At this moment, the TBR(L) judged BR3-12 was the best candidate for the available GBR(L)s. However, the UDP throughput via BR3-12 was saturated at around 15(*Mbps*), because the RSSI was not good enough. In other words, a radio condition of BR3-12 was better than that of BR3-13 only at the moment of the L2HO. The TBR(L) made another L2HO to BR3-13 3.5 seconds after the previous L2HO. Subsequently the association order was the same as the physical order. This kind of event happened in 6.2% of all the L2HOs in Mode 1, 6.3% in Mode 2. In addition, this had a dependence on the location of GBR(L)s. The phenomenon was likely to occur between BR1-11 and BR1-12, and between BR3-12 and BR3-13. This was because the radio propagation environments allowed a signal from BR1-11 and BR3-12 to reach farther. It is a possibility that a change of surroundings would generate or eliminate these occurrences. Therefore these events will have to be taken into account for future practical system configurations. A seamless communication is required in this bridge-tangled communication mode.

4.7. TCP Performance over L2HOs

This section analyzes TCP performances over L2HOs in the Singlepath configuration. TCP throughput, Congestion Window Size (cwnd), Slow Start Threshold (ssthresh), Round Trip Time (RTT) and Retransmission Timeout (RTO) were measured to analyze its behavior over L2HOs. Ubuntu10.04LTS (Kernel 2.6.32 with Web100 patch) was employed for an Operating System (OS) on both the Ground PC and the Train PC. The TCP version was TCP CUBIC which is a default congestion control algorithm for the Linux kernel. TCP flow was generated on the Train PC by Iperf and sent to the Ground PC. TCP information on the Train PC (Sender) was obtained by Web100. All packets were captured by Wireshark on both PCs. A measuring method for our field trial was as follows.

An experimental section is approximately extended to 5(*km*) long. The test train runs at 270(*km/h*). It takes about 70(*sec*) to pass through the section. All the preparations had to be done before the train entered the area. It is impossible to manipulate something and make it active after a measurement is started. The measurements were as simple as possible.

On the Ground PC working as a receiver, a receiving port had been open for Iperf and packet monitoring had been started by Wireshark before the test train entered the section. On the Train PC as a sender, Wireshark had started capturing packets, Web100 had been set up to obtain TCP information and an Iperf command had become ready to run to generate a TCP flow before the test train entered the section. When the train approached the trial section, we accessed MR from the Train PC in order to monitor and store its logs. Once the train entered the section and a MR log showed an establishment of a MIPv4 tunnel, at first Web100 started a measurement of TCP parameters and secondly Iperf made a TCP connection and pushed its flow. Logs of HA, FAs, 11 of GBR(L)s were automatically sent to a syslog server. A log of the TBR(L) was buffered on itself during a test and withdrawn after the test finished. The MIPv4 Frame structure is shown in Fig. 3-14. The MSS (Max Segment Size) for our trial was 1,396(*Bytes*) and a Frame Size was 1,514(*Bytes*).

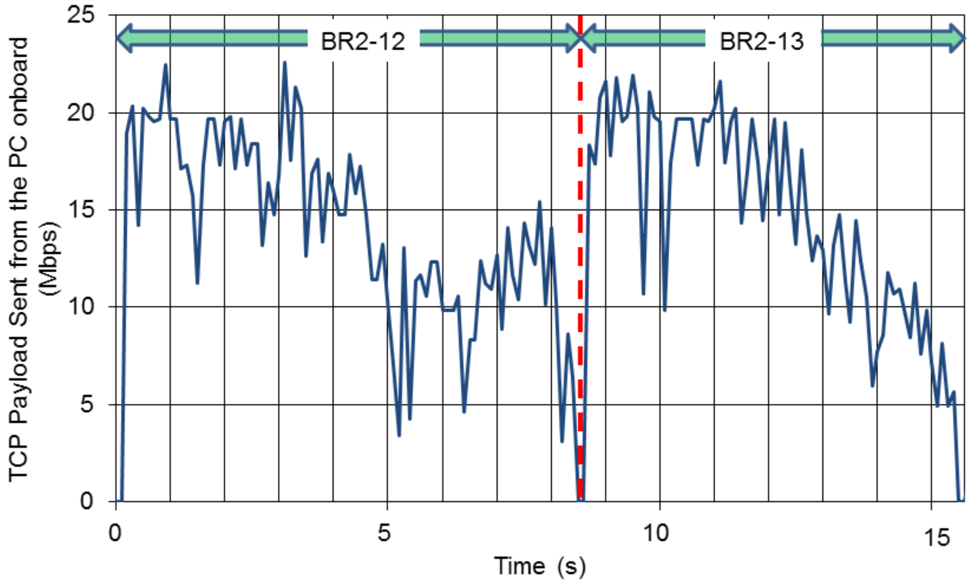
4.7.1. Departing Scenario (Mode 1)

In order to discuss TCP behaviors over L2HOs, a result on adjacent two GBR(L)s (BR2-12 and BR2-13) was extracted. Time on Fig. 4-4 starts when the TBR(L) associated with BR2-12. Fig. 4-4(a) is the sending rate from a LAN interface on the Train PC. The rate is referred to as TCP Rate. It was measured every 100(*ms*) by accumulating all the packet payloads. Fig. 4-4(b) shows cwnd, ssthresh, RTT and RTO. These were obtained by Web100. Advertised Window Size which was advertised from the Ground PC was abbreviated because it was always larger than the cwnd.

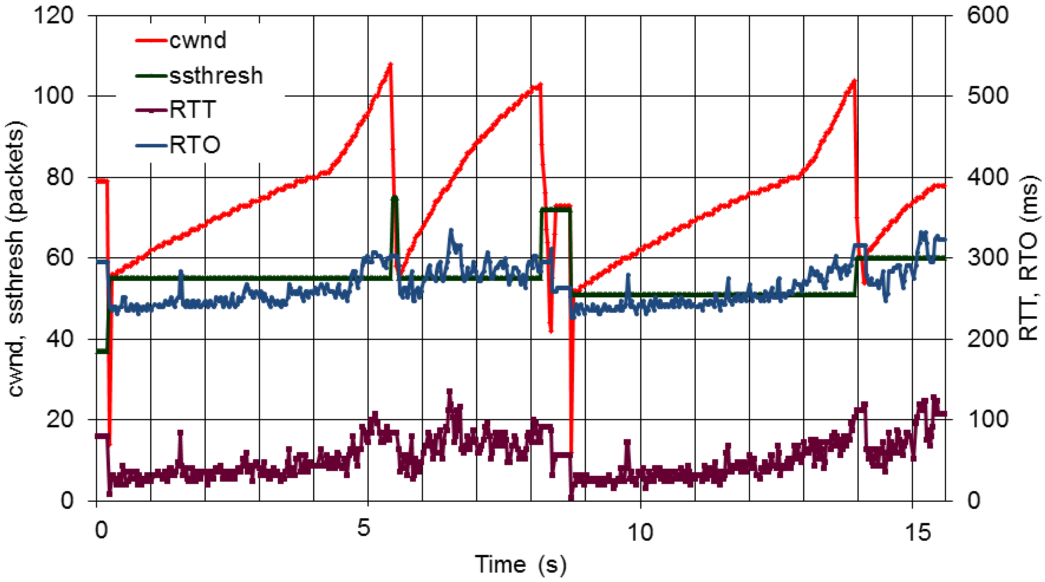
A broken line at 8.6(*sec*) on Fig. 4-4(a) shows a L2HO. At the L2HO, TCP Rate and the cwnd dropped dramatically. TCP waited for its RTO and the cwnd was decreased to one segment size. Fig. 4-5 is a TCP state transition over this L2HO at 8.6(*sec*) in Fig. 4-4. Here we define “L2HO Wait Time” as duration between the TCP’s last packet launch before a L2HO and the L2HO completion, “Retransmission Wait Time” as duration between the L2HO completion and TCP’s transmission resumption after a RTO expiration, and “TCP Downtime” as sum of L2HO Wait Time and Retransmission Wait Time. During L2HO Wait Time, a L2HO disables traffic forwarding by a physical break of wireless link. During Retransmission Wait Time, TCP waits for a RTO expiration although a L2HO has been completed. TCP does not resume communication right after a L2HO process finishes as shown in Fig. 4-5.

TCP waited for a RTO expiration over all L2HOs. Table 4-2 shows average TCP Downtime of all the seven L2HOs in the one-way trial. The average includes a L2HO depicted in Fig. 4-5. Although the number of L2HOs in a test run should be 10, the TBR(L) did not establish a wireless link with BR1-11 and BR1-14 in our trial. Thus the TBR(L) experienced seven L2HOs in total. The maximum of L2HO Wait Time was 134(*ms*), which was shorter than the minimum value of RTO (200(*ms*)). All L2HOs in this trial had been completed before TCP RTO expired. Fig. 4-5 must be a typical example of L2HOs in Mode 1. TCP Downtime during each L2HO matches a RTO value at that time.

Here, “L2HO interval” is defined as duration between the start of a L2HO and the start of the next L2HO. Assuming that the distance between adjacent GBR(L)s is 500(*m*) and a train speed is 270(*km/h*) as described in section 3.5.5, the L2HO interval is 6.7(*sec*). Average TCP Downtime was 334(*ms*). Therefore TCP Downtime occupied 5.0% of the L2HO interval. This wasted time must be reduced in order to improve TCP performances over L2HOs.



(a) TCP Rate Sent from the Train PC



(b) TCP Parameters

Fig. 4-4 TCP Performances over a L2HO in Mode 1

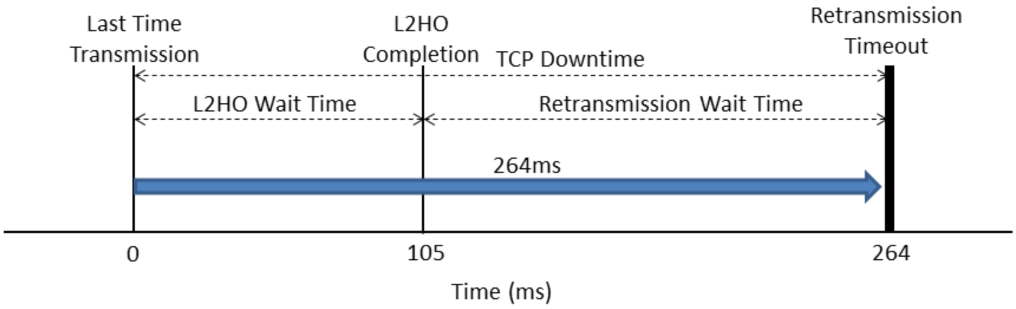


Fig. 4-5 TCP State Transition over L2HO at 8.6sec in Fig. 4-4

Table 4-2 Average TCP Downtime at L2HO in Mode 1

	L2HO Wait Time	Retransmission Wait Time	TCP Downtime
Consumed Time (ms)	115	219	334

TCP resumed communication by Slow Start after a RTO expiration caused by the L2HO. RTT was less than 10(*ms*) because the electro-magnetic wave was in the best condition after the L2HO in Mode 1. Therefore the cwnd increased to 2^5MSS=32MSS in 50(*ms*) (5RTT). The cwnd was able to become larger than the ssthresh in a short duration and TCP changed its status to Congestion Avoidance Mode. TCP Rate quickly increased to around 20(*Mbps*) after the L2HO.

TCP Rate gradually decreased in each GBR(L) cell as the TBR(L) moved away from the active GBR(L). This mechanism was; (1)RSSI decreased, (2)RTT increased, (3)the number of ACKs in unit of time (ACK Receiving Rate) decreased and (4)TCP Rate decreased. Further explanation comes below. As RSSI deteriorated, the number of packets lost in the wireless link increased. Retransmissions of dropped packets by the GBR(L) and the TBR(L) increased RTT, and further, retransmissions made the following packets wait for being forwarded in the sending buffer of the wireless interface on both the GBR(L) and TBR(L). This was another cause of the RTT increase. When RSSI decreased, both the GBR(L) and TBR(L) changed their modulation speed of IEEE 802.11g and the physical bandwidth of the wireless link was contracted. It temporarily raised the amount of buffered data, which also made RTT worse. The RTT gradual increase made an ACK reception interval at the Train PC longer. It means that the ACK Receiving Rate is becoming smaller. TCP sends data packets with a Self-Clocking mechanism. The less frequently the sender TCP receives ACKs, the fewer data packets are pushed out from the TCP. This is the reason that TCP Rate deteriorated from 12(*sec*) to 14(*sec*) in Fig. 4-4(a), though the cwnd got larger in that duration in Fig. 4-4(b).

Data packets were lost on the wireless link at 5.5(*sec*) and 14.0(*sec*). The ssthresh was reset and Congestion Avoidance Mode was re-started. The cause of these packet losses was an excessive expansion of the cwnd, compared to the capacity of the wireless link. In these two cases, the Train PC got three or more Duplicated ACKs and did Fast Retransmission and Fast Recovery with the ssthresh of around 60 segment sizes. Although the TCP Rate experienced a brief drop after each packet loss, these events did not affect the TCP performance.

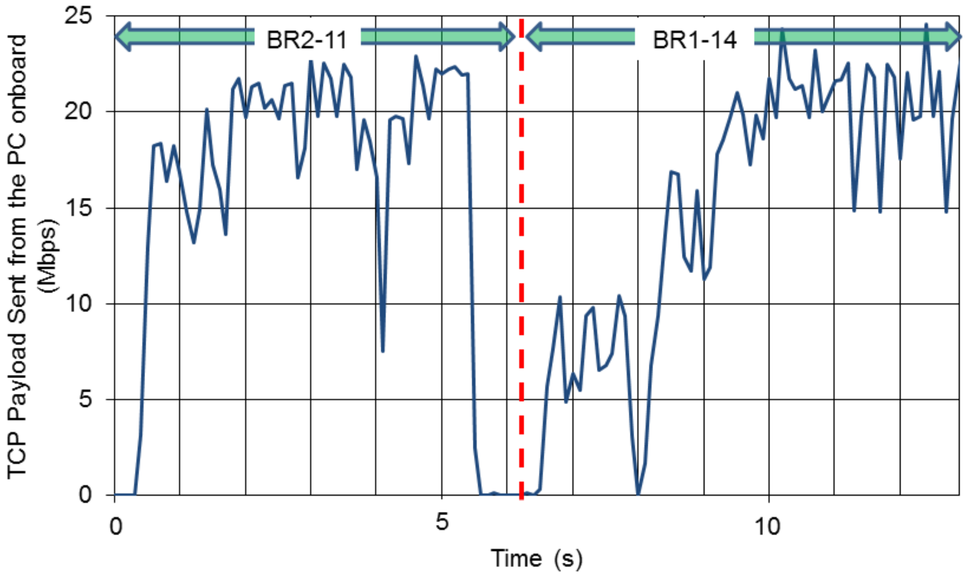
4.7.2. Approaching Scenario (Mode 2)

TCP behaviors over L2HOs are discussed here in the same manner as in Mode 1. A result on adjacent two GBR(L)s (BR2-11 and BR1-14) was extracted in Fig. 4-6. Time on Fig. 4-6 starts when the TBR(L) associates with BR2-11. Fig. 4-6(a) is TCP Rate from a LAN interface on the Train PC. Fig. 4-6(b) shows cwnd, ssthresh, RTT and RTO. Advertised Window Size which was advertised from the Ground PC was abbreviated because it was always larger than the cwnd. A broken line at 6.2(*sec*) on Fig. 4-6(a) shows a L2HO. Table 4-3 shows average TCP Downtime of 15 L2HOs which the TBR(L) has experienced over arbitrary adjacent GBR(L)s in Mode 2. It also includes the 6.2(*sec*) case in Fig. 4-7.

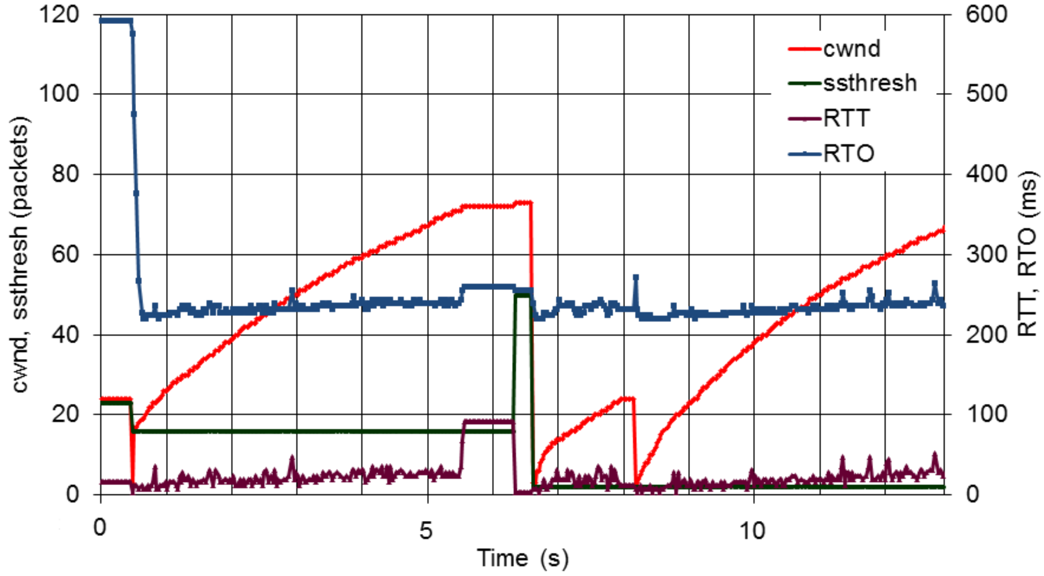
As described in section 3.6.3, RSSI which the TBR(L) receives from a new GBR(L) just after each L2HO is quite weak (around -84(*dBm*)) in Mode 2. Due to the feeble RSSI, it seemed to take a longer time to make an association of IEEE 802.11g. Authentication packets for WPA (Wi-Fi Protected Access) might have been lost and retransmitted. Therefore L2HOs in Mode 2 were longer than ones in Mode 1.

Focus on a ratio of TCP Downtime to the L2HO interval. When a distance between adjacent GBR(L)s and a train speed are estimated as is the case with in Mode 1, The L2HO interval is 6.7(*sec*). Since Average TCP Downtime was 909(*ms*) in Mode 2, TCP Downtime occupied 13.6% of the L2HO interval.

Four hundred mili-seconds in TCP Downtime was due to L2HO itself, the rest was caused by a suspension of TCP transmission. A solution to reduce Retransmission Wait Time was proposed in [42]. Even if the method was implemented in our system, we still would have a long L2HO Wait Time of 400(*ms*). TCP is not a protocol to transmit time-sensitive applications such as VoIP (Voice over IP). If TCP were the only protocol to be forwarded in the system, a method proposed in [42] would be a nice solution. However when VoIP is used over UDP, L2HO Wait Time of 400(*ms*) deteriorates its quality. Our system transfers not only TCP but also all protocols. Therefore a solution must be effective for all protocols, even when it was taken to make TCP performances better over L2HOs. In other words, a communication suspension of 400(*ms*) should not be allowed for each L2HO completion. As discussed above, in order to improve TCP performances over L2HOs, **a system is required to have traffic forwarded during L2HO Wait Time**.



(a) TCP Rate Sent from the Train PC



(b) TCP Parameters

Fig. 4-6 TCP Performances over a L2HO in Mode 2

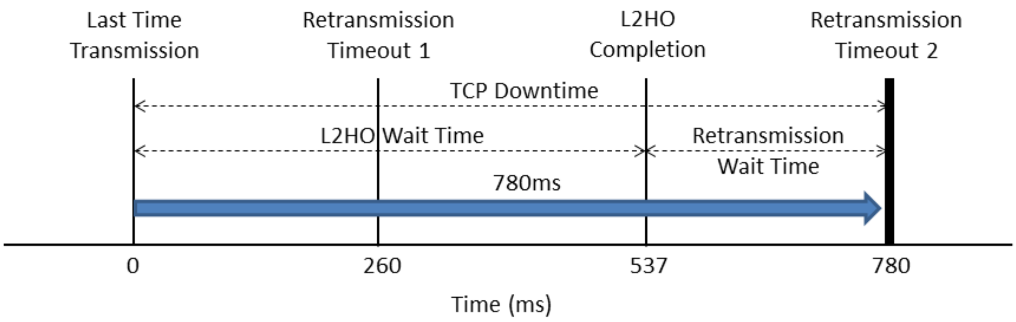


Fig. 4-7 TCP State Transition over L2HO at 8.6sec in Fig. 4-6

Table 4-3 Average TCP Downtime at L2HO in Mode 2

	L2HO Wait Time	Retransmission Wait Time	TCP Downtime
Consumed Time (ms)	400	509	909

4.8. TCP Rate Model

This section shows a model of TCP Rate which can be obtained by the IEEE 802.11g Communication System. Here "TCP Rate Model" means to acquire a relationship between the Trajectory Distance (see Section 3.5.3 for the definition) and TCP Rate on the basis of two relationships: (1) between the Trajectory Distance and RSSI which is received on the TBR(L) as depicted in Fig. 3-11 and (2) between RSSI and TCP Rate.

At first, consider the relationship (1). Let the measured RSSI shown in Fig. 3-11 be expressed by a linear approximation with the least square method. Let Trajectory Distance be d and RSSI be r. The relationship is formulated as follows.

$$r = -0.050d - 55.6 \quad (0 \leq d \leq 600\text{m}) \tag{4-1}$$

Consider the relationship (2). The relationship was obtained by the following experiment. TCP traffic was generated by Iperf on the Train PC and it was sent to the Ground PC. Payloads of the TCP packets which left the Train PC were measured by Wireshark. This is the same manner as in Section 4.7. At the same time, RSSI which was received on the TBR(L) was observed by the same method as described in Section 3.5.4. This measurement was done for both Mode 1 and Mode 2. Fig. 4-8 shows measured RSSIs and TCP Rates for both Mode 1 and Mode 2, which are distributed along a line. The least square method for all the data gave an approximated line as follows.

$$b = 0.732r + 63.2 \qquad (r \geq -86.4(dBm)) \tag{4-2}$$

Where TCP Rate is b. Formula (4-1) and (4-2) gives the relationship between the Trajectory Distance and TCP Rate as follows.

$$b = -0.0366d + 22.5 \qquad (0 \leq d \leq 600\text{m}) \tag{4-3}$$

Formula (4-3) shows the expected TCP Rate for each Mobile Station running at 270km/h in the IEEE 802.11g Communication System. d = 0 means the place where a GBR(L) is set up. TCP Rate given by formula (4-3) repeats every 500(*m*). Fig. 4-9 depicts formula (4-1) and (4-3) with three GBR(L)s which are positioned at 0(*m*), 500(*m*) and 1,000(*m*) on the X-axis. Fig. 4-9 assumes that the signal from each GBR(L) is emitted in the right direction in the figure. TCP Rate and RSSI are overlapped in the vicinity of each GBR(L), because two adjacent wireless cells are overlapped. In these sections, the TBR(L) makes an association with one of the two GBR(L)s.

Although the measured RSSIs shown in Fig. 4-8 are distributed along the same line for both modes, the distributed range differs from each other. A large part of data with RSSI of -75(*dBm*) or lower was for Mode 1, whereas a large part of data with RSSI of -60(*dBm*) or higher was for Mode 2. This distribution indicates that the TBR(L) works within relatively farther distance from the active GBR(L) in Mode 1 and the TBR(L) works within relatively closer distance from the active GBR(L) in Mode 2. This is caused by the L2HO characteristics for each Mode (See Section 3.6.3).

In Mode 1, a L2HO does not always take place just after the TBR(L) enters a new GBR(L) cell to which it is expected to be connected. It makes its best effort to keep the active association until one of the L2HO triggers (See Section 3.6.2) has occurred. Therefore the TBR(L) worked near an edge of the previous GBR(L) in spite of an availability of new better GBR(L), which resulted in low RSSI observations of -75(*dBm*) or lower from the previous GBR(L). The distance between the TBR(L) and the new GBR(L) became large by the time a L2HO trigger occurred. This characteristic also resulted in the TBR(L) missing the best range of RSSI from the new GBR(L). In many cases, RSSI deteriorated to -60dBm or lower by the time the TBR(L) got a connection to the new GBR(L).

In Mode 2, the TBR(L) keeps the wireless link with the active GBR(L) until the TBR(L) passes by the GBR(L). Just before the passing, the distance between the communicating two wireless bridges are very close and RSSI which the TBR(L) receives is quite large. This is the reason why a large part of data with RSSI of -60dBm or higher belongs to Mode 2. The TBR(L) must make an association with the next GBR(L) which is located 500(*m*) from the TBR(L) after it has passed by the previous GBR(L). This characteristic resulted in TCP downtime of 909(*ms*) as described in Section 4.7.2. In other words, a L2HO in Mode 2 takes place when the TBR(L) is within the range of lower RSSI. Since the TBR(L) is isolated from any GBR(L) within that range in many cases, there is a little measured data of TCP Rate for lower RSSI. From the discussion above, ranges of the Trajectory Distance which the TBR(L) works for each mode are shown by broad arrows on the top of Fig. 4-8.

L2HOs for each mode are modeled as follows. For Mode 1, a L2HO is assumed to start when RSSI falls under -84(*dBm*) and suffer from TCP downtime of 300(*ms*). For Mode 2, a L2HO is assumed to start when the TBR(L) passes by the active GBR(L) and suffer from TCP downtime of 900(*ms*).

An expected TCP Rate for each mode is calculated as follows. The IEEE 802.11g Communication System assumes that trains run at 270(*km/h*), which gives a relationship between the Trajectory Distance *d*(m), and time *t*(sec), of *d* = *75t*. An expected TCP Rate in each wireless cell in Mode 1 $b_{1(\mathrm{cell})}$, is calculated as follows.

$$b_{1(cell)} = \frac{\int_{t_{he}}^{t_{hs}} b_{(t)}\, dt}{T} = \frac{\int_{1.2}^{7.6} (-0.0366 \cdot 75t + 22.5)\, dt}{6.7} \quad (4\text{-}4)$$

Where, *T* is the L2HO interval (See Section 4.7.1 for the definition) and *T* = 6.7(*sec*) (= 500(*m*) / 75(*m/s*)). t_{hs} is the time when the L2HO process starts, which has been assumed when RSSI falls under -84dBm, so $t_{hs} = 7.6$. t_0 is the time when TCP downtime is completed for the previous L2HO, $t_{he} = t_{hs} + 0.3 - 6.7 = 1.2$. Therefore the expected TCP Rate in each wireless cell in Mode 1 becomes $b_{1(cell)} = 10.4\ (Mbps)$. Since the Wireless Link Failure Rate is 5.2%, an expected TCP Rate from start to finish in Mode 1 $b_{1(\mathrm{ave})}$, is calculated by multiplying $b_{1(\mathrm{cell})}$ and 0.948.

$$\boldsymbol{b_{1(ave)} = 9.86\ (Mbps)} \quad (4\text{-}5)$$

The expected TCP Rate from start to finish in Mode 2 $b_{2(\mathrm{ave})}$, is calculated in the same manner.

$$\boldsymbol{b_{2(ave)} = 13.7\ (Mbps)} \quad (4\text{-}6)$$

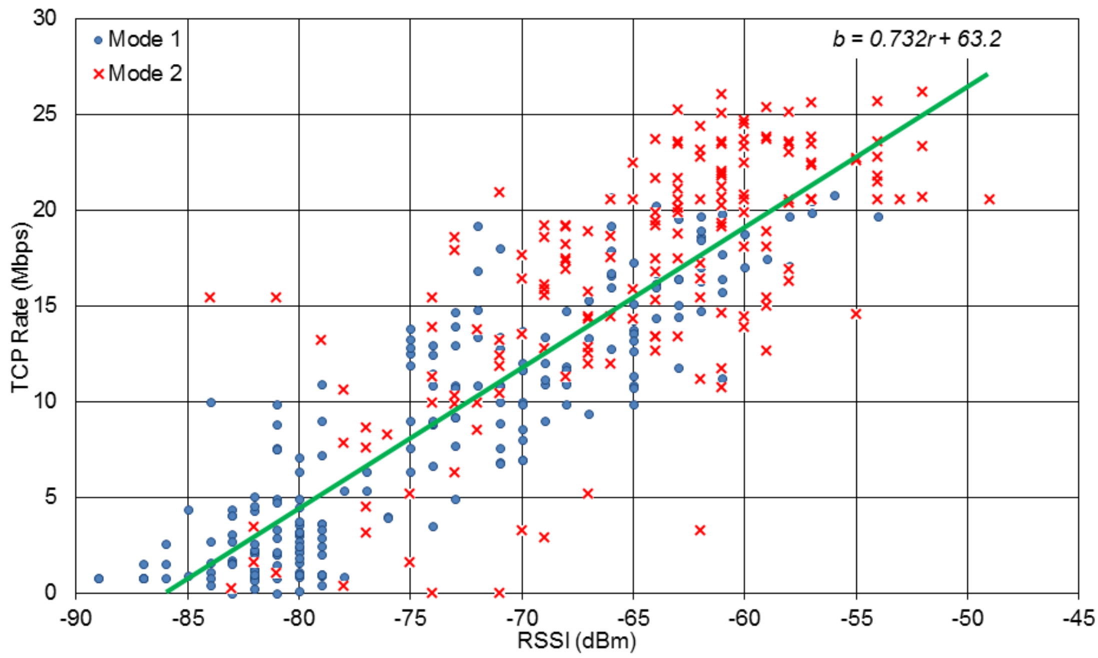


Fig. 4-8 RSSI vs TCP Rate

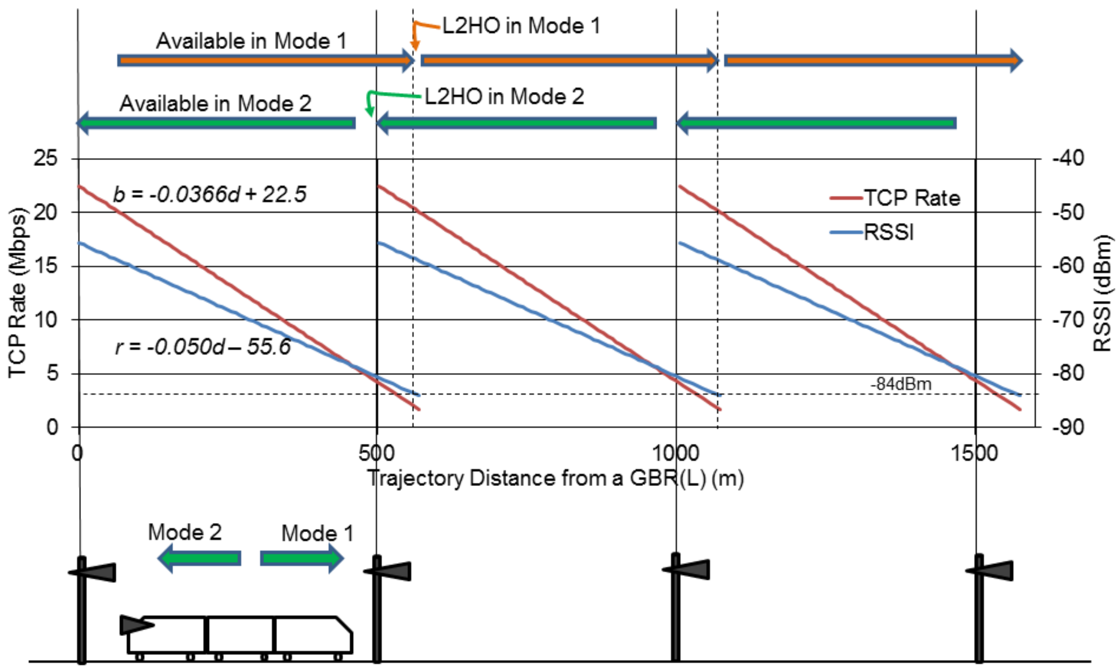


Fig. 4-9 TCP Rate Model

4.9. Requirements to improve Performances of the IEEE 802.11g Communication System

The largest problem of the IEEE 802.11g Communication System with a Singlepath Configuration is communication disruptions due to L2HOs and Wireless Link Failures. Consider Downtime of L2HOs. TCP Downtime is longer than that of UDP, because TCP needs to wait for RTO expirations whereas UDP does not. In TCP cases, not only a L2HO itself but also a RTO caused by a L2HO is another issue. Communication performance of both TCP and UDP must be improved within the system. When a solution maintains TCP connectivity during communication disruptions, the countermeasure is able to be adapted to keep UDP connectivity. This research focuses on improving TCP performances.

Time components composing TCP Downtime over a L2HO were L2HO Wait Time and Retransmission Wait Time. Therefore causes of communication disruptions were the following three.

A) Physical switching of communication channels due to L2HOs. (L2HO Wait Time)

B) Transmission stalls for RTO expirations after L2HOs (Retransmission Wait Time)

C) Wireless Link Failures

IEEE 802.11g which was originally developed for fixed or walking speed communications was applied to high speed mobile communications. Wireless Link Failures (Cause C) was seemed to be caused by radio synchronization faults due to high speed mobility. The results showed that Wireless Link Failures occurred on an arbitrary GBR(L) with the probability of 5.2%. As for TCP Downtime (Cause A and Cause B), TCP Downtime occupied 5.0% and 13.6 % of the L2HO interval in Mode 1 and Mode 2, respectively.

A ratio of communication stall duration to the whole communication period is calculated. The ratio is referred to as Communication Stall Duration Rate. In Mode 1, communication was impossible due to Wireless Link Failures in 5.2% of all the communicating period. Within the remaining time (94.8% of the whole time), L2HOs blocked traffic forwarding in 5.0%. Therefore the Communication Stall Duration Rate in Mode 1 statistically becomes 9.9% (= 0.052+(1-0.052)x0.05). The rate in mode 2 is also calculated in the same manner. It gives 18.1% (= 0.052+(1-0.052)x0.136) for the Communication Stall Duration Rate in Mode 2.

In order to improve communication performances, the Communication Stall Duration Rate must be reduced. Radio technologies propose two approaches to achieve this goal: a reduction of the rate of Wireless Link Failures and a shortening of L2HO process time. However, one of the requirements of the IEEE 802.11g Communication System is to construct a system with high financial efficiency with the use of commercially available international standard technology such as IEEE 802.11g. IEEE 802.11g must not have any modification, away from its standard configuration.

Approaches from the viewpoint of modifying radio technologies were eliminated. On the other side, from an aspect of networking technologies, a solution is required to continue traffic forwarding even during L2HOs and Wireless Link Failures. This is a method to let Layer 3 compensate for instability on Layer 1 and Layer 2. This research targets the reduction of the Communication Stall Duration Rate by an appropriate design of Layer 3 with the best effort to avoid any specialized implementations. Delay Tolerant Network (DTN) is a good solution to overcome communication disruptions. However DTN architecture has to wait for a physical link recovery and this solution has no choice but to accept communication disruptions during physical switching (Cause A). Therefore this solution does not match our requirements to have traffic forwarded during L2HOs and Wireless Link Failures.

Consider again the causes of communication disruptions with a policy to make up for instability on Layer 1 and Layer 2 by Layer 3. Requirements must be clarified to reduce the Communication Stall Duration Rate by networking technologies. Cause A and cause C have the same root on the basis of Layer 3, because both of them are problems relating to a halt of traffic forwarding due to a link being down on Layer 2. The TBR(L) is able to recover from a Wireless Link Failure when it moves to another GBR(L) cell. Cause C (a Wireless Link Failure) can be regarded as a longer version of cause A (L2HO Wait Time). In order to solve these two problems, it is required **to forward traffic while a Layer 2 link is down**. Cause B arises from cause A. A settlement of cause A may solve cause B. However in order to make a development goal clear, **to eradicate TCP Timeout caused by L2HOs** is set as another requirement. IEEE 802.11g Communication System transfers all transport protocols as well as TCP. Countermeasures must work for all the protocols including UDP when they are installed to reduce the Communication Stall Duration Rate. From the discussion above, there are three Requirements in which the IEEE 802.11g Communication System must satisfy.

(1) To enable traffic forwarding while a Layer 2 link is down

(2) To eradicate TCP Time Out caused by L2HOs

(3) To be applicable to all transport protocols

The following chapters describe improvements of the IEEE 802.11g Communication System in order to satisfy these Requirements.

4.10. Summary

This Chapter verified that the IEEE 802.11g Communication System performed in accordance with the designing intentions. The field trials were done on a commercial high speed rail system and the speed of the test train was kept at 270km/h. It was the maximum speed for the commercial service.

Our experimental results revealed communication performances on the IEEE 802.11g Communication System as shown in Table 4-4. Results showed that the IEEE 802.11g Communication System working in Mode 2 had a TCP bandwidth of 13.7(*Mbps*) even while a mobile node was moving at 270(*km/h*). We obtained a larger throughput than the target throughput of 10(*Mbps*). On the other side, however, Table 4-4 also clarified a problem of communication stall durations caused by downtimes over L2HOs and Wireless Link Failures.

In order to reduce Communication Stall Duration Rate, requirements to improve the IEEE 802.11g Communication System were considered. Our policy does not permit any customizations on IEEE 802.11g. Instabilities on Layer 1 and Layer 2 must be compensated for by Layer 3. These discussions brought three Requirements to be satisfied as follows.

(1) To enable traffic forwarding while a Layer 2 link is down

(2) To eradicate TCP Time Out caused by L2HOs

(3) To be applicable to all transport protocols

Table 4-4 Communication Performance on the IEEE Communication System

Examined Contents	Results	
IEEE802.11g Link (Wireless Link Failure)	Failed in 5.2%	
Round Trip Time	Average: 9.95(*ms*), Standard Deviation: 5.79(*ms*)	
UDP	Mode 1	Average: 16.3(*Mbps*) Max: 25(*Mbps*) or higher
	Mode 2	Average: 17.7(*Mbps*) Max: 25(*Mbps*) or higher
TCP	Mode 1	Average: 9.86(*Mbps*) Max: Around 20(*Mbps*)
	Mode 2	Average: 13.7 (*Mbps*) Max: Around 22(*Mbps*)
Communication Stability (Communication Stall Duration Rate)	Mode 1	9.9%
	Mode 2	18.1%

Chapter 5. Proposal of the Bicasting-Multipath Mobile IPv4

The IEEE 802.11g Communication System which was proposed in Chapter 3 and verified in Chapter 4 had only a single path between the ground network and the train, and all traffic went through this path. It is natural that the traffic forwarding is disrupted when a L2HO breaks the singular physical transmission channel. In order to solve this problem, this chapter proposes a method to improve the IEEE 802.11g Communication System with satisfying three Requirements held up in Section 4.9.

In order to realize “packet loss compensation during L2HOs” and “improvement of fault tolerance during Wireless Link Failures” at the same time, we propose “Multiplexing of wireless links between the ground network and each train network” and “Bicasting traffic between the redundant paths.” Two wireless links between the ground and a train are redundantly established. Each link is recognized as different IP routes (Paths) by MP-MIPv4. This is a bicasting architecture of traffic over two MIPv4 tunnels, which is named “Bicasting-Multipath Mobile IPv4.”

This chapter describes our proposal of the Bicasting-Multipath Mobile IPv4. A MP-MIPv4 network for its platform is also designed and the characteristics are considered with experimental results. The results have shown that IPLB (IP-based Load-Balancing) is the best load-balancing solution for the IEEE 802.11g Communication System. The Bicasting-Multipath Mobile IPv4 must govern a bicasting mechanism. Bicasting has to be started or stopped in accordance with occurrences of L2HOs or Wireless Link Failures. A way to control bicasting is described in Chapter 6.

5.1. Introduction

In order to support increasing network access requirements in mobile environments, we are developing the IEEE 802.11g Communication System. Through Chapter 4, it has proven that the IEEE 802.11g Communication System realizes a maximum TCP throughput of around 20(*Mbps*) while moving at a high speed. On the other side, we have revealed that the system suffers from instabilities due to frequent L2HOs and Wireless Link Failures. Section 4.9 set out three Requirements which the IEEE 802.11g Communication System had to satisfy in order to solve those issues. This chapter discusses how to improve the IEEE 802.11g Communication System to meet these Requirements.

(1) To enable traffic forwarding while a Layer 2 link is down

(2) To eradicate TCP Time Out caused by L2HOs

(3) To be applicable to all transport protocols

With the Singlepath configuration shown in Fig. 3-5 and Fig. 3-13, communications are done through the TBR(L), which has been set up at an edge of the test train. Chapter 4 reported differences of communication characteristics between Mode 1 (the train runs with the TBR(L) at the rear edge) and Mode 2 (at the front edge). Although the result showed some differences, both modes realized a maximum TCP throughput of around 20(*Mbps*). Therefore, with another TBR set up at the other edge of the train, two wireless links become active at the same time between the ground network and the train. We must obtain redundant paths with an adequate usage of each of them. During either a L2HO or a Wireless Link Failure, traffic is bicasted over those redundant paths. In the remaining time, other traffic is unicasted on each IEEE 802.11g link.

The IEEE 802.11g Communication System was designed on a MIPv4 platform. One of the policies is not to modify anything on Layer 2 and lower. With a consideration of these policies, for an establishment of two paths between the ground network and the train network, we decided to leverage Multipath Mobile IPv4 (MP-MIPv4) as an extension of MIPv4 on Layer 3 and recognize each path on Layer 3. Since each MIPv4 tunnel is established on each wireless link, bicasting has to be done over the redundant MIPv4 tunnels. We propose an implementation of a bicasting architecture on a MP-MIPv4 platform, which is named "Bicasting-Multipath Mobile IPv4."

This chapter describes our proposal of the Bicasting-Multipath Mobile IPv4. It works on a MP-MIPv4 platform. MP-MIPv4 characteristics are reported with experimental results and then a MP-MIPv4 network platform is designed for the Bicasting-Multipath Mobile IPv4. The Bicasting-Multipath Mobile IPv4 must govern a bicasting mechanism. Bicasting has to be started or stopped in accordance with occurrences of L2HOs or Wireless Link Failures. Bicasting control is described in Chapter 6.

The organization of this chapter is as follows. Section 5.3 stresses the necessity of the Bicasting-Multipath Mobile IPv4 and proposes the solution. Section 5.4 designs the IEEE 802.11g Communication System with Dualpath Configuration and discusses how to load-balance traffic over two paths established by MP-MIPv4. Section 5.5 reports communication test results of the IEEE 802.11g Communication System with Dualpath Configuration working on Per-Packet Load-Balancing (PPLB). The results reveal that PPLB is an inadequate load balancing algorithm for our situation. Section 5.6 appeals that Destination IP-based Load-Balancing (IPLB) is an appropriate algorithm to satisfy three Requirements set out in Section 4.9 for the IEEE 802.11g Communication System.

5.2. Related Works

5.2.1. Multipath Mobile IP

Conventional MIP was able to establish merely a single MIP tunnel between HA and MR. Even when plural communication media were available to use, MR had to choose one of them. MP-MIP [13] removed this limitation and became able to establish plural MIP tunnels at the same time as shown in Fig. 5-1. Communication bandwidth can be cumulated by this technology and traffic is then load-balanced on each tunnel.

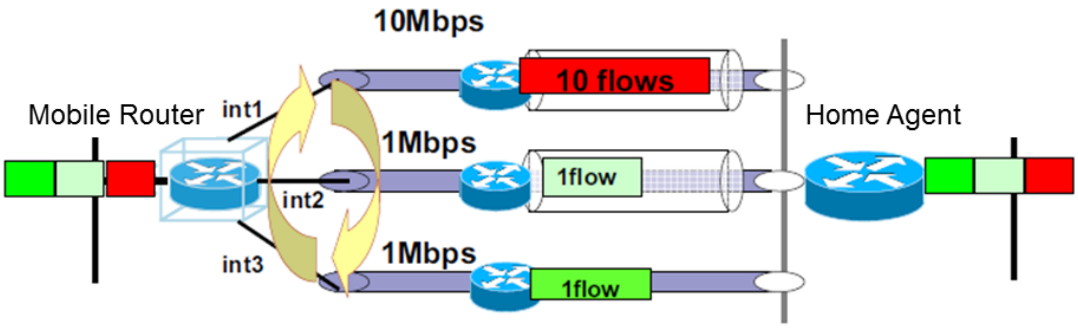


Fig. 5-1 Multipath Mobile IPv4 (MP-MIPv4) [13]

5.2.2. Performance Enhancement by TCP Proxies

TCP connections should be established between end nodes to communicate with each other. Some methods were proposed to split a TCP connection along its communication path in some special circumstances. Two examples of communication characteristics are described below as backgrounds of these proposals.

The first case is a communication line with a high rate of random packet losses. TCP is not able to distinguish random packet losses which are likely to occur on wireless links from burst packet losses due to congestions on its communication path. TCP interprets that the latter is the cause of all these packet losses and controls its flow. A random packet loss rate is generally high on wireless links. Therefore, in cases that a TCP connection goes through wireless links, TCP reduces the Congestion Window (cwnd) by its congestion control whenever random packet losses occur. This nature deteriorates TCP throughput.

The second case is a communication line with a large RTT. In TCP, the cwnd is the number of bytes which are allowed to be sent from a sender. It is counted up from the first unacknowledged sequence number in the sent segments. Here, assumed that the advertised window size is always larger than the cwnd. The cwnd is equivalent to the inflight size (sent but unacknowledged data size) per RTT in average. Therefore, TCP throughput is given by cwnd/RTT. In order to obtain sufficient TCP throughput on communication lines with a large RTT such as Satellite communications and intercontinental communications, large cwnd matching with large RTT is required. It is well-known that the best cwnd which achieves the most effective data forwarding is the size of Bandwidth*Delay Product (BDP). Maintenance of the cwnd depends on a congestion control algorithm implemented in TCP. The basic implementation is Additive Increase Multiplicative Decrease (AIMD). In congestion avoidance mode in TCP Reno, the increase speed of the cwnd is MSS/RTT. It is quite slow in a large RTT situation. Furthermore, when the cwnd increases to around the BDP, then packet losses occur, TCP Reno reduces the cwnd to half of the last cwnd before the event by a Multiplicative Decrease implementation. It takes quite a long time to increase the cwnd again. It is difficult to obtain a sufficient cwnd on a long RTT communication line.

In order to combat these issues, some methods were proposed to split a TCP connection at both ends of a wireless link and isolate the TCP connection from the wireless link [43] [44] [45] [46] [47] [48]. These methods are referred to as “TCP Splitting” in this paper. All the papers have a basic common idea where a TCP is split into a wireless section and wired sections on both sides of the wireless section as shown in Fig. 5-2. In some proposals, one of the proxies works as an end host and a TCP is split into two sections. This difference is not an essential issue. The TCP proxies reply with Local ACKs (See Table 1-1) for data receptions and buffer the packets. The packets are forwarded to the other TCP proxy over a TCP connection on a wireless section and then delivered to the target end host. There are various proposals for transport protocols between TCP proxies such as TCP Reno, TCP Vegas, TCP Westwood, SCTP based on TCP Reno, SCTP based on TCP Vegas and so on. An application-based flow control over UDP was also mentioned in [48]. The application performs a TCP-like flow control. It is essentially the same as TCP based solutions.

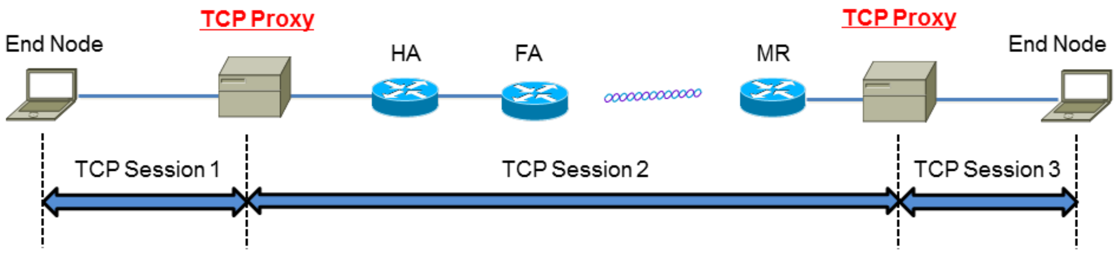


Fig. 5-2 Performance Enhancement by TCP Proxies

In a TCP Splitting method, an end node establishes a TCP connection with a TCP proxy through wired links. Few packet losses are expected and RTT is quite small. End nodes are sheltered from a poor wireless link. They recognize the communication line as fast and error free. However data which is destined to the other end node is only buffered on the near side TCP proxy and it is still in the process of forwarding. Packets have no choice but to be transmitted through a slow wireless link with heavy packet losses.

5.2.3. Packet Loss Compensation by Bicasting during L2HOs

In mobile communications, mobile stations have to move from a ground station to another under the same subnet of ground networks in addition to L3HOs where a mobile station crosses a network border. These are L2HOs. Since a L2HO does not require any updates of routing tables, it generally takes shorter time than a L3HO. However packet forwarding still stalls during a L2HO process, which causes packet losses. “Bicasting” was proposed to avoid these packet losses [49] [50] [51] [52] [53]. According to a basic idea proposed in the past, adjacent wireless cells of ground stations are overlapped to each other as depicted in Fig. 5-3. A mobile station making a L2HO establishes plural wireless links with available ground stations at the same time. Traffic is bicasted (or multicasted when the number of links are three or more) over the links. The communication is continued by packets safely traveled through one of the links.

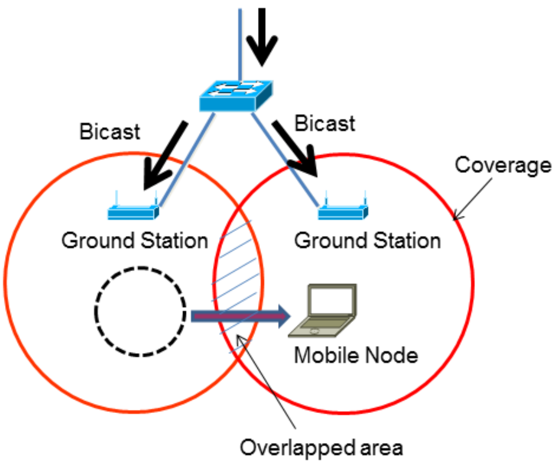


Fig. 5-3 Packet Loss Compensation by Bicasting during L2HOs

5.3. Proposal of the Bicasting-Multipath Mobile IPv4

The IEEE 802.11g Communication System which was proposed in Chapter 3 and verified in Chapter 4 had only a single path between the ground network and the train, and all traffic went through the path. It is natural that the traffic forwarding is disrupted when a L2HO breaks the singular physical transmission channel. In order to solve this problem, this chapter proposes a method to improve the IEEE 802.11g Communication System with satisfying three Requirements held up in Section 4.9. Three Requirements are as follows.

(1) To enable traffic forwarding while a Layer 2 link is down

(2) To eradicate TCP Time Out caused by L2HOs

(3) To be applicable to all transport protocols

We have two existing solutions which are likely to satisfy these Requirements. They are “TCP splitting by TCP proxies” described in Section 5.2.2 and “Bicasting during L2HOs” described in Section 5.2.3. TCP splitting by TCP proxies shelters End Nodes from a wireless link which suffers from a high random packet loss rate and/or high latency. When it is applied to the IEEE 802.11g Communication System, adequate buffering on TCP proxies must isolate IEEE 802.11g links from the rest of the network and protects End Nodes from L2HOs. On the other side, since a Wireless Link Failure takes more than 10 times longer than RTT or RTO in a normal situation, the buffering on the proxies may fail to guard End Nodes. Also this solution works only for TCP as the name indicates. The IEEE 802.11g Communication System must not depend on protocols on Layer 4 and higher. All protocols, applications and services on those layers perform on the network platform. This consideration eliminated “TCP splitting by TCP proxies.”

Consider bicasting methods over a L2HO. Proposed methods [49][50][51][52][53] have a common idea where two paths between the ground network and mobile terminal are established and packets are bicasted onto both paths as depicted in Fig. 5-3. Generally “two paths” are: (1) the active current path which a mobile node is being connected to, and (2) an expected path through the next ground station to which the mobile station moves. Assumptions to employ these conventional technologies are: (1) cell coverage of two adjacent ground stations are overlapped, and (2) two paths are constructed between each of two ground stations and a mobile terminal when the mobile terminal is in the overlapped section. On the other side, the TBR(L) fails to make a connection with a GBR(L) with the possibility of 5.2%. The IEEE 802.11g Communication System has a lack of certainty in making a wireless link association. If one of conventional proposals were applied to the IEEE 802.11g Communication System, the TBR(L) and GBR(L)s could not bicast any packets when the TBR(L) failed an association with one of the two GBR(L)s. Furthermore, the TBR(L) and the train network is isolated from the Internet until the TBR(L) leaves the failed cell and is able to connect with the next GBR(L).

In order to realize “packet loss compensation during L2HOs” and “improvement of fault tolerance during Wireless Link Failures” at the same time, we propose “multiplexing of wireless links between the ground network and each train network” and “Bicasting traffic between the redundant paths.” Two wireless links between the ground and a train are redundantly established. Each link is recognized as different IP routes (Paths) and they are bundled by MP-MIPv4. When a L2HO or a Wireless Link Failure occurs on one of the paths, packets are bicasted on both paths and the session can be maintained through the other active path. In other words, the proposal is a bicasting solution on an IP Layer on a MP-MIPv4 platform. This solution is implemented on Layer 3, thus has no dependence on Layer 4 and higher. It is able to satisfy Requirement (3). This chapter explains the MP-MIPv4 platform on which wireless links between the ground network and each train network are multiplexed and packets are bicasted between the redundant paths. Also this chapter considers how to load-balance traffic between the MIPv4 paths.

5.4. Design of the IEEE 802.11g Communication System with Dualpath Configuration

5.4.1. Radio Transmission Channels for Dualpath Configuration

The Singlepath Configuration shown in Fig. 3-5 and Fig. 3-13 transmits all traffic through the TBR(L) set up at an edge of the train. Chapter 4 reported differences of communication characteristics between Mode 1 where the train moves with the TBR(L) at the rear edge of the running direction and Mode 2 where the train moves with the TBR(L) at the front edge. Results showed some differences but both modes brought the maximum throughput of around 20(*Mbps*). Therefore, the second wireless link can be established between the ground and the train, when another TBR is set up at the other edge of the train. In our proposal, traffic is bicasted on these two paths during L2HOs and Wireless Link Failures, and other traffic is forwarded on each path for the remaining time. Two TBRs should not suffer from a L2HO at the same time making bicasting effective. This is why the additional TBR was set up at the other edge. The setup with two paths is referred to as Dualpath Configuration in this paper.

A system deployment is depicted in Fig. 5-4. The Dualpath Configuration employed the same devices as the Singlepath Configuration. GBRs, GANTs, TBRs and TANTs have a suffix of (R) and they are distinguished from devices with a suffix of (L) in the Singlepath Configuration. Each set of a GBR(R) and a GANT(R) was set up at the same place as a set of a GBR(L) and a GANT(L) was deployed. A set of two ground stations at the same location is lined up in order as depicted in Fig. 5-5 such as BR1-11 and BR4-11, BR1-12 and BR4-12. A Signal from each GANT(R) was emitted in the opposite direction of 180 degrees from each GANT(L). TANT(R), a counterpart antenna on the test train, was placed at the other driver’s cabin. The same channel was generated on GANT(L) and GANT(R) which were set up at the same location. Interferences of IEEE 802.11g were avoided by the beam directivity and a train’s body. GBR(L)s and GBR(R)s worked on a different SSID (Service Set IDentifier). The TBR(L) and the TBR(R) respectively associated with GBR(L)s and GBR(R)s.

Chapter 4 discussed characteristic differences of Mode 1 and Mode 2. In the Dualpath Configuration depicted in Fig. 5-4, regardless of the TBR(L) or the TBR(R), one of them which was placed at the front edge of the running test train worked in Mode 2 and the other TBR on the rear edge of the train performed in Mode 1.

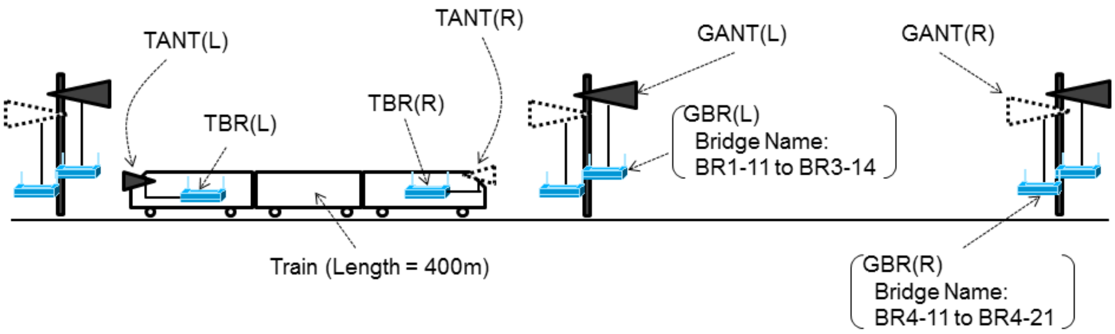


Fig. 5-4 Configurations of Wireless Links (Dual-Path)

5.4.2. Network Topology for Dualpath Configuration

A network topology for the Dualpath Configuration is shown in Fig. 5-5. As described in Section 3.7, this system is required to work on a MIPv4 platform. MP-MIPv4 is an extension of MIPv4 and able to establish plural paths between HA and MR. Therefore MP-MIPv4 was employed for the platform of the Dualpath Configuration.

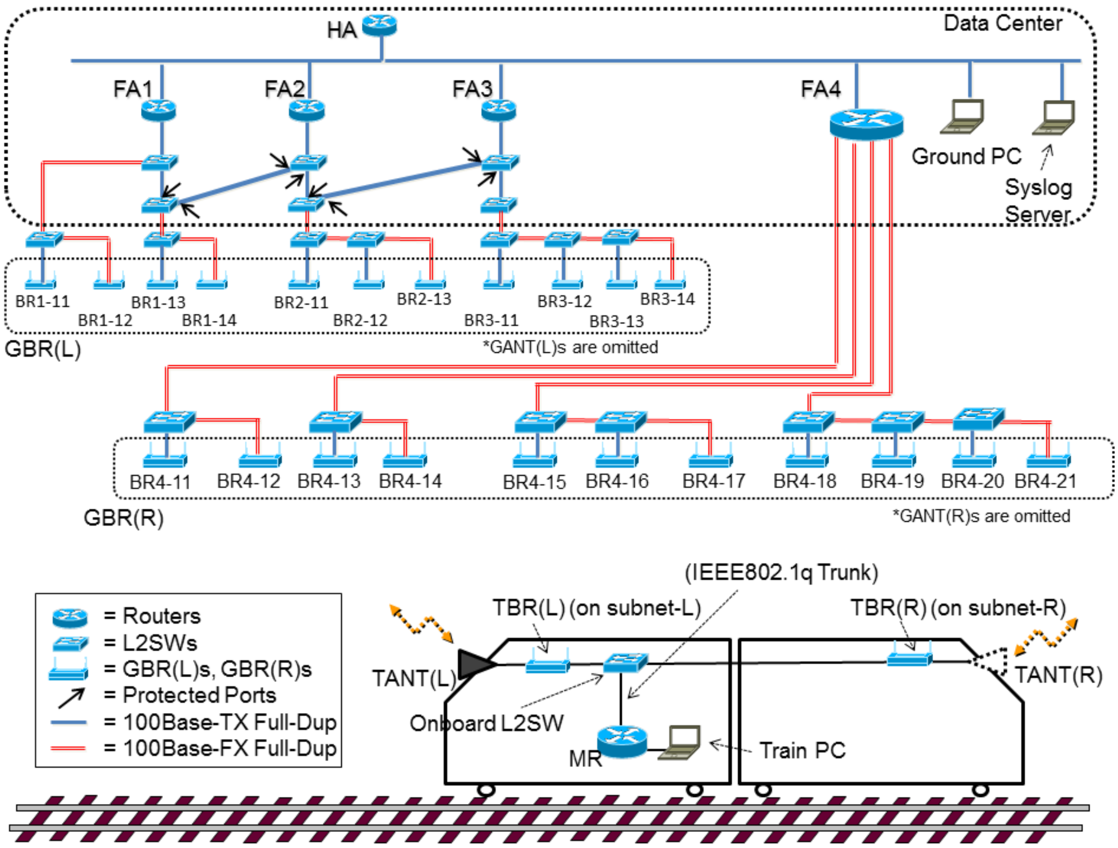


Fig. 5-5 Dual-Path Network Configuration (Experimental)

HA, MR, FA1~FA3 which are located in Fig. 5-5 are the devices used in the Singlepath Configuration. FA4 was additionally set up on the Singlepath Configuration (see Fig. 3-13). A path via FA1, FA2 or FA3 and the other path via FA4 are logically recognized as different IP routes by MP-MIPv4, and thus dualpaths were established. Only one FA (FA4) was set up on the additional path. This was a result of no requirements for L3HO tests on the new path because verifications of L3HOs had been already done between FA1, FA2 and FA3 as discussed in Section 4.4. A FA is also able to handle 11 GBRs, though the optimum number of GBRs under each FA is around 40 as discussed in Section 3.7.1.

The TBR(L) and the TBR(R) were located in different subnets on a train network. A link between MR and Onboard L2SW is an IEEE 802.1q Trunk. The TBR(L) and the TBR(R) were connected to different VLANs on the same physical interface on MR. MR is able to recognize these two paths as different networks to each other and establish two different paths (MIPv4 tunnels) on each route.

A path going through FA1, FA2, FA3, GBR(L)s and the TBR(L) is referred to as Path(L) and a path going through FA4, GBR(R) and the TBR(R) is referred to as Path(R). One of the paths going through at the front edge of the running test train worked in Mode 2 and the other path at the rear edge of the train performed in Mode 1.

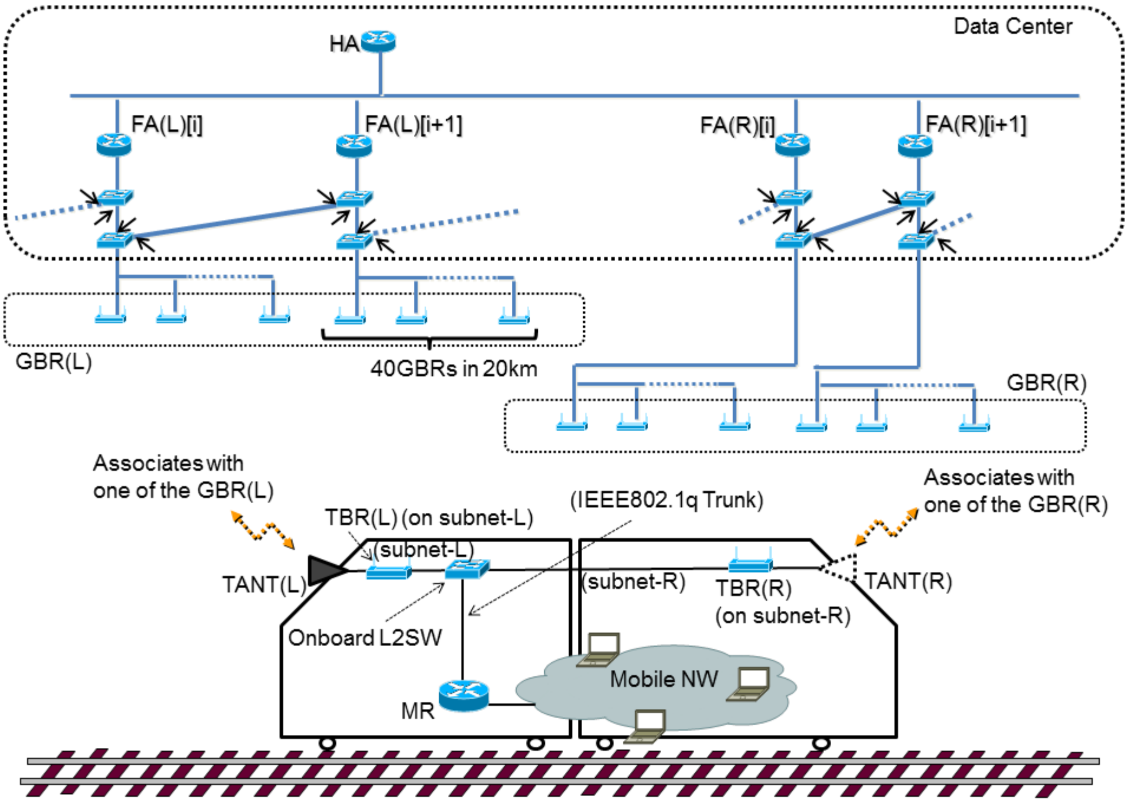


Fig. 5-6 Dual-Path Network Configuration (Optimized)

As for the links drawn in Fig. 5-5, Ethernet cables of 100Base-TX Full-Duplex were used for the links drawn with blue single lines, and the other links drawn with red double lines were connected by optical fibers with the use of media converters. They worked on 100Base-FX Full-Duplex. Therefore the bottleneck of the communication is on the IEEE 802.11g link between one of the GBRs and a TBR.

For an additional consideration with the basis discussed in Section 3.7.1, a better configuration for the IEEE 802.11g Communication System with Dualpath Configuration is as follows and depicted in Fig. 5-6. The required numbers of FAs each of which accompany 40 GBRs are set up. Adjacent subnets under FAs are connected with shortcuts by L2SWs which support a protected ports solution. The required number depends on the distance which should provide coverage for the whole system. Each FA, in other words 40 GBRs, is able to cover 20(*km*). For the Dualpath Configuration, two sets of the system above are set up for Path(L) and Path(R) and they are deployed in the manner instructed in Fig. 5-4 and Fig. 5-5.

5.4.3. Load Balancing Methods for TCP Traffic on Dualpath

Load balancing methods for TCP traffic on Dualpath can be broadly classified into two groups as follows.

(1) per-packet Load-Balancing (PPLB)

A packet forwarding path is chosen per packet without any consideration about TCP sessions. In accordance with the order of packets output from a sending buffer of HA or MR, odd packets take one path while even packets transmit through the other path.

Generally speaking, Transmission latency in wireless communications has ever-changing characteristics, which are obvious from results shown in Fig. 4-4 and Fig. 4-6. In PPLB, a difference of the transmission latency on the two paths causes packet reception disorders which corrupt the sending order. TCP interprets such situations as packet losses and performs Retransmission Control and Congestion Control. Frequent disorders of packet reception decrease the Congestion Window of TCP, which does not allow TCP to increase its throughput.

(2) Session-base Load-Balancing (SBLB)

Packets of each TCP session are always forwarded on the same path. Therefore when a L2HO occurs on the path on which TCP is transmitting, the same event occurs as a L2HO case in the Singlepath Configuration. Since SBLB relies on TCP sessions to load balance their flows, it is not applicable to the other protocols from TCP.

5.5. Performances in PPLB

In SBLB, all packets of a certain TCP session always go through the same path. When a L2HO occurs on a path, TCP sessions communicating on the path suffer from the same event as they have experienced during a L2HO in the Singlepath configuration. Communication characteristics on each path in the Dualpath configuration with SBLB are completely the same as those in the Singlepath configuration.

In PPLB, on the other side, the forwarding path is decided per-packet. PPLB must show different characteristics from the Singlepath configuration. This section reports UDP and TCP performance evaluations over PPLB. As described in Section 5.4.3, PPLB decides forwarding paths for each packet by the per packet algorithm without any consideration about TCP sessions and IP addresses. A difference of transmission latency on two paths causes packet reception disorders which corrupt the sending order. This section evaluates how large the disorder affects UDP and TCP performances.

5.5.1. UDP Performance

UDP throughput was measured in the same manner as described in Section 4.6. Iperf was used to generate UDP traffic. It was sent from the Train PC to the Ground PC with the constant sending rate of 50(*Mbps*). The Reception rate on the Ground PC was observed. The payload size of each packet was 1,200(*Bytes*) (MAC frame size was 1,242(*Bytes*)). All packets were captured on the Ground PC by Wireshark. The UDP throughput was calculated every 0.1(*sec*) by accumulating all the payloads of the packets which arrived at the Ground PC. The observed UDP throughput is shown in Fig. 5-7.

In this experiment, the train ran with the TBR(L) at the front edge and the TBR(R) at the rear edge. It was a movement in the left direction in Fig. 5-5. When the TBR(L) made an association with BR3-14, the first MP-MIPv4 tunnel was established. After making sure an establishment of the path, UDP traffic was started from the Train PC to the Ground PC. The first packet was received at the Ground PC at time 0. Once the TBR(R) at the rear edge of the test train associated with one of the GBR(R)s and the second path created, the PPLB algorithm started to work for load-balancing. In this experiment, the TBR(R) suffered from a Wireless Link Failure with BR4-21. Therefore, the second path was established while the TBR(R) was connected with BR4-20. The first packet which was forwarded through the second path reached the Ground PC at 20.189(*sec*). When the TBR(L) at the front edge of the test train passed by BR1-11 (the last GBR(L) in the trial section), the number of physically available links became one. The dualpath was ceased. The IEEE 802.11g link between the TBR(L) and BR1-11 went down at 71.586(*sec*).

The UDP throughput fluctuated between 25(*Mbps*) and 55(*Mbps*) during the Dualpath communication. An average was 38.7(*Mbps*). The throughput showed sharp drops at 29.3(*sec*) and 58.7(*sec*). In these cases, two independent L2HOs on both Path(L) and Path(R) occurred shortly after each other. The result showed that PPLB cumulated the communication bandwidths of both paths for UDP.

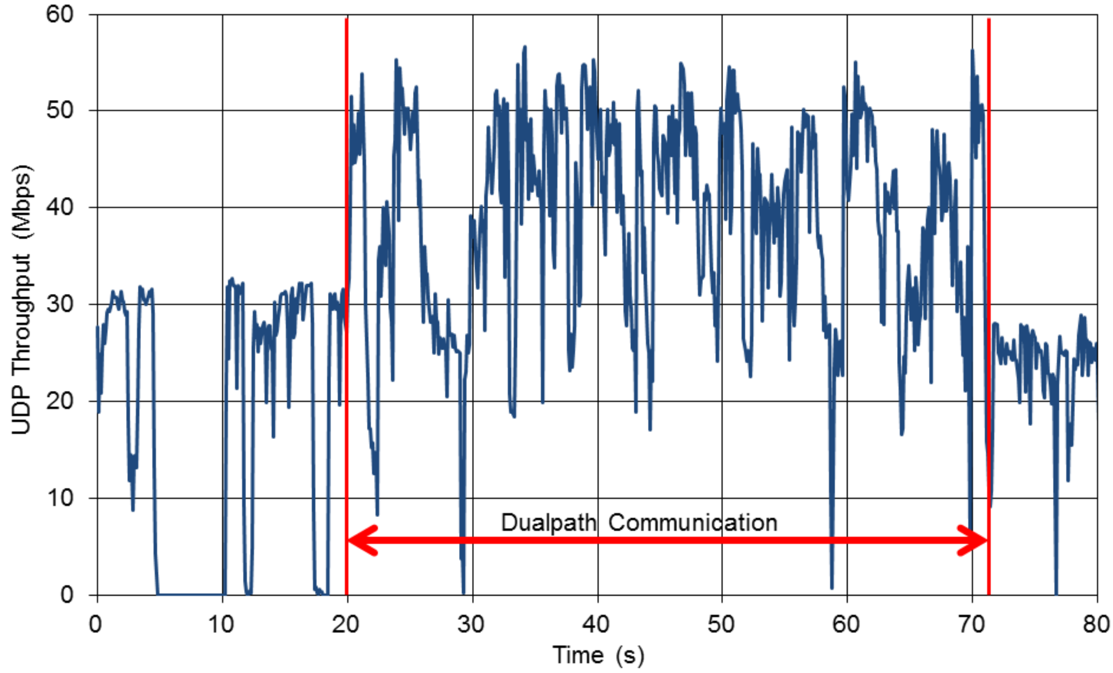


Fig. 5-7 UDP Throughput on MP-MIPv4 platform with PPLB

5.5.2. TCP Performance

TCP throughput was measured in the same manner as described in Section 4.7. Iperf was used to generate TCP traffic which was sent from the Train PC to the Ground PC in Fig. 5-5. All the packets were captured by Wireshark on both PCs. The MSS for our trial was 1,396(*Bytes*) and a Frame Size was 1,514(*Bytes*). These are the same settings as in the Singlepath configuration. Fig. 5-8 is TCP Rate sent from a LAN interface on the Train PC. It was measured every 100ms by accumulating all the packet payloads. The time on the x-axis originates from when the Train PC sent the first packet.

In this experiment, the train ran with the TBR(L) at the front edge and the TBR(R) at the rear edge. It was a movement in the left direction in Fig. 5-5. The duration while the Dualpath is active is defined as in the UDP case. Both paths became active at 1.916(*sec*) after the TBR(R) was initiated. Path(L) went down and the Dualpath was ceased at 53.281(*sec*). The TBR(L) experienced a Wireless Link Failure at BR2-11 between 21.079(*sec*) and 26.325(*sec*).

TCP Rate frequently dropped to 0. Unlike UDP characteristics, TCP Rate in Fig. 5-8 is not the sum of Fig. 4-4 and Fig. 4-6. While the TBR(L) was suffering from a Wireless Link Failure at BR2-11, TCP Rate stayed almost 0 in spite of a healthy link on the other path. The causes of this are as follows.

A thorough investigation revealed that a L2HO always occurred at one of the paths whenever TCP Rate dropped to 0. The other path was working well during these events. A traffic flow chart at one of these occurrences was produced in Fig. 5-9 on the basis of a Wireshark log. In this modeling process, Delayed Acknowledgements, one of the features in popular TCPs, was eliminated to make it simple. When one of the paths experienced a L2HO, all the packets on the path were dropped. Since packets were alternately load balanced onto two paths by the PPLB algorithm, one out of every two packets was lost in both directions of communication. From a viewpoint of the sender TCP, an ACK came back for every four data segments. Therefore an output rate from the sender TCP decreased to 1/4 in every RTT because TCP controlled an output timing of data segments by the Self-Clocking feature. After the last ACK had been forwarded to the L2HO path, the sender TCP did not receive ACKs anymore. Now the sender TCP halted sending data segments and started to count down the RTO timer. The stall duration waiting for a RTO expiration is the root cause of TCP Rate of 0. This behavior is not an accident but an inevitable occurrence due to one of the TCP natures. In a flow control by PPLB, Fig. 5-9 shows the typical TCP traffic flow when one of the paths is experiencing a L2HO whereas the other is forwarding traffic. This result has revealed that TCP throughput does not become the sum of that of two paths (Fig. 5-8 is not the total of Fig. 4-4 and Fig. 4-6) unlike UDP.

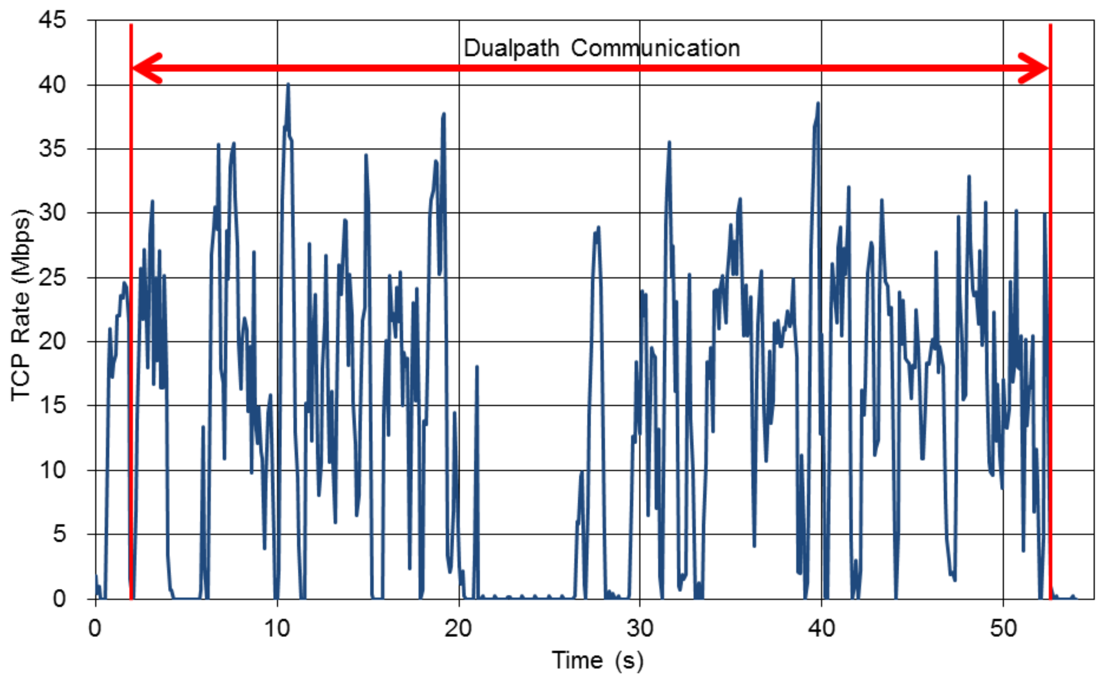


Fig. 5-8 TCP Rate Sent from Train PC

In order to analyze a TCP behavior during a Wireless Link Failure on one of the paths, a TCP traffic flow chart was generated in the same manner as the TCP behavior investigation over a L2HO. The flow chart is shown in Fig. 5-10. During the event, one out of every two packets was lost. A packet loss rate was exactly 50%. This is the same characteristic as the L2HO case has shown. Furthermore, a Wireless Link Failure always lasts much longer than a L2HO. Fig. 5-10 revealed a pattern of traffic flow during the event. The sequence in Fig. 5-10 consists of RTT + 3*RTOs per block of packet flow. The block was repeated. RTO was roughly between 250(*ms*) and 300(*ms*). RTT was much shorter than RTO and thus was neglected. The interval of the block was between 750(*ms*) and 900(*ms*). This is why Fig. 5-8 has very small peaks during the Wireless Link Failure. This result has shown that a Wireless Link Failure on one of the paths in the PPLB configuration suppresses a TCP throughput to almost 0 in spite of a normal operation on the other path.

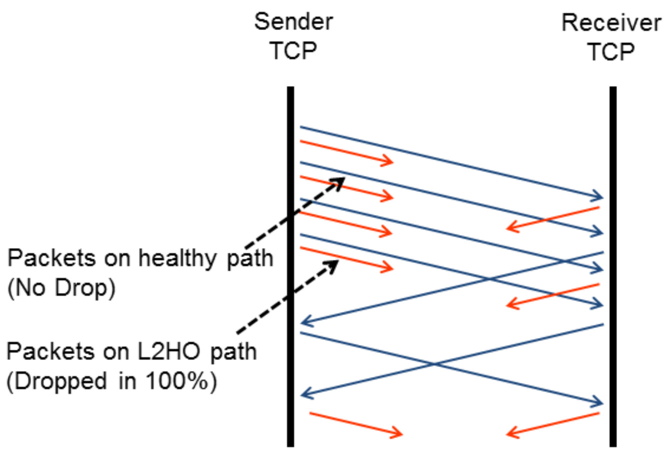


Fig. 5-9 TCP flow over a L2HO

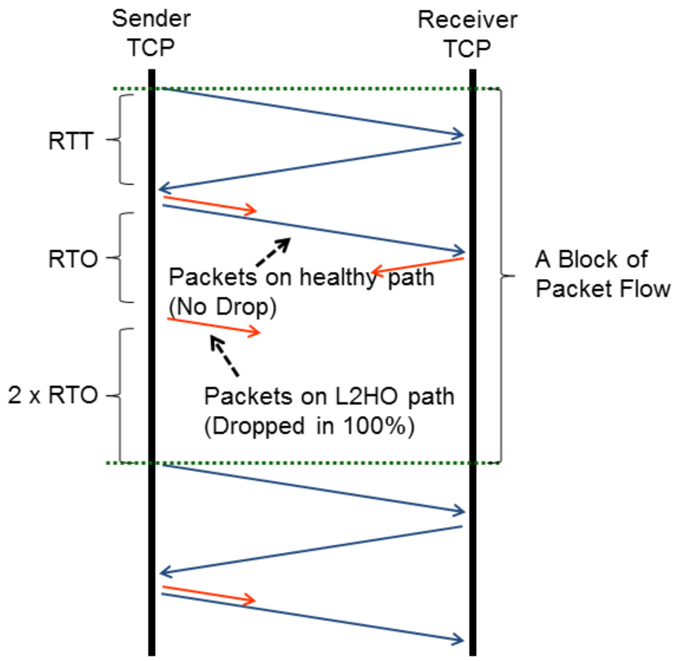


Fig. 5-10 TCP flow while Single Wireless Link Failure (the other link works well)

5.6. Destination IP-based Load Balancing

From the experimental results and analysis on TCP as discussed in Section 5.5.2, TCP has significant troubles in the PPLB topology unless both paths properly forward traffic. A difference of transmission latency on two paths causes packet reception disorders which corrupt the sending order. TCP interprets such situations as packet losses and reduces a congestion window size by Retransmission Control and Congestion Control. The congestion window reduction due to packet reception disorders in PPLB is a fundamental behavior of TCP. Thus PPLB has a lot of problems to be solved. On the other side, the SBLB solution can be regarded as a system with two simple singlepaths. Since those two paths are independent of each other, traffic forwarding is stalled during L2HOs and Wireless Link Failures on either path. In order to tackle this issue, cooperation of both paths is more effective than letting them work independently. It is a bicasting solution of TCP flows while a L2HO is taking place. Therefore the IEEE 802.11g Communication System with Dualpath Configuration is designed based on the SBLB algorithm and targeting to reduce TCP Downtime to zero during L2HOs.

With only considering TCP, SBLB must be the optimum solution. However, a load balancing solution based on TCP sessions does not support other transport protocols. The IEEE 802.11g Communication System must work for not only TCP but also all transport protocols as described in Section 4.9. Therefore, instead of a simple SBLB, the IEEE 802.11g Communication System took an

IP-based Load Balancing solution (IPLB). IPLB takes paths based on destination IP addresses for each packet, and thus packets for each TCP session take the same path. IPLB is also applicable to all the other transport protocols. IPLB was our decision instead of SBLB.

HA and MR independently decided paths for each flow. Here the word “independently” means that a flow from HA toward MR and a flow in the opposite direction go through the same path in some cases or take the different paths in the other cases even for the same TCP flow. Flows in the same direction were equally load-balanced by a round robin manner according to destination IP addresses.

5.7. Summary

This chapter proposed the Bicasting-Multipath Mobile IPv4 in order to satisfy three Requirements set up in Section 4.9. It is an architecture which (1) establishes two paths between the ground network and the train network, (2) recognizes the paths by MP-MIPv4 and (3) bicasts traffic over the paths while an IEEE 802.11g link is under trouble. This chapter especially explained a MP-MIPv4 platform on which wireless links were multiplexed and packets were bicasted between the redundant paths. Also this chapter considered how to load-balance traffic between the MIPv4 paths and concluded that IPLB was the best load-balancing algorithm for the IEEE 802.11g Communication System with Dualpath Configuration. With considerations in this chapter, we have completed a design of the network platform for the Bicasting-Multipath Mobile IPv4.

Section 5.3 considered a system which is able to satisfy the three Requirements set out in Section 4.9 for the IEEE 802.11g Communication System and proposed the Bicasting-Multipath Mobile IPv4 for a solution.

Section 5.4 designed the IEEE 802.11g Communication System with Dualpath Configuration where another IEEE 802.11g link was mounted on the Singlepath configuration. These two paths were recognized on Layer 3 using MP-MIPv4. PPLB and SBLB were considered to load-balance TCP flows.

Section 5.5 analyzed UDP and TCP performances on the IEEE 802.11g Communication System with Dualpath Configuration working on PPLB. When a L2HO or a Wireless Link Failure took place on one of the IEEE 802.11g links, TCP halted its communication and had to wait for RTO expiration(s) to resume it, though the other IEEE 802.11g link was still in good condition. These results revealed that PPLB was an inadequate load balancing algorithm for our situation.

Section 5.6 considered SBLB. A SBLB algorithm is not able to satisfy the third Requirement set out in Section 4.9, because it uses TCP session information to load-balance traffic. Therefore the IEEE 802.11g Communication System employed IPLB for its load balancing algorithm, instead of SBLB.

Chapter 6.
Bicasting Architecture of the Bicasting-Multipath Mobile IPv4

This Chapter describes a design and an implementation of a bicasting architecture between paths in the Bicasting-Multipath Mobile IPv4. The bicasting architecture works on IP Layer between redundant paths on MP-MIPv4. It bicasts packets between the paths while either Path(L) or Path(R) is suffering from L2HOs or Wireless Link Failures. This chapter also explains a L2HO prediction and bicasting control in accordance with the prediction.

6.1. Introduction

The Bicasting-Multipath Mobile IPv4 bicasts traffic on Layer 3 to both redundant paths established by MP-MIPv4. In order to let the architecture work on a MP-MIPv4 platform, it must be designed and implemented with careful consideration of MP-MIPv4 characteristics. This chapter describes a design of a bicasting architecture and its implementation.

The Bicasting-Multipath Mobile IPv4 controls bicasting by a L2HO and a Wireless Link Failure. In order to satisfy the Requirements of the IEEE 802.11g Communication System held up in Section 4.9, the Bicasting-Multipath Mobile IPv4 bicasts traffic while either a L2HO or a Wireless Link Failure is taking place. Here bicasting has to be started before an occurrence of either of them. TCP stops communication just after the event. Even if the bicasting is started after a detection of a link being down, target traffic is no longer there and thus TCP has to wait for a RTO expiration. Therefore the Bicasting-Multipath Mobile IPv4 has to predict both a L2HO and a Wireless Link Failure before the start of its process. This chapter describes a way to predict both of the events and an implementation of bicasting.

The organization of this chapter is as follows. Section 6.2 designs a bicasting architecture with careful consideration of a MP-MIPv4 platform with IPLB working on it. Section 6.3 describes an implementation of the architecture onto the experimental IEEE 802.11g Communication System and explains behaviors of the Train Duplicator and the Ground Duplicator (bicasting devices). Section 6.4 proposes a method to predict a L2HO and a Wireless Link Failure. It is based on RSSI which the TBRs receive. Section 6.5 describes a L2HO judging algorithm based on RSSI and its accuracy. Section 6.6 summarizes this chapter.

6.2. Fundamental Design of a Bicasting Architecture on a MP-MIPv4 Platform

Fig. 6-1 shows a simplified Dualpath Configuration. MP-MIPv4 establishes MIPv4 Tunnels between HA and MR. Bicasting is executable outside or inside of the tunnels. Options to do it outside of the tunnels and inside of the tunnels are respectively referred to as Option A and Option B.

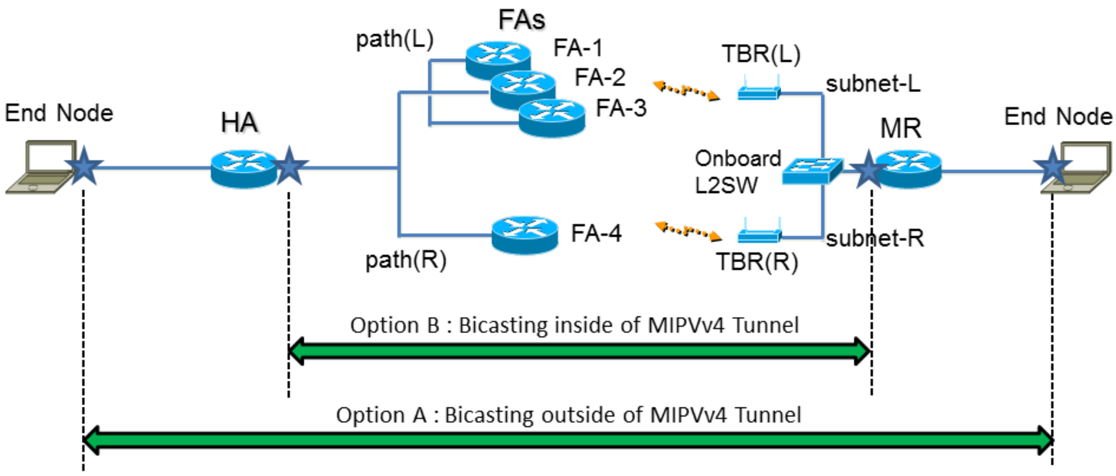


Fig. 6-1 Two Options for Bi-Casting

Option A has two Requirements to bicast packets to Path(L) and Path(R) without fails.

i. Copied packets must have a different destination IP address on their IP headers from original packets in order to let HA or MR working on IPLB forward original and copied packets to different paths. It also must be assured for copied packets to reach requested End Nodes by the different (Dummy) IP address.

ii. HA and MR decides forwarding paths for each packet by destination IP addresses in a round robin manner. Requirement (i) overrides a destination IP address of copied packets. Even if destination IP addresses of the original packet and the copied packet are different from each other, it is meaningless when they are forwarded to the same path by a round robin manner. Therefore HA and MR have to recognize if it is original or copied and sends them to different paths.

In Requirement (i), the easiest way of generating a copied packet is to implement a multi-homing architecture on all End Nodes. However, End Nodes in the IEEE 802.11g Communication System are PCs for an unspecified number of general users and it is impossible to customize them. Another option is to install two proxy servers in both sides of the MIPv4 Tunnels.

The locations are left of HA and right of MR in Fig. 6-1. The proxies generate copied flows which have virtual destination IP addresses from the original flows. The counterpart proxy has to match real IP addresses and virtual IP addresses for each End Node after reception of original and copied packets.

In order to meet Requirement (ii), HA and MR have to manage original sessions and copied sessions to forward them to different paths to each other. However, the IEEE 802.11g Communication System must work on commercially available routers with MP-MIPv4 to converge itself with other media such as LCX Communication System and cellular systems in the future. HA and MR are the key devices to do this. If some peculiar implementations were done on these devices, the functions would be required forever on HA and MR. It might be detrimental to replace them to the latest model, when higher performance routers become available in the market. The above discussion eliminated Option A.

Consider Option B. Option B had two choices of physical positions to generate copied flows. The first choice was to implement a bicasting architecture on HA and MR. It is HA and MR that capsules original packets from End Nodes and forwards them to the MIPv4 tunnels. When bicasting is required, HA and MR may forward all packets to both paths, instead of choosing one of the paths for each packet. However, as well as the discussion for Requirement (ii) of Option A, customizations of HA and MR must not be our choice. Thus this idea was rejected. The second choice was to install dedicated devices for bicasting. The location is between HA and FA for downlink packets (from the ground to the train), and between Onboard L2SW and MR for uplink packets (from the train to the ground). This option is able to make the bicasting function as a component separate from the routers, which makes it possible to replace the bicasting hardware and commercially available routers such as HAs and MRs independently.

A frame format of packets going through a bicasting device inserted between HA and FAs is shown in the top of Fig. 3-14. Also a frame format of packets going through a bicasting device inserted between Onboard L2SW and MR is shown in the bottom of Fig. 3-14. Therefore, a traveling path of each packet can be identified by its GRE key. In order to bicast a packet to both paths, the following procedures are required; (1)copy the original packet, (2)modify some header fields including GRE key as shown in Table 6-1 or Table 6-2, and (3)push the modified packet to the link. Table 6-1 shows header fields which should be changed for downlink packets on the bicasting device between HA and FAs. Table 6-2 shows header fields which should be changed for uplink packets on the bicasting device between Onboard L2SW and MR. The modified packet is routed or switched by the modified header information. It is forwarded to the other path from the original packet.

Table 6-1 Header Fields to be Modified for Bicasting over Paths (HA to MR)

Field to be Modified	Original Value	Modified Value
Destination MAC Address *1	MAC Address of FA1, FA2 or FA3	MAC address of FA4
	MAC address of FA4	MAC Address of FA1, FA2 or FA3
Destination IP address in the first IP header	IP Address of FA1, FA2 or FA3	IP address of FA4
	IP address of FA4	IP Address of FA1, FA2 or FA3
GRE key	ID for Path(L)	ID for Path(R)
	ID for Path(R)	ID for Path(L)

*1 In our trials, the HA and the FAs were in the same subnet. If the next hop to each FA from a HA is the same device (another router is placed between a HA and FAs), this implementation is dispensable.

Table 6-2 Header Fields to be Modified for Bicasting over Paths (MR to HA)

Field to be Modified	Original Value	Modified Value
Destination MAC Address	MAC Address of FA1, FA2 or FA3	MAC address of FA4
	MAC address of FA4	MAC Address of FA1, FA2 or FA3
VLAN ID *1	VLAN ID for Subnet-L	VLAN ID for Subnet-R
	VLAN ID for Subnet-R	VLAN ID for Subnet-L
GRE key	ID for Path(L)	ID for Path(R)
	ID for Path(R)	ID for Path(L)

*1 If the TBR(L) and the TBR(R) are allocated to physically different interfaces on a MR, this implementation is dispensable because IEEE 802.1q is not used.

When a packet on Path(R) which originally has a MAC address or an IP address of FA4 is modified, the modified packet has to have the correct destination on its header. This is because MR roams among FA1 FA2 and FA3 for Path(L). A method to choose the appropriate FA is described in Section 6.3.1.

From the discussion above, we decided to take Option B. A network configuration including bicasting devices is depicted in Fig. 6-2. The bicasting device on the ground is referred to as the Ground Duplicator; the one on the train is referred to as the Train Duplicator. When it is simply mentioned as Duplicators, the word includes both the Ground Duplicator and the Train Duplicator.

The Duplicators must control the start and the stop of bicasting. The Train Duplicator is responsible for this governance. When it predicts a L2HO occurrence, not only it starts bicasting but also it gives the Ground Duplicator an order of bicasting. The Ground Duplicator starts bicasting with the notification. Reversely, when the Train Duplicator detects the completion of the L2HO, it stops bicasting and informs the Ground Duplicator. The command has the Ground Duplicator stop bicasting. A method to predict L2HOs is described in Section 6.4 and 6.5 in detail.

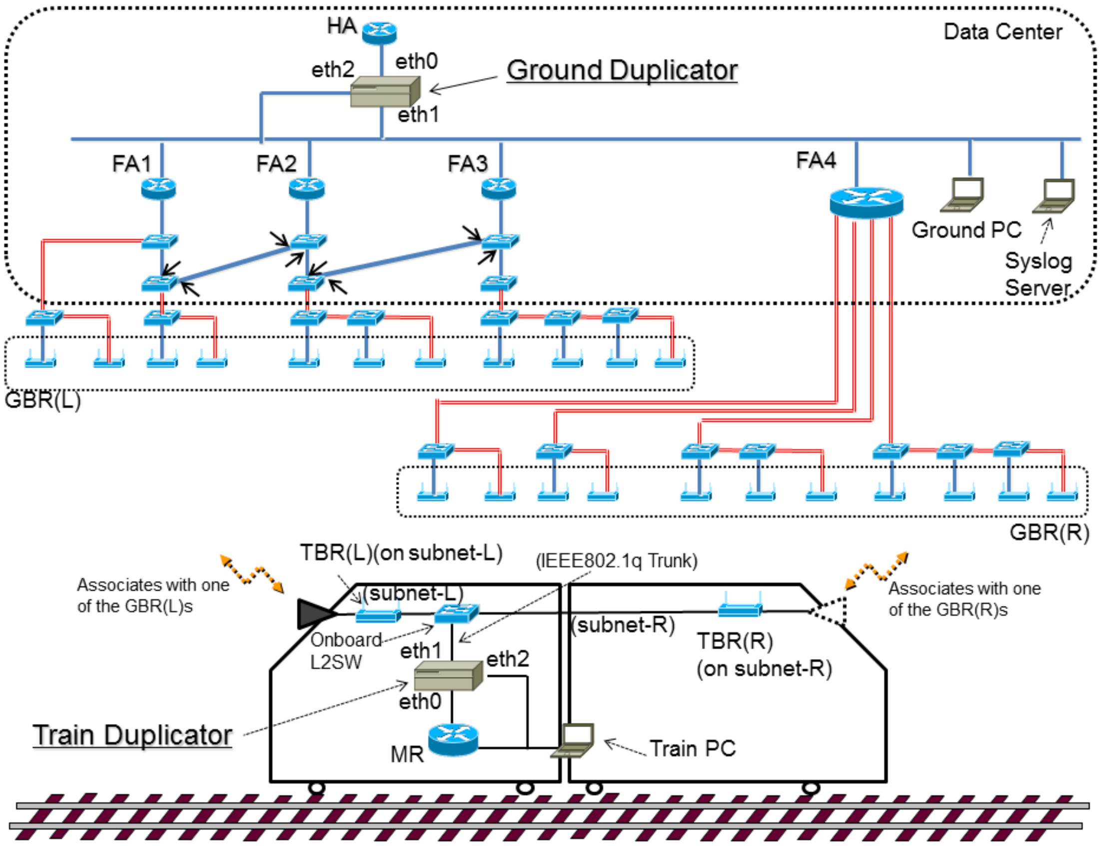


Fig. 6-2 Packet Duplicators.

6.3. Duplicators' Behaviors

6.3.1. Train Duplicator

Ubuntu10.04 LTS Linux Kernel-2.6.32-24 was employed for the operating system of the Train Duplicator. The Train Duplicator equips three interfaces. Roles of the interfaces are shown in Table 6-3.

Table 6-3 Interfaces and their roles on the Train Duplicator

Interface	Role
Eth0	A bridging interface on the MR side. No IP address is assigned.
Eth1	A bridging interface on the Train L2SW side. No IP address is assigned.
Eth2	An interface in the mobile network. An IP address is assigned in the network. The SNMP manager uses this interface. This interface sends packets commanding start or stop bicasting to the Ground Duplicator.

Functions requested for the Train Duplicator are as follows.

(1) To bridge between eth0 and eth1, and cache the latest packet header

(2) To predict a L2HO and detect its completion

(3) To send a packet commanding start or stop bicasting to the Ground Duplicator

(4) To bicast and control the order of GRE packets during L2HOs

These items are explained below.

(1) To bridge between eth0 and eth1, and cache the latest packet header

Although eth0 interface and eth1 interface were basically bridged for packets, GRE packets and the other packets were bridged in different manners from each other. Packets other than GRE including MIPv4 binding update packets, SNMP packets between the Train Duplicator and the TBRs, for example, were not bicasted, but simply forwarded between the two interfaces. On the other side, GRE packets traveling between upper networks of HA and lower networks of MR must be bicasted during L2HOs. In order to configure headers of duplicated packets, information of Modified Value in Table 6-2 is required. In order to obtain the information, headers of the latest packets which had been forwarded to each of the two paths were cached regardless of the bicasting status.

(2) To predict a L2HO and detect its completion

Cisco Air-BR1310GJ-K9 (BR1310) which was employed for both the TBR(L) and the TBR(R) retains the latest RSSI in the MIB table on the device. The entry of the MIB table was polled every 125ms by SNMP get-requests. The SNMP manager to check these TBRs was installed on the Train Duplicator. The Train Duplicator predicted a L2HO and detected its completion by the observed RSSI values. A method of the predictions is described in detail in Section 6.4 and 6.5.

(3) To send a packet commanding start or stop bicasting to the Ground Duplicator

The Ground Duplicator started and stopped bicasting by a command through a packet from the Train Duplicator. A reason to have implemented like this is described in Section 6.4. The Train Duplicator must send a packet to let the Ground Duplicator work in accordance with an intention. Since these requests were required to be notified in a short period, UDP was used for a transport protocol. A special payload format was newly defined for these two commands.

Packets ordering the Ground Duplicator to start bicasting may be lost on an IEEE 802.11g link, because they are sent when the wireless link is about to go down due to a L2HO. In order to avoid a loss of a command packet, we used a time difference between an application process time and a forwarding latency of the command packet. The command packet for bicasting leaves eth2 interface on the Train Duplicator. After it goes through MR, it comes back to eth0 interface on the Train Duplicator. Now it has a forwarding latency for the return trip. On the other side, the Train Duplicator is able to start bicasting by its internal process. A bicasting procedure is started by the time the command packet returns. Even if MR forwards the command packet to the L2HO path, the Train Duplicator copies and bicasts the packet to the other path. The packet then can reach the Ground Duplicator. When a packet makes an order to stop bicasting, the Train Duplicator stops bicasting by the time the packet returns from MR. The Train Duplicator does not make an unnecessary copy of the command.

(4) To bicast and control the order of GRE packets during L2HOs

Packets are bicasted while a L2HO is ongoing. The Train duplicator overwrote header fields of each packet which arrived at eth0 interface and sent them from eth1 interface. Header fields which must be modified are shown in Table 6-2. Bicasted packets must be forwarded to the active FA which is on the MIPv4 tunnel. A FA to which bicasted packets should be forwarded changes as the train moves. Therefore new headers must be composed with the latest information to support L3HOs. The latest headers which MR has wrapped for a capsulation have the information about the active FA on the MIPv4 tunnel at that time. The latest header information for both Path(L) and Path(R) was cached as described in (1) of this section. For instance, in order to bicast packets originally traveling on Path(R), a destination MAC address, a VLAN ID and GRE key were obtained from the latest cache of the packet header for Path(L), and then the header fields of the original packet were modified.

The IEEE 802.11g Communication System bicasts GRE packets in accordance with predictions of L2HOs. Bicasting is started before a L2HO occurs and it is stopped after the L2HO is completed. Therefore, not all packets which have been forwarded on the L2HO path are dropped. Duplicated packets may reach a receiver as well as original packets. A L2HO path generally suffers from a low RSSI and latency of the path is likely to be high. Packets flowing on the L2HO path have an inclination to arrive at a receiver with a long delay from the other path. These duplications and disorders may cause TCP to reduce its congestion window size. It must be avoided to deliver the second packet of the pair to a receiver TCP. The IEEE 802.11g Communication System implemented an order control on Layer 3. An IP header of a GRE packet is added on by MR in order to encapsulate the original packet (See the bottom of Fig. 3-14). The IP ID field in the added IP header was used to achieve an order control. An original number on the IP ID field of a GRE packet which was received at eth0 interface was overwritten by a sequential number in the output order of eth1 interface, regardless of the bicasting status and paths to which the packet is forwarded. When packets are bicasted, a copied packet has the same number that the original one has.

These bicasted packets were recovered in the proper order of the IP ID at the Ground Duplicator. While bicasting was being operated, the Ground Duplicator kept monitoring the IP ID field and retained the largest IP ID of GRE packets which were received at eth1 interface on the device. When a packet with a smaller IP ID arrived at the Ground Duplicator, the device dropped the packet because it must be a duplicated reception. While unicasting was being operated, no duplicated reception inevitably occurred, then the Ground Duplicator simply forwarded all GRE packets from eth1 interface to eth0 interface. Note that the IP header having the manipulated IP ID is the second IP header of GRE packets which were received at eth1 interface on the Ground Duplicator as depicted in Fig. 3-14. This section explained an order control for uplink packets. The same order control was implemented for downlink packets.

The Train Duplicator bicasted not only TCP but also all the packets which were encapsulated by GRE. Although this paper discusses only TCP, the Duplicators do not have any dependence on transport protocols. They work for all protocols.

Traffic which had been on the L2HO path was bicasted by the Duplicators. When a L2HO was predicted on Path(L), packets on the path were copied, modified and bicasted to the other Path(R), but packets originally on Path(R) were not bicasted.

6.3.2. Ground Duplicator

Ubuntu10.04 LTS Linux Kernel-2.6.32-24 was employed for the operating system of the Ground Duplicator. The Ground Duplicator equips three Interfaces. Roles of the interfaces are shown in Table 6-4.

Functions requested for the Ground Duplicator are as follows.

(1) To bridge between eth0 and eth1, and cache the latest packet header

(2) To receive packets commanding the start or the stop of bicasting from the Train Duplicator and control packet forwarding in accordance with the direction

(3) To bicast and control the order of GRE packet during L2HOs

Function (1) worked in the same manner that the Train Duplicator did. As described in Function

(2), the Ground Duplicator started and stopped bicasting in accordance with an order from the Train Duplicator. When packets are bicasted, header fields shown in Table 6-1 were modified for assembling a duplicated packet.

Table 6-4 Interfaces and their roles on the Train Duplicator

Interface	Role
Eth0	A bridging interface on the MR side. No IP address is assigned.
Eth1	A bridging interface on the Train L2SW side. No IP address is assigned.
Eth2	An interface in a ground network. An IP address is assigned in the network. This interface receives packets commanding start or stop bicasting from the Train Duplicator.

6.4. L2HO Predictions based on RSSI

In order to control the start and the stop of bicasting, it is required to predict a L2HO before its occurrence and detect its completion. Here, prediction before an event is quite important. TCP halts a communication just after a L2HO occurs. Even when a bicasting algorithm is initiated after a L2HO process has started, traffic to be bicasted no longer exists there. TCP has to wait for a RTO. Therefore bicasting must be started before a L2HO starts.

The IEEE 802.11g Communication System predicted the events by RSSI which each TBR received from one of the GBRs. RSSI observation is possible on an active ground bridge of each IEEE 802.11g bridge groups (GBR(L), GBR(R)), and both the TBR(L) and the TBR(R). Here, the active ground bridge means the one with which a TBR is associating. Two active GBRs, one of the GBR(L)s and one of the GBR(R)s, changes as two TBRs roam with the train movement. For RSSI measurements on the ground side, the active GBRs must be identified first. A hopping of the active GBR requires changing the target of SNMP get-requests. This control results in a complexity of the system. On the other side, for observations on the TBR(L) and the TBR(R), the measurement targets are always the same. Therefore, we decided to obtain RSSI values from the TBR(L) and TBR(R) for the IEEE 802.11g Communication System. RSSI on both TBRs were observed every 125(*ms*) by SNMP get-requests.

6.5. L2HO Prediction and its Accuracy

The SNMP manager on the Train Duplicator sent SNMP get-requests every 125(*ms*) to both the

TBR(L) and TBR(R) and obtained RSSI values for both of them. This section discusses methods to predict a L2HO based on received RSSI and its accuracy. Note that a TBR responds with an invalid value meaning “no data”, in case that the entry is requested when the TBR is isolated from any GBR due to L2HOs or Wireless Link Failures.

6.5.1.L2HO Prediction and its Accuracy on the Front BR

Fig. 6-3 is a typical RSSI in Mode 2 where the test train moves with a TBR at the front edge. A TBR, one of either the TBR(L) or the TBR(R), which is located at the front end of the train is called “Front BR”. Which of the TBRs is positioned there depends on the direction of the train. The Front BR performs in Mode 2. Fig. 6-3 has revealed that a RSSI in Mode 2 has a peak just before a L2HO in each wireless cell. GANTs and TANTs are directional antennas with a half value angle of 40 degrees. GANTs were set up at 3.0(m) away in the perpendicular direction from the center of two rails. The signal from each GANT was directed in the parallel to the rail track. When a Trajectory Distance (see Section 3.5.3 for the definition) gets too close, a directional angle becomes too large and a gain on that angle drops too low. This results in these peaks just before L2HOs. We used this occurrence to predict a L2HO. A L2HO for the Front BR was predicted by a sharp drop of RSSI. The Train Duplicator started bicasting with this prediction and made an order of the same action to the Ground Duplicator. Also the Train Duplicator interpreted a RSSI increase after a L2HO prediction as a completion of the L2HO. It stopped bicasting with the detection and informed the Ground Duplicator of the event. This method successfully predicted L2HOs with accuracy of 88.2%.

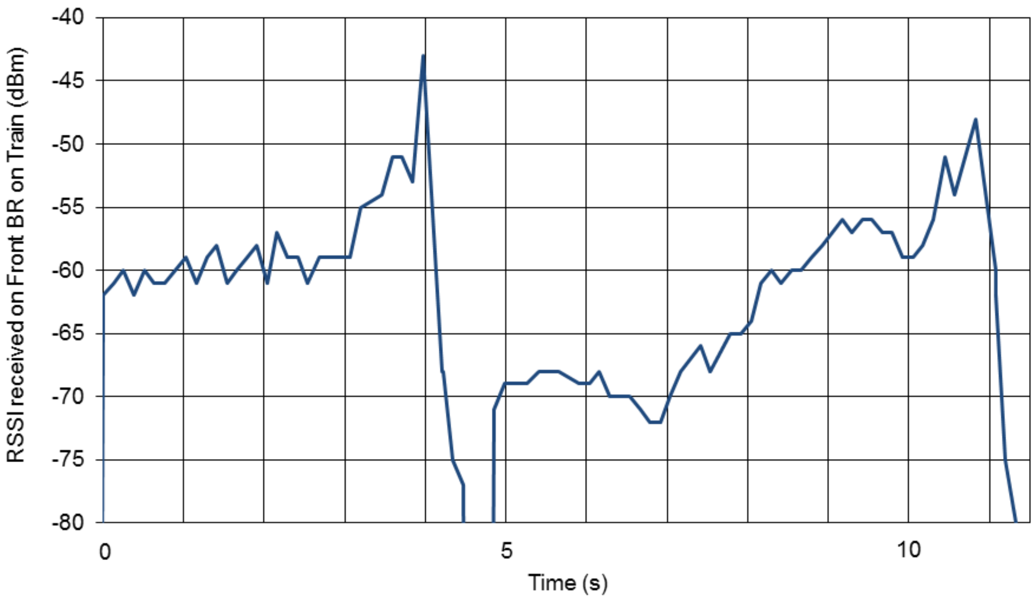


Fig. 6-3 Typical RSSI Received by Front TBR (In Mode 2)

6.5.2. L2HO Prediction and its Accuracy on the Rear BR

Fig. 6-4 is a typical RSSI in Mode 1 where the test train moves with a TBR at the rear edge. A TBR, one of either the TBR(L) or the TBR(R), which is located at the rear end of the train is called “Rear BR”. The Rear BR performs in Mode 1. A RSSI peak in the vicinity of a GBR did not always occur. In Mode 1, it must be immediately after a L2HO when a peak occurs. In some cases, a RSSI followed a monotone decreasing as a trajectory distance got larger after a L2HO. The Rear BR communicating with a GBR does not always initiate a L2HO process just after it moves to another wireless cell generated by another GBR. It tries to keep the current connection until one of the triggering events occurs. If a Trajectory Distance becomes larger than the distance which gives a RSSI peak by the time a L2HO is initiated by a trigger, a RSSI in Mode 1 does not have a peak in the cell. Regardless of an appearance of a peak, a RSSI deteriorates as the train goes farther. Therefore, we introduced a threshold to judge a L2HO. The threshold is referred to as “L2HO threshold.” When a RSSI had fallen under this L2HO threshold, a L2HO was predicted. This prediction let the Duplicators start bicasting. While a RSSI was higher than the L2HO threshold, the Duplicators just relayed traffic.

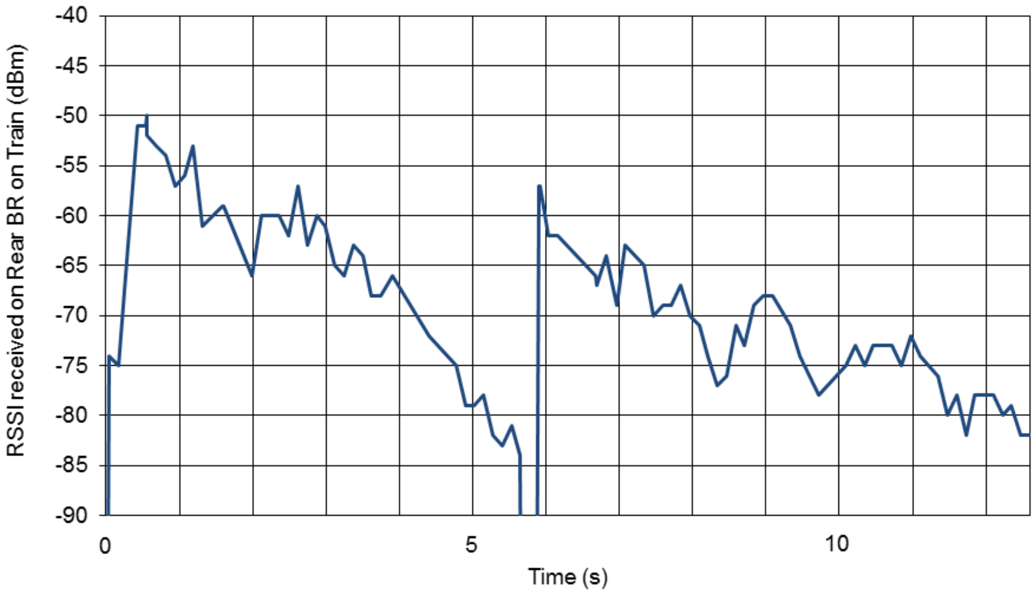


Fig. 6-4 Typical RSSI Received by Rear TBR (in Mode 1)

We considered RSSI values just before each L2HO in order to choose a L2HO threshold. We obtained RSSI values just before each L2HO in 105 L2HOs which were processed between the Rear BR and arbitrary counterpart GBRs. A cumulative probability distribution where a RSSI value just before each L2HO is below a certain number is shown in Fig. 6-5. Fig. 6-5 is prediction accuracy with a L2HO threshold. The selection of a L2HO threshold is arbitrary. A larger L2HO threshold gives a high accuracy of a L2HO prediction. For instance, a L2HO threshold of -70(*dBm*) can predict about 90% of L2HOs. A L2HO threshold of -68(*dBm*) or higher brings accuracy of 100%. A higher accuracy shakes down the number of TCP timeouts over L2HOs and reduces (improves) a Communication Stall Duration Rate.

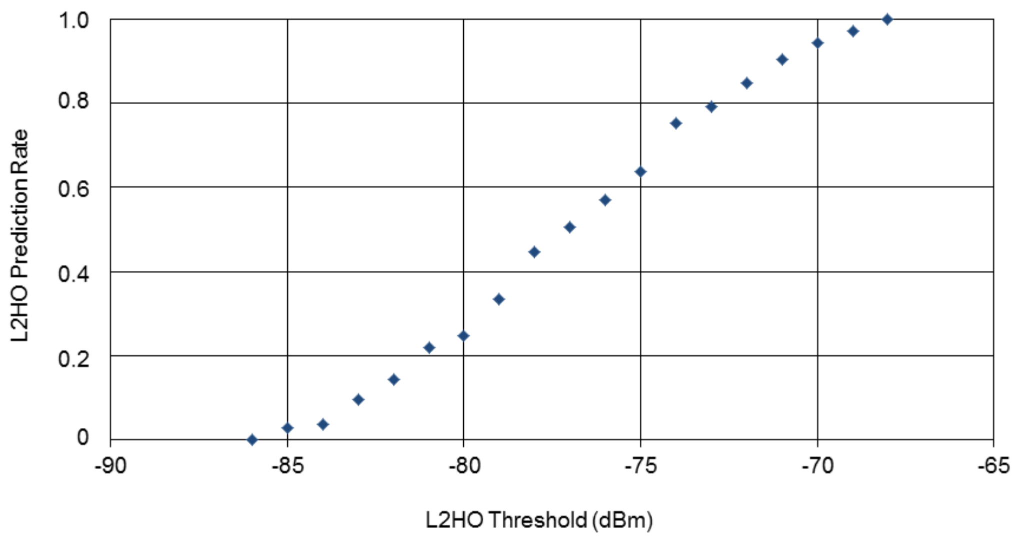


Fig. 6-5 L2HO Threshold and L2HO Prediction Rate

The best L2HO threshold must be -68(*dBm*) only with a consideration based on Fig. 6-5. However, this is not so simple. If a L2HO threshold were set to -68(*dBm*), all L2HOs would be accurately predicted. In this case, bicasting would be started long before each L2HO because RSSI would fall under -68(*dBm*). This means that traffic is bicasted even when a unicast is sufficient to forward the traffic. Unnecessary bicasted packets occupy a limited communication bandwidth. Therefore, a higher L2HO threshold may not bring a desired result.

Consider False Negative and False Positive on the Rear BR. False Negative means "No Bicasting during a L2HO" due to a failure of L2HO prediction. It results in communication instability. False Negative is given by "1 – (Prediction Rate in Fig. 6-5)" and depicted in Fig. 6-6. On the other side, False Positive means "Bicasting in the remaining time before L2HOs", which is undesired bicasting. It results in making communication speed slower. Bicasting is done while RSSI is under a L2HO threshold. A duration rate while the TBR works under a L2HO threshold is worth one while dispensable bicasting is done. The rate is False Positive and also shown in Fig. 6-6. Both False Negative and False Positive are desired to be as low as possible. However, they have a trade-off relationship with each other.

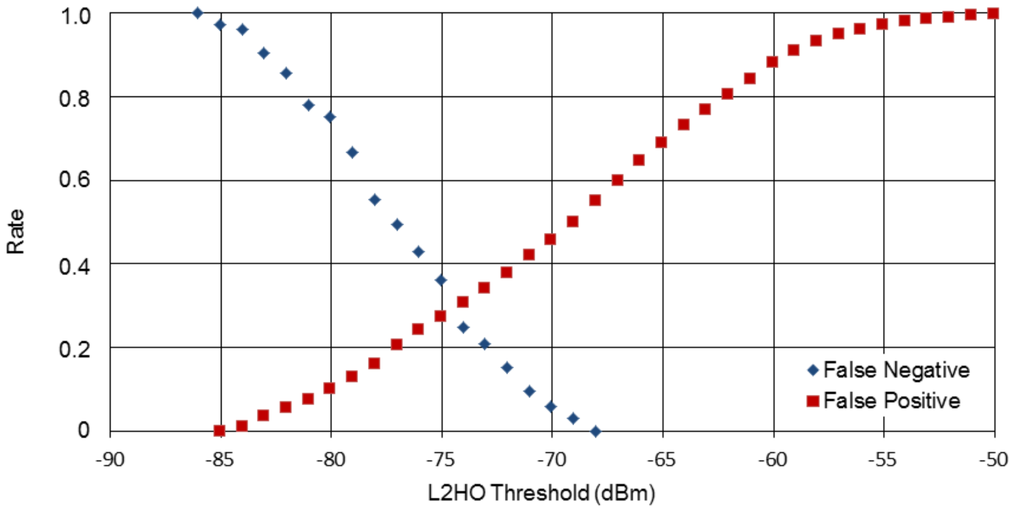


Fig. 6-6 Falase Negative and False Positive

6.5.3. Future Works for L2HO Prediction

The experimental IEEE 802.11g Communication System predicted all L2HOs on all the GBRs with the same algorithm. This section discusses improvements of the algorithm. At first, consider a judgment of a L2HO on the Rear BR. Here, just beside the next GBR to which the Rear BR roams, RSSI which the Rear BR receives from the current active GBR is defined as "RSSI on Edge." Since a L2HO takes place in an overlapped section of two adjacent GBR cells, a L2HO never occurs until the Rear BR enters the next GBR cell. In other words, a L2HO never occurs until RSSI which the Rear BR receives falls under RSSI on Edge. As described in Section 3.5.5, since distances between each two adjacent GBRs are not unique due to physical constraints, RSSI on Edge varies for each GBR. Fig. 3-11 and Fig. 4-9 shows a relationship between the Trajectory Distance (See Section 3.5.3 for the definition) and RSSI, also we know distances between each two adjacent GBRs. Therefore RSSI on Edge for each GBR can be obtained. When an appropriate L2HO threshold for each GBR is derived with RSSI on Edge taken into account, False Negative can be reduced without raising False Positive.

Consider a judgment of a L2HO on the Front BR. Since it was difficult to determine whether the TBR works as the Front BR or the Rear BR in our experiments, the same algorithm was applied to both the Front BR and the Rear BR. Therefore, the Duplicators continued bicasting traffic until RSSI on the Front BR became higher than the L2HO threshold after each L2HO. The Duplicators must obtain information from the train and find out roles of the TBRs for each run. Since the L2HO threshold for the Front BR is used for a detection of a L2HO completion, it should be set at a lower level, in the range of -75(*dBm*) ~ -80(*dBm*), in order to stop bicasting as quick as possible.

6.6. Summary

This chapter reported our design of a bicasting architecture of the Bicasting-Multipath Mobile IPv4 onto the experimental IEEE 802.11g Communication System. Section 6.2 designs a bicasting architecture with a careful consideration of a MP-MIPv4 platform with IPLB working on it. The Bicasting-Multipath Mobile IPv4 realized bicasting on Layer 3 by modifying packet headers inside of the MIPv4 tunnels. Section 6.3 describes a detailed implementation of the architecture onto the experimental IEEE 802.11g Communication System. Functions on the Duplicators were classified and their behaviors were explained. Section 6.4 stressed the importance of L2HO predictions before a L2HO or a Wireless Link Failure occurs. The proposed method is based on RSSI which the TBRs receive. Section 6.5 describes a L2HO judging algorithm based on RSSI. The algorithm achieved accuracy of 88.2% for L2HOs on the Front BR, while accuracy on the Rear BR depends on a configurable L2HO threshold.

Chapter 7. TCP Performances in the Bicasting-Multipath Mobile IPv4

This chapter reports experimental results of the Bicasting-Multipath Mobile IPv4. The field trials were done on a commercial high speed rail system and the speed of the test train was kept at 270km/h. The results have revealed that the Bicasting-Multipath Mobile IPv4 realizes an average TCP Rate of 16.4(*Mbps*) and reduces Communication Stall Duration Rate to 0.67%, which was originally 9.9% in Mode 1 and 18.1% in Mode 2. Finally, we have established a mobile communication system which has a stable communication bandwidth of 10(*Mbps*) or more during high speed movements.

7.1. Introduction

The IEEE 802.11g Communication System with a Singlepath Configuration had a problem of high Communication Stall Duration Rate due to L2HOs and Wireless Link Failures, though it realized the maximum TCP Rate of around 20(*Mbps*). Therefore we proposed the Bicasting-Multipath Mobile IPv4 which multiplexes wireless links between the ground network and each train network, and bicasts traffic between the redundant paths while either path is suffering from the damaging events. Chapter 5 and Chapter 6 described our design and implementation of the architecture. This chapter reports results of communication trials for the Bicasting-Multipath Mobile IPv4. The trials were done in real situations of a high speed rail system. The results have revealed that the Bicasting-Multipath Mobile IPv4 reduces Communication Stall Duration Rate to 0.67%, which was originally 9.9% in Mode 1 and 18.1% in Mode 2. At the same time, our architecture was capable of communicating at an average TCP Rate of 16.4(*Mbps*). We successfully configured a practical communication system for high speed rail systems.

The organization of this chapter is as follows. Section 7.2 explains how our experiment has been done for the Bicasting-Multipath Mobile IPv4. Section 7.3 considers the results of the trial. Section 7.4 provides farther discussion about expected TCP Rates with a variation of L2HO thresholds. Section 7.5 summarizes this chapter.

7.2. Measuring Method of Bicasting Performances

TCP flow was generated by Iperf on the Train PC depicted in Fig. 6-2 and sent to the Ground PC. All packets were captured by Wireshark on both PCs. In addition, packets going through the eth1 interface on both the Train and Ground Duplicators were also captured in order to verify bicasting performances. This measuring method is the same as in the trials for the Singlepath configuration system described in Section 4.7.

A major parameter to be configured is a L2HO threshold to judge a L2HO occurrence on the Rear BR. As described in Section 6.5.2, a higher L2HO threshold results in not only a higher accuracy of a L2HO prediction but also making bicasting duration longer. There is a trade-off relationship between improving accuracy of L2HO prediction and reducing bicasting duration. For our trial, we chose -71(*dBm*) for a L2HO threshold, because the figure minimized the sum of False Negative and False Positive. On the other side, there is no room for an adjustment of accuracy of L2HO prediction for the Front BR and it is 88.2% as described in Section 6.5.1.

7.3. Evaluation of the Bicasting-Multipath Mobile IPv4

7.3.1. Unique Occurrences in the Test

This section describes unique occurrences that happened randomly during this trial, though it does not mean that they will be identical in subsequent trials.

(1) The running direction of the train and Roles of TBRs

The test train ran with the TBR(R) as the Rear BR (Mode 1) and the TBR(L) as the Front BR (Mode 2). It was a movement in the left direction in Fig. 6-2. The speed of the test train was maintained at 270(*km/h*).

(2) Wireless Link Failures

The TBR(L) experienced a Wireless Link Failure with BR2-11.

(3) Active GBRs when a TCP connection was established

When a SYN packet initiating a TCP connection was sent from the Train PC to the Ground PC, the Front BR was connected with BR3-11 and the Rear BR was connected with BR4-20. For all results in this trial, time originates from when the SYN packet was sent.

(4) Active GBRs when the Dualpath was ceased

When one of the Dualpath was ceased, bicasting lost its effect. It is usually when the Front BR passes by the last GBR of the test section and loses its connection. In this trial, the last GBR was BR1-11 because the test train ran with the TBR(L) as the Front BR. The elapsed time of this event was 50.0(*sec*). The Rear BR was connected with BR4-12 at that time.

(5) Traffic forwarding path

HA chooses a forwarding path for each packets going toward MR by its destination IP address. MR does the same process for packets going in the opposite direction. They use a round robin fashion as described in Section 5.6. A traffic forwarding path in the trial was as follows.

- For Data traffic (Train PC to Ground PC)

  Path(R) : A route through the Rear BR (Mode 1)
- For ACK traffic (Ground PC to Train PC)

  Path(L) : A route through the Front BR (Mode 2)

(6) Others

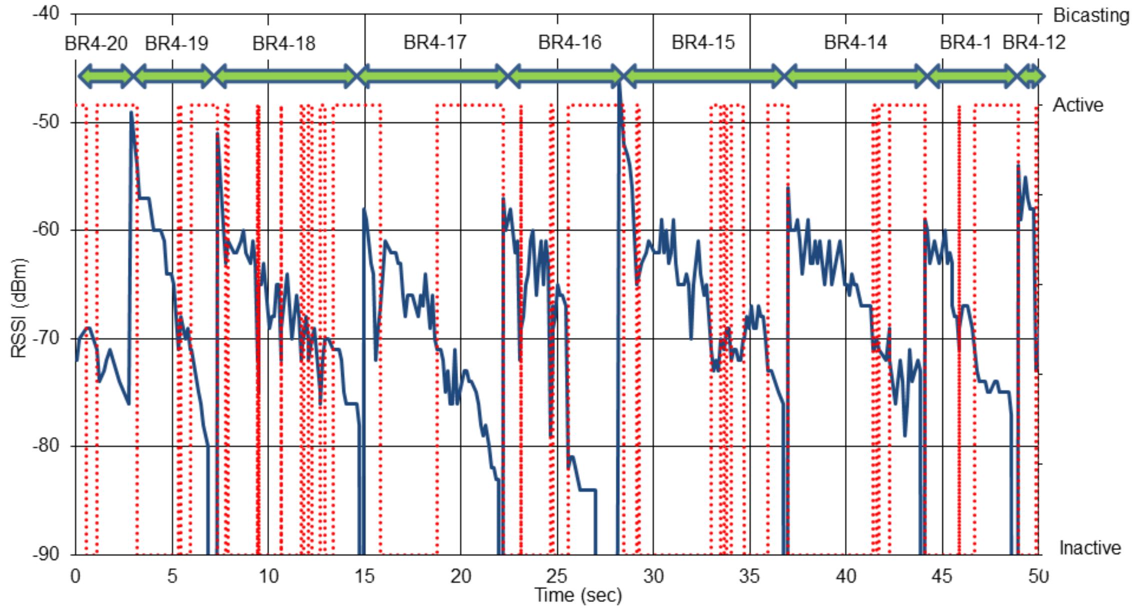
The TBR(L), the Front BR, made an association with BR1-11 before BR1-12 and lost the connection within one second (See Fig. 7-1(b)). This was because of an overlap of cells as described in Section 4.6.2.

7.3.2. L2HO Prediction and Bicasting Control

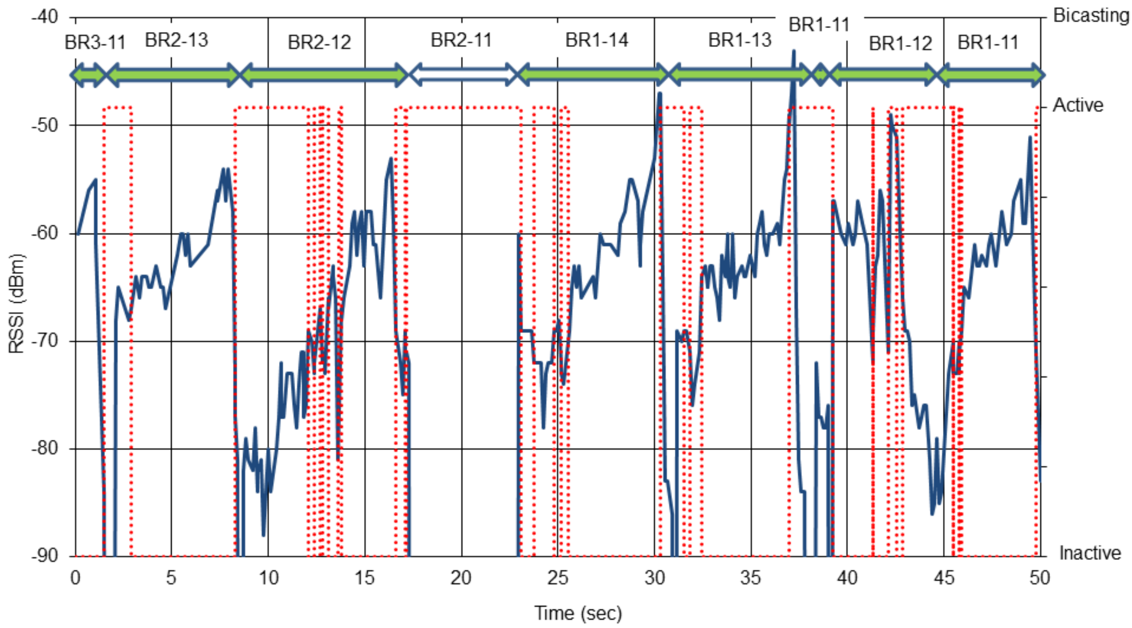
Fig. 7-1 shows RSSI observed on the Rear BR and the Front BR. Fig. 7-1(a) is for the Rear BR working in Mode 1 and Fig. 7-1(b) is for the Front BR in Mode 2. They were measured in the same manner as described in Section 3.5.4. The time on the x-axis originates from when the Train PC sent the first (SYN) packet. It was at 50.0(*sec*) when the Front BR lost an IEEE 802.11g connection and the Dualpath was ceased. The duplicators activated bicasting in the time slots which are indicated by red broken lines in Fig. 7-1.

(a) The Rear BR (the TBR(L) worked)

The Rear BR experienced eight L2HOs in the test run of 50.0(*sec*). Fig. 6-5 gives accuracy of L2HO prediction of 90.5% for a L2HO threshold of -71(*dBm*). In this experiment, the Train Duplicator accurately predicted all of the eight L2HOs. RSSI fell under -71(*dBm*) more than 1.0(*sec*) prior to each L2HO, which triggered the Train Duplicator to start bicasting. Throughout each L2HO occurrence, traffic was being bicasted. RSSI got larger just after a L2HO completion, which let the Train Duplicator stop bicasting. RSSI fluctuated and sometimes dropped under the L2HO threshold, which resulted in bicasting even though a L2HO did not occur.



(a) Rear BR (Mode 1) : TBR(R) worked



(b) Front BR (Mode 2) : TBR(L) worked

Fig. 7-1 Received RSSI and L2HO Prediction with L2HO Threshold of -71dBm

The sum of all bicasting durations was 21.2(*sec*) throughout the whole experimental duration of 50.0(*sec*). Here, it is assumed that communication is impossible due to a L2HO while RSSI is -86(*dBm*) or lower, because TCP Rate becomes 0 when RSSI is -86.4(*dBm*) in formula (4-2). The measured number of such RSSI was 16 and the interval of RSSI observation was 125(*ms*). This gives the sum of Communication Stall Duration (See Section 4.1 for the definition) 2.0(*sec*) in this experiment. Traffic needs to be bicasted during Communication Stall Duration. However, bicasting in the remaining time was undesired. Therefore a needless bicasting was done for 19.2(*sec*) in total. As a result, a False Positive on the Rear BR in this trial was 0.40.

(b) The Front BR (the TBR(R) worked)

The Front BR experienced five L2HOs and suffered from a Wireless Link Failure on BR2-11 from 17.3(*sec*) to 22.9(*sec*). Section 6.5.1 showed accuracy of L2HO prediction on the Front BR (Mode 2) is 88.2%. In this experiment, the Train duplicator accurately predicted all of the five L2HOs and a Wireless Link Failure, and successfully informed the Ground Duplicator of these occurrences. With these notifications, the Ground Duplicator started to bicast traffic just before each event.

7.3.3. TCP Performances

In this trial, Data traffic (Train to Ground) went through the Rear BR and ACK traffic (Ground to Train) went through the Front BR as described in Section 7.3.1. When a L2HO was predicted on either path, traffic which had originally been on the L2HO path was bicasted to the other path.

Fig. 7-2(a) shows TCP Rate sent from the Train PC and forwarded by the Train Duplicator. It was measured every 100(*ms*) by accumulating all the packet payloads. Bicasting was activated in the time slots which were indicated by broken lines in Fig. 7-1 (a). In these durations, TCP Rate which was forwarded by the Train Duplicator includes bicasted traffic. Therefore it is twice as large as TCP Rate sent from the Train PC. Durations without measured RSSI data in Fig. 7-1 (a) indicate that IEEE 802.11g link remains down due to a L2HO or a Wireless Link Failure. In these durations, the Rear BR was not able to forward traffic and hatched sections in Fig. 7-2 (a) indicate these durations.

Fig. 7-2 (b) shows ACK Rate sent from the Ground PC and forwarded by the Ground Duplicator. It was measured every 100(*ms*) by counting up all the ACK packets. Bicasting was activated in the time slots which were indicated by broken lines in Fig. 7-1 (b). In these durations, ACK Rate which was forwarded by the Ground Duplicator includes bicasted traffic. Therefore it is twice as large as ACK Rate sent from the Ground PC. Durations without measured RSSI data in Fig. 7-1 (b) indicate that IEEE 802.11g link remains down due to a L2HO or a Wireless Link Failure. In these durations, the Front BR was not able to forward traffic and hatched sections in Fig. 7-2 (b) indicate these durations.

Fig. 7-3 shows Congestion Window Size (cwnd), Slow Start Threshold (ssthresh), Round Trip Time (RTT) and Retransmission Timeout (RTO). These were obtained by Web100. Advertised Window Size which was advertised from the Ground PC was abbreviated because it was always larger than the cwnd.

Analyze TCP performances drawn in Fig. 7-2. TCP Rate dropped to zero only once at 22.0(*sec*). The Singlepath configuration suffered from frequent L2HOs occurring every 6.7(*sec*) and TCP experienced timeouts at all the L2HOs. Fig. 7-2 has proven that the Bicasting-Multipath Mobile IPv4 can dramatically improve communication stability. As a result, **an average of TCP Rate throughout 50.0(*sec*) was 16.4(*Mbps*)**, which satisfied the target communication speed of 10(*Mbps*) in the IEEE 802.11g Communication System.

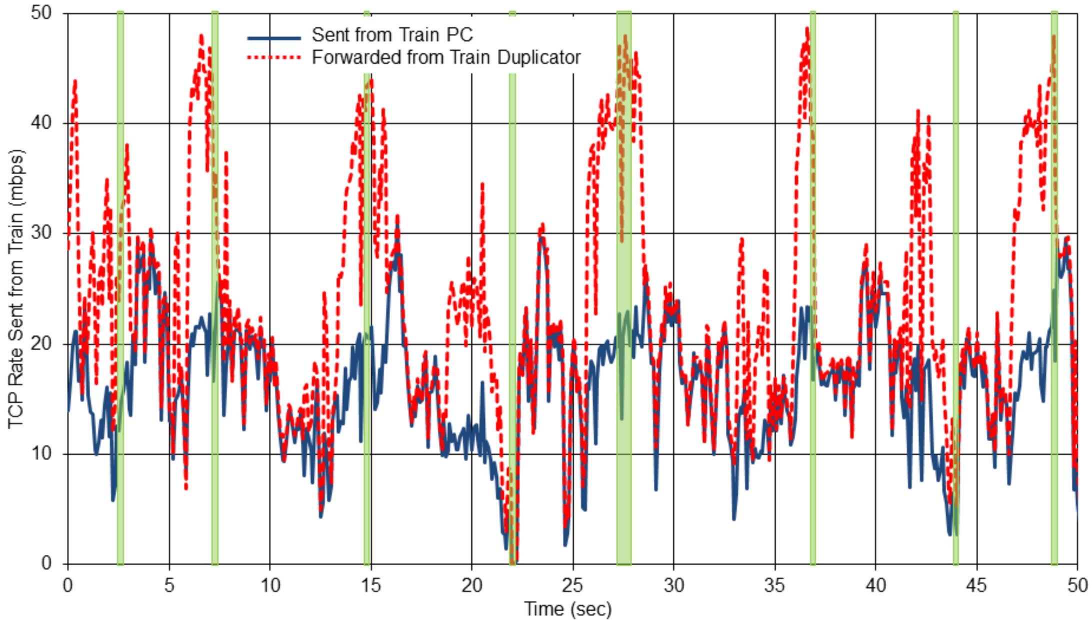
The cwnd was frequently reset as recognized in Fig. 7-3. These events were due to packet losses. In order to avoid duplicated receptions of the same packet while being bicasted, the duplicators discarded packets which had smaller IP ID than the largest IP ID of all the received packets as described in Section 6.3.1 (4). The latency of the path on which copied packets travel is usually smaller than the other (L2HO) path on which original packets travel. Therefore, just after bicasting was activated, the first copied packet arrived at the counterpart Duplicator prior to original packets which left the sender side Duplicator before the first copied packet left. Since the original packets had smaller IP ID than the first copied packet, the original packets which arrived after the first copied packet were discarded by the counterpart Duplicator. TCP had to retransmit these discarded packets. As described above, just after bicasting was started, packets were likely to be lost and then the cwnd was simultaneously reset. However, TCP was able to recover quickly after each Fast Retransmission, because RTT was quite small in the IEEE 802.11g Communication System. These adverse impacts on TCP due to packet losses are negligible unless TCP suffers from a Timeout.

Discussions are given below for TCP performances over L2HOs and during a Wireless Link Failure.

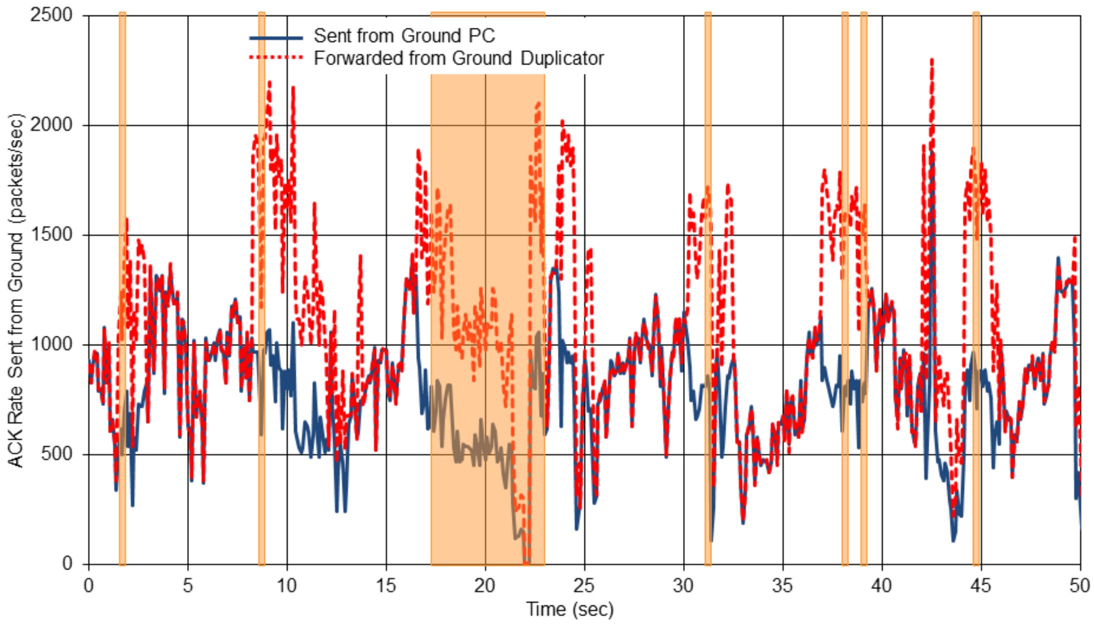
(1) L2HO Cases on the Rear BR

As a typical case of successful prediction of a L2HO on the Rear BR, verify a L2HO from BR4-19 to BR4-18 at 7.1(*sec*) (See Fig. 7-1(a)). As the train moved, RSSI which the Rear BR (TBR(L)) received deteriorated. RSSI fell under -71(*dBm*) at 6.0(*sec*), which led the Train Duplicator to predict a L2HO. Both Duplicators started to bicast traffic.

Traffic going through the Rear BR was Data traffic (Fig. 7-2 (a)) as described in Section 7.3.1(5). Therefore, we now focus on the forwarding of this traffic from the Train PC to the Ground PC. During being bicasted, the original traffic from the Train PC was forwarded through the Rear BR, and the duplicated traffic was forwarded through the Front BR. Thus TCP Rate from the Train Duplicator was twice as large as that from the Train PC as shown in Fig. 7-2 (a). Communication was continued by packets traveled through the Front BR even while the L2HO was taking place on the Rear BR. A communication stall was avoided by starting to bicast traffic before the L2HO occurrence. The Rear BR associated with BR4-18 at 7.2(*sec*) and the L2HO was completed. RSSI which the Rear BR received became around -50(*dBm*), which stopped bicasting on both Duplicators.



(a) TCP Rate Sent From Train



(b) ACK Rate Sent from Ground System

Fig. 7-2 Traffic Rates on Bicasting-Multipath MIPv4 Architecture with L2HO Threshold of -71dBm

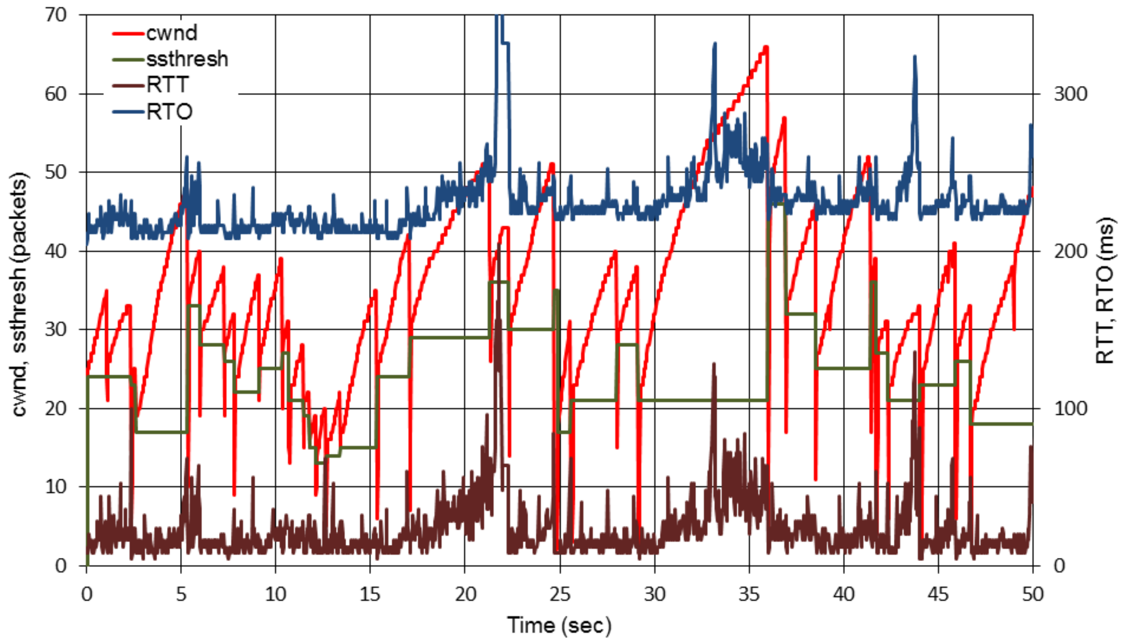


Fig. 7-3 TCP Parameters on Bicasting-Multipath MIPv4 Architecture with L2HO Threshold of -71dBm

(2) L2HO Cases on the Front BR

As a typical case of successful prediction of a L2HO on the Front BR, verify a L2HO from BR3-11 to BR2-13 at 1.5(*sec*) (See Fig. 7-1 (b)). RSSI which has been stable acutely drops and a L2HO on the Front BR suddenly starts in Mode 2. This kind of events was seen on this L2HO. The Train Duplicator detected an occurrence and predicted a L2HO. The Duplicators started to bicast traffic.

Traffic going through the Front BR was ACK traffic (Fig. 7-2 (b)) as described in Section 7.3.1(5). Therefore, we now focus on the forwarding of this traffic from the Ground PC to the Train PC. During being bicasted, the original traffic from the Ground PC was forwarded through the Front BR, and the duplicated traffic was forwarded through the Rear BR. Thus ACK Rate from the Ground Duplicator was twice as large as that from the Ground PC as shown in Fig. 7-2 (b). Communication was continued by packets traveled through the Rear BR even while the L2HO was taking place on the Front BR. A communication stall was avoided by starting to bicast traffic before the L2HO occurrence.

(3) Case of a Wireless Link Failure on the Front BR

This trial suffered from a Wireless Link Failure on BR2-11 from 17.3(*sec*) to 22.9(*sec*). A Wireless Link Failure is triggered by a L2HO. After a TBR leaves an active GBR in a L2HO process, it sometimes fails to make an association with a new GBR. Therefore, a Wireless Link Failure can be predicted by the same algorithm as for a L2HO prediction. In this experiment, RSSI which the Front

BR received from BR2-12 sharply dropped at 16.6(sec), which led the Train Duplicator to predict a L2HO. Then the Duplicators started to bicast traffic. Bicasting had been continued until the Front BR associated with BR1-14 and RSSI became larger than the configured L2HO threshold of -71(*dBm*) at 23.1(*sec*). It was ACK traffic that was traveling through the Front BR. During the Wireless Link Failure, ACK Rate from the Ground Duplicator was twice as large as that from the Ground PC due to bicasted traffic as shown in Fig. 7-2 (b). Bicasting maintained the communication during the Wireless Link Failure.

Both TCP Rate and ACK Rate dropped to zero at 22.0(*sec*), which was during the Wireless Link Failure. It was because the Rear BR experienced a L2HO from BR4-17 to BR4-16. The Train Duplicator successfully predicted this L2HO and both Duplicators started to bicast traffic. However, the Front BR was suffering from the Wireless Link Failure and thus bicasting was ineffective. In other words, traffic forwarding was halted on both paths at around 22.0(*sec*). This is a rare event and it is impossible to eradicate these kinds of exceptions. From discussions above, it has been proved that the Bicasting-Multipath Mobile IPv4 can forward traffic during a Wireless Link Failure as long as another L2HO does not occur on the other path.

7.3.4. Communication Stall Duration Rate

TCP experienced a Timeout in the test duration of 50.0(*sec*) and its RTO was 335(*ms*). Therefore **the Communication Stall Duration Rate was 0.67%**. On the other side, a negative contribution of each event to the Communication Stall Duration Rate is estimated with a statistical approach. The calculation is based on assumptions as follows.

(1) TCP Downtime is 0.3(*sec*) in a L2HO for which prediction fails (See Table 4-2), because the Train duplicator is able to detect a L2HO and start bicasting after its occurrence even in a case where the duplicator fails to predict it in advance.

(2) The Front BR and the Rear BR do not suffer from a L2HO at the same time.

(3) During a Wireless Link Failure on a path, a L2HO takes place once on the other path. Prediction for this L2HO is always successful (but ineffective). TCP Downtime is 0.3(*sec*) in a L2HO on the Rear BR during a Wireless Link Failure on the Front BR. TCP Downtime is 0.9(*sec*) in a L2HO on the Front BR (See Table 4-3) during a Wireless Link Failure on the Rear BR. This is because the Front BR consumes the L2HO Wait Time of about 0.4(*sec*) as described in Section 4.7.2, though the first Retransmission packet is sent about 0.3(*sec*) after the L2HO occurrence. TCP has to wait for a doubled RTO (0.6(*sec*)) after the failure of the first retransmission.

(4) Uplink Traffic and downlink traffic always take different paths.

(Front BR)

Since accuracy of L2HO prediction is 88.2% for the Front BR (See Section 6.5.1), an average interval of L2HOs for which prediction fails is 56.8(*sec*) ($\approx 6.7 \div (1 - 0.882)$). Here, TCP Downtime is assumed to be 0.3(*sec*). This communication stall event occupies 0.53% of the total communication duration. A L2HO on the Front BR occurs while the Rear BR is suffering from a Wireless Link Failure. Since the Wireless Link Failure Rate on the TBR is 5.2%, the interval of this kind of a L2HO is 129(*sec*) ($\approx 6.7 \div (1 - 0.052)$). Here, TCP Downtime is assumed to be 0.9(*sec*) while the Rear BR is suffering from a Wireless Link Failure. This communication stall event occupies 0.70% of the total communication duration. As a result, a negative contribution of events occurring on the Front BR to the Communication Stall Duration Rate is 1.23%.

(Rear BR)

Since accuracy of L2HO prediction is 90.5% for the Rear BR (See Section 6.5.2 and Fig. 6-5), an average interval of L2HOs for which prediction fails is 70.5(*sec*) ($\approx 6.7 \div (1 - 0.095)$). Here, TCP Downtime is assumed to be 0.3(*sec*). This communication stall event occupies 0.43% of the total communication duration. The interval of L2HOs on the Rear BR occurring in a Wireless Link Failure on the Front BR is 129(*sec*) and TCP Downtime is assumed to be 0.3(*sec*). This communication stall event occupies 0.23% of the total communication duration. As a result, a negative contribution of events occurring on the Rear BR to the Communication Stall Duration Rate is 0.66%.

From the discussion above, the Communication Stall Duration Rate with a L2HO threshold of -71(*dBm*) statistically becomes 1.89%. Since the experiment was done only once, a difference between the observed value of 0.67% and the statistic value is unavoidable. An important result we have to stress here is the reducing effect of the Communication Stall Duration Rate by our proposed method. The original Communication Stall Duration Rate was 9.9% in Mode 1 and 18.1% in Mode 2 as described in Section 4.9. Comparing with these values, both the observed value and the statistic value were dramatically reduced. Our proposed method is able to improve the Communication Stall Duration Rate.

The trial has proven that the Bicasting-Multipath Mobile IPv4 is able to satisfy the Requirements set up in Section 4.9, which are "(1)**To enable traffic forwarding while a Layer 2 link is down**" and "(2)**To eradicate TCP Time Out caused by L2HOs**", though there are some minor exceptions. These exceptions are as follows.

(1) Failures of L2HO prediction

(2) L2HO occurrences during a Wireless Link Failure on the other path

(3) Coincidences of L2HOs on both paths

7.4. L2HO Threshold and Expected TCP Rate

The results described in this chapter have proven that a bicasting architecture realizes a high communication stability. These experiments were done with a single TCP session. For farther detailed considerations, this section discusses TCP performances of multiple TCP sessions which are load-balanced over both paths by IPLB. The largest difference due to the number of TCP sessions is an occupancy rate of the bandwidth. When a lot of TCP sessions are established, the IPLB algorithm load-balances them over both paths and the paths become completely occupied. In case that bicasting is disabled, the cumulated bandwidth of the paths is 23.56(*Mbps*) and the whole bandwidth is available to be used for communication, though communication is seriously instable due to a L2HO and a Wireless Link Failure. Bicasting consumes doubled communication resources by sending duplicated packets. Bicasting is to obtain communication stability with the cost of communication bandwidth. This section evaluates a consumed communication capacity by bicasting and estimates an expected TCP Rate.

7.4.1. Communication Model

TCP Rate Model of the Bicasting-Multipath Mobile IPv4 is estimated on the basis of the TCP Rate Model derived in Section 4.8. Fig. 4-9 shows a model of a Singlepath system. Here the system has dualpaths and thus the system configuration is as depicted in Fig. 5-4. Assuming that the train runs in the right direction in Fig. 5-4. Time originates when the TBR(R) working as the Front BR has initiated a L2HO from the middle GBR(R). This time is also when the TBR(R) has passed by the GBR(R). Now TCP Rate through the Front BR, b_f, is obtained by substituting $d = -75\ (t - T)$ in Formula (4-3). Here, the speed of the test train was negative 75(*km/h*), because the assumed running direction of the train is opposite from Fig. 4-9. Let T be a L2HO interval and $T = 6.7(sec)$.

$$b_f = at + b_m - aT \quad (t_{fhe} \le t \le T) \tag{7-1}$$

Where $a = (-0.366) \times (-75) = 2.745$, $b_m = 22.5$. Let t_{fhe} be the time when the TCP Downtime on the Front BR has finished. $t_{fhe} = 0.9(sec)$ in accordance with the assumption given in Section 4.8. TCP Rate through the Front BR, b_f, is shown in the bottom half of Fig. 7-4.

The TBR(L) working as the Rear BR, on the other side, has passed by the left GBR(L) in Fig. 5-4 at the time of $-\frac{1}{5}T$, because the length of the test train is 400(m). Therefore TCP Rate through the Rear BR, b_r, is obtained by substituting $d = 75\ (t + \frac{1}{5}T)$ in Formula (4-3).

$$b_r = -at + b_m - \frac{1}{5}aT \quad (t_{rhe} \le t \le t_{rhs}) \tag{7-2}$$

Let t_{rhe} be the time when the TCP Downtime has finished in the previous L2HO on the Rear BR. $t_{rhs} = -\frac{1}{5}T + 7.6 = 6.3(sec)$, $t_{rhe} = t_{rhs} + 0.3 - T = -0.1(sec)$ in accordance with the assumption described in Section 4.8. TCP Rate through the Rear BR is shown in the top half of Fig. 7-4.

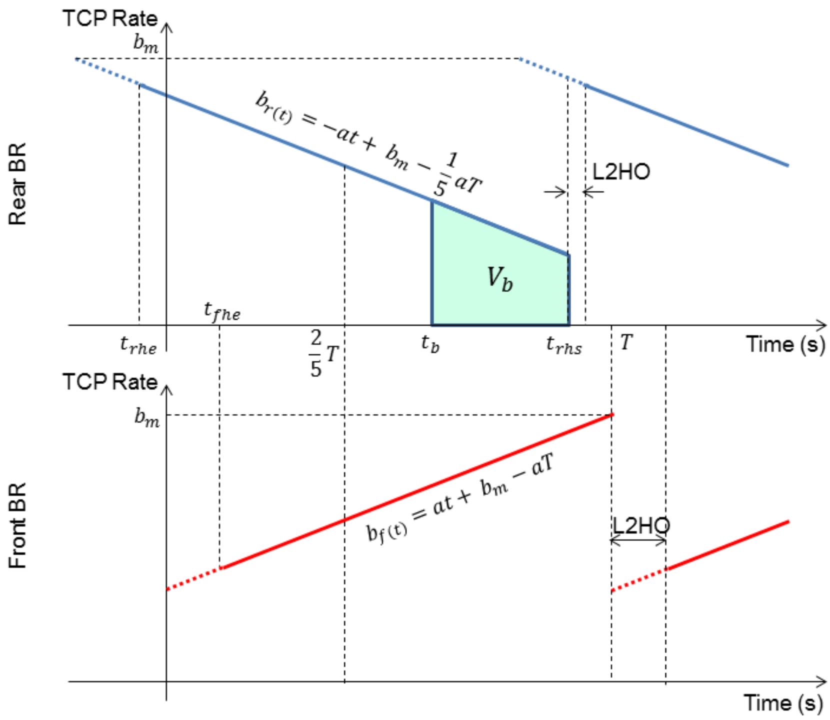


Fig. 7-4 Communication Model

The bicasting during a L2HO on each TBR is assumed as follows. The Front BR always successfully predicts a L2HO just before its occurrence and bicasting is activated by the predictions. A detection of L2HO completion on the Front BR is optimized by the method described in Section 6.5.3 and bicasting is stopped at the same time when the L2HO is completed. The Rear BR predicts a L2HO in accordance with a configured L2HO threshold and then bicasting is started. Bicasting is stopped as soon as the L2HO process is completed.

In our experiments, traffic was bicasted from a path suffering from a L2HO or a Wireless Link Failure to the other healthy path. However, in order to preserve TCP Fairness on the path to which bicasted traffic is forwarded, traffic on either path is assumed to be bicasted to the other path when a L2HO occurs on either of the paths. In this case, both paths forward the same packets. As described in Section 6.3.1(1), while traffic is being bicasted, the IEEE 802.11g Communication System communicates with earlier received packets coming from either of the paths. The Duplicators discard all dual packets which are received secondly and thus the discarded packets do not contribute to communication. Although which path can transmit packets earlier depends on an ever-changing radio field, packets traveling through a path having a wider bandwidth are assumed to arrive earlier. Therefore, bicasting wastes the bandwidth of narrower path.

7.4.2. Expected Bandwidth

A wasted bandwidth by bicasting is estimated as follows.

(1) Wasted bandwidth by bicasting from the Rear BR to the Front BR

The relationship between RSSI which is received on the Rear BR r_r and time t is obtained by substituting $d = 75\ (t + \frac{1}{5}T)$ in Formula (4-1). Formula (7-3) provides the time t_b when bicasting is started by giving a configured L2HO threshold for r_r.

$$r_r = -3.75t - 0.75T - 55.6 \tag{7-3}$$

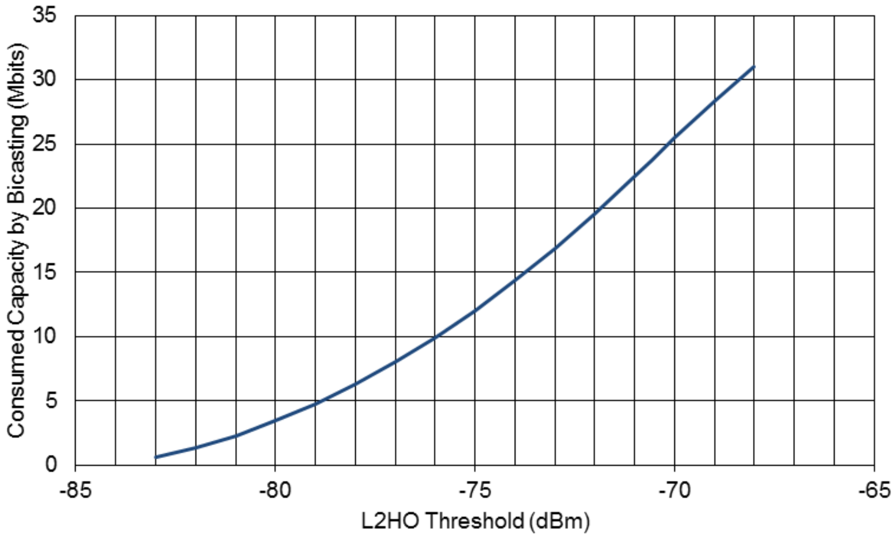


Fig. 7-5 Consumed Capacity by Bicasting

Which path has a smaller bandwidth depends on time. Formula (7-1) and (7-2) give the time for $b_f = b_r$ as $\frac{2}{5}T$. For $t < \frac{2}{5}T$, the Front BR has a smaller bandwidth. For $t > \frac{2}{5}T$, the Rear BR becomes slower. At $t = \frac{2}{5}T \approx 2.7(sec)$, RSSI which is received on the Rear BR is 70.7(dBm). Therefore, with a L2HO threshold of -71(dBm) or lower, a bandwidth on the Rear BR was consumed for discarded traffic during bicasting. When a L2HO threshold is configured as -70(dBm) or higher, the bandwidth on the Front BR is wasted from the start of bicasting to $t = \frac{2}{5}T$ and the bandwidth on the Rear BR is wasted after $t = \frac{2}{5}T$. The total wasted capacity by bicasting $V_b(Mbits)$ is formulated as follows and it is shown in the graph of Fig. 7-5.

$$V_b = \begin{cases} \int_{t_b}^{\frac{2}{5}T} b_f\, dt + \int_{\frac{2}{5}T}^{t_{rhs}} b_r\, dt & (t_b < \frac{2}{5}T) \\ \int_{\frac{2}{5}T}^{t_{rhs}} b_r\, dt & (t_b \geq \frac{2}{5}T) \end{cases} \tag{7-4}$$

(2) Wasted bandwidth by bicasting from the Front BR to the Rear BR

As the communication model in Section 7.4.1 described, when a L2HO occurs on the Front BR, bicasting is started as soon as the L2HO process starts and is stopped just after the process is completed. Therefore no packet is wasted during the process. No communication bandwidth is consumed for discarded traffic.

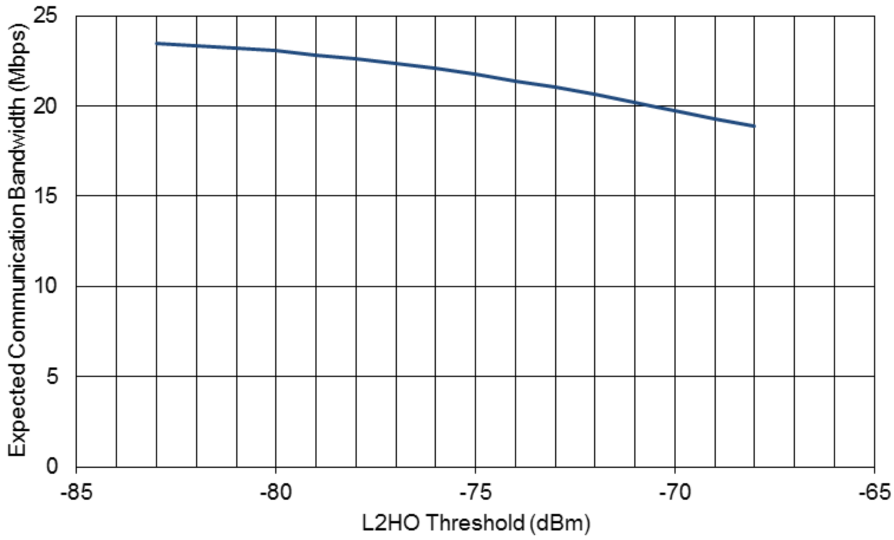


Fig. 7-6 Expected Bandwidth vs L2HO Threshold

From the discussion above, a communication capacity which is formulated in (7-4) is wasted during each L2HO interval of 6.7(sec). Thus an expected bandwidth b of the IEEE 802.11g Communication System with Dualpath Configuration is given by subtracting V_b/T from the sum of formula (4-5) and (4-6).

$$b = 23.56 - \frac{V_b}{T} \tag{7-5}$$

Formula (7-5) is shown in Fig. 7-6. Fig. 7-6 indicates a trade-off relationship between communication bandwidth and communication stability. When a L2HO threshold is configured higher in order to improve communication stability, the amount of undesired bicasted packets increases, which makes communication bandwidth smaller. A L2HO threshold must be decided in accordance with a designing policy. For example, if reduction of communication bandwidth is needed to be suppressed under 10% (this means that the required communication bandwidth is 21.2(*Mbps*)), a L2HO threshold should be set at -74(*dBm*). Accuracy of L2HO prediction for this threshold is 75.2% as shown in Fig. 6-5.

7.5. Summary

This chapter reported trials of the Bicasting-Multipath Mobile IPv4. The largest motivation to propose the Bicasting-Multipath Mobile IPv4 was to improve communication stability. The IEEE 802.11g Communication System with a Singlepath Configuration reported in chapter 4 realized an average TCP Rate of 13.7(*Mbps*) in Mode 2. However, TCP communication froze for 18.1% of the whole communicating duration. The Bicasting-Multipath Mobile IPv4 aimed at reducing the Communication Stall Duration Rate and stabilizing TCP communication over frequent L2HOs in the IEEE 802.11g Communication System.

The Bicasting-Multipath Mobile IPv4 was implemented on the IEEE 802.11g Communication System and its communication performances were evaluated in real situations. Communication performances on the Bicasting-Multipath Mobile IPv4 are shown in Table 7-1. Our results proved that the Bicasting-Multipath Mobile IPv4 was able to reduce Communication Stall Duration Rate to 0.67% with TCP Rate of 16.4(*Mbps*). The Bicasting-Multipath Mobile IPv4 realized both high communication speed and low Communication Stall Duration Rate at the same time. We have successfully configured a practical communication system for high speed rail systems.

Table 7-1 TCP Rate and Communication Stall Duration Rate

L2HO Threshold (*dBm*)	TCP Rate (*Mbps*)	Communication Stall Duration Rate	
		Measured (%)	Estimated (%)
-71	16.4	0.67	1.89

Chapter 8.
Conclusion

In order to meet requests for an Internet access in high speed mobile environments, an even faster access line is required. We proposed the Media Convergence System as an ideal communication system for future high speed mobile entities and focused on IEEE 802.11g as a pivot wireless communication medium of the Media Convergence System. This paper designed a high speed mobile communication system based on IEEE 802.11g (the IEEE 802.11g Communication System). An experimental IEEE 802.11g Communication System was constructed on a commercial high speed rail system and its performances were evaluated through trials.

Chapter 1 described a background of this research and overviewed this paper. Chapter 2 discussed ideal high speed communication systems in the future based on surveys of train communication technologies so far. The consideration led a result where a Media Convergence System which can unify various wireless communication media would be the desired high speed mobile communication system for the future. Chapter 3 through Chapter 7 is divided into two parts as depicted in Fig. 1-2. Part 1 consists of Chapter 3 and Chapter 4, in which they stressed a necessity of a pivot wireless communication medium of the Media Convergence System and explained that IEEE 802.11g satisfied all the requirements to be the medium. The IEEE 802.11g Communication System was proposed, designed and constructed on a commercial high speed rail system, and then performances of that system were evaluated. Trial results proved that the IEEE 802.11g Communication System realized the maximum application throughput of around 20(*Mbps*). On the other side, it suffered from very frequent L2HOs which degraded the communication quality. Part 2 consists of Chapter 5 through Chapter 7. In order to solve problems caused by L2HOs, Part 2 proposed the Bicasting-Multipath Mobile IPv4 and it was verified through trials. Trial results proved that the Bicasting-Multipath Mobile IPv4 improved the communication quality over L2HOs and also stabilized communication.

Conclusions for each chapter are as follows. Chapter 2 surveyed various train communication systems with their history and summarized their characteristics. As for communication media for present high speed rail systems, a Digitalized LCX Communication System, a Satellite Communication System and a Wi-Fi Communication System were reported. These three communication media have advantages and disadvantages to each other, thus it is unrealistic to cover all the tracks with a single wireless communication medium. We need flexibility on a system configuration with a freedom of choice of communication media. Adequate communication media should be installed in adequate areas. The Media Convergence System can recognize plural wireless communication media and load-balance traffic over those media. The Media Convergence System is the one we should design for the future.

Chapter 3 proposed IEEE 802.11g as a pivot communication medium in the Media Convergence System. The major requirement for the pivot medium is high communication performances with high financial efficiency. Using IEEE 802.11g became our main focus. The major goal of our research was set to achieve an average application throughput of 10(*Mbps*) with the use of IEEE 802.11g while a mobile station is traveling at around 300(*km/h*).

This chapter also reported system designs to apply IEEE 802.11g to high speed mobile communications. As for Layer 1, a radio transmission channel was established above the track. The validity of this design was proven through experiments, which clarified that the IEEE 802.11g Communication System had a capability of communicating at an average throughput of around 10(*Mbps*) within a distance between adjacent ground stations of 500(*m*). As for Layer 3, An FA to which MR on a train visits next can be perfectly identified unless the train suddenly leaves its intended route. With this peculiarity taken into account in network designs, a L3HO was separated from a L2HO. This method reduced packet losses due to a L3HO. In accordance with the designs discussed in this chapter, an IEEE 802.11g Communication System for trials was constructed on a commercial high speed rail system.

Chapter 4 verified that the IEEE 802.11g Communication System performed in accordance with the designing intentions. The field trials were done on a commercial high speed rail system and the speed of the test train was kept at 270km/h. It was the maximum speed for the service. Our experimental results revealed communication performances on the IEEE 802.11g Communication System as shown in Table 8-1. Results showed that the IEEE 802.11g Communication System working in Mode 2 had a TCP bandwidth of 13.7(*Mbps*) even while a mobile node was moving at 270(*km/h*). We obtained a larger throughput than the target throughput of 10(*Mbps*). On the other side, however, Table 8-1 also clarified a problem of communication stall durations caused by downtimes over L2HOs and wireless link failures.

In order to reduce Communication Stall Duration Rate, requirements to improve the IEEE 802.11g Communication System were considered. Our policy does not permit any customizations on the IEEE 802.11g. Instabilities on Layer 1 and Layer 2 had to be compensated for by Layer 3. These discussions brought three Requirements to be satisfied as follows.

(1) To enable traffic forwarding while a Layer 2 link is down

(2) To eradicate TCP Time Out caused by L2HOs

(3) To be applicable to all transport protocols

Table 8-1 Communication Performance on the IEEE Communication System

Examined Contents	Results	
IEEE802.11g Link (Wireless Link Failure)	Failed in 5.2%	
Round Trip Time	Average: 9.95(*ms*), Standard Deviation: 5.79(*ms*)	
UDP	Mode 1	Average: 16.3(*Mbps*) Max: 25(*Mbps*) or higher
	Mode 2	Average: 17.7(*Mbps*) Max: 25(*Mbps*) or higher
TCP	Mode 1	Average: 9.86(*Mbps*) Max: Around 20(*Mbps*)
	Mode 2	Average: 13.7 (*Mbps*) Max: Around 22(*Mbps*)
Communication Stability (Communication Stall Duration Rate)	Mode 1	9.9%
	Mode 2	18.1%

Chapter 5 proposed the Bicasting-Multipath Mobile IPv4 in order to satisfy three Requirements set up in Section 4.9. It is an architecture which (1) establishes two paths between the ground network and the train network, (2) recognizes the paths by MP-MIPv4 and (3) bicasts traffic over the paths while an IEEE 802.11g link is under trouble. This chapter especially explained a MP-MIPv4 platform on which wireless links were multiplexed and packets were bicasted between the redundant paths. Also this chapter considered how to load-balance traffic between the MIPv4 paths and concluded that IPLB was the best load-balancing algorithm for the IEEE 802.11g Communication System with Dualpath Configuration. With considerations in this chapter, we have completed a design of the network platform for the Bicasting-Multipath Mobile IPv4.

Chapter 6 reported our design of a bicasting architecture on a MP-MIPv4 platform and an implementation of the Bicasting-Multipath Mobile IPv4 onto the experimental IEEE 802.11g Communication System. The Bicasting-Multipath Mobile IPv4 activated bicasting when either a L2HO or a Wireless Link Failure occurred. Here, bicasting had to be started before an occurrence of either of them. Even if bicasting is started after a detection of a link being down, target traffic is no longer there and thus TCP has to wait for a RTO expiration. The IEEE 802.11g Communication System predicted the events by RSSI which each TBR received from one of the GBRs. For the Front BR working in Mode 2, a L2HO was predicted by an occurrence of a RSSI peak. This method successfully predicted L2HOs on the Front BR with the rate of 88.2%. For the Rear BR working in Mode 1, on the other side, we introduced a threshold to judge a L2HO. The threshold is referred to as “L2HO threshold.” When a RSSI fell under this L2HO threshold, a L2HO was predicted and then bicasting was started by Duplicators. Accuracy on the Rear BR depends on a configurable L2HO threshold.

Chapter 7 reported trials of the Bicasting-Multipath Mobile IPv4. The largest motivation to propose the Bicasting-Multipath Mobile IPv4 was to improve communication stability. The IEEE 802.11g Communication System with a Singlepath Configuration which was reported in chapter 4 realized an average TCP Rate of 13.7(*Mbps*) in Mode 2. However, TCP communication froze for 18.1% of the whole communicating duration. The Bicasting-Multipath Mobile IPv4 aimed at reducing the Communication Stall Duration Rate and stabilizing TCP communication over frequent L2HOs occurring in the IEEE 802.11g Communication System.

Communication performances of the Bicasting-Multipath Mobile IPv4 were evaluated in real situations. The result is shown in Table 8-2. It proved that the Bicasting-Multipath Mobile IPv4 was able to reduce Communication Stall Duration Rate to 0.67% with TCP Rate of 16.4(*Mbps*). The Bicasting-Multipath Mobile IPv4 realized both high communication speed and low Communication Stall Duration Rate at the same time. We have successfully configured a practical communication system for high speed rail systems.

Table 8-2 TCP Rate and Communication Stall Duration Rate

L2HO Threshold (*dBm*)	TCP Rate (*Mbps*)	Communication Stall Duration Rate	
		Measured (%)	Estimated (%)
-71	16.4	0.67	1.89

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