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A Bayesian Network Reliability Modeling for FlexRay Systems

Kuen-Long Leu, Yung-Yuan Chen, Chin-Long Wey, Jwu-E Chen and Chung-Hsien Hsu

Abstract**—**The increasing importance of FlexRay systems in automotive domain inspires unceasingly relative researches. One primary issue among researches is to verify the reliability of FlexRay systems either from protocol aspect or from system design aspect. However, research rarely discusses the effect of network topology on the system reliability. In this paper, we will illustrate how to model the reliability of FlexRay systems with various network topologies by a well-known probabilistic reasoning technology, Bayesian Network. In this illustration, we especially investigate the effectiveness of error containment built in star topology and fault-tolerant midpoint synchronization algorithm adopted in FlexRay communication protocol. Through a FlexRay steer-by-wire case study, the influence of different topologies on the failure probability of the FlexRay steer-by-wire system is demonstrated. The notable value of this research is to show that the Bayesian Network inference is a powerful and feasible method for the reliability assessment of FlexRay systems.

Keywords**—**Bayesian Network, FlexRay, fault tolerance, network topology, reliability.

I. Introduction

DRIVE-BY-WIRE (DbW) or *x-by-wire* technology in the automotive industry replaces the traditional mechanical and hydraulic control systems with electronic control systems using electromechanical actuators and human-machine interfaces such as pedal and steering feel emulators. Examples include electronic throttle control, steer-by-wire and brake-by-wire. However, electronic control systems have higher probability of incurring fatal interferences such as electromagnetic interference (EMI), particle strike or crosstalk than mechanical and hydraulic systems. As a result, the reliability issue is crucial to the safety-critical *DbW* systems. The reliability validation of developed *DbW* systems is required to guarantee the system reliability compliant with the safety norms, such as IEC 61508 or ISO 26262. For this end, we need to perform the assessment of safety and reliability during the development of safety-critical electronic automotive systems.

Recently, FlexRay has attracted much attention upon applying to safety-critical *DbW* systems because of fault-tolerant mechanisms (FTMs) provided in the communication protocol specification. Besides, FlexRay also supports variable network topologies: bus, star or hybrid of bus and star. The reliability of communication between distributed FlexRay nodes can be assured by, for example, frame CRC checking, fault-tolerant clock synchronization and redundant bus, etc. [1]. Hence, assessing fault-tolerant effectiveness of those FTMs is necessary to obtain a prior estimation of whole system's reliability. For this purpose, academia and industry [2-5] have paid much effort for proposing effective assessment methodologies and experimental platforms. However, in this study, we focus on another issue rarely addressed currently: How could the different network topologies affect the reliability of FlexRay systems? To study this issue, reliability verification ought to be raised from communication level to system level where the communication media is only regarded as a component of the whole FlexRay system. Although the FTMs can effectively enhance the FlexRay system's reliability, they let the reliability analysis become more complex as well. Thus, a feasible methodology for reliability analysis with consideration of all the related fault-tolerant attributes in FlexRay systems is required. Candidate for reliability modeling schemes could be the Fault Tree Analysis (FTA), Markov Chains, Petri Nets, Binary Decision Diagram (BDD) or Bayesian Network (BN). Among these techniques, we adopt the BN to model the reliability of FlexRay systems because of its high flexibility and feasible state-space.

Bayesian Network (BN) is widely used for representing uncertain knowledge in probabilistic systems. The main feature of BN is that involving the local conditional dependencies is impossible by directly specifying the causes that influence a given effect [6]. Literature [7-8] had showed that it is possible and convenient to combine dynamic fault tree (DFT) with the modeling and analytical power of BN. The modeling flexibility of the BN formalism can accommodate various kinds of statistical dependencies that cannot be included in the DFT formalism. In this work, we will demonstrate how to verify the system reliability for various topologies and model the effectiveness of FTMs through applying BN to FlexRay systems. A *steer-by-wire* (SBW) system was chosen as the case study to illustrate how to estimate system's reliability through the BN inference.

First of all, the BN for a SBW system will be constructed. Based on the BN, given the failure probability of each primary component in the SBW system, the reliability of FlexRay SBW system can be derived through the λ-π messages propagation algorithm called *Belief Updating* [6]. Furthermore, we will also demonstrate how to model the fault-tolerant midpoint synchronization algorithm for FlexRay nodes [1], into BN so that its effectiveness on improving system reliability can be acquired.

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The remaining of the paper is organized as follows: In Section II, basic concept of the Bayesian Networks will be introduced. Then we will illustrate how to apply BN to the reliability verification of the FlexRay SBW system in Section III. Section IV summarizes all the estimation results for each network topology and provides valuable observations from these results. Section V describes how can BN model the synchronization scheme in reliability analysis and valuable quantitative results are provided. Conclusions and future work appear in Section VI.

II. Bayesian Networks

Bayesian Networks (also known as *belief nets*, *causal networks*, *probabilistic dependence graphs*, etc.) are a popular formalism for representing uncertain knowledge in Artificial Intelligence [6]. BN has proven to be a powerful formalism to express complex dependencies between random variables (RVs). RVs can be in a number of states. The number of states can either be infinite (continuous RVs) or finite (discrete RVs). In this paper, we only consider discrete RVs. A BN inference could proceed from two viewpoints: *qualitative* and *quantitative* parts*:*

1) *Qualitative part*: a directed acyclic graph (DAG), such as the one shown in Fig. 2(b), with nodes representing RVs and directed arcs (from parent to child) representing causal or influential relationships between variables.
2) *Quantitative part*: consisting of conditional probability distributions of each node given its respective parents, and marginal probability distributions of the nodes without parents (root nodes). Together, the qualitative and quantitative parts of the BN determine the joint probability distribution of all the random variables presented in the model.

For each node, a conditional probability table (CPT) is embedded to contain each possible value of the variables associated to a node, and all the conditional probabilities with respect to all the combination of values of the variables associated to the parent nodes. For each *root variable* (variable without parents), the marginal prior probabilities are assigned. The quantitative analysis is based on the *d-separation* and conditional independence assumptions [6]. Based on these assumptions, the joint probability distribution is determined using the Chain Rule and encoded in the BN structure (or graph), between the variables. The joint probability distribution of a set of variables $\{X_1, X_2, \ldots, X_n\}$ can be factorized as in Eq. (1)

$$P[X_1, X_2, \ldots X_n] = \prod_{i=1}^{n} P[X_i \mid \text{Parent}(X_i)] \quad (1)$$

The basic inference task of a BN consists of computing the posterior probability distribution on a set of query variables *Q*, given the observation of another set of variables *E* called the *evidence* (i.e. $P(Q|E)$). The query variable Q could be assigned based on analysis demands. For cases that all RVs tend to be analyzed separately, *Q* will be set to a singleton composed of just one particular variable for each computation. Such computation may be sufficient in several applications. However, there may be cases requiring the computation of the posterior joint probability of a given set *Q* of variables. On the other hands, for cases that the analyst may desire to observe given the evidence *E*, the variable of each marginal posterior probability $P(X|E)$ for each variable *X*. Thus the algorithm called *Belief Updating* is adopted to derive the demanded results.

Recently, the popularity of BN starts to grow among system reliability analysts [6-8,13]. In this paper, we utilize the Bayesian network to model a FlexRay system and demonstrate how to assess the system reliability through the *Belief Updating*. Furthermore, a modeling issue in BN called *Multistate variables* [7,8] is considered when modeling the synchronization scheme adopted in the FlexRay cluster. The details could be found at Section V.

III. BN Reliability Modeling of FlexRay systems

A. Steer-by-wire example

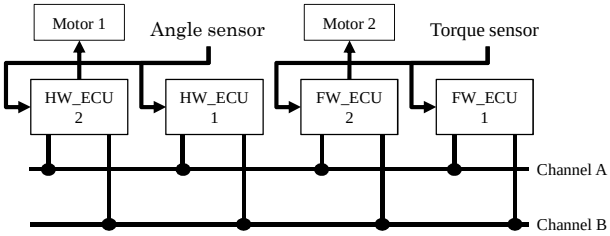


Fig. 1. A steer-by-wire system with passive bus topology

A SBW system proposed in [9] consists of two parts, steering wheel and front wheel. It contains four ECUs and two motors as shown in Fig. 1. The four ECUs have been implemented by FlexRay nodes, in which HW_ECU2 is a duplication of HW_ECU1 for steering wheel part. Likewise, FW_ECU1 and FW_ECU2 are grouped as a fault-tolerant unit for front wheel part. HW_ECUs are responsible for receiving steering wheel angles from the angle sensor, and sending the angle information to FW_ECUs through the FlexRay channel. Once FW_ECUs receive angle information, they will be based on the desired angle and current vehicle speed to calculate and output the torque of the motor to achieve the desired front wheel control. Meanwhile, the torque sensor collects the torque of the front motor, then FW_ECUs send the torque information to HW_ECUs through FlexRay Bus in order to produce the adjustable steering feel that is generated by the hand motor.

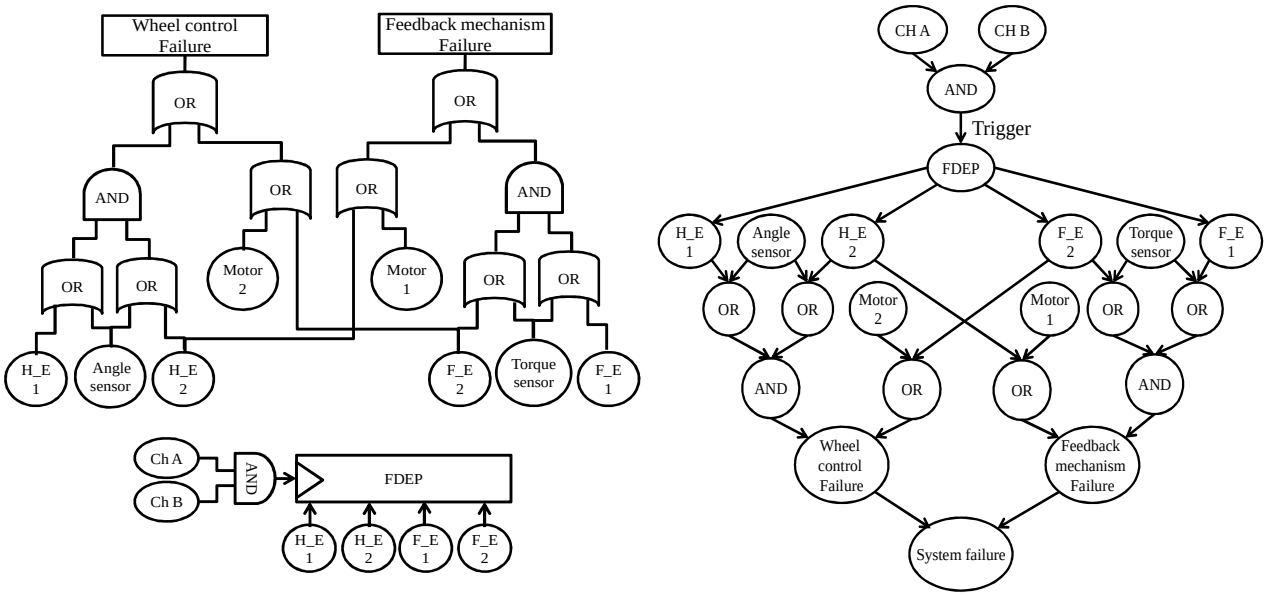


Fig. 2. (a) DFT for the steer-by-wire system illustrated in Fig. 1 and (b) the corresponding BN

B. BN modeling for various network topologies

FlexRay protocol supports three types of network topologies: bus, star and hybrid combination of these two topologies. When implementing a star topology, an additional hardware, termed as star coupler, is required so that the hardware cost is relatively higher than FlexRay system with simple bus topology. Typical network topologies enumerated in FlexRay protocol specification [1] were adopted to implement the communication network of SBW systems, and the equivalent BN for each network topology configuration is also given in the following subsections.

B.1 Passive bus topology

As Fig. 1 shows, the four FlexRay nodes are connected through redundant bus, Channel A and Channel B. Additionally, only the HW_ECU2 is connected to Motor 1 and FW_ECU2 is connected to Motor 2, respectively, although duplicated ECUs are adopted. For the adopted SBW system, there are two system failure modes. One is the wheel control failure, which represents the wheel not turned as expectation. The other is the feedback mechanism failure. In a SBW system the vehicle driver relies on the steering feel to sense the force of front wheel tire-road surface contact which is virtualized according to the feedback information. Therefore failed feedback process may lead drivers to make wrong steering decisions. The corresponding DFT is illustrated in Fig. 2(a) where the CH, H_E and F_E are the abbreviations of Channel, HW_ECU and FW_ECU, respectively. Then the algorithm proposed in [7-8] was used to convert the FT into BN. Each gate in DFT is represented by a node embedded with corresponding conditional probability table (CPT). In Fig. 2(b), the nodes H_E1 and H_E2 are combined with an AND node because H_E2 is a duplicate of H_E1. Contrarily, there is no duplication for motor 2 and wheel angel sensor, and therefore, OR node is used. We note that FDEP node is employed in Fig. 2(b) to describe the effect of channel failures on the FlexRay nodes. The trigger event of FDEP node is the output of an AND gate whose inputs are CH A and CH B. This FDEP manifests that when both of CH A and CH B fail, the four ECUs are also regarded as failure because the message transmission must rely on the correct function of the channels A or B.

B.2 Dual channel single star

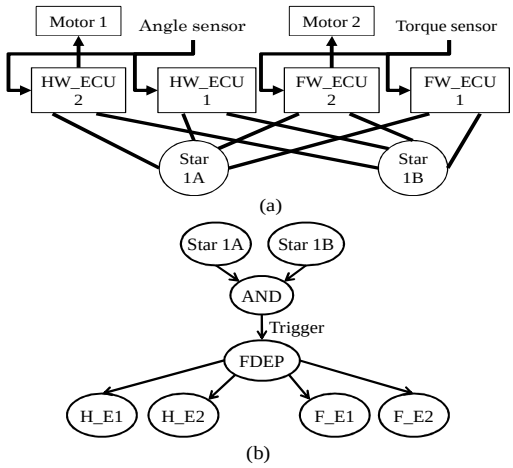


Fig. 3. (a) Dual channel single star topology and (b) the corresponding BN where only nodes connected to the FDEP node are illustrated

Similar to the bus topology shown in Fig. 1, a two-star topology can support redundant communication channels as well. The incoming signal received by the star coupler is actively driven to all communication ECUs. The logical structure (i.e., the ECU connectivity) of this topology is identical to that shown in Fig. 3. Because the BN for Fig. 3(a) is mostly equivalent to the BN in Fig. 2(b) except the FDEP part (as shown in Fig. 3(b), the trigger event of FDEP gate changes to the AND result of two star couplers, Star 1A and Star 1B), only the FDEP node is presented to demonstrate the influence of different topology.

B.3 Single channel cascaded star

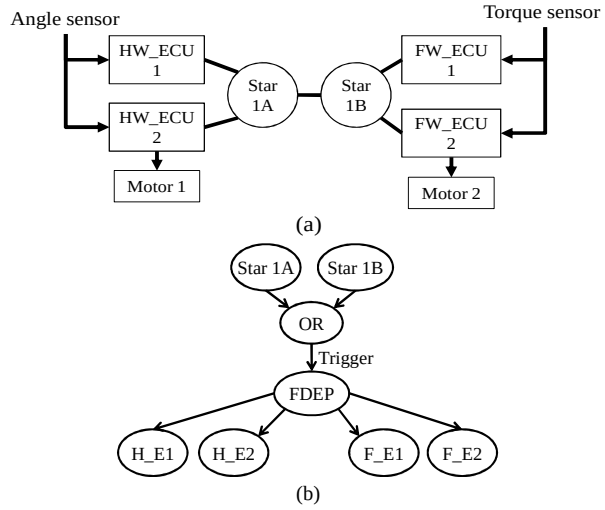


Fig. 4. (a) Single channel cascaded star topology and (b) the corresponding BN where only nodes connected to the FDEP node are illustrated

Fig. 4(a) shows a single channel network built with two star couplers. Each node has a point-to-point-connection to one of the two star couplers. The first star coupler (1A) is directly connected to the second star coupler (1B). Therefore, the failure of one of two star couplers will cause the communication malfunction.

IV. Reliability Assessment of FlexRay system

When assessing the system reliability, the failure rate of each component must be given. In this study, the failure distribution of all components is assumed to be exponential with the failure rates (expressed as number of failure per hour, in *f*/*h* unit). We adopt the cumulative failure distribution function $F(t) = 1- R(t) = 1-e^{-\lambda t}$ to derive the failure probability of each component. Table I summarizes the failure probability for each component. Failure rates for channels, sensors and motors in Table I are referred to [10]. On the other side, failure rates of the star coupler and FlexRay ECUs are not available in published literature based on the best of our knowledge. Thus for each star coupler and ECU, failure rates in Table I are referred to their similar components. The failure rate of each star coupler is referred to the failure rate of network switch [11] which can be viewed as behaviorally similar to the star couplers. The failure rate of each ECU is referred to [10] which provided the failure rate for a microprocessor. However, a FlexRay ECU consists of a host CPU, the communication controller and bus driver, and therefore, the ECU failure rate can be expected to exceed the failure rate of a microprocessor. Consequently, we assign the failure rate of each ECU a greater value than the microprocessor's failure rate.

TABLE I
FAILURE PROBABILITY FOR EACH COMPONENT, EVALUATED AT t = 500 h

Component	Failure Rate (f/h)	Failure Probability (t = 500h)
HW_ECU 1,2; FW_ECU 1,2	$6.28*10^{-4}$	0.269481
Channel A,B	$8.75 * 10^{-4}$	0.730854
Star 1A, 1B	$0.17* 10^{-4}$	0.025178
Motor 1,2	$7.9 * 10^{-7}$	0.001184
Angle sensor, Torque sensor	$6.06*10^{-5}$	0.086891

TABLE II
SYSTEM UNRELIABILITY FOR EACH TOPOLOGY

Topology Type	Failure Probability (for each failure mode)	System unreliability
T_1: Dual channel bus	0.461343	0.70985
T_2: Dual channel single star	0.343077	0.56845
T_3: Single channel cascaded star	0.358813	0.58888

Forward (*predictive*) propagation mechanism of BN can be used to derive the priori probability of the *TE* (top event). Therefore the system unreliability at a mission time t = 500h can be acquired. The results for three topologies considered in this study are summarized in Table II. We should point out that 'Wheel control Failure' and 'Feedback mechanism Failure' shown in Fig. 2(b) have the same occurring probability for a particular topology type. If one of these two failure modes happens then the SBW system fails. So the priori probability for *TE* as the system unreliability is obtained according to the OR result of the two failure modes as shown in the Table II. If we rank the hardware cost among all topologies by the number of used star couplers, then the rank is: $T_1 < T_2 = T_3$. On the other hand, the rank of system unreliability is: $T_2 < T_3 < T_1$, which shows that the system with topology T_1 has the lowest reliability among three network topologies.

V. Modeling FlexRay synchronization service

FlexRay is a time-triggered communication system. A basic assumption for such a time-triggered system is that all ECUs in the system have a common time base. However, there is no global time in a FlexRay system. Each ECU is equipped with its own clock. Consequently, there must have a distributed clock synchronization mechanism in which

each ECU can synchronize itself to the system by adapting its local time to the global time based on the timing of transmitted sync frames from other ECUs. A fault-tolerant midpoint clock synchronization algorithm (FTMSA) is used to provide a common time base to all ECUs [1]. The concept of this algorithm can be simply divided into four steps: receiving sync frames from other ECUs, calculating the timing offsets between itself and other synchronization ECUs, discarding the *k* largest and the *k* smallest offset values and computing the midpoint value by averaging the largest and the smallest of the remaining offset values. The resulting value is assumed to represent the ECU's deviation from the global time base and serve as the correction term. Table III shows how to determine the *k* value which is based on the number of received sync frames, i.e. available offset values.

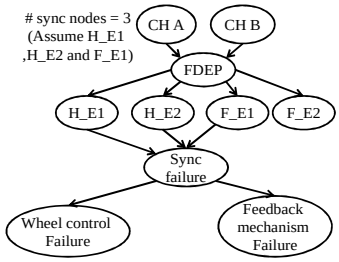
TABLE III
K VALUES FOR VARIOUS NUMBERS OF RECEIVING SYNC FRAMES [1]

Number of values	*k*
1-2	0
3-7	1
>7	2

According to Table III, it is transparent that the clock synchronization can still work even when some sync ECUs crash. For example, if there are three sync ECUs in our SBW system, then one faulty sync ECU could be tolerable. Two or three faulty sync ECUs will cause the failure of synchronization service because there is at least one ECU which cannot receive any correct sync frames. To model the effectiveness of the FTMSA, a new BN node termed as "Sync failure" is inserted into the BN illustrated in Fig. 2(b) and the corresponding cause-effect relation must be maintained. For the sake of clarity, only the nodes relevant to the "Sync failure" node are extracted from Fig. 2(b) and the resulting BN is shown in Fig. 5. In this case study, we assume that once the clock synchronization is lost, the steering control will also be affected because the ECUs will not be able to receive frames correctly under this situation. Hence, the synchronization failure is treated as a cause for the wheel control failure and feedback mechanism failure. Similar BN modeling concept can be applied to other topologies T_2 and T_3 as well. To more accurately model the effect of faulty ECUs on synchronization failure, we further classify a ECU potential failures into three failure modes: babbling idiot (represented as *FM(1)*), sending no frames (*FM(2)*), and sending wrong frames (*FM(3)*). We note that the star coupler is capable of identifying the failure of babbling idiot originated from faulty ECUs and isolating them, so modeling such error containment capability of the star coupler in the BN reliability assessment is imperative to raise the accuracy of the analysis.

Contrast to the BNs in Fig. 2(b), 3(b) and 4(b), where the state of an ECU could be either in working state or in failed state, the BN in Fig.5 is transferred to a so-called *multistate* system. Although a multistate system can be modeled by constructing individual fault trees for each possible combination constituted by various states [12], the multistate feature can be easily modeled into a BN through the CPT construction as exhibited in Fig. 5. Thus the modeling complexity significantly reduces.

The CPT in Fig. 5 shows that the passive bus topology cannot prevent any babbling idiot caused by ECUs. On the contrary, star couplers are able to tolerate the error of babbling idiot by isolating the faulty ECUs which produce the phenomenon of babbling idiot. In our SBW system, there are three sync ECUs, so only one faulty sync ECU generating babbling idiot can be tolerated. When two faulty sync ECUs occur the babbling idiot phenomenon, the remaining sync ECU can still send the sync frames out but it fails to receive any sync frames from other sync ECUs. Therefore, this ECU itself will eventually enter the synchronization failure state. Clearly, the CPT of BN for T_2 and T_3 can be constructed through modifying the CPT in Fig. 5 by changing the 2^{nd}~4^{th} rows of the probability of synchronization failure, *P(Sync failure)*, from 1 to 0. Furthermore, to concentrate on the fault-tolerant effectiveness of the star coupler, in this paper we assume only the *FM(1)* can lead system to sync failure state.



H_E1	H_E2	F_E1	*P*(Sync failure)
W	*W*	*W*	0
W	*W*	*FM(1)*	1
W	*FM(1)*	*W*	1
FM(1)	*W*	*W*	1
W	*FM(1)*	*FM(1)*	1
FM(1)	*W*	*FM(1)*	1
FM(1)	*FM(1)*	*W*	1
FM(1)	*FM(1)*	*FM(1)*	1

$$\Pr(ECU = W) = \exp(-\lambda \cdot t)$$
$$\Pr(ECU = FM\,(1 \text{ or } 2 \text{ or } 3)) = 1/3(1-\exp(-\lambda \cdot t))$$

Fig. 5. BN for modeling the synchronization failure of T_1 with the corresponding CPT, where '*W*' represents working state

CPTs for ECUs to their children OR gates in Fig. 2(b) are omitted but they should need to be reconstructed by similar way with consideration of only *FM(2)* and *FM(3)*. Each ECU node in Fig. 5 has four states: *FM(1)*, *FM(2)*, *FM(3)* and *W*.

The prior probabilities of the ECU node in the four different states are also reported in Fig. 5. In this study we assume the occurring probabilities for the three failure modes are equivalent, therefore their prior probabilities are equally shared from the failure rate of the ECU. Thus we can define π(ECU) for nodes H_E1, H_E2, F_E1 and F_E2 while π(ECU) = (Pr(ECU=*FM(1)*), Pr(ECU=*FM(2)*), Pr(ECU=*FM(3)*), Pr(ECU=*W*)) = ($1/3*(1-e^{-\lambda t})$, $1/3*(1-e^{-\lambda t})$, $1/3*(1-e^{-\lambda t})$, $e^{-\lambda t}$). ECUs cannot transmit frames when the dual channel (bus or star) is failed. So there are two possibilities to cause all ECUs enter the *FM(2)*: sending no frame state. One is from ECU itself, the other is from the

communication media failure. Consequently, the message $\pi_{Sync\ failure}$(ECU) that three nodes H_E1, H_E2, F_E1send to the Sync failure node as shown in Fig. 5 can be computed by:

$$\pi_{SF}(ECU) = \alpha \cdot \lambda(ECU)\pi(ECU) = \alpha \cdot (1,1,1,1) \cdot \sum_{\boldsymbol{u}} p(x \mid \boldsymbol{u}) \prod_{i=1}^{2} \pi_{ECU}(u_i)$$

$$= \begin{cases} 1 \cdot \pi(ECU = FM(1)), \\ 1 \cdot [\, p(\neg SF \mid +FM(2), +FDEP) \cdot \pi(ECU = FM(2)) \cdot \pi(\neg \text{FDEP}) \\ \quad + p(\neg SF \mid \neg FM(2), +FDEP) \cdot \pi(ECU \neq FM(2)) \cdot \pi(+\text{FDEP}) \\ \quad + p(\neg SF \mid +FM(2), \neg FDEP)] \cdot \pi(ECU = FM(2)) \cdot \pi(\neg \text{FDEP}) \\ 1 \cdot \pi(ECU = FM(3)), \\ 1 \cdot \pi(ECU = W) \end{cases}$$

where *SF* represents the Sync failure and each λ(ECU) received from the descendants of nodes H_E1, H_E2, F_E1 is set to (1,1,1,1) here. Table IV shows the results of system unreliability derived from dichotomy and multistate modeling schemes for various topology types.

TABLE IV
ERROR CONTAINMENT CAPABILITY OF STAR COUPLER BY MULTISTATE BN MODELING

Topology Type	System unreliability (dichotomy)	System unreliability (multistate)
T_1: Dual channel bus	0.70985	0.70424
T_2: Dual channel single star	0.56845	0.41432
T_3: Single channel cascaded star	0.58888	0.4396

From Table IV we observe that the system unreliability of T_2 and T_3 for multistate model is lower than dichotomy model because the multistate model takes the failure modes of a node as well as the error containment capability of star coupler into account. Consequently, the fault-tolerant power of star coupler can be precisely modeled, and therefore, the lower failure probability derived from the multistate model reflects the effectiveness of fault tolerance offered by the star coupler. It is evident that the multistate model can dramatically raise the accuracy of reliability assessment. We also observe that the system failure probabilities of T_1 are almost the same for both modeling schemes because the passive bus topology has no ability to guard any babbling idiot failure. In summary, we demonstrate that the multistate modeling mechanism can effectively model not only the error containment capability of star couplers but also the influence of synchronization failure on FlexRay system reliability. The proposed modeling methodology is very useful when evaluating the reliability of the FlexRay safety-critical automotive systems.

VI. Conclusions and Future Work

In this paper, we have illustrated how to apply BN to a FlexRay system for rapidly attaining a prior estimation of the system reliability. Quantitative results show various network topologies could lead to the notable difference in the probability of the system failure. We also demonstrate how to model the FTMSA, one of the most important FTMs in a FlexRay protocol into the BN reliability analysis. Through extending the BN from the dichotomy to a multistate model, the effectiveness of the FTMSA as well as the fault-tolerant power of star coupler on reliability improvement can be obtained. Therefore the potential and suitability of BN inference for modeling FlexRay system reliability is validated. The related issue under investigation is how to utilize the BN inference to obtain a reliable FlexRay system design which is accordant with the popular safety criteria such as IEC 61508 or ISO 26262.

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