Application of OFDM transmission method for railway signalling system via track circuit

Ryo Higuchi¹,*, Hiroshi Mochizuki¹, Hideo Nakamura¹, Ryo Ishikawa², Minoru Sano² and Satoshi Nishida²

¹Nihon University, College of Science and Technology, Narashinodai, Funabashi, Chiba, Japan
²Kyosan Electric Mfg. Co., Ltd., Heian-cho, Yokohama, Kanagawa, Japan

*E-mail: csro14075@g.nihon-u.ac.jp

Abstract. At present, railway signalling systems in which control information is transmitted via track circuits (rails) have been deployed in many applications, such as automatic train control (ATC) systems in Japan. In these systems, it is difficult to increase the transmission speed due to the transmission characteristics of rails. To overcome this problem, we have proposed a new transmission method using orthogonal frequency division multiplexing (OFDM) and evaluated a configuration in which data judgment using majority decision was applied for improving the bit error rate (BER) characteristics. In this paper, we describe an FPGA implementation of our proposed method and the performance of the implemented devices.

1. Introduction
Currently, railway signalling systems using track circuits (rails) are widely used, for example, automatic train control (ATC) systems[1-2]. Here, a track circuit as a transmission medium offers superior safety[3] compared with radio systems[4-7], such as the ease of implementing countermeasures against disturbance radio waves. These systems have some problems, however, such as the strong influence of unique railway noise inherent to trains and the difficulty of increasing the transmission speed due to the use of the audible frequency band[8]. To solve these problems, we have been looking at introducing orthogonal frequency division multiplexing (OFDM) transmission into the orbital circuit. In OFDM, it is possible to overlap many carriers within a limited frequency by narrowing the spacing between subcarriers.

In the present research, we designed a data allocation method of improving the bit error rate (BER) characteristics for realizing a railway signalling system employing OFDM transmission. And we examined an implementation using a field programmable gate array (FPGA), which is a programmable device. More specifically, we implemented a transmitter, serving as the OFDM signal generator, and evaluated the output characteristics.

2. Characteristics of transmission using a track circuit
In this section, we describe the track circuit used as the current transmission medium. As shown in figure 1, the track circuit is configured by insulating the rail at about 1 km intervals and constitutes a
closed circuit for the electrical signal. DC current from the train also flows on the rail. By adding an impedance bond at the insulation joint, a bypass path is secured.

As shown in figure 2, the track circuit exhibits high attenuation in the high-frequency region of 10 kHz and higher. Since it is not possible to use a frequency band like that used in general wireless communication, the signals are transmitted in the audio frequency band. Therefore, the transmission speed of the digital ATC systems currently in practical use is limited to about 300 bps. Also, the noise is generally different from the target white noise. For example, the noise contains a large amount of harmonic components of commercial frequencies included in the return current. For example, figure 3 shows that the spectral distribution of noise in a train using three-phase alternating current with a commercial frequency of 50 Hz is dominated by noise having peaks at multiples of the sixth harmonic of the commercial frequency (300 Hz). Another feature is that it fluctuates over time.

Next we describe the configuration of the ATC. As shown in figure 4, the signal transmitted from the track circuit passes through the receiving coil of the train and is subjected to signal processing, such as demodulation, to obtain data, such as target train speed information. The target train speed obtained in this way is compared with the current train speed, and the train speed is adjusted. This is the mechanism that controls the train.

![Figure 1. Example track circuit configuration.](image1)

![Figure 2. Frequency characteristics of rail as a transmission medium.](image2)
3. Railway Signalling system using OFDM transmission

A model was created based on the characteristics of the orbital circuit transmission shown in the previous section. A block diagram of a railway Signalling system using OFDM transmission is shown in figure 5. OFDM transmission is a multi-carrier schemes using multiple carriers and, thanks to the orthogonal relationship, does not suffer from interference even if the transmission bands between subcarriers overlap. Therefore, OFDM allows the frequency utilization efficiency to be increased, and it is considered effective in a narrowband transmission line.

| Table 1. Four dimensions in computer simulation. |
|-----------------------------------------------|
| Modulation method | QPSK |
| Subcarriers       | 219  |
| Transmission rate per carrier | 10 bps |
| Transmission band  | 5.12-7.39 kHz |
For railway noise that has a peak at a specific frequency, there is a possibility that the BER characteristics can be improved by placing the same data on multiple carriers. Based on the above, a basic performance evaluation was carried out using a model based on the simulation data shown in Table 1. In OFDM, Single Side Band (SSB) transmission is adopted because a symmetric spectrum is generated on either side of the carrier frequency. Also, Quadrature Phase Shift Keying (QPSK) is employed. QPSK uses four types of signals with carrier phases that differ by 90 degrees, and therefore, 2 bits per carrier are transmitted.

Figure 6 shows the BER characteristics obtained by computer simulation for each subcarrier when railway noise and white noise are added. As shown in figure 6, it is confirmed that bit errors are concentrated on specific subcarriers in the railway noise, whereas errors are uniformly generated in each subcarrier in the white noise. It means that BER characteristics are dramatically improved by applying an error correction function for the subcarriers in which BER characteristics are worse.

4. Method of improving BER characteristics

Next, we consider a method for improving the BER characteristics. It is conceivable that railway noise having a peak at a specific frequency generates a high level of bit errors on a specific carrier. Therefore, it is thought that the BER performance can be improved by placing the same data on multiple carriers. We investigated a method of allocating data to each subcarrier for improving the BER performance. First, as shown in the upper part of figure 8, the same data was assigned to three adjacent subcarriers, and a method of determining data by majority decision was examined. As a result, it was confirmed that two adjacent subcarriers did not simultaneously contain errors for railway noise at multiples of the sixth harmonic of 300 Hz, so that the signal can be transmitted without error by majority decision.

However, it is conceivable that the commercial frequency fluctuates in an actual environment. Therefore, as a result of computer simulations taking this into consideration, it was confirmed that there was an error on two adjacent subcarriers at the same time. This is because, when the harmonic component and the center frequency of the subcarrier do not coincide with each other, this has an influence on the main lobe of two adjacent subcarriers.

Next, the same data was allocated to subcarriers having intervals different from the frequency intervals of harmonic components, as shown in the lower part of figure 7. As a result, even when there is frequency fluctuation of the railway noise, errors are not caused. Specifically, in this model, the same data was assigned to three carriers at 730 Hz intervals. In the conventional model, the same data was allocated to three adjacent carriers at 10 Hz intervals. We confirmed by computer simulation that the BER performance can be improved compared with the conventional allocation.
5. Review and evaluation of FPGA implementation

The foregoing sections describe a specific method of applying OFDM transmission to a railway signal system. We examined an implementation using FPGA for practical application to an ATC system. The computer simulation was performed using MATLAB/Simulink, so we decided to implement the FPGA based on this model. A description of the FPGA was generated from the model used in MATLAB/Simulink using the Hardware Description Language (HDL), as shown in figure 8. The FPGA was built in the FPGA development environment and was implemented in SRAM of the FPGA by USB using FPGA-in-the-loop simulation (FILS). The output was checked with a PC via USB.

The flow was as follows: The model was changed to generate HDL code from the MATLAB/Simulink model. For example, some MATLAB/Simulink programs were rewritten to programs corresponding to HDL code. In addition, it was necessary to consider implementation efficiency, such as conversion from floating point numbers to fixed point numbers. The block diagram is the same as in figure 5. The computer simulation specifications were the same as those in table 1.

Figure 9 shows the differences between the MATLAB/Simulink computer simulation model of the transmitter and the model implemented in FPGA. From figure 9, it was confirmed that the two outputs were equal since there were no differences between the MATLAB/Simulink computer simulation model and the FPGA implemented model. Likewise, an FPGA model was also created for the receiver. As a result of comparing the outputs of the MATLAB/Simulink computer simulation model of the receiver and the model implemented in FPGA, we confirmed that the two outputs were equal because there were no differences. Figure 10 shows the result of observing the spectrum of the analog signal of the FPGA model designed based on the above with an oscilloscope. As shown in figure 10, it was confirmed that the designed transmission band from 5.12 to 7.39 kHz appeared. In these results, we verified that the fundamental functions are realized in the developed OFDM transceiver using FPGA.

![Figure 7. Improved data allocation method.](image)

![Figure 8. Flow of FILS.](image)
6. Conclusion
We investigated a system for transmitting railway signals by OFDM and showed its basic composition. In addition, we also evaluated a BER performance improvement method that takes into account the nonuniformity of the BER characteristics between subcarriers. We showed that basic functions can be implemented in FPGA. In the future, the system will be installed in the FPGA of both the transmitting unit and the receiving unit. In the receiver, the analog signal from the transmitter is converted to a digital value by a digital to analog converter (DAC), and data is restored by the receiver model created by MATLAB/Simulink, thereby verifying a match with the data generated in the transmitter. We will consider introducing a mechanism for detecting the start time point of FFT at demodulation by inserting a guard interval in the transmitter. Specifically, as the number of IFFT points of the transmitting section, 576 points are transmitted by repeating the first 64 points as a guard interval after the original 512 points. The reception unit detects the start time point of the FFT by performing correlation processing.

In future works, we will attempt to employ a Reed-Solomon code and study the detailed allocation of this code to overcome the restriction of rail transmission characteristics. And we will conduct performance evaluation by actual field tests.

References
[1] T. Takashige, Japan Railway & Transport Review, 21, 44-50 (1999)
[2] R. Ishikawa, D. Koshino, H. Mochizuki, S. Takahashi, H. Nakamura, S. Nishida, M. Sano, WIT Transactions on The Built Environment, 114, 309-18 (2010)
[3] J. Wybo, Safety Science, 110(B), 268-75 (2018)
[4] H. Dong, B. Ning, B. Cai, Z. Hou, IEEE Circuits and Systems Magazine, 10(2), 6-18 (2010)
[5] N. Miyaguchi, D. Uchiyama, I. Inada, Y. Baba, N. Hiura, WIT Transactions on The Built Environment, 155, 175-83 (2015)
[6] M. Sneps-Sneppe, D. Namiot, 22nd Conference of Open Innovations Association (FRUCT) (2018)
[7] C. Sravani, M. Jagannath, K. Adalarasu, International Journal of Pure and Applied Mathematics, 118(18), 2185-94 (2018)
[8] I. Saiapina, M. Babaiev, O. Ananieva, 2nd International Scientific and Practical Conference “Energy-Optimal Technologies, Logistic and Safety on Transport” (2019)