Schedulability Comparisons between Priority Queue and FIFO Queue for CAN Messages with Offsets

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ABSTRACT: The Controller Area Network (CAN) is a widely used in-vehicle network and its schedulability is particularly important. In a CAN system, implementing the priority queues is better than FIFO queues with respect to the schedulability, which is widely recognized by users. In this paper, we investigate whether and how much implementing the priority queues is better than FIFO queues when the offset assignment for CAN messages is conducted. Our results show that usually the priority queues are better, whereas the FIFO queues are better in some specific situations. Furthermore, we propose a new scheduling method for obtaining the advantages of both queues, which improves the schedulability effectively.

KEY WORDS: information, communication, and control, controller area network, inter-vehicle communication, real-time systems, real-time communications, scheduling theory, schedulability analysis [E2]

1. Introduction

The Controller Area Network (CAN) was designed as a simple, efficient and robust broadcast communications bus for in-vehicle networks; and it has been widely used by automotive manufacturers in recent decades. In the utilization of CAN, real-time constraint is particularly important, which requires that all the messages should meet their deadlines. For this reason, schedulability analysis for CAN messages has been proposed⁽²⁾⁽³⁾, which calculate the worst-case response time (WCRT) of every message, and compare it with the deadline to determine whether the real-time constraint is guaranteed.

However, the sophistication and complexity of in-vehicle communications have seen a notable increase in the number of transmitted messages, and make the bus utilization higher and higher in recent years. In order to match the real-time constraint in this situation, many researches investigated the scheduling for CAN messages. Effective approaches such as message queue selection, offset assignment have been proposed⁽⁴⁾⁽⁵⁾⁽⁶⁾⁽⁷⁾⁽⁸⁾.

Priority queue and FIFO queue are the two common queues almost supported by all CAN controllers. Although using a FIFO queue obtains the simplicity and the faster queue management, which is seemed an attractive solution to improve the performance of the system⁽⁴⁾, the disadvantage of the FIFO queue is that it introduces significant priority inversion — the situation that a low-priority message delays high-priority messages — and results in degraded schedulability of CAN messages. For this reason, it is better to implement a priority queue than a FIFO queue for a CAN device, which is recommended by previous work⁽⁵⁾.

The offset assignment for CAN messages is an effective approach for decreasing the WCRT, which has been confirmed on both the priority queues implemented systems and the FIFO queues implemented systems⁽⁹⁾⁽¹²⁾. However, the issue that whether the priority queue is still better than the FIFO queue when the offset assignment is conducted has not been concerned by previous work.

In this paper, we conduct the experiments based on the WCRT calculation methods of references (9) and (12) to compare the schedulability between the priority queue and FIFO queue for CAN messages with offsets. In the experiments, a large number of simulated message sets generated with the bus utilization from 30% to 80%, and a real-world messages set provided by an automobile manufacturer are investigated. Based on the comparison results, first, we summarize the pros and cons of both the queues; and show that the FIFO queue is better in some specific situations. Second, we introduce a new scheduling method that uses the two types of queues in one station for obtaining the advantages of both schemes. The experimental results on a real-world message set show that the combination of the priority and FIFO queues can achieve higher schedulability than either a priority or a FIFO queue alone.

The rest of this paper is organized as follows. Section 2 describes the terminology, notation and system models. Section 3 introduces the related work. Section 4 shows the schedulability comparisons, followed by Section 5 that discusses the differences between the priority queue and FIFO queue when the worst case occurs, and summarizes the pros and cons. Section 6 proposes the new scheduling method that uses the two types of queues in one station, and shows the evaluations. The paper is concluded in Section 7.

2. System Model

2.1. The Controller Area Network

CAN is a serial broadcast bus that sends and receives short real-time control messages⁽¹⁾. The CAN bus is designed to connect several stations and to operate at a maximum speed of 1 Mbit/sec. A simple CAN bus architecture is shown in **Fig. 1**.

Fig. 1 An example of CAN bus architecture

Each message transmitted on a CAN bus is required to have a unique identifier (ID). The ID may be 11 bits (standard format) or 29 bits (extended format). When a CAN controller attempts to transmit a message, it has to wait until a bus idle period is detected. If two or more stations start to transmit messages simultaneously, the bus arbitration is triggered and the ID is used as a priority (a message with a smaller ID has higher priority) to determine which message will be transmitted among those contending for the bus.

The messages are queued in the stations before being transmitted to CAN bus. The queue is memory, implemented as dual ports and shared between the host processor and CAN controller. According to the ordering mechanism, the queues are classified to priority and FIFO. **Fig. 2** is an example of how the queues work. In this example, the host processor queues ID:1 message into the queue in which ID:2 and ID:3 messages already existed. In **Fig. 2(a)** where a priority queue is implemented, the

(a) A priority queue equipped CAN station

(b) A FIFO queue equipped CAN station

Fig. 2 Message queueing

CAN controller attempts to transmit the highest priority message (ID:1) to CAN bus first. On the other side, when a FIFO queue is implemented, as shown in **Fig. 2(b)**, the CAN controller attempts to transmit the oldest message (ID:2) to the CAN bus first.

2.2. Notations

The system is assumed to be composed of a single CAN bus and several CAN stations. The stations, denoted U_i ($i \in Z^+$), are classified according to the type of their queues. Therefore, a PQ-station implements a priority queue, whereas a FQ-station implements a FIFO queue. A PQ-station is assumed to provide that the highest priority message in the station is entered into arbitration whenever the bus arbitration starts. A FQ-station is assumed to ensure that the oldest message in the station is entered into arbitration whenever the bus arbitration starts.

The transmitted messages in a system are considered as a message set. Each message, denoted τ_i ($i \in Z^+$), has static properties which comprise priority P_i , maximum transmission time C_i , period T_i , and offset O_i .

The value of P_i is equal to the ID of τ_i . τ_i has higher priority than τ_j if $P_i < P_j$. Since each CAN message has a unique ID in the system, for any two messages τ_i, τ_j ($i \neq j$), $P_i \neq P_j$ holds.

The maximum transmission time C_i is determined by the number of data bytes, bit stuffs and the inter-frame space, which is calculated by the formula below⁽¹¹⁾.

$$C_i = \left(\left\lfloor \frac{g + 8s_i - 1}{4} \right\rfloor + g + 8s_i + 13 \right) t_{bit} \quad (1)$$

In the formula $g = 34$ for standard CAN (11-bit IDs) or $g = 54$ for extended CAN (29-bit IDs). t_{bit} denotes the time it takes to transmit one bit. s_i denotes the number of bytes in the data field of the message.

It is assumed that all messages are periodic messages and reoccur infinitely. Therefore, T_i is the interval between two consecutive occurrence of τ_i ; and O_i is the instant at which τ_i firstly occurs. Each instant that τ_i occurs, denoted A_i^n ($n = Z_0^+$), is defined as an arrival of τ_i . Hence it is $A_i^0 = O_i$.

The properties of a message τ_i are described in **Fig. 3**. In the figure, the horizontal axis represents time; up-pointing arrows represent the arrivals. The white boxes represent messages transmissions; and the number in each box represents the priority.

The WCRT of τ_i , denoted R_i , is the worst-case delay that τ_i may experience between its arrival and transmission completion. R_i is compared with the deadline, denoted D_i , to determine whether τ_i is schedulable or not — τ_i is schedulable if $R_i \leq D_i$. Therefore, the system is schedulable if $R_i \leq D_i$ holds for all the messages.

Because it is hard to evaluate the schedulability of same system scheduled by different method, deadline rate and worst-case response time rate (WCRR) have been proposed for the

Fig. 3 The properties of a message

quantitative evaluation of schedulability⁽⁸⁾⁽¹⁰⁾⁽¹²⁾. Considering the fact that a deadline is always assigned according to the ratio of the period in a real automotive system, the deadline rate of a message is defined as the ratio of deadline to the period, and the WCRR is the ratio of WCRT to the period. Let DR_i and $WCRR_i$ denote the deadline rate and WCRR of τ_i respectively. DR_i and $WCRR_i$ are calculated by following equations:

$$DR_i = (D_i / T_i) * 100\% \quad (2)$$

$$WCRR_i = (R_i / T_i) * 100\% \quad (3)$$

Based on these definitions, τ_i is schedulable if $WCRR_i \leq DR_i$. Furthermore, for the same system scheduled by different methods A and B, the schedulability of method A is higher than B if the maximum $WCRR_i$ of A is smaller than that of B.

2.3. Effects of the Offset Assignment

The offset assignment decreases the WCRT by avoiding multiple messages being transmitted simultaneously. A comparison of messages transmission with and without offsets is shown in Fig. 4. In the example, U_1 has two messages τ_1 ($P_1 = 1$, $C_1 = 1$, $T_1 = 4$) and τ_2 ($P_2 = 2$, $C_2 = 1$, $T_2 = 8$); U_2 has one message τ_3 ($P_3 = 3$, $C_3 = 1$, $T_3 = 16$). In the situation where no offset is assigned (i.e., offsets of all messages are 0), τ_1 delays τ_2 ; τ_1 and τ_2 delay τ_3 in the worst case. While assigning an offset value 2 to O_2 avoids τ_1 and τ_2 to be transmitted simultaneously, hence the WCRTs of both τ_2 and τ_3 are decreased.

3. Related Work

Schedulability analysis for CAN messages has been firstly investigated by Tindell et al⁽²⁾⁽³⁾. They proposed the WCRT

Fig. 4 Effects of the offset assignment

calculating method so that the real-time constraint of CAN message can be guaranteed. This research has then been improved by successive studies. The most recent achievement is the study proposed by Davis et al, which corrected some mistakes and revised the original analysis method⁽¹¹⁾.

According to these studies, it is known that a CAN message will be delayed by all the other high-priority messages in the worst case. To relieve this problem, the offset assignment for CAN messages has been discussed by Matustani et al⁽⁶⁾, Grenier et al⁽⁷⁾ and Chen et al⁽⁸⁾, respectively. Meanwhile, Iiyama et al and Kurachi et al proposed the WCRT analysis methods for offset-assigned CAN messages, which have confirmed that the offset assignment reduces the WCRT effectively⁽⁹⁾⁽¹⁰⁾.

Fig. 5 The WCRR comparing results on 50 message sets which are generated by the NETCARBENCH with bus utilization from 30%~80%

Because all the above researches aimed at the systems that only comprise PQ-stations, Davis et al proposed the analysis method which is able to calculate the WCRTs of messages in the FQ-stations used systems⁽⁵⁾. The study illustrates that implementing PQ-stations is better than FQ-stations with respect to the schedulability.

While Davis's study did not consider the offset assignment. For this reason, Chen et al proposed their method for calculating the WCRT of the FIFO-queued messages with offsets. The study has confirmed that the offset assignment also effectively decreases the WCRT for the FQ-stations implemented systems⁽¹²⁾.

However, to the best of our knowledge, no published research has compared the two types of queues in a CAN system, with the respect to the WCRT, when the offset assignment is conducted. This leads our studies in this paper.

4. Schedulability Comparison Experiments and Results

In this section we explain the schedulability comparison experiments and their results. The experiments are conducted on 50 test systems. All the stations in each system are assumed to be PQ-stations when the schedulability results corresponding to the priority queue are calculated, whereas the schedulability results corresponding to the FIFO queue are calculated by assuming all the stations to be FQ-stations. Iiyama's method⁽⁹⁾ and Chen's method⁽¹²⁾ are employed in the WCRT calculation for PQ-stations implemented system and FQ-stations implemented system, respectively.

The message sets of the test systems are generated by the NETCARBENCH⁽¹³⁾ — a very popular automotive message sets generator. The following configurations are conducted on the

message sets:

- (1) The message sets are generated with the bus utilization from 30% to 80%.
- (2) Offset assignment for each message set is conducted by the NETCARBENCH.
- (3) Deadline of each message is assigned to equal to its period. Hence deadline rate of each message is 100%.
- (4) Priorities of the messages are assigned based on the deadline monotonic rule — the message with shorter deadline gets higher priority.

The results are depicted in **Fig. 5** and **Fig. 6**. In the figures, the red lines with square markers depict the maximum WCRR or WCRT results when PQ-stations are implemented; the dark blue lines with cycle markers depict the maximum WCRR or WCRT results when FQ-stations are implemented; the pink lines with cross markers depict the average WCRR or WCRT results when PQ-stations are implemented; the light blue lines with triangle markers depict the average WCRR or WCRT results when FQ-stations are implemented.

First, we focus on the WCRR results shown in **Fig. 5**. We observe that the implementation of PQ-stations awards higher schedulability in all the tested systems — its maximum WCRR of each message set is smaller. Moreover, all the messages meet their deadlines even the bus utilization is 80%. On the other side, the implementation of FQ-stations causes both the average and maximum WCRRs to be increased. The increases are more obvious when the bus utilization becomes high. In the extreme situation, implementing FQ-stations causes the maximum WCRR to be over 3 times as large as that of PQ-stations used situation. However, we also observe that the differences in the maximum WCRR results are much larger than that in the average WCRR

Fig. 6 The WCRT comparing results on 50 message sets which are generated by the NETCARBENCH with bus utilization from 30%~80%

(a) The WCRT results

(b) The WCCR results

Fig. 7 The WCCRs and WCRTs of all messages in a message set with bus utilization 51.4%

results, which indicates that the WCCRs of most messages do not become very worse when FQ-stations are used.

Second, we focus on the WCRT results shown in Fig. 6. We observe that although the implementation of FQ-stations still causes the increase of the average WCRTs, the maximum WCRTs of the FQ-stations implemented situations are smaller than that of the PQ-stations implemented situations. Also, the differences are more obvious with the increase of the bus utilization.

To show more detailed results, we pick out a message set from the above experiments and show the WCCRs and WCRTs of all messages in the message set. From the WCRT results, as shown in Fig. 7(a), we observe that with the decrease of the priorities (increase of the priority values) the WCRTs of messages in PQ-stations increase faster. The higher priority messages in PQ-stations have shorter WCRTs, whereas the lower priority messages in FQ-stations have shorter WCRTs. Moreover, when FQ-stations are implemented the maximum WCRT is shorter. However, the advantages of FQ-stations are not shown in the WCCR results. As shown in Fig. 7(b), the maximum WCCR is smaller when PQ-stations are implemented.

5. Discussions

Although Section 4 illustrated that in the tested systems implementing PQ-stations is better than FQ-stations with respect to the schedulability, the phenomenon — the maximum WCRT becomes short when the FQ-stations are implemented — indicates that the FQ-stations may be better in some specific situations. For

this reason, in this section we discuss the differences between a PQ-station and FQ-station when the worst case occurs. Then, we summarize the pros and cons of both stations, and point out the specific situations where implementing FQ-stations are better with respect to the schedulability.

5.1. The Differences between a PQ-station and a FQ-station when the Worst Case Occurs

In a CAN system where all stations are PQ-stations and the offset assignment is conducted, the worst case of the message τ_i in the system is defined to be included in the following situations:

At least one message in each station with a priority higher than or equal to P_i arrives simultaneously⁽⁹⁾.

All the situations that meet above descriptions must be treated as the candidates and be checked by the calculation in order to find the WCRT of τ_i .

When FQ-stations are implemented, the priority inversion causes that the messages with priorities lower than τ_i have also to be considered in the worst case. Hence the worst-case candidates of τ_i change to the follows:

At least one message in each station with a priority higher than or equal to $\{P_j\}$ arrives simultaneously. $\{P_j\}$ is a set of priorities of messages in the station that transmits τ_i ⁽¹²⁾.

We give examples to explain the differences when the worst case occurs. Assume that a system consists of 3 stations and 6 messages. Properties of this message set are described in Table 1. When the system implements PQ-stations, one worst-case candidate of τ_2 exists, in which τ_2 arrives with τ_1 simultaneously, as shown in Fig. 8(a). In the figure, τ_6 exists because the message transmission on CAN bus is based on non-pre-emptive scheduling. Therefore, in the WCRT calculation, the low-priority message with the maximum transmission time is assumed to occupy the bus just before the simultaneously started instant in each candidate⁽¹¹⁾. Hence R_2 is 3.

Table 1 An example message set

U_i	τ_i	P_i	T_i	C_i	O_i
U_1	τ_6	6	8	1	0
U_2	τ_4	4	8	1	0
U_2	τ_1	1	8	1	3
U_2	τ_3	3	8	1	4
U_3	τ_2	2	8	1	1
U_3	τ_5	5	8	1	0

Because U_3 has two messages τ_2 and τ_5 , the set of priorities of messages in U_3 is $\{P_2, P_5\}$. Therefore, when FQ-stations are implemented, there are 4 worst-case candidates of τ_2 — (1) τ_4 and τ_5 ; (2) τ_1 and τ_5 ; (3) τ_3 and τ_5 ; (4) τ_1 and τ_2 arrive simultaneously, respectively. The worst case is the candidate (2) — τ_1 and τ_5 arrive simultaneously — as shown in Fig. 8(b). Hence R_2 is 5. We observe that in the worst case, priority inversion in the station causes τ_2 to wait for the transmission of τ_5 . Moreover, when τ_5 attempts to be transmitted to the bus it has to wait for the transmission of τ_3 , hence τ_2 is indirectly delayed by τ_3 .

Although the priority inversion causes the high-priority message τ_2 to experience longer WCRT, the WCRT of a low-

Fig. 8 The differences between a PQ-station and a FQ-station when the worst case occurs

priority message — for example, τ_5 — can be decreased by it. The worst cases of τ_5 is shown in **Fig. 8(c)(d)**. When the system implements PQ-stations, the worst case of τ_5 occurs when τ_5 and τ_1 arrive simultaneously, as shown in **Fig. 8(c)**. In this situation, τ_2 will be transmitted earlier than τ_5 , which causes τ_5 to experience the WCRT 6. However, when FQ-stations are implemented, τ_5 arrives earlier thus it will not be delayed by the transmission of τ_2 , as shown in **Fig. 8(d)**. Therefore R_5 is decreased to 4.

5.2. Specific Situations where FQ-station is Better

In a PQ-station, low-priority messages can be delayed by high-priority messages without concerning the queuing order, which ensures the transmission of high priority message as soon as possible. In contrast, in a FQ-station the priority inversion causes the high-priority messages to experience longer WCRTs, whereas it prevents the low-priority messages from being delayed by the successive high-priority messages. Hence the WCRTs of the low-priority messages will be decreased. Because a low-priority message usually has longer WCRT than a high-priority message no matter what kind of stations are implemented, the maximum WCRT in a FQ-station is usually smaller than that in a PQ-station.

However, the WCRR is determined by the WCRT and the period. In fact, a high-priority message usually has a shorter period than a low-priority message, and the difference in the period is much larger than the difference in the WCRT. These factors cause that the maximum WCRR usually exists in the high-

priority messages even if the low-priority messages have larger WCRTs. However, it also indicates that when the low-priority messages and high-priority messages have same period, implementing FQ-stations is possible to achieve higher schedulability than PQ-stations.

To verify the observations, two message sets, in which the messages of each station have the same period, are generated and the comparison experiments are conducted. The results are shown in **Fig. 9**. This time the implementation of FQ-stations achieves higher schedulability — the maximum WCRR is decreased when FQ-stations are implemented, and the difference of the maximum WCRR is more obvious in the message set with high bus utilization.

6. Scheduling Messages with Both Priority and FIFO Queues

Since both of the queues have their pros and cons in the schedulability performance, implementing the two types of queues in one CAN station is considered as a solution to obtain both the advantages. In this section, we explain our investigation on scheduling CAN messages with both priority and FIFO queues. First, in Section 6.1 we will introduce the CAN stations that are equipped with both a priority queue and a FIFO queue (called P&F-stations). Second, in Section 6.2 we propose a messages scheduling method for the system that implements P&F-stations. Finally, the evaluations for the implementation of P&F-stations are shown in Section 6.3.

(a) The results of the message set with bus utilization 52.5%

(b) The results of the message set with 79.7% bus utilization

Fig. 9 The WCRR results of the specific message sets

6.1. P&F-station

A P&F-station is designed to be equipped with both a priority queue and a FIFO queue (e.g., the R32C/160 group ECU from Renesas⁽¹⁴⁾). The queues can be used to queue and transmit any CAN messages in the station. When the station starts to transmit and more than one message exists in each queue, the highest priority message in the priority queue arbitrates with the oldest message in the FIFO queue. Then the higher priority message between them will be transmitted to the bus first.

In Fig. 10, we give an example to explain the transmission mechanism of a P&F-station. In this example, the station has 4 messages, in which ID:1 and ID:2 messages are in the FIFO queue; ID:3 and ID:4 messages are in the priority queue. When the CAN controller is able to start the transmission, the oldest message (ID:2) of the FIFO queue arbitrates with the highest priority message of the priority queue (ID:3). Then the ID:2 message is selected by the CAN controller and attempts to be transmitted to CAN bus.

6.2. The Proposed P&F Scheduling Method

According to the special transmission mechanism of the P&F-station, the priority queue is able to be used to prevent the high-priority messages from being delayed by the transmission of the low-priority messages. Meanwhile, the FIFO queue can be used to decrease the maximum WCRR of the messages in the station. Our proposed messages scheduling method for P&F-stations implemented system is described as follows:

Fig. 10 The transmission mechanism of a P&F-station

- (1) Assume all the messages to be in the priority queue.
- (2) Calculate the WCRRs of all messages.
- (3) For each station U_i , find the τ_i ($\tau_i \in U_i$) with the maximum WCRR.
- (4) Put the messages of U_i that have same period with τ_i into the FIFO queue. The other messages are put into the priority queue.

6.3. Evaluations for the Proposed Scheduling Method

To evaluate the effectiveness of the proposed scheduling method, we conduct it on a real-world message set provided by an automobile manufacturer, and compare the schedulability among the 3 situations that all the stations are implemented as PQ-stations, FQ-stations and P&F-stations, respectively. The message set has 65 messages and the bus utilization is 53.3%. The automobile manufacturer has configured all the properties of the message set.

The results are shown in Fig. 11. The comparison between PQ-stations and FQ-stations, shown in Fig. 11(a), illustrates that the implementation of PQ-stations is better than FQ-stations for the message set because the maximum WCRR in PQ-stations is smaller. While when P&F-stations are implemented and the messages are scheduled by the proposed method, the comparison between PQ-stations and P&F-stations shows that the implementation of P&F-stations achieves higher schedulability, as shown in Fig. 11(b).

7. Conclusions

In this paper, we investigated whether and how much priority queue is better than FIFO queue when the offset assignment for CAN messages is conducted. Our results showed that for common message sets implementing the priority queues is better than the FIFO queues with respect to the schedulability. In the extreme situation, implementing the priority queues makes the maximum WCRR to be decreased 2/3, comparing with the implementation of the FIFO queues.

However, we also observed that the WCRRs of most messages did not become very worse when FQ-stations are used. Moreover, implementing the FIFO queues is better in some specific situations, in which the low-priority messages and high priority-messages have same period. Considering that using the two types of queues in one station is able to obtain the both

(a) The WCRR comparison between PQ-stations and FQ-stations

(b) The WCRR comparison between PQ-stations and P&F-stations

Fig. 11 The WCRR comparison among PQ-stations, FQ-stations and P&F-stations

advantages, we proposed a new scheduling method for messages in the P&F-station that is equipped with both a priority queue and a FIFO queue. The evaluations showed the effectiveness of the proposed scheduling method on improving the schedulability.

In the evaluating experiments of P&F-stations, the offset assignment of the tested message set is conducted for the PQ-stations implemented system essentially. Therefore, a new offset assignment method for the P&F-stations implemented system should achieve higher schedulability. This will be considered as future work.

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