

Research on Fault Tolerance for the Static Segment of FlexRay Protocol

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Abstract— FlexRay is the next generation communication protocol in automotive network. But the development was hindered because most of the researches ignored transient fault in message transmission. In this work, a complete framework is presented to increase the reliability by retransmitting messages in the static segment. It includes system model, mathematical abstraction and a heuristic algorithm. Given a specification of the system model, our work will not only get the system satisfy the reliability goal but also optimize the bandwidth utilization rate. Simulation results show that our approach performs better than the existing algorithm in bandwidth utilization rate (-19.1%), reliability (+0.07%) and running time (-37.2%). In our opinion, this algorithm is so generic that it can be widely used in other time-triggered and reliability critical applications.

Keywords—Bandwidth utilization rate, Fault tolerance, FlexRay, retransmit message, static segment

I. INTRODUCTION

In modern high-end cars, like the BMW X7 series, it is common to see about 70 electronic control units (ECUs) exchanging 2500 electric signals inside the cars [1]. These ECUs are distributed in various parts of the car and are hardwired with different actuators or sensors. With the increase of the ECU number, traditional point-point links have been replaced by bus network [3]. FlexRay appeared as a fast, fault-tolerant next generation network protocols in 2004. Although FlexRay have a great advantage compared to other bus network protocol, its development was still be hindered for its lackage of an application layer scheme to prevent transient fault in the process of message transmit. And it cannot guarantee reliability [1].

Various techniques for network parameters optimization, time analyzing framework and task scheduling have been studied in the field of the FlexRay research. The work in [3] describes a FlexRay network parameters optimization method that focuses on the length of communication cycle with minimum worst case response times (WCRTs). Performance analysis framework for a network of ECUs that communicate via a FlexRay bus was introduced in [2]. Reference [5] provides solutions for different task scheduling policies based on a mix integer linear programming framework. However, only a few of them focus on reliability

of FlexRay. In 2010, Tanasa presents a framework of generating fault-tolerant message schedules by retransmitting messages in the static segment of FlexRay in [1]. But their algorithm cannot generate the optimal retransmission scheme in saving the bandwidth.

The main contribution of this paper is an algorithm of finding the retransmission scheme which performs better than the existing works in bandwidth utilization rate, reliability and running time. First, a system model and mathematical abstraction were made for the fault tolerance problem in FlexRay. Then a heuristic algorithm H-1 which can be used to find the optimal retransmission scheme in saving the bandwidth and at the same time satisfy the reliability goal was presented. At last, some simulation tests were done in Matlab2010. The results show that our approach performs better than the existing works in bandwidth utilization rate (-19.1%), reliability (+0.07%) and running time (-37.2%). In our opinion, this algorithm is so generic that it can be widely used in other time-triggered and reliability critical applications.

The rest of the paper is organized as follows. In Section II, formal model was proposed to analyze fault tolerance in the static segment of FlexRay. Section III introduces mathematical abstraction of the problem and a new heuristic retransmission algorithm. In Section IV, a simulation comparison test was designed for the algorithms. The conclusion of this paper was presented in Section V.

II. SYSTEM MODEL AND EQUATIONS

A. Media Access Control of the FlexRay

Our system model is based on the communication level of FlexRay. As shown in Figure 1, every communication cycle contains the static segment, the dynamic segment, the symbol window and the network idle time (NIT) [4]. Static segment are designed for time triggered messages using Time Division Multiple Access (TDMA) scheme. While the dynamic segment is using mini-slotting based scheme to transmit event triggered messages. The symbol window is a communication period in which a symbol can be transmitted on the network. The NIT is a communication-free period that concludes each cycle [4].

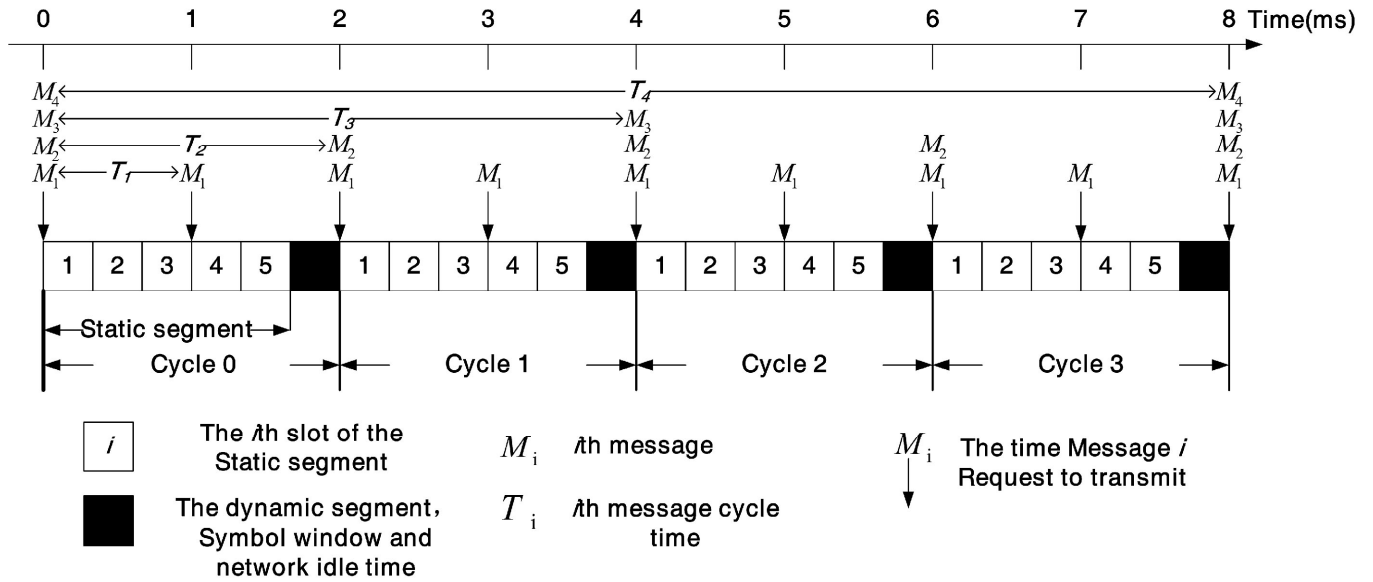


Figure 1. The system model including some parameters mentioned in our work.

This work only concentrates on the static segment. As shown in Figure 1, the static segment is made up of consecutive time intervals called slots. Each slot is allocated to a task and can be used to transmit one FlexRay message. If the task has no message to send, the slot goes empty [2].

B. System model

The system model is divided into two parts: the message model and the bus model.

Message model is a message set which includes n messages $M = \{M_1, M_2, \dots, M_n\}$ and some parameters about the message.

1) Cycle time: The cycle time set $T = \{T_1, T_2, \dots, T_n\}$. Cycle time T_i is the constant time interval between message M_i producing twice in succession.

2) Error rate: The message error rate set $P = \{P_1, P_2, \dots, P_n\}$. Error rate P_i is the failure probability of transmitting message M_i once.

3) Number of retransmission times: The number of retransmission times set $K = \{K_1, K_2, \dots, K_n\}$. K_i is the number of times that message M_i will be retransmitted in cycle time T_i .

The bus model is presented as follows:

1) Communication cycle length: FC . FC is the length of a communication cycle.

2) Number of slots: NS . It stands for the totally number of slots in one static segment.

3) Reliability goal: ρ . It means how reliable the system message transmission process needs to be.

4) Global probability of success: GP . GP is the probability that all messages transmit successfully in test period τ . If $GP > \rho$, it is believed that the system is reliable.

5) Test period: τ . τ is the statistical running time of the system.

As shown in Figure 1, there are 4 messages transmitting on the bus and the cycle time set is $T = \{1ms, 2ms, 4ms, 8ms\}$. FC is $2ms$ and NS is 5.

C. Equations

In order to find the optimal retransmission scheme in bandwidth utilization and satisfy the reliability goal, three equations need to be presented first. (1) and (2) were presented by Tanasa in [1]. K_i^L is defined as the lower bound of K_i which satisfy $GP > \rho$. In (3), the bandwidth utilization rate is defined as the ratio of the number of used slots to the number of slots supplied in τ , which can be used to show the situation of the used slots in τ .

$$GP = \prod_{i=1}^n (1 - P_i^{K_i+1})^{\frac{\tau}{T_i}} \quad (1)$$

$$K_i^L = \left\lceil \frac{\log \left(1 - \rho^{\frac{T_i}{\tau}} \right)}{\log P_i} - 1 \right\rceil \quad (2)$$

$$\text{Bandwidth utilization rate} = \frac{\text{used slots}}{\text{all slots}} = \sum_{i=1}^n \frac{K_i + 1}{T_i} \cdot \frac{FC}{NS} \quad (3)$$

In T_i , M_i will transmit once and retransmit K_i times. So $\sum_{i=1}^n (K_i + 1) \cdot \tau / T_i$ slots will be used to transmit or retransmit

all of the messages in τ . Then, there are τ/FC communication cycles supplying $NS \cdot \tau/FC$ slots in τ . Finally, (3) was proofed by getting the number of used slots in τ divided by the number of slots supplied in τ .

Tanasa regarded the number of used slot in one FC as its optimal objective in [1]. But we believe the bandwidth utilization rate is much more suitable than it. An analysis about this will be presented with the help of an example. This example has only one message M_1 with one retransmission $K_1=1$ and cycle time $T_1=10ms$. The FlexRay cycle is $FC=5ms$ with $NS=5$ slots in the static segment. Then the number of used slots in one FC can be computed as 0, 1 or 2. This is because there are two FC in one T_1 time. The transmission and retransmission of M_1 may happen in the first FC or the second one. As a result, the number of used slots in one FC is not a proper optimal objective for this problem because it only evaluates the situation of one FC and T_i may be longer than FC .

On the other side, the bandwidth utilization rate is much more suitable to be the optimal objective than the number of used slots in one FC . In the example above, the bandwidth utilization rate can be computed as 20% according to (3). Obviously, it shows the situation of used slots in test time τ instead of FC correctly. In our opinion, the optimization of the bandwidth utilization rate will reduce the complexity in schedulability analysis. And the parameter configuration process could also benefit from it in minimizing worst case response time [3]. In conclusion, the bandwidth utilization rate was regarded as the optimal objective in this work.

III. RETRANSMISSION ALGORITHMS

A. Mathematical Abstraction

Different from the existing works using (1) directly, it is found that after taking a logarithm computation to both side of $GP > \rho$ and some simple transformations, $GP > \rho$ will

be transformed into $\sum_1^n \frac{\log(1-P_i^{K_i+1}) \cdot \tau}{T_i \cdot \log \rho} < 1$ which can be

used to measure the effect of increasing one message's retransmission times. So the left part of it was defined as a new function $f_i(K_i)$ which can be regarded as the contribution of M_i retransmitting K_i times. The less $f_i(K_i)$, the more reliable the transmission will be.

$$f_i(k_i) = \frac{\log(1-P_i^{K_i+1}) \cdot \tau}{T_i \cdot \log \rho} \quad (4)$$

Then the reliable constrain $GP > \rho$ was transformed into $\sum_1^n f_i(K_i) < 1$. If $\sum_1^n f_i(K_i) < 1$ we can believe that the system is reliable. Then the mathematical abstraction of the problem was presented as follows. T, P, τ, ρ, FC, NS are all known.

The retransmission times set K should be computed to satisfy the reliability goal $\sum_1^n f_i(K_i) < 1$. The optimal objective is to minimize the bandwidth utilization rate $\sum_1^n \frac{K_i+1}{T_i} \cdot \frac{FC}{NS}$.

In order to describe the algorithm simply, another auxiliary function $g_i(K_i)$ was defined in (5). It describes the difference of contribution in retransmitting M_i from K_i to K_i+1 times.

$$g_i(K_i) = f_i(K_i) - f_i(K_i+1) \quad (5)$$

B. H-1 algorithm's idea

The basic idea of the H-1 algorithm is: in each loop, H-1 increases the currently most "effective" message's retransmission times K_i once until the reliability goal $\sum_1^n f_i(K_i) < 1$ is satisfied. The most "effective" message is the message that has the maximum ratio of contribution difference $g_i(K_i)$ to bandwidth utilization rate increase. For example, if H-1 retransmits M_i one more time, it will reduce $\sum_1^n f_i(K_i)$ by $g_i(K_i)$ and bandwidth utilization rate will increase $FC/NS \cdot T_i$ according to (3). The increase of the bandwidth utilization rate is considered as $1/T_i$ because both of FC and NS are constant. So the most "effective" message we select to increase its K_i is the message with maximum

value in $\frac{\text{contribution difference}}{\text{bandwidth utilization increase}} = g_i(K_i) \cdot T_i$.

C. H-1 algorithm description

In our algorithm below, K_i is initialized to K_i^L using (2) (line 2,3). Then in each loop (line 7), H-1 chooses the message with the maximum $g_i(K_i) \cdot T_i$ (line 9) and increases its retransmission times by one (line 11) to optimize the bandwidth utilization rate until the reliability goal is satisfied (line 7) or the bandwidth utilization rate is larger than 100% (line 8).

Input: Message set M , probability of failure set P , cycle time set T , reliability goal ρ , communication cycle FC and the number of slots in the static segment NS .

1. for $i \in \{1, 2, \dots, n\}$
2. compute K_i^L
3. $K_i = K_i^L$
4. compute $f_i(K_i)$
5. end for
6. $SumOfContribution = \sum_1^n f_i(K_i)$
7. while ($SumOfContribution > 1$)

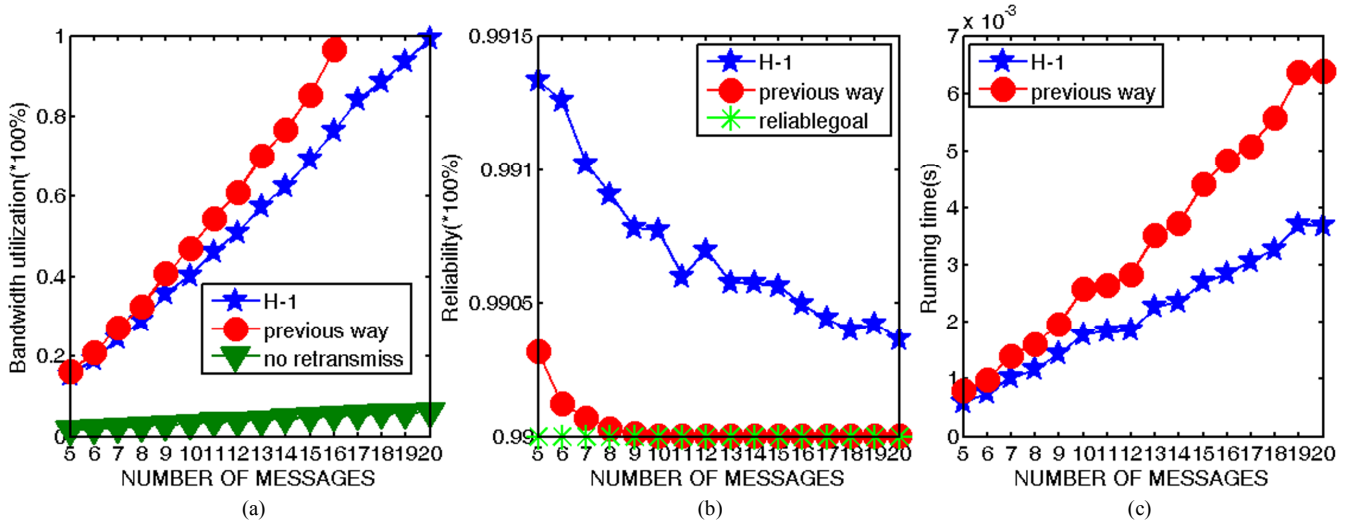


Figure 2. Simulation test result. (a) Bandwidth utilization rate. (b) Reliability. (c) Running time.

8. if $(\sum_{i=1}^n \frac{K_i+1}{T_i} \cdot \frac{FC}{NS} < 1)$ then
9. $j = \text{the message number with max } g_i(K_i) \cdot T_i \text{ in } \{g_1(K_1) \cdot T_1, g_2(K_2) \cdot T_2, \dots, g_n(K_n) \cdot T_n\}$
10. $\text{SumOfContribution} = g_j(K_j)$
11. $K_j = K_j + 1$
12. else return bandwidth overflow
13. end if
14. end while
15. return $\{K_1, K_2, \dots, K_n\}$

As noted before, the H-1 algorithm is a new method of finding the retransmission scheme which performs better than the existing work in bandwidth utilization rate, reliability and running time.

IV. SIMULATION TEST

As presented above, this work is focusing on finding the retransmission scheme which can satisfy the reliability goal and optimize the bandwidth utilization rate. So the simulation experiment concentrates on three evaluation indicators: the bandwidth utilization rate, the reliability goal is achieved or not and the running time.

16 cases were generated during the number of messages from 5 to 20 and for each case 100 examples were studied. For randomness and accuracy, each example will run 100 times and all of the examples were generated randomly by varying some message parameters. For example, T were selected from 5ms to 20ms, P were set 0% to 50%. While the others are assigned statically as follows: $FC = 5ms$, $NS = 150$, $\rho = 99\%$, $\tau = 1hour$. The entire simulation has been implemented in a Windows XP machine running a Intel(R) Pentium(R) Dual E6700 3.2GHz processor with MATLAB 2010a.

The average bandwidth utilization rate of each case was presented in Figure 2(a) and the bandwidth overflowing

times in 100 examples were shown in Figure 3. Compared to the existing works, our H-1 reduces the average bandwidth utilization rate by 19.1% and it also grows slower than Tanasa's in bandwidth overflowing times. Because our algorithm's optimal objective is the bandwidth utilization rate instead of the number of used slots in one FC . Figure 2 (b) shows the average reliability of each case. And the reliability insufficient times in 16×100 examples were plotted in Figure 3. Both of them satisfy the reliability goal without any reliability insufficient examples and our algorithm is a little bit more reliable (average +0.07%) than the previous ways. At last, we focus on the least concerned evaluation indicator: running time because H-1 is a static algorithm for the static segment. After time complexity analysis, H-1 is less or equal to the existing algorithm ($O(n^2)$). As shown in Figure 2(c), the average running time is reduced by 37.2% in our algorithm.

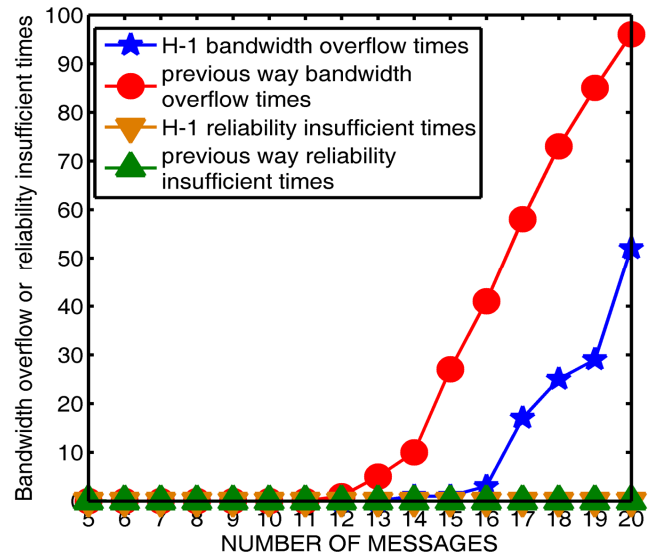


Figure 3. Bandwidth overflow and reliability insufficient times in 100 examples.

V. CONCLUSIONS

In this work, a complete framework is presented to increase the reliability by retransmitting messages in the static segment. It includes system model, mathematical abstraction and a heuristic algorithm named H-1 which aims at finding the optimal retransmission scheme in saving the bandwidth and satisfying the reliability goal. The simulation results show that H-1 algorithm performs better than the existing works not only in bandwidth utilization rate (-19.1%) but also in reliability (+0.07%) and running time (-37.2%). In our opinion, this algorithm is so generic that it can be widely used in other time-triggered and reliability critical applications.

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