Analysis of the Influence of CAN Bus Structure on Communication Performance

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Abstract. CAN bus is widely used in automotive distributed embedded systems. Its protocol makes it reliable and efficient in in-vehicle communication system and industrial control system. However, the limited communication bandwidth limits its transmission efficiency. In order to improve the transmission efficiency of CAN bus, the influence of CAN bus structure to the transmission performance is analyzed in this paper. A typical CAN bus network is set and the message transmission is simulated under different CAN bus structure based on CANoe, which is widely used to study the CAN bus. The influence of different network structure on the transmission performance is analyzed. The simulation result demonstrated that the multi-level-bus CAN network using gateway reduces busload and minimize message delay effectively. It is also demonstrated that the simulation method is able to be used to find the appropriate CAN bus network structure according the busload or message delay requirement.

Keywords: CAN bus network structure · Message delay · Busload · Transmission performance

1 Introduction

The controller aerial network (CAN) bus has the advantages of real-time transmission performance and it has been widely used in various vehicles with integrated electronic systems. CAN bus provide an infrastructure of control, monitoring, and diagnostic applications in vehicle. As the functions of vehicles are becoming more and more powerful, the number of electronic control units (ECU) in the on-board CAN bus communication network is also increasing, and the network structure is becoming more and more complicated. Therefore, the bus loading is increasing and even leads to communication delivery delays in messages under the extreme situation. Accordingly, the transmission performance of the entire CAN bus system getting worse and impacts the performance of the control system, especially for the advanced drive assistance systems. Therefore, CAN bus is required to have dependability attributes, especially the real-time performance of CAN network.

The CAN network is a multi-master message broadcast system, it works with a maximum signal rate of 1 Mbps [3]. In a CAN network, many short messages are

B. Li et al. (Eds.): IoTaaS 2019, LNICST 316, pp. 405–416, 2020.
https://doi.org/10.1007/978-3-030-44751-9_34

broadcasted to the entire network, which provides data consistency in every node of the system [4]. When the payload is increased, the real-time performance is not ensured. Some researches were focused on modifying the protocol to improve the transmission performance [5].

In this paper, we try to analyze the impact of CAN network structure to the transmission performance through the simulation of different network. By using the hierarchical structure of different real time requirement message, minimize CAN busload to minimize the possible message latencies. The simulation is carried based on software CANoe and simulation results will provide a reference for the CAN bus structure design.

CANoe software is a CAN network application system development tool developed by Vector company [1]. It not only has network detection and analysis functions, but also can realize semi-physical simulation through CAN bus hardware interface. It is often used to build CAN network to realize full digital simulation [2] to verify the design about the CAN bus. The CANoe software comes with the database management tool CANdb++. CANoe also provides a CAPL function library, which is convenient for users to program each node and analyze bus data.

2 Multi-level-bus CAN Network Structure

2.1 Organization of CAN Node

The CAN network adopts a serial bus topology. All ECU nodes are connected on the bus, and the message is transmitted through the bus while all the nodes in the bus can received the message simultaneously.

For a CAN network system, if there are less nodes, a single bus structure is enough to guarantee the real-time of messages transmission. However, if the CAN network has so many nodes that the busload increase a lot, the high density of message even cause bus congestion due to the single bus structure. As a result, the transmission delay of the message of node is increased to cause the message packet unable to be successfully sent before the message deadline which is called the transmission fails.

In order to improve the reliability of message transmission, the multi-level-bus structure is designed according to the speed of data transmission requirement. In this structure, the messages with different real-time transmission requirements in the CAN bus are placed in different CAN bus subnets, and gateways are added between the subnets to establish communication between subnets.

The multi-level-bus structure will reduce the busload of each CAN bus subnet and satisfies the real-time performance of message transmission. Multi-level-bus networks are usually divided into high-speed subnets and low-speed subnets.

We take a typical vehicle as example. It's an in-vehicle CAN bus network whose structure is composed of two bus subnets, namely a high speed bus and a low-speed bus. In high-speed CAN subnet, eight ECU nodes are mounted on high speed bus. These ECU nodes usually sending time-critical message which is important for the in-vehicle control system. The other 6 ECU nodes are placed in low speed bus, and they have less real-time requirement and is used in mission system. The CAN network is as in Fig. 1.

In the integrated system of CAN bus, the driver mission terminal acts as a gateway in the bus network and is mounted on two buses at the same time. It is responsible for data communication between the high speed bus subnet and the bus low speed subnet. All ECU nodes in the entire network are able to communicate by sending or receiving extended frames package through gateway. If the message is only need in subnet bus, it is transmitted in local subnet. This mechanism of multi-level-bus will reduce busload effectively.

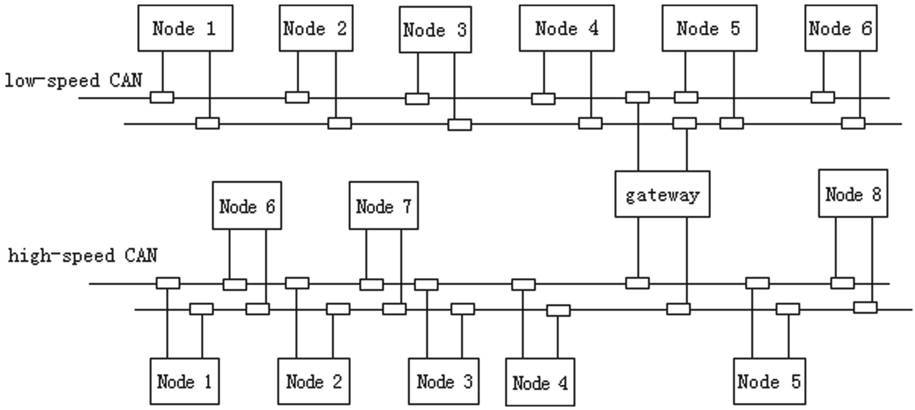

Fig. 1. Multi-level-bus CAN network structure with Gateway

2.2 Message Definition

In addition, in order to keep the communication efficiently, the different message packets sending periodic are designed to avoid bus using conflict. The packets of the nodes are sent in a periodic style with different cycle, and each message packet has a CAN ID except for the switch information interface box terminal and the driver mission terminal (gateway).

For the armored vehicle, the message packet using extended frames which the message packets with an CAN ID (identifiers) of 29 bits. The message with high priority CAN ID is in high speed subnet usually, and the lowest identifiers have the highest priority for bus contention according to the basic CAN identifier rules.

In CAN bus network, the message is sent cyclic such as message of motor rotation frequency is required to be updated every 10 ms, message of a temperature sensor is required to update every 20 ms, while some message is send sporadically. Each node may send different messages.

The sending period of some messages in the armored vehicle are listed in Table 1.

Table 1. Simulation parameters

Message ID	Node name	Data length	Send period/*ms*	CAN channel
0x4x	Node1	3	20	High speed
0x1x	Node2	4	40	High speed
0x6x	Node 3	5	10	High speed
0x2x	Node 4	8	10	High speed
0x7x	Node 5	5	40	High speed
0x8x	Node 6	1	Sporadic	High speed
0x3x	Node 7	8	10	High speed
0x5x	Node 8	7	20	High speed
0x35x	Node 1	4	40	Low speed
0x55x	Node 2	8	20	Low speed
0x33x	Node 3	8	10	Low speed
0x15x	Node 4	4	20	Low speed
0x25x	Node 5	6	20	Low speed
0x10x	Node 6	6	40	Low speed

3 Indicators of Transmission Performance

3.1 Busload

Busload is critical to consider the bus performance to ensure minimum delay of data. The lower busload will lead to less message delay generally. Busload is an important indicator for the CAN bus network performance.

Busload is defined as the ratio of the actual amount of data transmitted and the maximum amount of data the bus can transmit. For the CAN bus, the maximum amount of data is equal to the baud rate of the CAN bus due to the NRZ coding mechanism. Another definition is the ratio of bus busy time and bus idle time. Typically, the bus loading is expressed as the percentage of time the bus is busy for a period of time. The calculation formula of the busload is as (1):

$$\sum_{i=1}^{m} L_i/T, L_i = \left(8N_i + 47 + \left\lfloor \frac{34 + 8N_i}{5} \right\rfloor\right) \cdot T_{bit} \tag{1}$$

Here, the L_i is the size of message i, m denote the number of message in a test period of T, The term T_{bit} is the bit time of the bus, N_i denotes the data field length of message packet.

The busload is affected by many factors; the most influential is the message density. The message intensity is closely related to the transmission frequency and frame length of each message. For a special CAN bus system, the transmission frequency and frame length of each message are determined according to the protocol. In order to improve the bus transmission real-time performance, we can move to design the structure of the CAN bus network to reduce the message density under the requirement of successful message transmission.

The multi-level-bus structure with gateway can effectively reduce the pressure of transmitting packets on bus through dividing massage packets with different real-time requirement into subnets. According to the real-time requirements of the packets, nodes with different real-time requirements are placed in different transmission rate subnets, thus, for each subnet, the bus loading will reduce. The lower busload rate of the bus will be helpful for improving the real-time performance of bus data transmission.

3.2 Message Delay

Message delay is the time it takes for a message to be received from being ready to send. It is usually contain two parts, namely the transmission delay and the arbitration delay. The transmission delay is the time it taken for the message to be transmitted on the bus, which is related to the length of the message and the baud rate of the system. The arbitration delay is the time taken for the message waiting for the bus to be idle or being arbitrated. Since the CAN bus adopts the CSMA/CA communication mode, if a higher priority message is waiting to be transmitted, the bus preferentially transmits a high priority message, and the low priority message needs to wait for the next idle time of the bus and proceed on the next round. Accordingly, the message with the lower priority will have the longer arbitration delay.

In order to analyze the message transmission performance, the theoretical calculation of the response time of message transmission is analyzed firstly. The response time of message contains 3 parts as in (2):

$$R_i = C_i + J_i + W_i \tag{2}$$

The term J_i is the queuing jitter of message i, and gives the latest queuing time of the message. The term W_i represents the worst-case queuing delay of message i. The term C_i represents the longest time taken to physically send message i on the bus.

In the calculation of the C_i as in the formula of (3), N_i denotes the data field length of packet, and the filling size of the message i packets is written as $\left\lfloor \frac{34+8N_i}{5} \right\rfloor$, The term T_{bit} is the bit time of the bus [6, 8].

$$C_i = \left(8N_i + 47 + \left\lfloor \frac{34 + 8N_i}{5} \right\rfloor\right) \cdot T_{bit}, N_i = 1, 2, \ldots 8 \tag{3}$$

The W_i of a message consists both the time waiting for the higher priority messages pre-empting message and the second is the time waiting lower priority message that has already obtained the bus.

For messages with higher priority, since there is always a higher arbitration advantage, it is easier to obtain the bus usage rights, so the delay is smaller and always are easy to be successfully sent in transmission. However, for a message with a lower priority, if the bus adopts single-bus structure, the arbitration delay of the message will increase much due to the lower arbitration especially in the CAN network with many ECU nodes and high message density. If the message delay exceeds the dead-line of the message, it is called as transmission fail.

4 Simulation of Different Structure CAN Network

This paper focuses on the impact of network structure on the real-time performance of message transmission. For CAN bus with the same quantity of nodes and the same message density, the simulation is set up to analyze the real-time performance of the message in CAN network with multi-level-bus structure with the gateway. The main indicators are busload and message delay. We compare the message delay in CAN network with the single-bus structure and with multi-level bus structure separately. Furthermore, the busload is also tested in CAN network with different structures under the same situation that with the same message transmission period and the same number of ECU nodes. The influence of busload to message delay is analyzed.

4.1 Single Bus CAN Network

We outline a CAN bus network for message transmission that all nodes can send and receive messages, and the message with their own sending cycle. We study the transmission delay of the specified 7 messages with different priority in different CAN bus network.

Firstly, according to the organization of each node message, we create a CANdb++ database and define the sending cycle of each message. In addition, the relative environment variables of each node are defined. Based on the created database, a single bus CAN bus network is generated under the CANoe platform, as shown in Fig. 2.

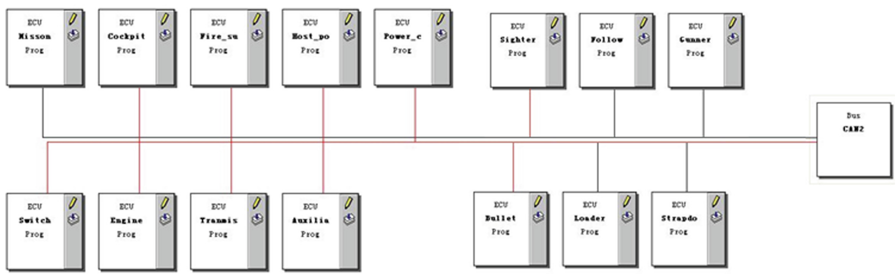

Fig. 2. Structure of Single CAN bus

4.2 Multi-level-bus CAN Network Structure

Generally, in the in-vehicle CAN bus, different message transmission periods and delay requirements are defined according to the data characteristics and real-time requirements of the nodes. For example, the real-time information of the engine needs to be transmitted at a high speed. Real-time performance of information of the entertainment comfort system is not very important. Accordingly, nodes with high real-time requirements are placed in high speed CAN subnet, and are transmitted in high baud rates. While nodes with low real-time requirements are placed in low speed CAN subnet, and messages are transmitted in with low baud rates. A multi-level-bus CAN network is built accordingly which contains CAN1 and CAN2 channels connected through a gateway. CAN1 is high speed and CAN2 is low speed subnet. Nodes in different subnets communicate with the other nodes through gateway when needed. The multi-level-bus CAN network structure is shown in Fig. 3, and the gateway will be set between the CAN1 and CAN2. In Fig. 3, the gateway is built in CAN1 named 'Mission'.

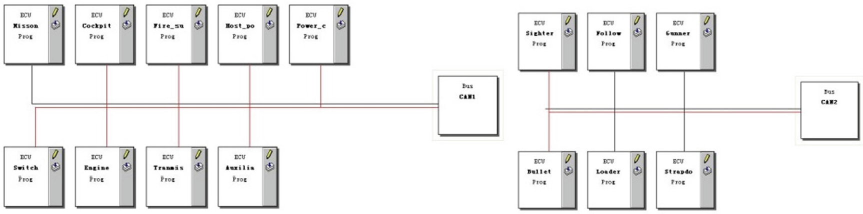

Fig. 3. Multi-level-bus CAN bus

4.3 Gateway Simulation

For the multi-level-bus CAN network, the sending and receiving of message are simulated based on the CAPL function, including the response to the environment variable, the response to the timer, and the response to the received message. In addition, the CAPL function is used to realize the information exchange function. It is used to transmit the messages from the gateway to the other subnet. The gateway node receives the message from the CAN1 channel, and transmits the data packets to the CAN2 channel.

4.4 Simulation Comparison Between Different CAN Network Structures

According to the message packet allocation of each ECU node, the sending period of each node message is set by a timer. First, the gateway node is disconnected from the chassis electrical control bus, and the bus network is work as a single-bus network. After starting the simulation, the busload of the entire chassis electrical control bus network is tested. The special 7 messages delay are also tested in the simulation of CAN network with single-bus. The busload is listed as in Table 2, and the message delay with different priority is shown in Table 3.

Table 2. Busload of single-bus network

Number of nodes	Busload
3	4.50%
4	6.82%
5	8.50%
6	13.46%
7	18.42%
8	19.34%
9	22.60%
10	25.94%
11	30.88%
12	33.75%
13	37.61%
14	40.63%
15	41.10%

Table 3. Message delays of single-bus network

The priority of message	Message delay
1	0.23
2	0.76
3	1.38
4	1.89
5	2.39
6	2.92
7	3.42

Similarly, the same message sending period and message amount is used. The communication simulation is set in the multi-level-bus CAN network and implemented. The busload of each subnet is listed in Table 4, and the specific 7 messages' delays are shown in Table 5.

Table 4. Busload of multi-level-bus network

Number of node	Low speed busload	High speed busload
3	4.00%	0.92%
4	6.32%	0.92%
5	4.50%	4.96%
6	8.96%	5.88%
7	13.92%	5.88%
8	13.92%	6.96%
9	14.83%	6.96%
10	15.98%	6.96%
11	15.98%	9.12%
12	18.85%	9.12%
13	23.79%	9.12%
14	23.79%	10.96%
15	27.65%	10.96%

Table 5. Message delays of multi-level-bus network

The priority of message	Message delay
1	0.23
2	0.31
3	0.31
4	0.82
5	1.31
6	1.85
7	2.34

5 Simulation Analysis

5.1 Experiment Data Analysis

According to the test data in the table, a trend graph showing the change of the busload with the number of nodes is as shown in Fig. 4. The busload keeps rising with the number of nodes increases. The busload is significantly higher using a single-bus network structure without a gateway than that of a multi-level-bus network structure with a gateway. If all nodes are connected on the same bus in single bus structure, the number of packets actually transmitted on the bus increases during same period of time, the busload increases accordingly. If the busload increases to a certain extent, bus congestion will occur. It will affect the real-time performance of messages transmission.

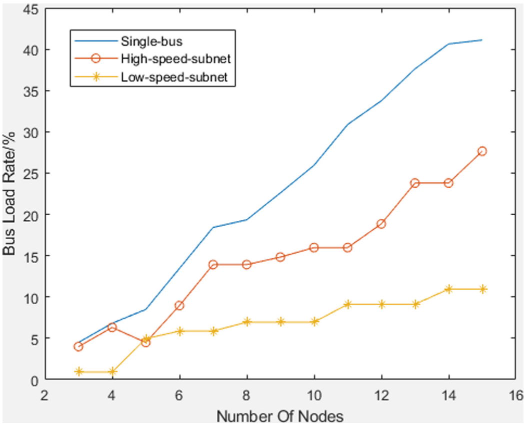

Fig. 4. Relationship between busload and number of nodes

The message transmission delay with different priority messages in both cases are shown in Fig. 5. And the improvement ratio is calculated in the Table 6. It can be seen that the message delay in multi-level-bus structure with gateway significantly reduced, especially the message with lower priority. By adding a gateway to the bus network to form a multi-level-bus structure, the pressure of transmission of a single bus message can be effectively reduced. Accordingly, the real-time performance of message is significantly enhanced. Therefore, the transmission performance of the multi-level-bus CAN network using gateway is significantly better than that of the single bus especially at the CAN network have many nodes.

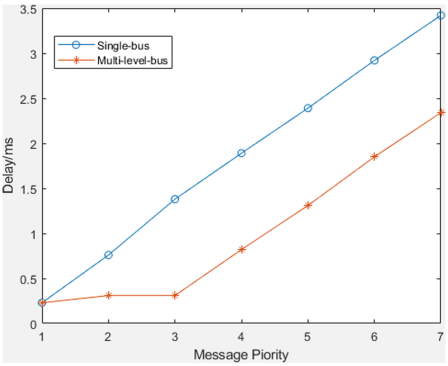

Fig. 5. Message delay in different CAN network

Table 6. Message delays reduce ratio

The priority of message	Message delays reduce ratio
1	0.00%
2	59.21%
3	77.54%
4	56.61%
5	45.19%
6	36.64%
7	31.58%

5.2 Further Discuss on Simulation

It is known that in an in-vehicle CAN bus network, there are some messages are time-critical. These messages have deadlines, if the message delay overpasses the deadline, it will cause a serious error. According to present study, it is recommended that the busload be kept below 35% on CAN bus to ensure the stable communication [6–8]. The simulation result also demonstrated that the message delay reduced to quite low over 30%.

Therefore, we can get the appropriate structure by the simulation. For the example in this paper, if the nodes in CAN network are less than 12, it is able to meet the busload requirement and need not use the multi-level-bus structure, otherwise, the multi-level-bus structure is able to improve the transmission efficiency by reducing the busload.

Accordingly, if the multi-level-bus network structure is adopted, the message transmission efficiency will be improved by reducing the busload. In addition, the multi-level-bus CAN network is able to isolate the low-speed bus from the high-speed bus to guarantee the stability of CAN bus system, especially benefit to guarantee the time-critical message transmission successfully to improve the performance of the vehicle.

6 Conclusion

This paper focuses on analyzing the influence of bus network structure to the communication performance, especially in busload and message delay. The CAN bus networks with different structure are set up and communication process is simulated. The simulation verified the transmission performance is improved by using multi-level-bus structure. The appropriate CAN bus network structure suggestion is available by the CAN bus simulation result.

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