Feasibility Test and Analysis for Heavy Haul Freight Using WDPS Based on MIMO-OFDM

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Abstract: The technical feasibility of a heavy haul freight using WDPS (Wireless Distributed Power System) was verified for the first time in Korea. That consisted of a master locomotive, 50 freights and a slave locomotive. The master and slave locomotives were equipped with WDPS to distribute traction and braking control command data. MIMO-OFDM, which is strong in multi-path, was applied to the WDPS, and a repeater was installed on the 25th freight to secure coverage even with signal attenuation according to the terrain (curve, gradient) of the driving section. The test was carried out at an average speed of 100 km/h in the approximately 21 km from Jillye station to Busansinhang station in Korea. As a result of the test, it was confirmed that the traction function, braking function, pantograph control function, MCB function, and safety circuit function of the heavy haul freight using WDPS were perfectly controlled. Additionally, the air braking time was reduced by about 50% compared to the centralized control as the braking was controlled by two locomotives at the same time. For the first time, the operational feasibility of heavy haul freight using WDPS based on MIMO-OFDM in the 2.4 GHz/5 GHz band with a relatively short propagation distance was verified.

Keywords: heavy haul freight; WDPS; MIMO-OFDM; braking performance; safety function

1. Introduction

In recent years, as the importance of rail freight transport has emerged as a solution to problems such as energy shortage and climate change, various technical attempts have been made to efficiently operate freight trains [1]. Australia, Canada, the United States, and China, which have a high distribution ratio of freight, have already operating heavy haul freight using wired/wireless distributed control technology as a way to further improve their freight capacity. The heavy haul freight has a shorter braking time, and thus a shorter braking distance, than the conventional centralized control [2]. When the position of the locomotive is not appropriate, the impact between freights due to the asynchronous control time may cause damage to the coupler or a derailment. The ECP braking system which is wired distributed control installed in all freights is connected to the train line to synchronize control signals, and is applied to the transportation of dangerous substances such as gas and oil that require precise control to secure operational stability. But the wired distributed control method has the disadvantage of installing and maintaining a trainline [3,4]. Another method, the existing wireless distributed control method, applies the FSK method in the 400 and 800 MHz band. The FSK method has a wide communication range and is resistant to diffraction, relatively simple device implementation, but has low frequency efficiency, so it is possible to transmit only the minimum information necessary for operation [5].

Many researchers have studied on heavy haul freight. Zhao et al. presented the minimum time delay of the distributed control signal between the control locomotive (master) and the controlled...
vehicle (slave) to minimize the longitudinal impact through dynamic simulation [6]. Gao et al. discussed brake performance when driving on steep slopes in locomotive-based distributed control [7]. Huang et al. proposed a method for synchronizing the four distributed wireless distributed modules to transport 50,000 tons in China, and verified this at the laboratory level [8]. Research on the operation of the heavy haul freight has been conducted since the 1970s and communication technology is still being applied, though technology has developed dramatically. WDPS technology in the 400 or 800 MHz band, which is currently used in many countries, has little radio wave loss and a wide communication range, but the transmission rate is limited to 19.2 kb/s [9]. Due to the development of mobile communication technology, large-capacity and high-speed wireless communication is being used for train control, operation, and maintenance [10–12]. In the case of freight, various sensors are requested to collect status information data using GHz band wireless communication and utilize it for maintenance [13,14]. For passenger trains, WiFi communication technology in the 2.4/5 GHz band is applied to communicate between onboard and wayside for communication-based train control [15–17].

This test is meant to confirm the possibility of using the GHz wireless technology while technically verifying the possibility of operating the heavy haul freight for the first time in Korea. In this paper, we describe the configuration for WDPS based on MIMO-OFDM and test results for control functions, the braking performance, and the WDPS performance.

Section 2 describes the system configuration of heavy haul freight with WDP and the main technologies applied to WDP, and Section 3 describes the measurement and test for heavy haul freight.

2. System Configuration

2.1. Overview of WDPS Development Methodology

To verify the operation feasibility of heavy haul freight in Korea, we developed a WDPS system that applied the MIMO-OFDM. For that, the railway undertaker, the vehicle manufacturer, the braking and propulsion control device manufacturer, and the wireless device manufacturer were involved in the WDPS development and test. Figure 1 is a flowchart that briefly introduces the methodology we developed for WDPS.

First, functional requirements, system requirements, and interface requirements of WDPS are derived based on the operational requirements of heavy haul freight (ex, target vehicle, length of train, operating speed, test section, etc.). The second step, the design and development for each technical field, is performed based on the requirements derived in the previous step. In the locomotive field, the S/W modification for the control logic of propulsion/braking and TCMS and the control circuit modification for the safety circuit configuration are performed. In the wireless field, a design to minimize interference factors through analysis of the propagation environment in the test section and a design for interface with the locomotive are performed. When development is completed for each technical field, a self-test is conducted, and if there is no problem, a system static test is performed with the heavy haul freight configuration by the operation requirements. At this step, in order to safely

![Diagram](Figure 1. WDPS development methodology.)
operate heavy haul freight, the braking performance, the main functions of the locomotive, and the safety functions that must be operated in an emergency must be confirmed. When all the essential functions and performance are satisfied in the static state, the next step is to check the function and system requirements of WDPS and the normal operation of heavy haul freight under the operating requirements. If the requirements of each stage are not satisfied, return to the system design stage to check the problems, draw up improvements and reflect them in WDPS.

The main operation requirements of heavy haul freight in this test were as follows.

- **Configuration of heavy haul freight**: That consisted of a master locomotive, 50 freights and a slave locomotive. The master and slave locomotives are equipped with WDPS to distribute traction and braking control command data.
- **Operation speed**: An average speed of 100 km/h
- **Test section**: The approximately 21 km from Jillye station to Busansinhang station in Korea.
- **Common requirement**: The heavy haul freight with WDPS should perform the same main function and safety function of the freight train operation using the existing centralized control.

### 2.2. Electrical Interface of Electric Locomotive

The tests were conducted on two electric locomotives: ID 8503 and ID 8506 (detailed technical specifications are given in Appendix A), operated by the KORAIL, and these locomotives consist of the main control units which are a master controller, a traction unit, a braking unit and CCU with DU. The TCN consists of the backbone by WTB [18] and the consist network by MVB [19]. The CCU communicates to traction and braking units for control and status data through the TCN. The CCU communicates the control data and status data of the propulsion/braking system with the TCN. The traction command by driver is 0~5 V analog input, the traction on/off is the digital input, and the electric and air braking commands are CAN communication.

### 2.3. WDPS Configuration for Distributed Control of Heavy Haul Freight

#### 2.3.1. WDPS-Based MIMO-OFMD

It was judged that the snake motion of the heavy haul freight in domestic freight line with many tunnels and curved sections would affect the signal attenuation. Therefore, in this test, MIMO-OFDM-based WDPS, which is strong in multipath fading environment and capable of high-speed data transmission, is applied and its performance is verified. OFDM processes data in parallel, as shown in Figure 2, divides a high-speed data stream at low speed, and transmits them simultaneously using a carrier frequency. Since the symbol interval is increased by using a low-speed parallel carrier, ISI is reduced, and by using multiple carriers, there is a strong advantage in frequency selective fading [20,21].

![MIMO-OFDM block diagram](image)

**Figure 2. MIMO-OFDM block diagram.**

Signal strength is affected by path loss, shading, and fading. In general, the signal strength ($L_0$) in a free space RSSI is defined as the ratio of transmit power ($P_t$) and receive power ($P_r$) as shown in
the following Equation (1), and is expressed in dBm as a value reflecting the strength of the received signal [22].

$$L_s = P_t \frac{P_r}{P_t} = 10 \log\left(\frac{4\pi d}{\lambda}\right)^2$$

(1)

Here $d$ is the distance between the transceiver and $\lambda$ is the wavelength. In general, the higher the frequency, the greater the loss of free space. In the case of a heavy haul freight, $d$ is constant. Therefore, NLOS according to curve, gradient and tunnels are the main factors to degrade communication performance rather than free space path loss according to distance. Installing an appropriate transceiver location is important. Therefore, we had secured the communication coverage of heavy haul freight by applying WiFi transceiver with 1 km coverage and additionally repeater as shown Figure 3.

To improve communication reliability, the WDPS, which was first applied in Korea, was resistant to multipath fading and employed MIMO-OFDM technology capable of transmitting large amounts of information [23].

![WDPS configuration and antenna installation.](image)

**Figure 3.** WDPS configuration and antenna installation.

### 2.3.2. WDPS Protocol

The master locomotive and the slave locomotive must communicate the control command information of the vehicle as shown in the Table 1 through the CCU. Therefore, WDPS requires an electrical interface with the CCU, braking unit, and master controller, and newly defined communication protocols between the CCU and the braking unit. In this paper, only the information types necessary for the operation are described.

| Interface       | Description                                                                 |
|-----------------|-----------------------------------------------------------------------------|
| WDPS ↔ braking unit | braking control command                                                      |
| WDPS ↔ CCU      | speed data, braking data, pantograph data, MCB data, moving distance, master or slave data, etc. |

### 2.4. Safety Circuit

All trains operating in Korea must be configured with a safety circuit to stop the train without intervention by a driver when an important device malfunction occurs. In the case of a heavy haul freight with WDPS, a safety circuit must be configured so that the emergency braking signal can simultaneously generate when (1) there is a communication failure and (2) if the emergency braking condition of locomotive ID 8503 or ID 8506 occurs.

The conditions for safety circuit operation are as follows:
1. The communication failure: when the wireless communication is cut off for more than 2 s, the safety circuit operates to generate and emergency braking command, and that the cause of failure is indicated on the DU.

2. The EB condition of ID 8503 or ID 8506 locomotive: Since the freights are non-powered, the emergency brake contact (EMBR) of the GDB in locomotives is connected to the WDPS to configure the safety circuit as follows, if any of the following configurations are interrupted, the emergency braking command generated. [GDB EMBR signal detection of master locomotive] → [WDPS] → [slave locomotive EB loop open] → [master locomotive EB command] → [EMBR signal of slave locomotive detection] → [WDPS] → [master locomotive EB loop open]

3. Measurement and Test

The test was carried out at an average speed of 100 km/h in the approximately 21 km section from Jillye station to Busansinhang station in Korea. The formation was as Figure 4. Instead of the existing FSK method, MIMO-OFDM, which is strong in multi-path, was applied to the WDPS, and a repeater was installed on the 25th freight train to secure communication coverage even with signal attenuation according to the terrain (curve, gradient) of the driving section.

3.1. Braking Performance Measurement and Analysis

In Korea, this test was the first to verify WDP and heavy-haul freight (it is approximately double existing capacity) on a running line. For safety reasons, when 50 freights were connected, it should be first confirmed whether service braking and emergency braking performance are normally applied in the field. We experimented in two cases: one was a centralized control where one locomotive controls 50 cars, and the other was a distributed control where two locomotives control each. In both cases, when braking command, the pressure and time at the BP and the BC in the locomotive were measured. Those at the BC in the 1st, 10th, 20th, 30th, 50th freight were measured [24]. As shown in Appendix B, Appendix C and the Table 2 below, the FSB test result, the brake equivalent response time is 16.6 s shorter than the centralized control, and the braking release time is 16.6 s shorter. Additionally, the EB test result confirmed that the brake equivalent response time is 2.3 s and the braking time is 25.8 s shorter than the centralized control. That is, in the distributed control of the heavy haul freight, the master locomotive at the front and slave locomotive at rear control the BP pressure at the same time, so that the braking action starts from the freight close to the locomotive. As a result, the transport capacity increased to double, and the braking and release time was also reduced by about 1.5 times.

3.2. WDPS Performance Measurement and Analysis

Before applying WiFi-based WDPS, the propagation environment for interference was measured in the test section. Since WiFi operates in the 2.4/5 GHz ISM band, it must be to check the effect
of the same band device used in houses and factories around the track. As a result of propagation environment, 2.4/5 GHz noise was less than $-90$ dBm, and a 2.4 GHz band AP with low signal strength was detected intermittently in the downtown area. It is determined that the detected AP will not significantly affect WDPS performance. Detailed WiFi specifications are given in Appendix D.

**Table 2. Braking test results.**

| Test Item | Brake Equivalent Response Time | Brake Release Times (Measured) |
|-----------|--------------------------------|-----------------------------|
| FSB       | Centralized control 23.6 s     | 25.4 s at 30th freight      |
|           | Distributed control 7.0 s      | 8.8 s at 20th freight       |
| EB        | Centralized control 5.9 s      | 44.2 s at 30th freight      |
|           | Distributed control 3.6 s      | 18.4 s at 20th freight      |

Measured WDPS SNR Analysis

The heavy haul freight was consisted as shown in Figure 4, and operated 21.365 km from Jillye station to Busansinhang station. There are five tunnels and 20 bridges in the test section, of which there are four tunnels over 1 km and one bridge over 1 km. The SNR results measured at the master locomotive are shown in the Figure 5. From Figure 5, we can see that WiFi-based WDPS is applicable to distributed control of heavy haul freight. The fluctuation of signal strength exists depending on the track environment within the test section, but no functional error occurred because the 2.4/5 GHz band signals did not drop below 10 dB simultaneously, except for one short point.

The section where the 1 and 2 occurred is an uphill gradient open area with three short bridges continuously, and the curve radius is $R = 1400$ and $\text{cant} = 150$. SNR fluctuation due to NLOS occurred for a short time in the corresponding section. This section 3 is a tunnel with a length of 2.5 km. It is a curved section while changing from an upper gradient to a down gradient at the entrance of the tunnel. At that time, the heavy haul freight train had a serious meandering behavior and the NLOS was happened, so the communication state was unstable. But no signal breakdown occurred because the 2.4/5 GHz band signals did not drop below 10 dB simultaneously, excluding an approximately 480-m section. At that point, the 2.4/5 GHz band signal dropped below 10 dB at the same time, but with very short moments, no functional error occurred in the WDPS operation. We can find an important fact that there was no frequency diversity effect in specific sections. Overall, the 5 GHz signal was more stable than 2.4 GHz in the test section, but it was confirmed that the attenuation of the signal was greater than 2.4 GHz in the specific section where tunnels, curves, and gradients existed simultaneously. These results are evidence that the higher the frequency, the more vulnerable to performance in NLOS condition under the influence of the characteristics more sensitive to fading.

Therefore, under the premise that frequency diversity is applied, the following methods can be considered for stable operation of WDPS. The first method should be arranged so that the wireless device satisfies the LOS condition when applying the high-frequency band. The second method when choosing a frequency, we can allocate two or more other channels in the 2.4 GHz band or consider the latest communication methods in the band below the 2.4 GHz band (e.g., LTE in 850, 950, 900 MHz, 1.8 GHz, etc.).

The section where 4 occurred is the open area, low slope and radius of curvature $R = 1000$, and $\text{cant} = 30$. There are five short bridges in a row. NLOS caused by the influence of this terrain is considered to be the cause of signal attenuation. 5 is open area, the upper gradient and $R = 2000$ with $\text{cant} = 40$. This is a section that passes over a bridge over 1 km in length and leads to a tunnel. This was a section in which LOS was not guaranteed. 6 is a section of three consecutive tunnels with 5.5 km length. Unlike the same tunnel section 3, 6 was a straight-line section, so the LOS was guaranteed. Therefore, the SNR was constant.
plans to improve antenna gains will be further studied. 

If the communication between WDPS is lost for more than 2 s, existing vehicles. Among the electrical interfaces of the WDPS, a safety circuit was constructed to stop the train without driver intervention. If the communication between WDPS is lost for more than 2 s, or the safety loop of the master loco or the slave loco is disconnected, the emergency stop is executed.

4. Conclusions

In this paper, we describe that the results of field tests for a heavy-haul freight with WDPS was applied for the first time in Korea. WDPS has designed an electric interface with the main devices of existing vehicles. Among the electrical interfaces of the WDPS, a safety circuit was constructed to stop the train without driver intervention. If the communication between WDPS is lost for more than 2 s, or the safety loop of the master loco or the slave loco is disconnected, the emergency stop is executed.
MIMO-OFDM, which is strong in multipath is adopted as a communication method. When constructing a 50 freights, the distance between the locomotives equipped with WDP is about 670 m, so a repeater was installed for the 25th freight to secure communication coverage. Through this test, we obtained as the following results.

1. We confirmed the operational applicability of distributed control technology for heavy haul freight with WDPS based on WiFi for the first time in Korea. Communication performance, braking performance, and train operation functions (propulsion/braking command, pantograph function, MCB function, and safety circuit) were verified on the track.
2. Due to the distributed control by WDPS, the braking tube pressure of the master locomotive and the slave locomotive was simultaneously controlled. Therefore, it was confirmed through measurement that the braking and release time of the heavy haul freight was about 1.5 times faster. This can be expected to improve the operational efficiency of freights.
3. Through SNR measurement of WDPS, it was confirmed that the topography of the track is a major influence on communication performance. Although the same tunnel section, the difference of SNR was confirmed according to the meandering section and the straight flat section due to continuous curves and gradients, that is, whether the LOS was guaranteed.
4. For the stable operation of WDPS, the first method should be arranged so that the wireless device satisfies the LOS condition when applying the high-frequency band. The second method when choosing a frequency, we can allocate two or more other channels in the 2.4 GHz band or consider the latest communication methods in the band below the 2.4 GHz band (e.g., LTE in 850, 950, 900 MHz, 1.8 GHz, etc.).

We verified the technical feasibility of the WiFi- and WDPS-based heavy-haul freight, and we expect to operate heavy haul freight trains in Korea through additional research such propagation modeling, optimizing transceiver locations and freight dynamic analysis, etc.

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**Abbreviations**

| Abbreviation | Description                              |
|--------------|------------------------------------------|
| AP           | Access Point                             |
| BC           | Brake Cylinder                           |
| BP           | Brake Pipe                               |
| CAN          | Controller Area Network                  |
| CCU          | Central Control Unit                     |
| DU           | Display Unit                             |
| EB           | Emergency Brake                          |
| ECP          | Electronic Controlled Pneumatic          |
| EMBR         | Emergency Brake contact Relay            |
| FSB          | Full Service Brake                       |
| FSK          | Frequency Shift keying                   |
| GDB          | General Distributed Board                |
| ID           | Identification                           |
| ISI          | Inter Symbol Interference               |
| KORAIL       | Korea Rail Corporation                   |
| LOS          | Line Of Sight                            |
| MCB          | Main Circuit Breaker                     |
| MIMO         | Multi-Input Multi-Output                 |
Appendix A

Table A1. ID 8500 Locomotive specifications.

| Type                     | Description                  |
|--------------------------|------------------------------|
| Electric feeding braking | AC 25,000 V 60 Hz            |
| power of traction control| 450 kN                       |
| Signal                   | VVVF-IGBT                    |
| network                  | TCN 2.0 (MVB, WTB)           |

Appendix B

Table A2. Full-service braking results [24].

| Measuring location | Centralized Control FSB | Distributed Control FSB |
|--------------------|--------------------------|--------------------------|
|                    | Brake Delay Time [s]     | Brake Equivalent Response Time [s] | Brake Release Delay Time [s] | Release Time [s] (0 bar) | Brake Delay Time [s] | Brake Equivalent Response Time [s] | Brake Release Delay Time [s] | Release Time [s] (0 bar) |
| Locomotive         | 1.4                      | 8.2                      | 6.3                      | 46.0                      | 1.2                      | 7.6                      | 5.4                      | 20.0                      |
| 1st freight        | 0.7                      | 8.4                      | 5.8                      | 19.8                      | 0.4                      | 8.6                      | 5.2                      | 17.0                      |
| 10th freight       | 1.2                      | 22.0                     | 3.0                      | 21.4                      | 1.0                      | 15.6                     | 6.5                      | 19.0                      |
| 20th freight       | 1.7                      | 26.0                     | 15.2                     | 40.8                      | 1.4                      | 13.6                     | 8.8                      | 21.4                      |
| 30th freight       | 4.4                      | 26.0                     | 20.0                     | 45.2                      | 2.0                      | 12.8                     | 9.2                      | 21.2                      |
| 50th freight       | 3.4                      | 32.0                     | 23.2                     | 43.6                      | 0.9                      | 10.6                     | 4.2                      | 12.6                      |

Appendix C

Table A3. Emergency braking results [24].

| Measuring Location | Centralized control EB | Distributed control EB |
|--------------------|------------------------|------------------------|
|                    | Brake Delay Time [s]   | Brake Equivalent Response Time [s] | Brake Release Delay Time [s] | Release Time [s] (0 bar) | Brake Delay Time [s] | Brake Equivalent Response Time [s] | Brake Release Delay Time [s] | Release Time [s] (0 bar) |
| Locomotive         | 0.4                    | 1.8                    | 37.0                    | 91.0 | 0.4                      | 1.7                      | 28.4 | 58.2                      |
| 1st freight        | 0.2                    | 2.87                   | 13.4                    | 24.0 | 0.2                      | 2.4                      | 13.8 | 24.4                      |
| 10th freight       | 0.7                    | 4.3                    | 23.4                    | 44.0 | 0.6                      | 4.0                      | 22.4 | 34.0                      |
| 20th freight       | 1.2                    | 5.8                    | 45.6                    | 68.2 | 1.2                      | 5.2                      | 27.8 | 39.8                      |
| 30th freight       | 1.7                    | 7.0                    | 46.2                    | 64.6 | 1.6                      | 5.4                      | 24.6 | 35.8                      |
| 50th freight       | 2.9                    | 8.7                    | 49.6                    | 65.2 | 0.4                      | 1.8                      | 13.0 | 21.4                      |
Appendix D

Table A4. WiFi specifications.

| Item                        | Description       |
|-----------------------------|-------------------|
| 2.4 G chip TX               | 18–23 dBm         |
| IEEE 802.11 b/g/n RX        | –90 dBm           |
| 5 G chip TX                 | 18–23 dBm         |
| IEEE 802.11a/n RX           | –90 dBm           |
| ANTENNA beam width          | 50° (Nominal)     |
| ANTENNA gain                | 8–12 dBi          |
| VSWR                        | 2.0: 1            |
| polarization                | Linear            |
| Impedance                   | 50 Ω              |

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