A Novel GSPN Based Interconnection Model for 5 G and CAN Heterogeneous Networks

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A Novel GSPN based Interconnection Model for 5G and CAN Heterogeneous Networks

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Abstract

The most existing interconnection schemes among the wired/wireless networks cannot be directly employed to the interconnection among 5G and wired industrial networks. This paper aims to investigate how to achieve the effective interconnection and modeling between 5G and controller area network (CAN). Firstly, a data priority classification scheduling algorithm is proposed to solve the scheduling problem of protocol conversion between 5G and CAN. Secondly, considering random and instantaneous transition characteristics of 5G and CAN networks, a reliable interconnection model is established by using the generalized stochastic Petri net (GSPN) method. Thirdly, QoS key indicators and the corresponding measurement method are proposed by considering different types of data. Finally, simulation and real experiments are conducted to confirm the feasibility and effectiveness of the established model.

Keywords: 5G, CAN, heterogeneous network, generalized stochastic Petri net, QoS evaluation indicators

1 Introduction

During the last decade, 5G communication technology has been rapidly developed and gradually integrated with the existing wired networks in industry to form heterogeneous networks for different applications [1], [2], [3], [4]. The integration of 5G with established protocols like CAN presents significant challenges due to their distinct operational paradigms. CAN has been extensively utilized in automotive and industrial control systems. Its message-oriented protocol is specifically designed to ensure real-time communication within environments with strict resource limitations. In contrast, 5G offers high data rates, low latency, and broad connectivity, but is fundamentally different from CAN in design. Traditional bridging techniques used to connect such disparate networks often suffer from high latency and limited scalability, failing to meet the stringent Quality of Service (QoS) requirements. To address these challenges, it is essential to develop effective interconnection frameworks and data management strategies that harmonize the capabilities of both 5G and CAN, ensuring seamless communication and optimal network performance [5]. Apart from CAN, other wired networks in industry include DeviceNet, ControlNet, ModBus, ProfiBus and Industrial Ethernet. To inytegrate these networks in industry requires the protocol conversion and interconnection modelling, which is a research topic attracted the attention of both academic and industry communities [6]-[8].

Up to now, a number of protocol conversion methods have been developed for the interconnection of different networks, e.g., a protocol conversion method was proposed to achieve data transmission between Profinet and Modbus to monitor industrial production process [9]. A distributed DMGB algorithm using the SINR model was proposed to achieve efficient global broadcast in dynamic multi-hop wireless networks, ensuring stability and bounded latency for continuously injected packets [10]. A Smart Collaborative Evolvement scheme for Virtual Group Creation was proposed to address customized industrial IoT requirements, utilizing a probabilistic model and spatio-temporal relationship maps to enhance performance in various scenarios [11]. A multi protocol conversion gateway based on IPv6 was created to realize the communication among ZigBee, Wi-Fi and Bluetooth [12]. A protocol conversion routing framework across multiple wireless Internet of Things platforms was proposed to achieve multiple protocol conversion [13]. However, with many potential applications of new 5G technology in industry, it is urgent to study the interconnection issue between 5G network and the existing wired networks in industry.

In general, the interconnection model is required to be established for heterogeneous networks. For instance, a network trusted interconnection model was created to achieve reliable interconnection [14]. A network node trust measurement model was developed to ensure the reliable interconnection of network nodes [15]. A protocol conversion model between IEC 61850 and Modbus was used to reduce the delay of data transmission [16]. A hybrid cellular information network and its protocol model were proposed to achieve communication between different network protocols [17]. A dynamic system model of filtering error was deployed to improve transmission performance of wired/wireless heterogeneous network [18, 19].

Moreover, a proxy model of IEEE 802.11ah heterogeneous network was proposed to predict the restricted access window (RAW) performance [20]. A local dynamic model using the SINR model was proposed to achieve distributed broadcasting in dynamic networks, with a randomized algorithm ensuring asymptotically optimal running time and high probability, accommodating localized topological changes [21]. A large-scale Multiple-Input Multiple-Output (MIMO) heterogeneous network model was proposed to confirm that the designed uplink caching can improve network performance [22]. It is clear that all the work mentioned above were mainly focused on the establishment of the interconnection model of some heterogeneous networks without 5G technology. When heterogeneous networks contain 5G devices, the corresponding interconnection model will be different. Therefore, it is necessary to investigate how to build the appropriate interconnection model for heterogeneous networks with 5G.

After the establishment of interconnection model for heterogeneous networks with 5G, it is necessary to study the key indicators and measurement methods of Quality of Service, such as transmission delay, and data packet loss rate are investigated [23]-[26]. The QoS indicators such as unit load, number of users and user throughput were developed for large heterogeneous wireless cellular networks, [27]. The QoS indicators of LoRaWAN network inlude bit error rate and signal-to-noise ratio [28]. The performance of LoRaWAN and NBIoT was compared according to field measurements [29]. Furthermore, a performance evaluation method was developed for wireless LAN devices to measure the entire throughput without special receiving requirements of user equipment [30]. A MIMO measurement method was created by using a low-cost and efficient single probe[31].

Table I shows a summary of some existing works described above. As can be seen, the existing methods have only solved part of the problems of interconnection modeling and protocol transformation scheduling,

Table 1 Comparative Analysis between the Contributions of This Article and the Existing Results in the Literature

Article	WWl[1]	WWi[2]	Ms[3]	Md[4]	QoS	QoSc[5]
[9]	✗	✗	✔	✗	✔	✗
[12],[13]	✗	✔	✔	✗	✔	✗
[17]	✗	✔	✔	✗	✗	✗
[20],[22]	✗	✗	✔	✗	✔	✗
[23]-[27],[29]-[31]	✗	✔	✗	✗	✔	✗
This paper	✔	✔	✔	✔	✔	✔

[1]between Wired and 5G wireless network
[2]between Wired and Wired network
[3]Modeling at same level
[4]Modeling at different level
[5]QoS considering different characteristics of data

Motivated by the above observations, this paper aims to create a new interconnection model for 5G and CAN, as well as its corresponding performance evaluation. Specifically, the following challenges and difficulties will be addressed:

- In the industrial Internet of Things application scenario, it is often necessary to connect and communicate among 5G devices and other smart devices with field-bus network. The first challenge is how to schedule 5G and CAN protocol conversion to guarantee communication quality of data transmission.
- By modeling 5G and CAN networks, the interaction and impact can be simulated to provide decision support for optimizing network performance and resource allocation. The second challenge is how to establish a reliable interconnection model between 5G and CAN.
- The existing performance evaluation methods do not consider network resource utilization, which are unsuitable for the limited channel resources and high real-time environments. How to establish the QoS evaluation indicators and measurement methods of heterogeneous network is the third challenge.

To deal with these challenges, a new interconnection model of 5G and CAN is investigated in this paper. It can generate a comprehensive solution for GSPN modeling and priority scheduling, providing good QoS performance to satisfy the requirements of real-time transmission and reliability. The contributions of the paper can be summarised below.

- A protocol conversion method based on protocol mapping is proposed to achieve network interconnection between 5G and CAN.
- By modeling heterogeneous networks with 5G and CAN, its interaction and impact can be simulated to provide decision support for optimizing network performance and resource allocation. The second challenge is how to establish a reliable interconnection model between 5G and CAN.
- A CAN end node and the protocol conversion gateway between 5G and CAN are designed, and a software and hardware experiment platform is built to test their effectiveness and real-time performance.

The rest of this paper is organized as follows. Section 2 presents a problem formulation of 5G and CAN interconnection. In Section 3, the interconnection modeling and QoS of 5G and CAN is proposed, including scheduling algorithm based on priority classification and GSPN modeling. Experiments are conducted in Section 4 to demonstrate the feasibility and performance of the proposed approach for 5G and CAN. Finally, a brief conclusion and future research are described in Section 5.

2 PROBLEM FORMULATION

2.1 Heterogeneous Integration of 5G and the existing networks

Fig. 1 shows the heterogeneous integration of 5G and the existing industrial measurement and control networks, where the whole heterogeneous network can be divided into three levels, namely perception layer, network layer and application layer.

- The perception layer collects processes and transmits the attribute information of the perception object through the data collector and controller that are directly bound to or connected with the object.

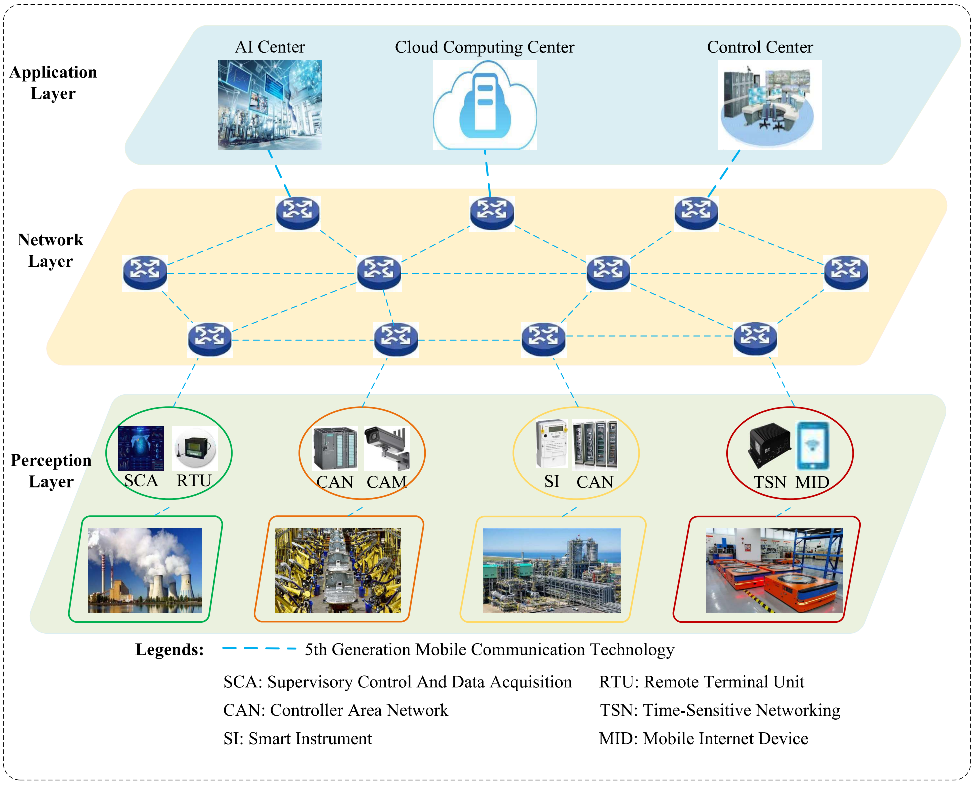

Fig. 1 Heterogeneous Integration of 5G and the existing Industrial Measurement and Control Networks.

- The network layer mainly uses wireless transmission to provide communication support for 5G fully connected factories, and smart gateways connect wired networks with wireless networks. It can transmit perceived information with high reliability and high security, and realize more extensive interconnection functions.
- The application layer serves as a connecting link to process perceptual data, form various industrial Internet services to meet the needs, and serve users through the human-computer interaction platform.

2.2 Problem Analysis of Heterogeneous Network Interconnection

Due to different protocols, 5G network cannot directly communicate with the existing industrial measurement and control networks. To achieve such an interconnection, the following problems need be addressed:

(1) Scheduling of data transmission – The existing industrial network scheduling methods focus on the link scheduling of multiple channels with the same protocol, which

do not consider the link scheduling between different protocols under the condition of the limited channel resources. However, for heterogeneous network with high real-time requirement, a large amount of data will cause network congestion. Therefore, it is necessary to study protocol conversion scheduling algorithm for 5G and CAN heterogeneous network.

(2) Interconnection model for 5G and CAN heterogeneous network – The existing industrial network interconnection model focuses on the interconnection between the wired network at the same level, which does not consider the random and instantaneous transfer characteristics of different production factors in 5G and CAN network system. However, for heterogeneous networks, it is difficult to achieve interconnection and interoperability when data are transmitted at different levels and across regions. Therefore, it is necessary to study the modelling problem of reliable interconnection for 5G and CAN heterogeneous network.

(3) Performance evaluation for 5G and CAN heterogeneous network – The existing performance evaluation usually does not consider different real-time requirements of production factors and different safety priorities during the manufacturing process. Therefore, according to different characteristics of management data and measurement and control data generated at different levels during the manufacturing process, the related QoS performance evaluation indicators and measurement methods need be investigated.

3 Reliability Analysis of 5G and CAN Interconnection

The above has presented the framework of 5G and the existing CAN network and analysed the corresponding problems. To solve these problems, a new 5G and CAN interconnection scheme is firstly presented.

3.1 Interconnection of 5G and CAN

According to different characteristics of the generated data during the manufacturing process, its hierarchical data transmission and protocol conversion scheduling algorithm should be investigated.

3.1.1 Protocol conversion scheduling

In the manufacturing process, different types of data flows have inherent priority characteristics based on their real-time and importance requirements. To ensure effective protocol conversion and data scheduling between 5G and CAN networks, this research introduces a priority-based classification method. Specifically, manufacturing data are categorized into four types: safety data, control data, monitoring data, and maintenance data. Data are scheduled for protocol conversion based on these priority levels to ensure timely transmission of high-priority data, thereby maintaining the system's real-time performance and reliability.

3.1.2 GSPN modeling

The reliable interconnection model for 5G and CAN heterogeneous networks is established based on the GSPN method, and the model validity will be verified by the structural analysis. The incidence matrix of the model is analyzed to represent the structural relationships between places and transitions within the GSPN model. This matrix plays a crucial role in understanding the flow of tokens across different states and identifying any potential structural issues. From this incidence matrix, the P-invariants are calculated, which are vectors that describe the distribution of tokens among various places. These P-invariants help ensure that certain properties, such as the conservation of tokens, remain consistent throughout the system's operation, thereby confirming the model's structural integrity and reliability. Additionally, the reach-ability graph is generated to explore all possible states and transitions within the model, further validating its robustness and ensuring there are no deadlocks or unreachable states. Finally, the structural characteristic of the model is analyzed by combining the reach-ability graph of the model. The whole GSPN model will be analysed in Section 3.3.

3.2 Protocol Conversion Scheduling for 5G and CAN

A data priority classification scheduling algorithm is proposed to optimize data transmission across 5G and CAN networks, which is based on prioritizing packets based on their urgency and importance. The algorithm begins by classifying incoming industrial data into four categories according to their real-time requirements: Class 1: safety for emergency actions with the highest real-time requirement, typically within 10ms, used for high-speed motion control; Class 2: control for data with high real-time requirements, ranging from 10ms to 1000ms, used for controlled plant operations; Class 3: monitoring for non-emergency alarms and general monitoring data without strict real-time requirements; and Class 4: maintenance for recording and downloading/uploading with the least time sensitivity. Fig. 2 shows the classification of industrial data.

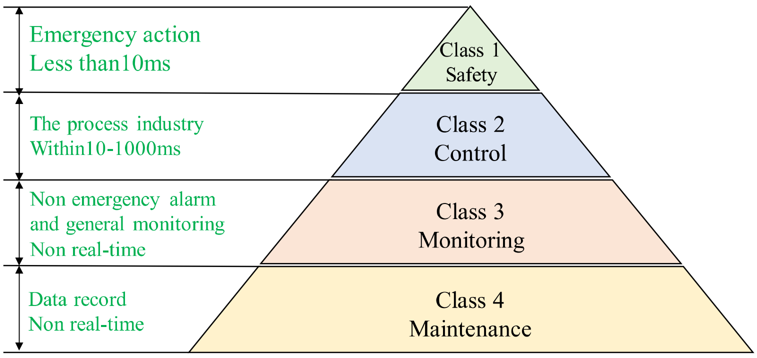

Fig. 2 Industrial Data Classification.

Once classified, the packets are placed into corresponding priority queues, where high-priority packets, particularly those in Class 1 and Class 2, are processed first. The algorithm employs a dynamic scheduling mechanism that allocates time slots to each queue, adjusting them in real-time based on current network conditions to minimize delays for critical data. This scheduling mechanism continuously monitors network traffic, dynamically adjusting time slot allocations based on the volume and priority of incoming data. For instance, during periods of high network load, more time slots are allocated to high-priority queues, ensuring that urgent data is transmitted promptly while managing lower-priority traffic within available bandwidth.

Additionally, traffic shaping and bandwidth allocation strategies are implemented to optimize network performance, whose bandwidth dynamically allocated based on current load and priority levels to minimize latency for high-priority streams while throttling lower-priority streams to prevent congestion and maintain network stability. The algorithm also includes robust error handling and re-transmission protocols, ensuring that any high-priority packets encountering transmission errors are immediately re-queued and prioritized for re-transmission in the next available time slot, guaranteeing reliable delivery of critical data even in the face of network disruptions. This integrated approach effectively balances the need for timely transmission of high-priority data with overall network stability, ensuring efficient and reliable communication across heterogeneous 5G and CAN networks.

Algorithm 1 shows the scheduling algorithm of 5G and CAN Protocol Conversion, which is based on priority classification. It assumes that there are n end-to-end data flows in 5G and CAN heterogeneous network. They are expressed as $S[n] = \{\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_n\}$. There are K different priorities $\mathcal{P} = \{C_1, C_2, \ldots, C_k\}$. Each type of priority can contain more than one end-to-end data flow. However, one data flow has and only has one priority. If the priority classification conditions $1 \leq C_j \leq K$ are met, the priority $\mathcal{F}_i$ of data flow is $C_j \in C$. The lower C_j means higher priority, which means that the corresponding data flow is more important. During the priority-based scheduling process, when there is a conflict between data flows with different priorities competing for the same channel, the channel resources will be allocated to data flows with higher priority.

The protocol conversion scheduling based on priority can quickly respond to high-priority data so that it can be processed as soon as possible. In the protocol conversion scheduling based on the fixed priority, each data has a priority, which can ensure that each data has a fair chance to be processed. Moreover, the fixed priority based protocol conversion scheduling can flexibly configure the priority of each data based on specific application requirements, achieving reasonably scheduling.

3.3 Analysis of 5G and CAN Model

The 5G network supports full duplex and the separation of up-link or down-link transmission in the frequency/time domain. Whether it is full duplex or half duplex mode, 5G has a unified frame structure. Therefore, the 5G node is regarded as an equivalent node in Heterogeneous Network Generalized Stochastic Petri Net (HN-GSPN) model. If there are n CAN nodes, these nodes are numbered from high to low based on the

Algorithm 1: Scheduling Algorithm of 5G and CAN Protocol Conversion Based on Priority Classification

Data: Data flow set $S[n] = \{\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_n\}$
Result: Data flow $\mathcal{F}_i$
if *the number of channels = 0* **then**
  Current link is not schedulable
end
if *data stream arrival time is consistent and channel is not occupied* **then**
  Current link is not schedulable
end
if *F[i].priority >max-priority* **then**
  max-priority = $\mathcal{F}[i]$. priority
end

priority of the sent data. All CAN nodes can be divided into four equivalent nodes of different types based on the data priority.

3.3.1 GSPN model definition

HN-GSPN is defined as a 7-tuple, i.e., HN-GSPN= $(P, T, F, W_{PR}, W_{PO}, M_0, \lambda)$, where $P = \{p_1, p_2, \ldots, p_m\}$ is a finite set of places representing all possible states in the model, T is a finite set of transitions, consisting of two disjoint sets $T = T_t \cup T_i$ with $T_t \cap T_i = \emptyset$, $T_t = \{t_1, t_2, \ldots, t_k\}$ is a finite set of timed transitions corresponding to the firing rates $\lambda = \{\lambda_1, \lambda_2, \ldots, \lambda_k\}$, and $T_i = \{t_{k+1}, t_{k+2}, \ldots, t_n\}$ is a finite set of immediate transitions; F (i.e., $F \subseteq (P \times T) \cup (T \times P)$) is a finite set of directed arcs between places and transitions, indicating the flow relationships within the model, and inhibition arcs are allowed in F but only exist from places to transitions; W_{PO} and W_{PR} are the post and pre incidence matrices; M_0 is the initial marking, $M_0 : P \to \mathbb{Z}$.

3.3.2 CAN to 5G up-link model

According to the task and working process of each node in the CAN to 5G up-link model, the up-link GSPN model can be described by Fig. 3. The model is divided into three modules, module 1 represents the CAN, module 2 represents the smart gateway, and module 3 represents the 5G equivalent node. The CAN to 5G up-link model includes 19 state places, 4 instantaneous transitions and 13 exponential time transitions $\{T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, T_{13}, T_{14}, T_{15}, T_{16}, T_{17}\}$ with the firing rates $\{\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8, \lambda_{13}, \lambda_{14}, \lambda_{15}, \lambda_{16}, \lambda_{17}\}$. If data process conforms to the negative exponential distribution with the mean value of $\lambda_i\ (i = 1, 2, \ldots, n)$, the unit is packets/sec. Note that the value of λ_i depends on real situation.

In Fig. 3, P_1 represents hybrid dataset, P_2 represents Class 1 dataset, P_3 represents Class 2 dataset, P_4 represents Class 3 dataset, and P_5 represents Class 4 dataset. As each node has at most one data to be sent at any instant, the places P_7, P_9, P_{11}, P_{13} are introduced to describe the queue length of data sets with different priorities, and

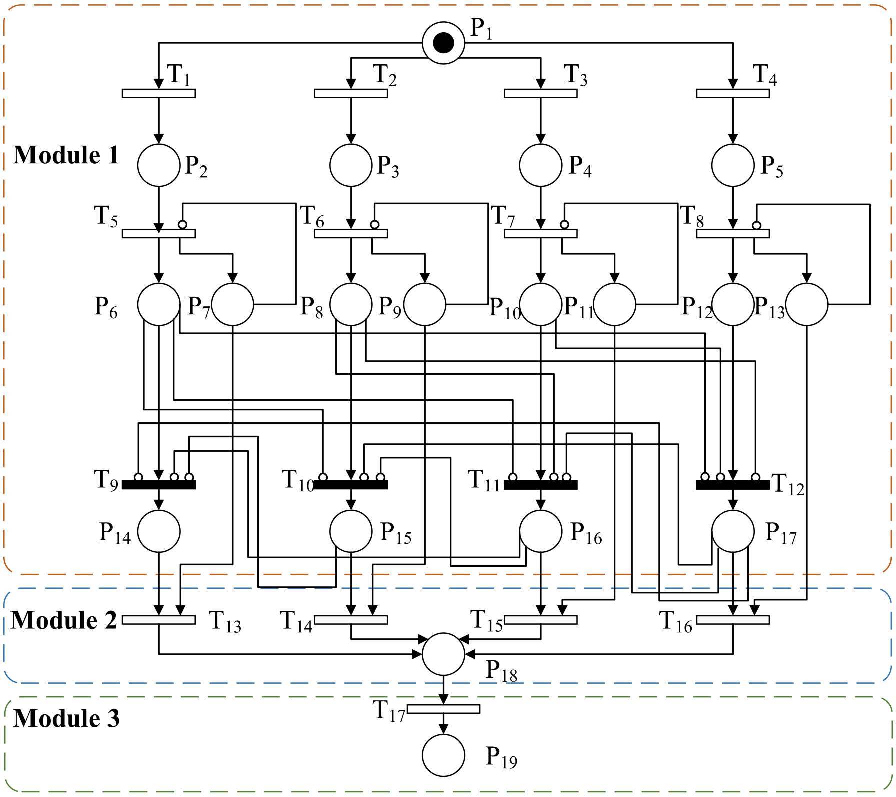

Fig. 3 CAN to 5G up-link model

the exponential time transitions $T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8$ represent data with different priorities. The places P_6, P_8, P_{10}, P_{12} represent the generated data with different priorities.

The transient transitions $T_9, T_{10}, T_{11}, T_{12}$ represent the arbitration process from the process of data with different priorities to the sending of data on the bus. The places $P_{14}, P_{15}, P_{16}, P_{17}$ represent the data to be sent on the bus after arbitration. The exponential time transitions $T_{13}, T_{14}, T_{15}, T_{16}$ indicate that the data of different priorities are transmitted to smart gateway through the bus, P_{18} indicates smart gateway, T_{17} indicates that data is transmitted to 5G node through 5G network, and P_{19} indicates 5G node.

3.3.3 5G to CAN down-link model

According to the tasks and working process of each node in 5G to CAN down-link, the down-link model can be described by Fig. 4. The model is divided into three modules, module 1 represents 5G equivalent node, module 2 represents smart gateway and module 3 represents the CAN. HN-GSPN down-link

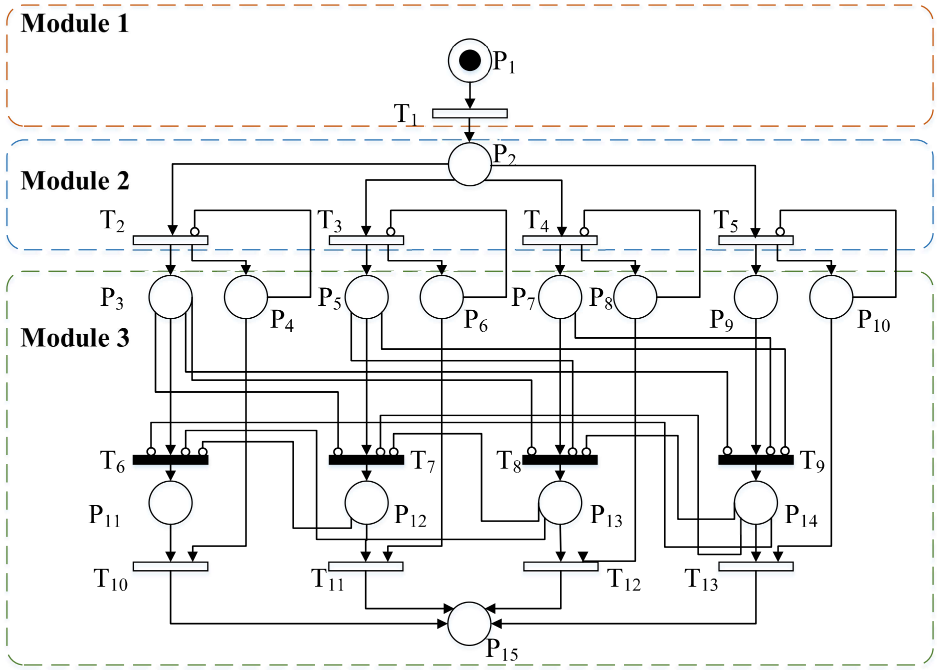

Fig. 4 5G to CAN down-link model.

model includes 15 state places, 4 instantaneous transitions and 9 exponential time transitions $\{T_1, T_2, T_3, T_4, T_5, T_{10}, T_{11}, T_{12}, T_{13}\}$, with their firing rates being $\{\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_{10}, \lambda_{11}, \lambda_{12}, \lambda_{13}\}$. If that the data process conforms to the negative exponential distribution with the mean value of $\lambda_i\,(i = 1, 2, \ldots, n)$, the unit is packets/sec. The value of λ_i depends on real situation.

In 5G to CAN down-link model, P_1 represents 5G terminal data set, and the exponential time transition T_1 represents 5G node data generation and transmission to smart gateway. P_2 represents smart gateway and T_2, T_3, T_4, T_5 represent the data transmitted to CAN node through the bus. P_3 represents Class 1 data set, P_5 represents Class 2 data set, P_7 represents Class 3 data set, and P_9 represents Class 4 data set. Considering that at most one data is to be sent at each node at any instant, the places P_4, P_6, P_8, P_{10} are introduced to represent the queue lengths of data sets with different priorities.

Adding suppression arcs at several nodes, the weight value of the suppression arcs represents the maximum number of data with different priorities that reach different nodes, which also reflects the maximum ability of the node to process data. It means that when the value is greater than or equal to the value, the node's processing capacity is saturated and cannot transmit new data. $P_{11}, P_{12}, P_{13}, P_{14}$ respectively represent the data of different priorities to be transmitted on the bus. The exponential time transitions T_6, T_7, T_8, T_9 represent the data of different priorities for arbitration, respectively. Since arbitration depends on the short completion time of hardware logic, it is almost instantaneous so that transient transition is introduced for description.

Considering that the existence of high priority data during the arbitration process of data with different priority will suppress low priority data, the suppression arcs are introduced from P_3 to T_7, T_8, T_9, P_5 to T_8, T_9 and P_7 to T_9. Moreover, CAN standard adopts non preemptive control. When a low priority data has been transmitted on the bus at a certain time, it is prohibited for a high priority data to preempt the bus. Therefore, the suppression arc is led from P_{14} to T_6, T_7, T_8, P_{13} to T_6, T_7, and P_{12} to T_6. The exponential time transitions $T_{10}, T_{11}, T_{12}, T_{13}$ represent data transmission on the bus, and P_{15} represents CAN target node.

3.3.4 Analysis of 5G and CAN model

The incidence matrix is used to describe the structure of the GSPN model. It can be represented by a matrix $A = |a_{ij}|_{m \times n}$, where $a_{ij}^{+} = 1, if\ (t_j, p_i) \in F$, $a_{ij}^{+} = 0, otherwise$. $a_{ij}^{-} = 1, if\ (t_j, p_i) \in F$. $a_{ij}^{-} = 0, otherwise$. $a_{ij} = a_{ij}^{+} - a_{ij}^{-}, i = \{1, 2, \ldots, m\}, j = \{1, 2, \ldots, n\}$. The rows and columns correspond to the places and transitions of the model, and the elements represent the relationship between the places and transitions. The incidence matrix A can also be used to analyze the logical relationship between the nodes in the model. This matrix A can be used to analyze the flow of tokens through the model and identify the areas of congestion.

The incidence matrix A can be used to calculate P-invariant $A^T X = 0, X(m \times 1)$, which is a vector that describes the distribution of the tokens among various places in the model, which remains the constant during model state changes and can be used to analyze the static structure of the model attributes. The detail derivation process of correlation matrix and P-invariant is shown in Section I-A of supplementary materials. Both the up-link model and the down-link model are bounded and reachable through P-invariant. As shown in Figs. 5 and 6, the CAN node transmits data to the gateway through the 5G network. The data with different priorities are in parallel relationship, and only one data packet can be transmitted in the CAN at any given time.

The 5G and CAN heterogeneous network model based on GSPN does not depend on specific application scenarios and system implementations, which can accurately describe the behavior and performance of the system, and can verify the correctness and feasibility of the model. Meanwhile, it has scalability, and the model can be modified and expanded according to the requirements of different industrial production processes.

4 EXPERIMENTAL RESULTS AND DISCUSSION

To verify the effectiveness of the GSPN based heterogeneous network model being established, both simulation and real experiments are conducted in this section.

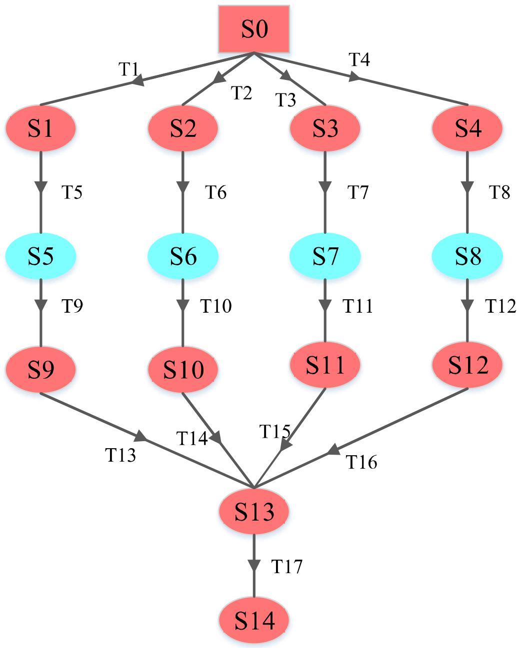

Fig. 5 CAN to 5G reach-ability graph.

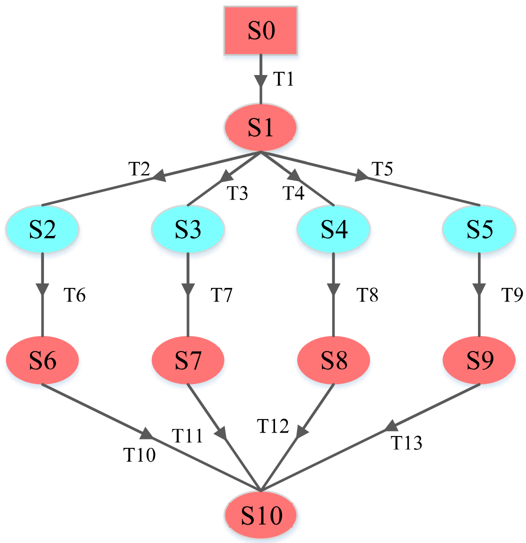

Fig. 6 5G to CAN reach-ability graph.

4.1 Simulation Experiment

The simulation environment is PIPEv4.3.0 which runs on a computer with Intel core i5 CPU @ 3.2GHz and 4.0GB RAM under Windows 10.

In the simulations, data generation is designed to emulate typical traffic patterns observed in industrial networks, particularly within the context of integrating 5G and CAN networks. Although the simulation software utilized does not support the detailed modeling of complex packet structures, such as headers and metadata, these conditions are approximated by simulating various types of data streams with distinct arrival rates and priority levels.

Each data stream is assigned a priority level within the simulation to approximate the varying real-time requirements seen in industrial networks, and the simulation is conducted over a defined period to capture the system's steady-state behavior, allowing us to analyze performance metrics such as latency and throughput, thereby providing insights into the interaction between 5G and CAN networks under different traffic conditions and evaluating the effectiveness of the proposed interconnection model.

The simulation environment generates data streams with varying arrival rates and assigned priorities, reflecting the relative importance of different types of industrial communication, including high-priority streams for real-time control data, moderate-priority streams for monitoring data, and low-priority streams for maintenance and bulk transfers. To measure the QoS key indicators of heterogeneous network under different environments, the samples of different transition process rate (λ_i) are selected in the HN-GSPN model to simulate the operation of heterogeneous network.

For the node P_i tested in the HN-GSPN, $\bar{N}_i$ represents data queue length of the node. When data queue length of HN-GSPN node reaches a stable state, the amount of the generated data is the same as that successfully transmitted, which is applicable to Little formula (i.e.,$L = \lambda W$). It can be used to obtain important performance indicators such as the throughput T ($T = \lambda_i L$) and average delay D ($D = \bar{N}_i/\lambda_i \times \big(1 - \bar{N}_i)\big)$ of the sent data.

4.2 Simulation Results and Analysis

The queuing data process rate of each node under the production environment is shown in Fig.7. The change in node queue length and throughput with data process rate is shown in Fig.8, and the change in average data transmission delay with data process rate is shown in Fig.9.

Furthermore, during the up-link transmission process, as the process rate of control data and monitoring data increases, the number of data queues in P_9 and P_{11} increases, while the number of data queues in P_7 and P_{13} decreases. Therefore, the queue length and throughput of nodes P_9 and P_{11} increase, while the queue length and throughput of nodes P_7 and P_{13} decrease continuously. The queue length at P_{18} in the gateway initially increases and then decreases, while the throughput of the 5G node continues to increase. The delay from CAN nodes with a high data processing rate to the gateway decreases from 10 ms to less than 1 ms. This demonstrates the system's efficiency in managing high-frequency data by prioritizing them in the transmission queue, thus significantly reducing the latency for critical data.

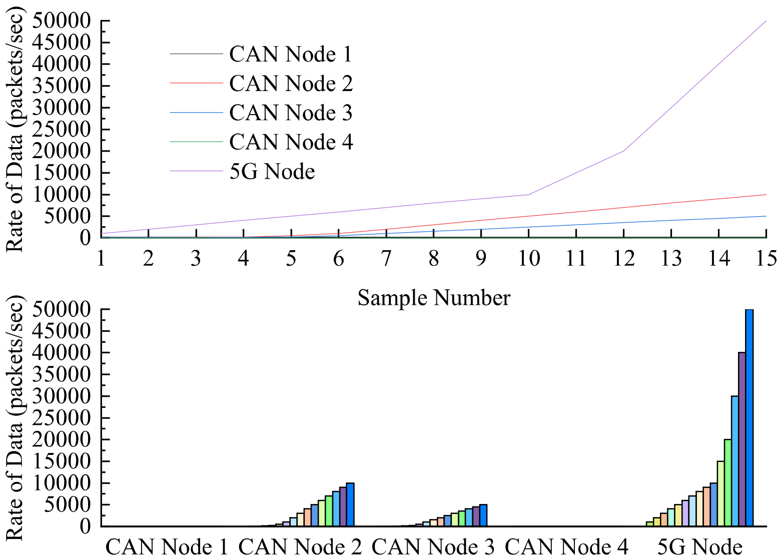

Fig. 7 Data processing rate of 5G node and CAN node under production environment.

Due to the blocking effect of high-frequency data, the delay from low-frequency data nodes decreases slowly to about 2 ms. The transmission delay from the gateway to the 5G node is always less than 1 ms. The total transmission delay from high-frequency CAN nodes to the 5G node is less than 1 ms, and the total transmission delay from low-frequency CAN nodes to the 5G node is less than 2 ms. These results highlight the system's ability to handle different data rates efficiently, ensuring that high-priority data are transmitted with minimal delay while still maintaining acceptable latency for lower-priority data.

During the down-link transmission process, as the 5G node data rate increases, the number of data packets waiting in P_2 increases. Consequently, the queue length and throughput of the 5G node P_1, as well as CAN nodes P_6 and P_8, continue to increase. Meanwhile, the queue length and throughput of nodes P_4 and P_{10} decrease due to high-priority data blocking. This is because node P_4 has higher priority than P_{10}, and the queue length and throughput of node P_4 are greater than those of P_{10} at the same rate. This behavior underscores the effectiveness of the priority-based scheduling algorithm in optimizing network resources by allocating more bandwidth to higher-priority nodes.

The transmission delay from the 5G node to the gateway is always less than 1 ms, and the transmission delay from the gateway to CAN nodes with high data processing rates is reduced from 14 ms to less than 1 ms. The delay to low data rate CAN nodes decreases from 14 ms to less than 2 ms, and the overall transmission delay from the 5G node to CAN nodes reduces from 14 ms to less than 2 ms. These results validate the system's capability to meet stringent real-time requirements, ensuring that both high and low data rate nodes achieve efficient and timely communication.

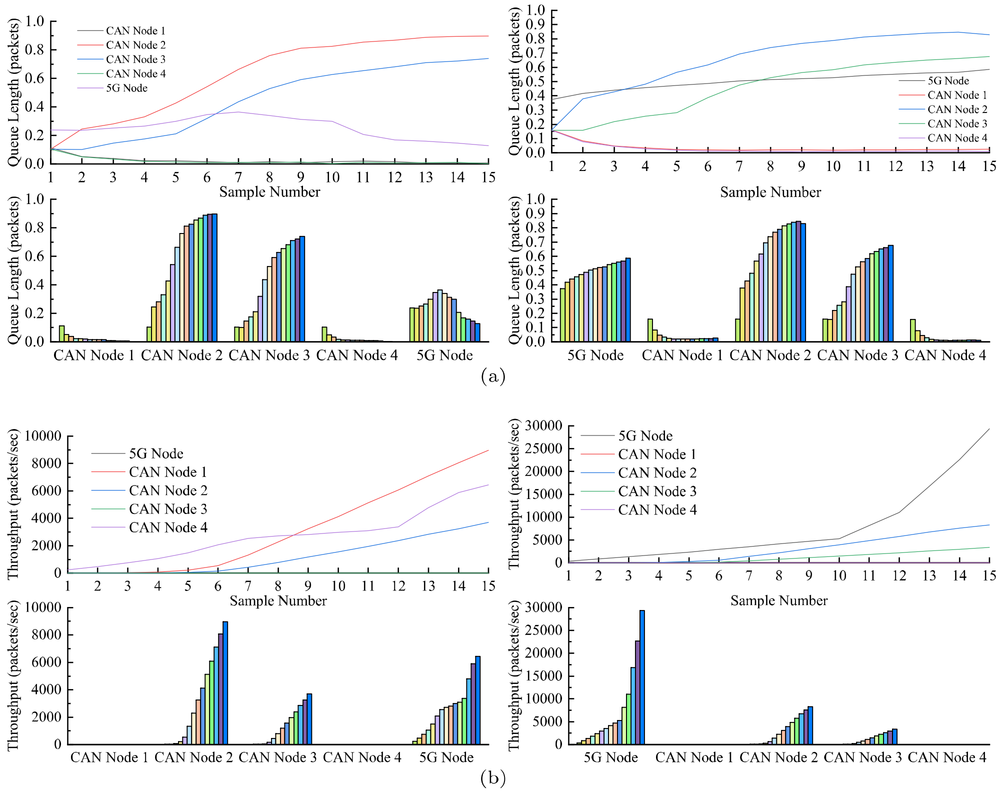

Fig. 8 Queue length and throughput under the Production environment. a) 5G to CAN down-link queue length and CAN to 5G up-link queue length; b) 5G to CAN down-link throughput and CAN to 5G up-link queue length throughput.

To verify QoS under other processing rates, another two experiments are operated: the data process rate of each node under the system environment and the data process rate of each node change under the fault environment. Similar to the analysis above, these two experimental results are shown in Section I. B of supplementary materials.

According to these three experiments, it is clear that the queue length, throughput and delay will change with the data process rate. Under the same rates, high priority data will block low priority data. Under different rates, high frequency data will block low frequency data. When low priority data occupy the bus, high priority data will be blocked. The blocking effect of high priority data on low priority data is far greater than that of low priority data occupying the bus on high priority data. Thus, heterogeneous network control algorithm based on priority classification can effectively realize the interconnection between 5G and CAN.

Moreover, the average delay of node sending data in the transmission process of 5G and CAN heterogeneous networks consists of three parts: the time spent by CAN node transmitting to the gateway, the time spent in protocol conversion in the gateway, and the time spent in transmission through 5G networks. The transmission delay on the CAN bus includes the waiting time caused by the temporary inability of

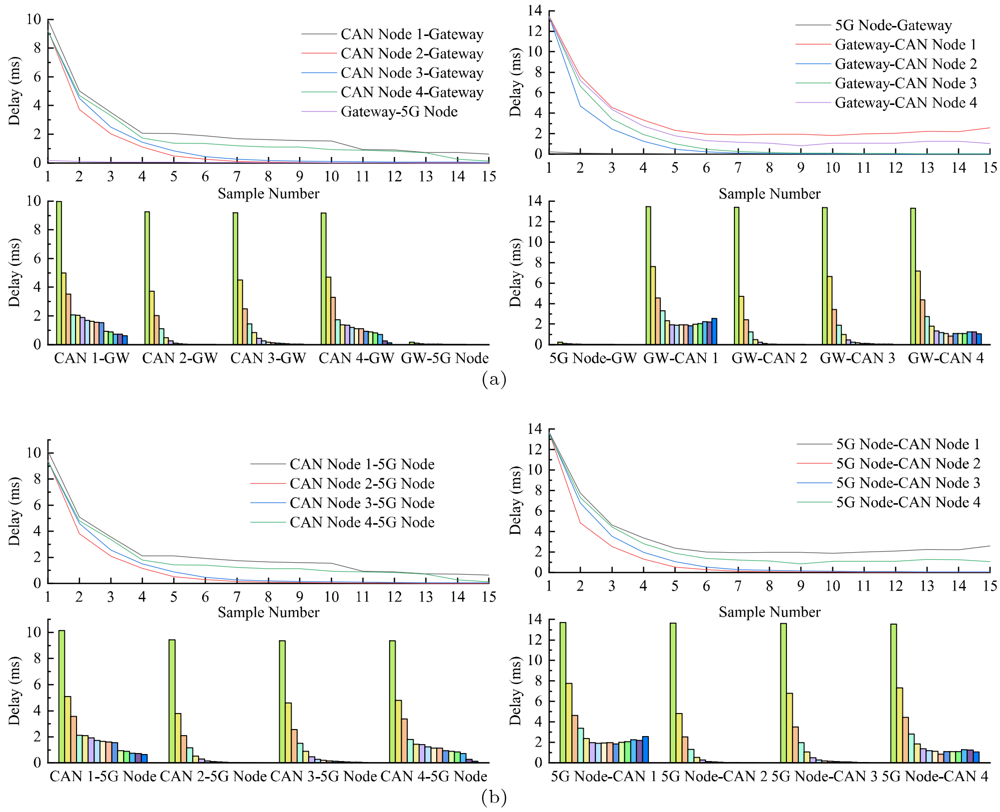

Fig. 9 Delay under the production environment. a) 5G to CAN down-link segmentation delay and CAN to 5G up-link segmentation delay; b) 5G to CAN down-link delay and CAN to 5G up-link delay.

high priority data to obtain bus resources when low priority data occupy the bus, the waiting time caused by the blocking effect of high priority data on low priority data, and the transmission time of data on the bus. The transmission delay in the gateway mainly includes the time for data priority classification and protocol conversion, and the transmission time in the 5G network.

4.3 Real Experiment

Fig. 10 presents the experimental platform used for testing the integration of 5G and CAN networks, which comprises several key components for a heterogeneous network environment, facilitating the evaluation of the proposed interconnection model under realistic conditions. The core of the platform is a PC equipped with an Intel Core i5 CPU @ 3.2 GHz and 4.0 GB of RAM, running Windows 10. This PC is used to monitor the configuration and operation of the entire heterogeneous network. It serves as the control center for the experiment, where network configurations are managed, and real-time performance data is collected and analyzed.

Fig. 10 The experimental platform used for testing the integration of 5G and CAN networks

The network includes two Raspberry Pi 4B-4GB devices, each functioning as a gateway between the 5G network and the CAN network. These Raspberry Pi devices are equipped with external 5G modules to communicate over the 5G network. The gateways play a crucial role in the experiment as they are responsible for the protocol conversion between 5G and CAN, ensuring seamless data transmission across the two networks. Each gateway handles data packets received from the 5G network, translating them into the CAN protocol, and vice versa. Thus, it can facilitate communication between the high-speed 5G network and the more specialized CAN bus system. A CAN analyzer is connected to the Raspberry Pi gateways to emulate the behavior of actual CAN nodes within an industrial environment. It generates and receives CAN messages, allowing the experiment to simulate various industrial communication scenarios. It also provides detailed insights into the performance of the CAN network, including metrics such as message latency, data throughput, and error rates.

The data flow within the experimental setup begins with the generation of data packets by the CAN analyzer, which are then transmitted through the CAN network to the Raspberry Pi gateways. The gateways convert these CAN messages into the 5G protocol and send them over the 5G network. The data packets are received by another Raspberry Pi gateway, where they are converted back into CAN messages and delivered to the appropriate CAN nodes. Throughout this process, the PC monitors the entire network's operation, recording performance metrics and ensuring that the system functions as expected.

4.4 QoS Performance Evaluation

Quality of Service (QoS) is the use of mechanisms or technologies that work on a network to control traffic and ensure the performance of critical applications with limited network capacity such as CAN. The real experiment provides a useful platform for QoS performance evaluation. It can analyse the delay of data transmission of CAN nodes through 5G network at different process rates and verify the effectiveness of the proposed protocol conversion control algorithm. The overall network traffic can be adjusted by prioritizing specific high-performance applications to realize effective cross-network transmission of data between 5G network and CAN network.

Since the protocol used by 5G network differs from the protocol used by CAN bus, a CAN analyzer is used to simulate CAN node sending and receiving 1000 frames of data by different process rates. Here, bidirectional protocol conversion is performed by two gateways. First, data is sent to the gateway by CAN analyzer, which are performed protocol conversion by adding IPV6 header before the data. Then, the gateway sends the data with IPV6 header to another gateway through 5G network.

After the data is parsed, IPV6 header is removed from another gateway and the data is converted to CAN data format suitable for transmission to CAN node. Finally, the converted CAN data is transmitted to CAN node to complete data transmission. In the whole process, protocol conversion is mainly completed in the gateway. According to the experimental results shown in Fig.11, the delay is within the reasonable range of 30ms - 40ms at different process rate. The delay fluctuation is large at a low process rate, and small at a high process rate. It is confirmed that the established model is feasible and effective.

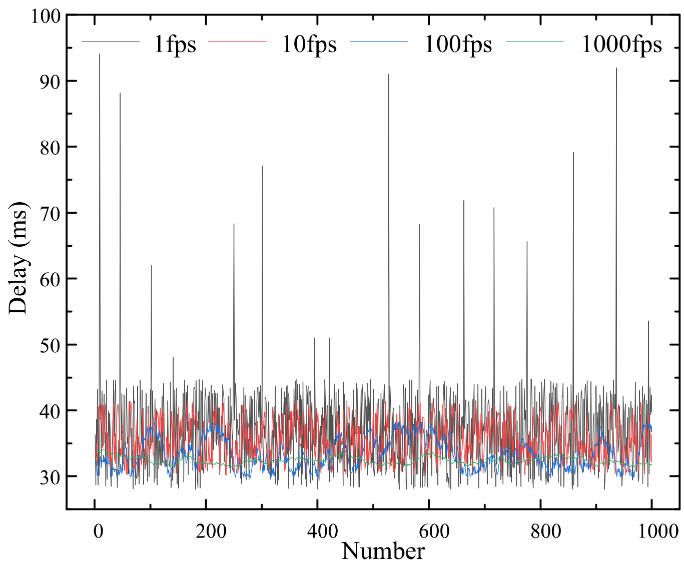

Fig. 11 Average transmission delay of heterogeneous networks at different frequencies.

5 CONCLUSION

In this paper, a new interconnection model was proposed for an efficient interconnection between 5G and CAN networks, which can integrate key characteristics of heterogeneous networks into the GSPN model and solve the interconnection problem of 5G and CAN networks. At first, the data was classified according to real-time requirements of industrial plants. Then, GSPN model was established and QoS key indicators were employed to evaluate the performance of heterogeneous networks. Finally, the feasibility and effectiveness of the established model was confirmed by simulation and real experiments. The main contributions of this paper can be summarized below.

- A new scheduling algorithm of protocol conversion based on data priority classification has been proposed by analyzing their interconnection characteristics, which achieves reliable data transmission across the 5G and CAN networks.
- A reliable interconnection model has been established based on the generalized stochastic Petri net method. It can accommodate random and instantaneous transition characteristics of 5G and CAN networks,
- The key evaluation indicators and measurement methods of heterogeneous network have been successfully investigated, which confirms that the proposed scheduling algorithm and the interconnection model are effective and can satisfy the real-time and reliability requirements for different types of data transmission in industry.

Our future work will be focused on how to extend the proposed method to time-sensitive networks and software definition networks in industry.

Data Availability The data that support the findings of this study are available from the corresponding author, [Zheyi Chen], upon reasonable request.

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7 Declarations

Conflict of interest Authors Zheyi Chen, Dajun Du, Minrui Fei and Huosheng Hu declare they have no financial interests.

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