Development of a Radio Communication System Simulator for Railway Applications

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Various radio communication systems are used in railway systems such as Communications Based Train Control (CBTC) systems, passenger information service systems, wireless sensor networks, etc. Designing or evaluating work to build radio communication systems used on railways is time consuming and expensive, given today's environment. Thus, as a contribution to this work, this paper describes the development of a simulation method to calculate transmission characteristics (receiving power, strength of interferences, bit error rates, flame loss rates, delays, etc.) with considering the railway-specific environment and usage. This paper describes features of the developed simulator and examples of simulation results.

Keywords: radio communication based train control, digital radio communication system, radio circuit design, simulation

1. Introduction

When introducing a radio communication system into railway operations and services, special care needs to be taken during the design and construction stage to reduce transmission errors and delays in order to ensure operational safety and stability. In particular, the propagation characteristics of radio waves, interferences and obstructions etc. along railway lines also have to be taken into account in the design of such systems, which requires expert knowledge about radio communication and significant effort. In addition, there are considerable costs involved in carrying out tests to probe the system performance and ensure it complies with the requirements specified in the related international standards such as IEC 62280, IEC 62773. Therefore, in an effort to reduce the cost and manpower required for design and testing, a system was developed that simulates data transmission characteristics (receiving power, strength of interferences, bit error rates, flame loss rates, delays, etc.) along a railway line. This paper describes simulation models, functions and input parameters of the simulator, and reports on simulation test results.

transmission control sub model” that corresponds to the data link layer of the OSI reference model (hereinafter called “L2”) contains error control functions, encryption functions, multiplex/de-multiplex functions. The “Wireless transmission line sub model” that corresponds to the physical layer in the OSI reference model (hereinafter called “L1”) contains modulation/demodulation functions and diversity functions. The “Radio propagation sub model”

Fig. 1 Outline of proposed basic simulation model

2. Simulation model

2.1 Basic idea for development of radio communication system simulator

Work has been conducted since 2007 on the development of a simulation system for radio communication systems for radio communication based train control systems [1]. A simulation model for railway application was already proposed, as shown in Fig. 1, in 2009 [2][3]. The 2009 simulation model is composed of three sub models, expressing the functions of lower layers below the second layer (data link layer) of the “Open Systems Interconnection (OSI) reference model” defined by the International Organization for Standardization (ISO). “The Wireless

Fig. 2 Detail of radio propagation sub model (L0)

that corresponds to the physical media (hereinafter called “L0”) contains functions to simulate radio wave propagation characteristics and the radio noise environment along railway lines (Fig. 2).

2.2 Radio propagation and noise simulation model

As shown in Fig.2, the “Radio propagation sub model” is a calculation model to simulate fluctuation in the strength of the desired signal, interferences caused by undesired signals, disturbance signals, and radio noise. The fluctuations in the strength of radio waves are calculated by combining well known probability-models [4][5][6] such as the path-loss model (Okumura-Hata model, Two-ray ground reflection model, etc.), the shadowing model (log-normal distribution model) and fading model (Nakagami-Rice distribution model).

In this model, Additive White Gaussian Noise (AWGN) is used as a radio noise source to simulate a drop in the Carrier to Interference and Noise Ratio (CINR) as in other radio communication simulations. However, in the railway environment, the power density of radio noise at the RF input port of a receiver varies with traction mode of a running train. Measuring tests performed on a running train, gave power density values of radio noise received on vehicles for each of the following operational modes: “Powering,” “Coasting,” “Braking,” and “Stopping.” Based on the measured results, a radio noise model for railway application was proposed, as shown in Fig.3.

Fig. 3 Proposed radio noise model for railway application

3. Development of the simulator

3.1 Implementation of the simulation model

The simulation model shown in Fig.2 was tested with a combination of three functions as shown in Fig.4. This simulator was given the name “RADTRACE.”

Initially when the simulator was tested in practice, the free open software “Scilab” was used for numerical computation, to program the functions in the sub models shown in Fig. 2. However, because of the generic nature of Scilab, large scale simulation execution was very time consuming. For example, around 120 days were needed to simulate the radio communication quality along a 27 km-long railway line.

Fig. 4 Structure of the simulator

Table 1 Input parameters for wireless transmission control sub model

Parameters	Settings or implemented models
Frame format	Any formats are settable (A frame format should be defined in external text file)
Error control	FCS (CRC-16, CRC-32) and RS (any coding rates are settable)
Cryptography	DES, 3DES

Table 2 Input parameters for wireless transmission line sub model

Parameters	Settings or implemented models
Modulation	BPSK, QPSK, $\pi/4$ DQPSK, 16QAM, 64QAM
Broad band modulation	None, Direct Spread Spectrum, OFDM
Data rate	Any rates are settable
Band limiting filter	Roll off filter (any roll-off rate value are settable)
Diversity	None, Selection combining, Maximal rate combining
Transmitter output power, RF distribution loss	Any values are settable

Table 3 Input parameters for radio propagation sub model

Parameters	Settings or implemented models
Carrier Frequency	Any frequency above 150 MHz can be for each base station and mobile station
Maximum Channel per 1 railway line	6 ch / line
Radio propagation model	Path-loss : Free space, Two-ray Ground Reflection Model, Hata-model, Egli's equation model Shadowing model : Log-normal distribution model Fading model : Nakagami-Rice model
Noise model	Constant AWGN model, Railway model
Delay profile	Given from data tables described in parameter files

○ Railway Line data file and Base Station data file

- Railway Line Alignment and Characteristics of radio propagation and noise at each position.
- Location of Base Stations, Direction of Antennae, Carrier Frequency, etc.

○ Train data file

Fig. 5 Input parameters for radio propagation sub model

Consequently, all the functions in the simulator were re-programmed using the standard programming language “C”, to improve calculation speed and remove the limit on simulation scale.

3.2 Input parameters for the simulator

All input parameters needed for the simulation were loaded into the simulator from text files (“Comma Separated Value” format). Tables 1, 2, 3 and Fig. 5 show the specific input parameters for each sub model described in section 2.

This simulator calculates the three dimensional positions of all base stations and on-board stations with the World Geodetic System 84 (WGS84) as shown in Fig. 5. The parameters for the shadowing model and the fading model could be set at any point along the railway line freely, to simulate site specific radio propagation characteristics. Evidently as well, the azimuth of the antenna off each base station and on-board station could be set to any direction. In addition, this simulator is able to accept data sets of measured radio propagation characteristics or those externally calculated by other radio propagation simulation methods (e.g. ray tracing method, ray launching method, etc.).

3.3 Output of the simulator

This simulator output the following calculation results for each position on the simulated railway line :

- Number of transmitted bits
- Number of error bits
- Number of corrected error bits
- Number of transmitted messages
- Number of correctly received messages
- Number of error detected messages
- Transmission delay time
- Received power of carrier wave (median value, 1 percentile, 99 percentile)
- Received power of noise and interferences

In addition, the simulator is capable to export internal calculation values (e.g. transmitted complex signals, received complex signals, etc.) generated in the simulator, to a text file.

4. Operational checks and verification of the simulator

To verify the developed simulator, the following checks were made:

- That all programmed functions were working, with no failures and that output results were correct.
- That the simulator was able to simulate performance of real radio equipment (e.g. comparison of calculated CNR-BER chart with real one).
- That the simulator was able to execute calculations on a large scale model comparable to a real railway line.
- Verification of the calculation errors in simulation results

Steps (a), (b), (c), have already been taken. The outcome of checks for step (b) appear in another paper [7]. This paper reports on some examples of the results for steps (a) and (c).

4.1 Checking and verification of L1 and L0 functions

This section describes the results from verification of the L1 model modulation/demodulation functions and functions to calculate strength of the carrier wave and radio noise in the L0 model.

Generally, digital modulation method Bit Error Rates (BER) depend on the Carrier power to Noise power Ratio (CNR). For example, Bit Error Rates on the QPSK (Quadrature Phase Shift Keying), $\pi/4$ shift QPSK and

16QAM (Quadrature Amplitude Modulation) are calculated by analytical equations (1), (2), (3) respectively.

QPSK

$$P_{e,QPSK} = \frac{1}{2} \operatorname{erfc} \left\{ \sqrt{\frac{\gamma_{CNR}}{2}} \right\} \quad (1)$$

$\pi/4$ shift QPSK

$$P_{e,\pi/4QPSK} = \operatorname{erfc} \left\{ \sqrt{\frac{\gamma_{CNR}}{2}} \right\} \left[1 - \frac{1}{2} \operatorname{erfc} \left\{ \sqrt{\frac{\gamma_{CNR}}{2}} \right\} \right] \quad (2)$$

16QAM

$$P_{e,16QAM} = \frac{3}{8} \operatorname{erfc} \left\{ \sqrt{\frac{\gamma_{CNR}}{10}} \right\} - \frac{9}{64} \operatorname{erfc}^2 \left\{ \sqrt{\frac{\gamma_{CNR}}{10}} \right\} \quad (3)$$

In (1), (2), (3), " γ_{CNR} " means average values of CNR, "erfc" means complementary error function shown as (4).

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt \quad (4)$$

Figure 6 shows the calculated results obtained by using the developed simulator. The theoretical values calculated using (1)-(4) are also shown with dotted lines in Fig. 6. Figure 6 also shows that the calculated results coincide with the theoretical values. This makes it possible to confirm that the modulator/demodulator function in the L1 model and functions to calculate strength of the carrier wave and radio noise in the L0 model work correctly.

4.2 Trial simulation on virtual railway line

This section reports on an example of the trial simulation results from a virtual railway line to demonstrate large scale simulation execution within a realistic calculation time. Figure 7 and Table 4 show the input parameters for a trial simulation. It was assumed that the length of the virtual railway line was 27 km with 9 base stations

Fig. 6 An example of comparison between calculated results and theoretical results

located along its length. It was also assumed that the virtual railway line ran from a metropolitan area to an urban area via an open area (viaduct area), and that the virtual train ran with a max speed of 100 km/h. The simulation results are shown in Fig. 8. Figure 8 reveals that transmission characteristics such as Frame Loss Rates (FLR), Bit Error Rates (BER) and receiving powers vary with train position and the propagation environment along the virtual railway line.

On this occasion the results shown in Fig. 8 were obtained in around 13 hours (calculator resources : Processor = Intel Xeon E5620, CPU Clock = 2.4 GHz, Memory = 64GB). This result means that it took around 0.006 – 0.012 second to simulate the transmission of 1 message. This confirms that large scale simulation can be performed in a realistic calculation time.

Table 4 Input parameters for the trial simulation

Parameters	Values
Length of railway line	27km
Number of base station	9 (planned stations) + 2 (sources of interference)
Calculation intervals in terms of train position	100m (total 271points)
Number of Transmitted message frames per 1 train position	2×10^4 (Ground → Train + Train → Ground) Total Bits = about 1.3×10^7
Error Correction	FCS-16 and RS
Modulation	$\pi/4$ shift QPSK
Data rate	9600bps
Diversity	Maximal Rate Combining
Career frequency	300MHz Band 4 ch x 2 (FDD)
Height of antennae	Base station =10m, Mobile station=5m
Radio propagation model	Fading model = Nakagami-Rice model (m=3dB ~ 12dB for each train position) Shadowing model = Log-normal distribution model (σ =0dB, 3dB, 6dB for each train position) Path loss model = Egli's equation model

Fig. 7 Configuration of virtual railway line for trial simulation

Fig. 8 An example of the trial simulation

5. Conclusion

A simulator was developed to support the design and performance evaluation of radio communication systems intended for use in a railway environment. This simulator calculates digital data transmission quality over radio communication systems deployed in railway systems, and takes into account wayside radio propagation characteristics and radio noise environment. The development project for this simulator was started to produce supporting simulation technology for the design and testing of radio communication systems used in train control systems. This paper shows simulation models and some examples of results of the verification and trial simulations. Hereafter, this simulator is planned to be used in practice for development projects for not only CBTC systems but also other radio communication systems. Evidently, verification test results will be used to improve the simulator. In addition, work will be pursued to develop the following:

- Optimization method for base station and channel allocation;

- Extension of the modulator/demodulator function to deal with future new radio communication technologies;
- Extension of the carrier frequency range to simulate millimeter waves.

Finally, research will continue to produce a total communication network simulator which is capable of simulating any kind of radio communication system used in a railway environment.

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