Analysis and Optimization of Real-time Performance of High-speed Train Communication Network

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Abstract. With the expansion of the scale of network system, the structure of high-speed railway train is more and more complex. The problems of real-time and reliability of network need to be solved. In this paper, aiming at the traditional train network communication mechanism, multi-objective particle swarm optimization algorithm is used to optimize the network design. The real-time performance of the network before and after optimization is simulated by OPNET. The experimental results show that the optimization algorithm in this paper can improve the real-time performance and reliability of the network.

Keywords: High speed train; Field bus; Real-time; Network optimization.

1. Introduction

The high-speed railway train is developing towards high-speed, intelligent and comfortable. Compared with the traditional train, the modern high-speed railway train communication network transmits more and more data types, and the amount of data is larger and larger. These data include train control information such as traction, braking, air conditioning, diagnosis information such as equipment fault information, maintenance information and voice video information such as station reporting. Therefore, modern high-speed railway train communication network should not only have the characteristics of strong real-time, high reliability and good security, but also have high communication rate and large data throughput capacity.

At present, many countries, for example, Germany, Japan and China have the configuration mode of coexistence of Ethernet and traditional train communication network, most of which use Ethernet to transmit the information of passenger information system, and also apply to program download, maintenance and detection, etc., which are mainly non real-time applications. Part of the trains use Ethernet to realize the data transmission of train operation. The data volume is small, the probability of collision is low, and the time delay is small. In reference [1] and [2], heterogeneous strategies are studied, and switched Ethernet is used to improve the real-time performance and compatibility of the network. Literature [3] and [4] discusses that the queuing theory can be used to analyze the average delay of information network.

However, traditional Ethernet can’t be directly applied in the field of industrial control, and there are two main defects in its communication mechanism: (1) The certainty and real time of communication network; (2) the reliability and stability of communication network. At present, the most widely used method to solve the problem of certainty and real-time in industrial applications is bus technology[5]. With the increase of network system scale and structure complexity, both analytical and simulation methods are faced with the problem of increasing computational complexity. The real-time performance of network refers to the limit of data transmission delay between two nodes. The main research methods include simulation method, queuing theory and network calculus. In the reliability analysis of real-time network system, connectivity and real-time need to be considered simultaneously[6]. Based on the theory of network calculus, this paper simulates the real-time performance of train communication network, aiming at analyzing and evaluating the real-time performance and reliability of the network, and providing the basis for the design and optimization of the system.
2. Structure of High Speed Railway Train Communication Network

The main purpose of topology design of train communication network is to control the whole train network. Train network control system is called Train Control and Management System (TCMS) in most trains. Taking the communication network of CRH1, CRH3 and CRH5 trains in China as an example, the system adopts "WTB + MVB" network as the train communication network[7]. Among them, train level bus WTB realizes train level operation control function, and vehicle level bus MVB realizes vehicle level bus control. Take CRH5 train as an example, TCMS is shown in Figure 1.

![Figure 1. Train Control and Management System](image1)

Figure 1. Train Control and Management System

The network is composed of train level bus WTB and vehicle level bus MVB, both of which use redundant media, and the protocol conversion between them is realized through the gateway located in the driver's cab at both ends of the train. The two cabs are respectively connected with the MPU (Main Processing Unit) serving as the overall control function of the train. Some models also call this equipment the CCU (Central Control Unit). CRH5 is divided into two power units as a whole: power unit No.1 consists of MC1, MH, TPB and T2 four cars; power unit No.2 consists of MC2, M2S, TP and M2 four cars. Each power unit is connected to each network node by an MVB bus running through four carriages. Each power unit has two pairs of MPUs, of which two MPU traction lines are mutually redundant to control all equipment on the signal bus such as traction and braking, while the other two passenger service lines are also mutually redundant to control air conditioning, door, toilet and other passenger services. The main functions of MPU include process data sending and receiving, logic judgment and processing, and fault diagnosis. The functional task period shall not exceed 100ms.

3. Network Communication Mechanism and Optimization

3.1. MVB Communication Mechanism

In MVB bus, a device has two address addressing, which are device address and port address[8]. The device address uniquely identifies the device, and each device has multiple port addresses. A port address can be configured as a source port or a destination port. MVB transmits message data according to device address, while port address is related to process data transmission. Each port address corresponds to a process data. In the same MVB bus, there can be multiple destination ports with the same address, but only one source port, that is, the same process data frame may be received by multiple devices. The master device broadcasts a master frame to the coincident device in the bus, which contains the device address to be polled. The slave device corresponding to the localization of the device will send a slave frame in 2-6us to respond to the master frame. The slave frame contains the message data information (or process data information) to be transmitted. Therefore, a message consists of a master frame and a slave frame, as shown in Figure 2, in which SB represents the frame start bit, ED represents the frame end bit, MSD and SSD represent the main frame start delimiter and slave frame start delimiter respectively.

![Figure 2. MVB message](image2)

MVB main equipment divides bus transmission time into fixed time slices of the same size. Each time slice is called BP (Basic Period). Generally, the basic period is 1ms. The basic period is composed of periodic phase, monitoring phase, event phase and protection phase. The periodic phase is used to send process data with strict requirements on time, while the monitoring phase, event phase and protection phase are aperiodic phase. The aperiodic phase is mainly used to transmit message data with low real-time requirements, as shown in Figure 3.
The sending of MVB message data is triggered by an event. The MVB main device will conduct an event tour to get the address of the device where all the message events collide. Since there may be multiple devices with message events suspended at the same time, the main device needs arbitration during the event tour. MVB message data is divided into high priority and low priority. Event tour is also divided into high priority event tour and low priority event tour. Only when the high priority event tour is completed and there are no pending high priority events, can the main device start the low priority event tour; when all the low priority message events returned from the tour are served, the main device will start the high priority event tour. There can only be one type of message data for each device on the bus. The w master can only poll high priority events, low priority events or both.

3.2. WTB Communication Mechanism

WTB communication mechanism is similar to MVB. A message consists of a main frame and a slave frame. The basic period of WTB is divided into periodic phase and asynchronous phase (accidental phase). The basic period is fixed at 25ms. In each basic period, the bus will poll one of the end nodes to check the integrity of train composition (such as train reduction or failure) and additional nodes (such as train addition). When the train composition changes, each node will inform the bus of the period to be polled, and the bus will establish a polling strategy based on this. Nodes with urgent process data can request that each basic period be polled, while nodes with non-urgent process data can request that each basic period be polled according to the characteristic period, a characteristic period is an integral multiple of the basic period. WTB process data communication process is similar to MVB. The bus first broadcasts a master frame to all devices, and the polled device responds to a slave frame, but the format of the master-slave frame of WTB and MVB is different, as shown in Figure 4. There is no message event arbitration process in message data communication process. If a device has message data to be sent, it will be set when sending process data frame or message data frame set a flag bit in the link control field to inform the bus that a message event has not been handled, and the bus will poll the device at the appropriate time after receiving it.

3.3. Optimization for Data Communication

Periodic scan table is an important basis for periodic polling of MVB and WTB buses, and its design will directly affect the operation performance of MVB and WTB. However, the gradient of periodic scan table generated by the basic rules defined in IEC 61375-1[9] is very large, the distribution of periodic variables is not uniform, and the impact of the timing of the report is not considered. In this section, multi-objective particle swarm optimization algorithm is used to optimize the design of periodic scan table.

According to the definition of IEC 61375-1, the range of basic period is \(1ms \leq T_{bp} \leq 2.5ms\), and the typical values are 1ms or 2ms. The longest characteristic period of bus periodic scanning is called macro period, which shall not exceed 1024 basic periods and 1024ms. A macro period consists of all periods in a macro period. Its duration is: if \(T_{bp} = 1ms\), it is 1024 basic periods; else if \(T_{bp} = 2ms\), it is 512 basic periods. Considering the periodic description set \(D\) which is composed of \(N\) periodic variables, for any period table, each periodic variable is defined as \(V_i = \{f_i, c_i, s_i\}, i \in \{1, 2, L, N\}, \quad c_i \in \{2^k\}, k \in \{0, 1, 2, L, 10\}\), where \(f_i, c_i, s_i\) represent the function code of the \(i^{th}\) period variable, the characteristic period and the basic number of the first
polling in a macro period. The function code determines the frame length. Macro period \( M = \max\{c_i\}, i \in \{1, 2, \ldots, N\} \). The periodic phase length of the \( i^{th} \) basic period of period table \( T \) is
\[
L_i^T = \sum_{j=1}^{N} g(i - s_j, c_j) t(f_j), \quad \text{where } g(x, c) = \begin{cases} 1, & x \geq 0, x \mod c = 0 \\ 0, & \text{else} \end{cases}
\]
The periodic phase length determines whether the periodic variable is polled in the \( i^{th} \) basic period, \( t(f) \) is the delay of message transmission corresponding to the corresponding function code. The longest periodic phase of period table \( T \) in a macro period is defined as \( L_{\text{max}} = \max\{L_i^T\}, i \in \{1, 2, \ldots, M\} \). The shortest periodic phase is defined as \( L_{\text{min}} = \min\{L_i^T\}, i \in \{1, 2, \ldots, M\} \). The difference between adjacent periodic phases of period table \( T \) is defined as \( S^T = \sum_{j=1}^{N} |L_{j+1}^T - L_j^T| \), where \( L_{M+1}^T = L_1^T \). The dissimilation degree of adjacent periodic phases in period table \( T \) is defined as \( Q^T = \frac{S^T}{M} \). Our objective optimization functions are as follows: (1) the longest periodic phase takes the smallest value \( L_{\text{max}} = \min\{L_i^T\}, T \in D \); (2) The shortest periodic phase takes the largest value \( L_{\text{min}} = \max\{L_i^T\}, T \in D \); (3) The maximum degree of dissimilation of adjacent periodic phases \( Q = \max\{Q^T\}, T \in D \). In this section, the multi-objective particle swarm optimization method in literature [10] and [11] is used to solve the model. Define priority weight as \( \lambda = [\lambda_1, \lambda_2], \lambda_1 \geq 0, \lambda_2 \geq 0, \lambda_1 + \lambda_2 = 1 \). Define utility function as
\[
\mu(T) = \lambda_1 \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} - L_{\text{min}}} + \lambda_2 \frac{Q^T - Q_{\text{min}}}{Q_{\text{max}} - Q_{\text{min}}},
\]
where \( L_{\text{min}} \) and \( L_{\text{max}} \) is the minimum and maximum \( L_i^T \) found by the algorithm respectively; \( Q_{\text{min}} \) and \( Q_{\text{max}} \) is the minimum and maximum \( Q^T \) found by the algorithm. The flow chart of the algorithm is shown in Figure 5.

![Figure 5. Flow chart of algorithm](image)

**Figure 5.** Flow chart of algorithm

The termination condition of the algorithm can run a certain algebra or the external swarm is not updated in the fixed algebra. At present, most of the multi-objective intelligent algorithms need to introduce external files or external swarms. The external swarms are not only used to retain the elite individuals in the process of algorithm execution, but also can guide the search direction of the algorithm and ensure the convergence of the algorithm.

4. Simulation and Result Analysis
We set up the network simulation project in OPNET, and use a server to realize the simulation test. The hardware of the server is configured as 8-core processor and 16g memory. We set the parameters of the simulation scene as shown in Table 1.
Table 1. Simulation parameters

| parameters     | value       |
|----------------|-------------|
| data interval  | 0.4ms       |
| period         | 1ms, 2ms    |
| transmission speed | 1.5Mbit/s |
| data length    | 33 bit + 296 bit |

Two groups of simulation experiments are carried out, with the basic period equal to 1ms and 2ms respectively. The time interval for data generation is set to 0.4ms, the data format supported by the bus is 33 bit master frame and 296 bit slave frame, the transmission rate is 1.5Mbit/s, and the simulation time is 500s. Other options are set by default. After running the simulation, the simulation results are shown in Figure 6 and Figure 7.

From the simulation results, it is obvious that our method can effectively reduce the network delay no matter the basic period is 1ms or 2ms by optimizing the communication mechanism.

5. Summary
With the development of modern communication technology, the communication network and control of high-speed railway train become more and more complex. How to solve the real-time and reliability is the main problem. At present, there are many related methods and technologies at home and abroad, but there are still many details to be studied in depth. The communication mechanism optimization method and related conclusions in this paper can provide system design reference for solving the above problems. It should be pointed out that in the real-time analysis of this paper, the fault recovery time of the equipment is not considered, but in the practical application, according to the setting of the timer, the fault recovery time using the fast spanning tree protocol is less than 2s. If the timer adjustment is not needed, the recovery time needs no more than 300ms. Some studies have shown that the time can be reduced to less than 100ms. The impact of this situation on network real-time needs further study in the future.

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References

[1] Carvajal G, Chun W, Fischmeister S. Evaluation of Communication Architectures for Switched Real-Time Ethernet[J]. IEEE Transactions on Computers, 2014, 63(1):218-229.

[2] Ashjaei M, Behnam M, Nolte T, et al. Performance analysis of master-slave multi-hop switched ethernet networks[C]. 2013 8th IEEE International Symposium on Industrial Embedded Systems, Porto, 2013:280-289.

[3] LIU Xian-Po. Study of Request Queue in P2P Networks System Based on the Queuing Theory[D]. Xi’an: Xidian University, 2008.

[4] Meng Kun. Research on Communication Network QoS Based on Queueing Theory[D]. Zhenjiang: Jiangsu University, 2008.

[5] NI Wen-bo, WANG Xue-mei. High speed train network and control technology[M]. Chen Du: Southwest Jiaotong University Press, 2010.

[6] ZHOU Jie-qiong. Real-time Communication Techniques of Train Communication Network Based on Switched Ethernet[D]. Beijing Jiaotong University, 2014.

[7] SHI Hong-mei. EMU control and management system[M]. Beijing: Beijing Jiaotong University Press, 2012.

[8] CHEN Jia-kai. Research on Optimization of Communication Mode on Train Communication Network and Reliability Analysis[D]. Zhejiang University, 2015.

[9] Train Communication Network, IEC 61375-1[S]. International Electrotechnical Committee, Geneva, 1999.

[10] Parsopoulos K E, Vrahatis M N. Particle Swarm Optimization method in Multi-objective problems[C]. Proceedings of the ACM Symposium on Applied Computing, 2002:603-607.

[11] LEI De-ming, WU Zhi-ming. Pareto Archive Multi-Objective Particle Swarm Optimization[J]. PR&AI, 2006, Vol.19(4):475-481.