Performance Analysis of Wireless Communication for High-speed Trains Based on SPN

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Abstract. The quality of service high-speed train wireless communication is very important for high-speed railway operation. Modeling and simulation is an effective method to formulate travel plans and improve operational efficiency. In this paper, the SPN is used to establish a wireless communication model of a high-speed train for normal communication states and several system fault recovery states. The parameters are obtained through calculation, and the model is simulated and analyzed using TimeNet. The simulation results show that under the parameters required by the specification, the normal working probability of wireless communication is close to 100%, and the probability of several kinds of failure recovery is more than 95%, which meets the high reliability requirements.

1. Introduction
The high-speed railway train control system is a complex system designed to ensure the safe operation of trains and to meet the transportation needs of different lines in a hierarchical form. It includes two parts: the on-board subsystem and the ground subsystem. Under the condition of mobile block, the Global System for Mobile Communications – Railway (GSM-R) is used for bidirectional information transmission between the on-board subsystem and the Radio Block Center (RBC). Its reliability is closely related to the security of the whole system. Under the condition of mobile block, during the operation of the train, the GSM-R carries a large number of traffic dispatching and operation services in the railway signal and control system. Its highly reliable quality of service (QoS) is crucial for high-speed railway operations. The railway wireless communication has high requirements for network reliability. With the continuous construction of high-speed railways, this requirement will become more obvious. Under the condition of highly trusted wireless communication, the multi-train tracking operation process is a spatiotemporal evolution process involving multiple factors such as communication, personnel, equipment, and environment. This process is a typical complex, multi-objective and nonlinear system. Complex systems are characterized by openness, uncertainty, and dynamics. It has the characteristics of complex hybrid dynamic systems such as discrete and continuous states coexisting, nonlinearity, and uncertainty. It is difficult to find accurate mathematical models and optimal solutions. Train operation model and solving technology is a very difficult task, and computer modeling and simulation method is a practical method to study this problem. By carrying out computer modeling and simulation research on the traffic flow operations in different line environments, it will provide theoretical basis for improving the safe operation efficiency of trains and formulating corresponding driving organization optimization and energy-saving operation schemes.

In recent years, many scholars have systematically studied the basic theory and applications of GSM-R by using UML state machines, Colored Petri Nets, Markov chain, and queuing theory. However,
with the increase of the traffic density and the gradual reduction of the tracking interval, the train traffic flow is becoming more and more complicated. It is very difficult to truly reflect the behavior of high-speed trains under complex conditions with traditional methods, especially not suitable for the fault tolerance of wireless communication and parallel processing of communication information.

At present, computer simulation of complex train traffic systems has been proven to be a powerful analysis method, and is being adopted by more and more researchers[9]. In order to solve the problem of low accuracy in the previous communication performance analysis, this paper studies the wireless communication performance of high-speed railway trains under complex conditions by using the method of SPN (Stochastic Petri Net). The SPN provides a good description method for the performance model of the system. The simulation technology can be used to solve the performance index of the model. The main advantage of this method is that the processing time of the workflow task can be arbitrary probability distribution, so it has higher accuracy and credibility compared with the existing methods.

2. Wireless Communication System Structure and Transmission QoS

Taking the wireless communication of the Chinese train control system as an example, the system schematic diagram is shown in Figure 1. It consists of several parts, such as BTS (Base Transceiver Station), BSC (Base Station Controller), MSC (Mobile Switching Center). BTS completes the communication and management functions between the communication network and the train; BSC is the control and management part of the base station subsystem. It is mainly responsible for wireless network management, monitoring of wireless resources, and wireless base stations. In addition, it also controls the establishment, persistence, and teardown of wireless connections between mobile stations and BTS; MSC implements basic switching functions in the network, and realizes the communication connection between the train and the RBC (Radio Block Center). RBC is a secure computer system that generates movement authorization information based on information from external signal systems (such as interlocking equipment) and train location and integrity reports exchanged with on-board equipment to ensure the jurisdiction of the train.

![Figure 1. Structure diagram of high-speed train wireless communication system](image)

The GSM-R system provides transparent data transmission channels in the application of train control systems. The QoS index proposed by the train control system for the transparent transmission channel provided by the GSM-R network is based on the unique security requirements and safe guards of the train control system itself, including the registration of the GSM-R network before entering the train control section, the connection establishment of the vehicle communication unit to the wireless blocking center, and the quality of data transmission[10]. At present, the QoS indicators for train control data transmission services are mainly determined by the connection establishment time, connection establishment failure probability, maximum end-to-end transmission delay, connection loss probability, transmission interference time, transmission recovery time, and network registration delay. Table 1 shows the QoS
indicators for GSM-R network data transmission services.

Table 1. QoS indicators for GSM-R network data transmission services

| Service Quality                          | Value                        |
|-----------------------------------------|------------------------------|
| connection establishment time           | ≤8.5 s (95%), ≤10 s (100%)   |
| connection establishment failure probability | ≤1%                          |
| maximum end-to-end transmission delay   | ≤0.5 s (99%)                 |
| connection loss probability             | ≤1% h                        |
| transmission interference time          | <0.8 s (95%), <1 s (99%)     |
| transmission recovery time              | >20 s (95%), >7 s (99%)      |

3. SPN Model of Wireless Communication System for High-speed Train

Due to the many random characteristics of wireless communication systems in practical applications, it is necessary to obtain the probability properties of the system in a stable state during analysis. The SPN can obtain the system's transition rate matrix on its reachability graph, thereby calculating the stability probability of each state of the continuous-time Markov chain isomorphic to the SPN. Therefore, SPN is very suitable for analyzing the performance indicators of the system[11,12].

SPN is based on the basic Petri net, and assigns a random delay time between the implementation of each transition. Its mathematical definition is a five tuple  \( SPN=(P,T;F,W,M_0,\lambda) \), Where  \( P \) represents the place,  \( T \) represents the transition,  \( F \) represents the arc,  \( W \) represents the weight,  \( M_0 \) represents the initial system identification, and the variable  \( \lambda \) represents the firing rate which reflects the average number per unit time in the case of implementation. The average implementation rate  \( t = \frac{1}{\lambda} \) is called the average implementation delay or service time of the transition  \( T \).

The SPN model of the high-speed train wireless communication system consists of the following two parts: normal communication model with random characteristics and system fault recovery model.

3.1. Normal Communication Model with Random Characteristics

The model in Figure 2 shows the normal communication state. In this model, the communication process from the transition  \( Send \) to the transition  \( RBCrev \) indicates that the train reports position information to the RBC, and the place  \( MSGVTR \) indicates the communication status of the position information. If there is a wireless communication failure in this process, the place  \( CONNECTED \) does not contain a token. The arcs of  \( RBCloss \) and  \( VCCloss \) connected to the place of  \( CONNECTED \), and the arcs of connecting the place of  \( NEWPRO \) and  \( Drop \) indicate the inhibitor arc. The inhibitor arc meets the transition activation conditions, and activate the fault handling transition  \( RBCloss \). Then, the transition  \( RBCloss \) writes communication fault information into the place of  \( RFault \), which is the mapping of the fault log, describes the event fault, and realizes the fault location representation of communication interruption and data transmission errors.

The communication process from the transition  \( RBCrev \) to the transition  \( VCCrev \) indicates that the RBC sends mobile authorization information to the train, and the place  \( MSGRTV \) indicates the communication status of the mobile authorization information. If a communication failure occurs in this process, the inhibitor arc also meets the transition activation conditions at this time, and the fault processing transition  \( VCCloss \) is activated. The transition  \( VCCloss \) writes communication fault information to the place  \( VFAULT \) to form a communication fault log.

The process from the transition of  \( VCCrev \) to the transition of  \( Drop \) is the emergency braking caused by the communication failure of the train. If the communication data packet is lost, a fail-safe principle should be adopted, and the train must take emergency braking measures. The place  \( NEWPRO \) describes the state of the train waiting for the RBC instruction. If RBC data packet loss occurs at this time, the token in the place  \( NEWPRO \) activates the transition  \( Overtime \). High-speed trains run at non-uniform speed during the emergency braking operation. To simplify the calculations, it is assumed that the train braking deceleration is constant  \( a_{max} \) and the train emergency braking time is  \( t = \frac{V_f - V_0}{a_{max}} + t_s \), Where
\( t \) is the emergency braking time, \( v_f \) is the braking termination speed, \( v_0 \) is the initial braking speed, and \( t_s \) indicates the idling time of the emergency braking. The transition \( \text{Drop} \) writes emergency braking fault information into the place \( \text{PFault} \) to generate an emergency braking fault log, thereby realizing the expression of emergency braking fault location.

**Figure 2.** Model of normal communication

**Figure 3.** Model of communication recovery

### 3.2 System Fault Recovery Model

The establishment of wireless communication SPN model is mainly considered from the perspective of the QoS and fault recovery, so as to realize the simulation evaluation analysis of wireless communication system. The train and RBC are usually in a normal communication state, but there are many factors that cause wireless communication failures such as transmission errors, connection losses and handover.

Figure 3 is a SPN model of communication recovery model, where the transition \( \text{Disconnect} \) indicates that the link was disconnected when a failure occurred, and the place \( \text{Disconnected} \) indicates that the wireless communication is disconnected at this time. The process from the transition \( \text{Reqr} \) to \( \text{Resp} \) indicates an attempt to re-establish a link, and the place \( \text{Connected} \) indicates a return to the normal wireless communication. The transition \( \text{AUError} \) indicates that the connection re-establishment failed. The exponential distribution transition Disconnect indicates that the wireless communication connection is lost and failed. According to the GSM-R network train control communication technology specifications in table 1, GSM-R communication connection loss probability is a small probability event with a
value $\leq 10^{-2}/h$, that means $\lambda_2 = \frac{10^{-2}}{60 \times 60} = 2.7778 \times 10^{-6} / s$. The transition *Disconnect* can also monitor the time required for communication data loss in the GSM-R. This time is deterministic, and the specification requires that the time is not greater than 1 second, taking $t = 1s$. The exponential distribution transition *Loss* indicates the time required for successful re-establishment after the GSM-R communication connection is lost. According to the GSM-R train control transmission service QoS indicator requirements, the corresponding time requirement from the initiation of the data connection request to the correct reception of the link response is $<8.5s$ (95%), $\leq 10s$ (100%). In order to improve the simulation accuracy, according to the definition, it can be known that the shorter the duration of the request-response process, the better. Therefore, when the model is established, the best response period is 8.5s (95%). In parameter assignment, according to the exponential distribution function $F(x, \lambda) = 1 - e^{-\lambda x}$ ($x \geq 0$), So $\lambda_3 = \frac{- \ln(1-0.95)}{8.5} = 0.3524$.

According to the GSM-R network train control communication technical specifications in table 1, the deterministic transition *Reqr* requires that the probability of end-to-end call connection setup time not to exceed 7.5s is 99%, and the simulation takes execution time $t = 7.5s$.

Transmission errors refer to data transmission failures that occur due to the interference of communication conditions and other factors. The measure adopted for this type of error is to repeat the last error operation for a short time. The transmission error model is shown in Figure 4.

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**Figure 4.** Model of transmission errors

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**Figure 5.** Model of handover

Exponential distribution transition *TError* indicates the transmission error condition, the transmission error probability conforms to the exponential distribution law, and the QoS index in table 1 requires the
transmission recovery period $T_{\text{Error}} > 20s$ (95%), $T_{\text{Error}} > 7s$ (99%). In order to improve the simulation accuracy, according to the definition, it is known that the longer the error-free recovery process is, the better. Therefore, when the model is established, the best recovery period is 20s (95%), and the exponential distribution parameters are obtained as $\lambda_5 = \frac{-\ln(1-0.95)}{20} = 0.1498$. Exponential distribution transition $T_{\text{Recover}}$ indicates the error recovery situation. According to the QoS, the period of transmission interference required is $T_{\text{Recover}} < 0.8s$ (95%), $T_{\text{Recover}} < 1s$ (99%). In order to improve the simulation accuracy, according to the definition, it is known that the shorter the duration of the error interference process is, the better. Therefore, when the model is established, the best parameter is 0.8s (95%), and $\lambda_1 = \frac{-\ln(1-0.95)}{0.8} = 3.7447$.

When a train passes an adjacent base station, a handover communication control handover occurs. A handover is an inevitable event that a train runs at high speed under the control of a GSM-R communication system. The SPN model of handover is shown in Figure 5.

In Figure 5, the transition $\text{Str}$ indicates the communication state before the handover. For simplicity, let's set the distance between base stations to 30km and the speed of the train to 300km/h, then the time distribution is $t = \frac{30 \times 0 \times 60}{300} = 360s$. The deterministic transition $\text{Reconnect}$ indicates the time parameter required for re-establishment of the handover. According to the GSM-R technical specifications in table 1, it is known that the maximum time for communication interruption in the handoff is 0.5s. The deterministic transition $\text{Reconnect}$ indicates a fixed time delay. Exponential distribution transition $HPro$ is an end-to-end communication and information processing process with delay characteristics. According to the QoS index requirement, in the GSM-R communication system, the maximum end-to-end delay is $\leq 0.5s$ (99%). The end-to-end delay obey the exponential distribution law, and the value is $\lambda_5 = \frac{-\ln(1-0.99)}{0.5} = 9.2103$. The transition $CHerror$ indicates a channel failure event, and the transition $CHrec$ indicates a channel repair event. According to the parameters in the specification, $\lambda_6 = 0.000002778$, $\lambda_7 = 0.001667$.

4. Simulation and Results Analysis
We performed simulation tests on the above models in TimeNet[13]. TimeNET is developed by the performance evaluation team of Berlin University of science and technology [14,15], based on SPNExpress and GreatSPN. The original TimeNET is the optimization of SPNExpress software, which includes all components of the current version of SPN, and supports the modeling description of extended deterministic and SPN, in which the transitions can be constant, uniform distribution, triangular distribution, etc. According to different types of Petri Nets, TimeNET also integrates several different algorithms to analyze SPN.

The TimeNet provides a visual description of the Probability Density Function curve description, as well as statistics of various network composition elements, Petri net compilation and numerical calculation. After designing the system model, we set attribute values and weights for each transition and place according to the above parameter analysis, and perform system inspection, verification, and evaluation. TimeNET is composed of basic network elements, including place, transition, arc, and text. The transitions can be divided into exponential transition, immediate transition, deterministic transition, and general transition according to the type of activation time function.

The TimeNet definition uses a special syntax. A performance calculation can include numbers, flags, and delay parameters, algebraic operators, and the following basic calculations:
- $P \{<\text{logic} \_\text{condition}>\}$: indicates the probability of the corresponding logic_condition;
- $P \{<\text{logic} \_\text{condition}> \text{IF} <\text{logic} \_\text{condition2}>\}$: Calculate the probability of logic_condition1 occurring under the conditions where logic_condition2 occurs;
- $E \{<\text{marc} \_\text{func}>\}$: represents the value of the expression marc_func related to the mark;
We implemented a simulation test in a server. The server hardware was configured with an 8-core processor and 16G memory, and a dynamic transient simulation method was used. The simulation time is set to 60s. Table 2 lists the simulation conditions of the network parameters.

**Table 2. Simulation conditions of the network parameters**

| parameter          | value  |
|--------------------|--------|
| network bandwidth  | 1Gb/s  |
| request service times | 1000   |
| communication cycle | 200ms  |
| length of the data | 256bit |

Figure 6 reflects the probability curve of the GSM-R network status in the normal communication model. It can be seen that during simulation, the probability of normal operation is close to 100%.

**Figure 6. Normal communication probability curve**

Figure 7 reflects the execution probability of the place $\text{TRP}$ in the transmission error model. It can be seen from the simulation curve that when the end time $t = 60s$, the average $\text{TRP}$ probability is 0.0027, which means the average probability of communication transmission error is 0.0027.

**Figure 7. Communication transmission error probability curve**

Figure 8 reflects the execution probability of the place $\text{CONNECTED}$ in the handover model. It can be seen from the simulation curve that the probability that the system can normally complete the handover is greater than 95% during the process.
From figures 6, 7 and 8, it can be seen that the deviation between the simulation results based on SPN model and the values measured in the actual system is very small, which can prove that our method has good accuracy.

5. Conclusion
The high-speed train wireless communication system is a complex dynamic system combining network and control. With the continuous development of modern communication technology, how to resolve the contradiction between reliability, security and efficiency is the main problem in this field. In this paper, the performance of high-speed train wireless communication is simulated and analyzed by using SPN. It should be pointed out that this paper only studies the QoS index of train control data transmission service in GSM-R network, and there are more relevant indexes to be considered in the follow-up study. In addition, in the modeling of system SPN, only the time-dependent characteristics are reflected, and the hierarchical modeling characteristics and model extensibility are lacked, which are the parts that need to be improved in the future research.

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**Figure 8. Handover success probability curve**

From figures 6, 7 and 8, it can be seen that the deviation between the simulation results based on SPN model and the values measured in the actual system is very small, which can prove that our method has good accuracy.
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