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Reliability analysis for wireless communication networks via dynamic Bayesian network

YANG Shunqi[1], ZENG Ying[2,3,*], LI Xiang[2], LI Yanfeng[2], and HUANG Hongzhong[2]

1. School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China;
2. School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China; 3. China University of Petroleum at Karamay, Karamay 834000, China

Abstract: The dynamic wireless communication network is a complex network that needs to consider various influence factors including communication devices, radio propagation, network topology, and dynamic behaviors. Existing works focus on suggesting simplified reliability analysis methods for these dynamic networks. As one of the most popular modeling methodologies, the dynamic Bayesian network (DBN) is proposed. However, it is insufficient for the wireless communication network which contains temporal and non-temporal events. To this end, we present a modeling methodology for a generalized continuous time Bayesian network (CTBN) with a 2-state conditional probability table (CPT). Moreover, a comprehensive reliability analysis method for communication devices and radio propagation is suggested. The proposed methodology is verified by a reliability analysis of a real wireless communication network.

Keywords: dynamic Bayesian network (DBN), wireless communication network, continuous time Bayesian network (CTBN), network reliability.

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1. Introduction

With the rapid development of radio-frequency technology, wireless communication turns to be an essential technology in business, transportation, and daily life [1]. As the transmission rate of communication increases, its defects such as disconnecting from the internet appear gradually. A reliable wireless communication network becomes more and more important, and more research is devoted to reliability analysis of wireless communication networks [2–4]. Radio propagation reliability [5], communication device reliability [6], and wireless communication network reliability [7] are three of the hottest issues in communication reliability analysis. Sufficient scientific achievements are applied to the former two topics, but wireless communication network reliability analysis is still a difficult problem. How to quantify the impacts of devices and radio propagation reliability on the full networks is one of the most important questions that need to be solved urgently.

For radio propagation reliability, one of the most popular analytical methods is to evaluate the path loss [8], which is the most effective factor in radio communication. Research on path loss released by international communication sectors provides influence factors of communication scenarios [9], line-of-sight (LOS) probability [10], and antennas [11]. Path loss models provide an empirical model to describe a linear proportionality between the communication distance and path loss under different scenarios. Existing radio propagation reliability models [12] adopt the lognormal distribution to fit the distribution of communication distance and derive the probability distribution function (PDF) of path loss, which can be applied to evaluate the radio propagation reliability via the threshold of path loss value.

The communication station is an infrastructural device for wireless communication networks. It includes several electronic components such as the voltage-controlled oscillator (VCO), the band-pass filter (BPF), and the low-noise amplifier (LNA) [13]. For a single component, there are many methods to evaluate the reliability such as finite element simulation [14]. However, if these components are integrated into one device, the complex logical structure and dynamic characteristics make it difficult to analyze the reliability of this device. Particularly, in a wireless communication network, there are several failure distributions for each node, including discrete distributions and continuous distributions. Therefore, further research is required for analyzing this station.

Existing studies on dynamic network reliability analysis have proposed several methods including the Markov regenerative process [15], the dynamic fault tree [16], and the dynamic Bayesian network (DBN) [17]. Among these

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*Corresponding author.

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methods, DBN is one of the most efficient tools to evaluate the dynamic impact on the system. Existing algorithms for DBN include the discrete-time Bayesian network (DTBN) [18] and the continuous-time Bayesian network (CTBN) [19]. The DTBN has been sufficiently studied and applied to dynamic network reliability analysis with components following different failure distributions, but it needs high memory cost and cannot be applied to non-temporal variables. CTBN, however, provides a closed-form solution that can be applied to reliability and sensitivity analysis.

For a wireless communication network, its device failure is a temporal event, however, radio propagation failure is affected by non-temporal factors such as communication distance, terrain shading, and LOS [12]. Therefore, reliability analysis for a wireless communication network should consider different dynamic elements. CTBN is one of the suitable methods for multiple heterogeneous nodes and provides a closed-form solution that can integrate the binary discrete events into a temporal system expediently. Therefore, this paper proposes a generalized CTBN with a 2-state conditional probability table (CPT) which can be applied to DBN with mixed failure distributions.

2. DBN

The failure process of complex systems always has complex dynamic characteristics related to failure time and sequence. Motivated by this complexity, DBN is proposed to overcome the deficiencies of static Bayesian network (BN) in dynamic reliability analysis. Different from static BN, DBN extends its model for temporal system analysis issues. Meanwhile, DBN considers more logic gates including a warm spare (WSP) gate. Events in DBN have a temporal distribution associated with them. According to different temporal representations, two main modeling methods (DTBN and CTBN) for DBN have been proposed.

As one of the most popular approaches, DTBN provides a standard inference engine for DBN, which can be applied to various kinds of system reliability analysis. In a DTBN, mission time is divided into serval intervals, and the marginal probability density (MPD) & conditional probability density (CPD) of each node is replaced by the marginal probability table (MPT) and CPT. However, as the state space of a DTBN is discrete, it can only get an approximate solution in a specific time interval. The size of CPT will increase exponentially with the increasing number of nodes and time intervals. For a complex system such as the wireless communication network, DTBN modeling is time-consuming and inapplicable. Thus, as an optimized algorithm, CTBN is proposed. Events in CTBN are following continuous failure distributions. All of the MPD & CPD are presented in forms of functions. For example, the conditional PDF $f_{T|A,B}(T|A,B)$ of AND node T in Fig. 1(a) with a CTBN formalism [19] is shown as

$$f_{T|A,B}(T|A,B) = u(b-a)\delta(t-b) + u(a-b)\delta(t-a) \quad (1)$$

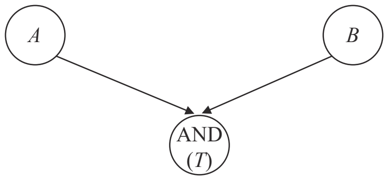
where

$$u(x) = \begin{cases} 0, & x < 0 \\ 1/2, & x = 0 \\ 1, & x > 0 \end{cases},$$

for $x \neq 0, \delta(x) = 0$, and $\int_0^{\infty} \delta(t)\mathrm{d}t = 1$, $\int_0^{\infty} f(t)\delta(t-\tau)\mathrm{d}x = f(\tau)$.

A	1	2
P	$F_A(t)$	$R_A(t)$

B	1	2
P	$F_B(t)$	$R_B(t)$

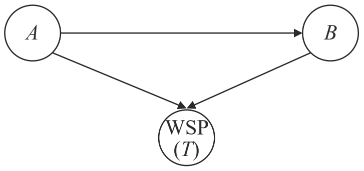


A		1		2	
B		1	2	1	2
T	1	1	0	0	0
	2	0	1	1	1

(a) AND gate

A	1	2
P	$F_A(t)$	$R_A(t)$

A		1	2
B	1	$P(B=1\mid A=1)$	$P(B=1\mid A=2)$
	2	$P(B=2\mid A=1)$	$P(B=2\mid A=2)$



A		1		2	
B		1	2	1	2
T	1	1	0	0	0
	2	0	1	1	1

(b) WSP gate

Fig. 1 MPT and CPT for the logic gates

Through $f_{T|A,B}(T|A,B)$, $F_T(t) = F_A(t)F_B(t)$ can be derived. With the closed-form solution of PDF, CTBN can get precise reliability at an instant time. However, there is no CTBN inference engine for general distribution. For these problems, this paper proposes a CTBN formalism with a 2-state CPT, as shown in Fig. 1.

In Fig. 1(a), $P(A=1) = F_A(t)$ denotes the failure probability of node A, while $P(A=2) = R_A(t) = 1 - F_A(t)$ denotes the reliability of node A.

For AND gate,

$$P(T=h|\mathrm{Pa}(T_i)=p_i)=\begin{cases}1, & h=\max(p_i)\\ 0, & \text{otherwise}\end{cases}.$$

For OR gate,

$$P(T=h|\mathrm{Pa}(T_i)=p_i)=\begin{cases}1, & h=\min(p_i)\\ 0, & \text{otherwise}\end{cases}$$

where $\mathrm{Pa}(T_i)$ is the parent node of node T, p_i and h denote the state of each node and are equal to 1 or 2. Based on this fundamental theory, the CPT for dynamic logic gate in the DBN can be derived.

WSP [19] is a typical dynamic logic gate in the DBN which defines a dormant node and a primary node. As shown in Fig. 1(b), node B is a standby node of node A. When node A is working, node B works in a dormant condition, and its hazard rate λ_B is reduced by a dormancy factor α, $0 \leqslant \alpha \leqslant 1$. Node B will change into working condition after node A fails.

Assume that $f_B(t)$ and $f_{\alpha B}(t)$ are the PDFs of node B in working condition and dormant condition respectively. t_A and t_B denote the failure time of nodes A and B.

Typically, when the failure time distributions of nodes A and B follow the exponential distribution, i.e., given $f_A(t_A)=f_B(t)=\lambda \mathrm{e}^{-\lambda t}$ and $f_{\alpha B}(t)=\alpha\lambda\mathrm{e}^{-\alpha\lambda t}$, the CPT of node B can be presented in Table 1.

Table 1 CPT of node *B* in Fig. 1(b)

B	A	
	1	2
1	$1-\dfrac{\mathrm{e}^{-\lambda t}\left(1-\mathrm{e}^{-\alpha\lambda t}\right)}{\alpha(1-\mathrm{e}^{-\lambda t})}$	$1-\mathrm{e}^{-\alpha\lambda t}$
2	$\dfrac{\mathrm{e}^{-\lambda t}\left(1-\mathrm{e}^{-\alpha\lambda t}\right)}{\alpha(1-\mathrm{e}^{-\lambda t})}$	$\mathrm{e}^{-\alpha\lambda t}$

Via CPT of node B, we can obtain the marginal probability $F_B(t)$ and $R_B(t)$ through (2) and (3).

$$F_B(t)=P(B=1)=\sum_{i=1}^{2}P(B=1|A=i)P(A=i)=$$
$$1-\frac{1}{\alpha}\mathrm{e}^{-\lambda t}+\frac{1-\alpha}{\alpha}\mathrm{e}^{-\lambda(1+\alpha)t}, \tag{2}$$

$$R_B(t)=P(B=2)=\sum_{i=1}^{2}P(B=2|A=i)P(A=i)=$$
$$\frac{1}{\alpha}\mathrm{e}^{-\lambda t}-\frac{1-\alpha}{\alpha}\mathrm{e}^{-\lambda(1+\alpha)t}=1-F_B(t). \tag{3}$$

The marginal probability of node B is the same as the CTBN results in [19], however, with the modeling method of CPT, this methodology can be conveniently applied to system reliability analysis via Bayesian network toolbox (BNT) for Matlab [20].

3. Methodology

3.1 Radio propagation reliability evaluation

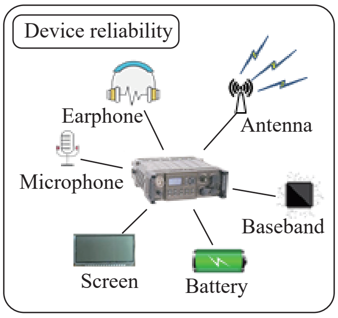
As introduced in Section 1, radio propagation reliability [21−24] is influenced by shadow fading and communication distance. In our previous work [12], Okumura-Hata model [8] and the lognormal distribution were used to model the closed-form solution of the PDF of path loss value L, which denotes the signal attenuation under different communication scenarios, and can be applied to radio propagation reliability evaluation. According to previous research, L follows the normal distribution, and its threshold L_T is given by [12], the reliability of radio propagation can be obtained as

$$R=\int_0^{L_T}\frac{1}{(19.5-2.84\lg h_b)\sqrt{2\pi}\sigma_{\ln d}}\cdot$$
$$\exp\frac{[l-((19.5-2.84\lg h_b)\mu_{\ln d}+69.55+26.16\lg f_c-13.82\lg h_b-\alpha(h_{\mathrm{re}})+C_{\mathrm{cell}}+C_{\mathrm{terrain}})]^2}{(19.5-2.84\lg h_b)^2\sigma_{\ln d}^2}\mathrm{d}l \tag{4}$$

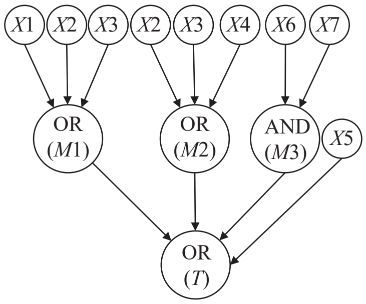
where d denotes the communication distance, and $\ln d \sim \mathrm{N}(\mu_{\ln d},\sigma_{\ln d}^2)$. h_b and h_{re} denote the effective height of the base station and the receiving station; C_{cell}, C_{terrain} and $\alpha(h_{\mathrm{re}})$ are the correction factors for communication cell type, terrain and h_{re}.

3.2 Devices reliability analysis

In reliability analysis of a wireless communication network, devices' failures are typical temporal events that follow an exponential distribution [25−27]. It is worth noting that the proposed method is also applicable to the non-exponential case. However, the failure life of electronic products usually follows an exponential distribution, which is adopted in this paper. The radio station is the main device in this network. As shown in Fig. 2(a), the communication-related components in a radio station are provided. According to this structure, DBN for communication function can be modeled and shown in Fig. 2(b), and the description for each node is shown in Table 2.



(a) Communication related components in a station



(b) DBN of communication station

Fig. 2 Communication station

Table 2 Description for each node in Fig. 2(b)

Node	Description	Node	Description
T	Communication fails	*X*3	Antenna fails
*M*1	Transmitting failure	*X*4	Earphone fails
*M*2	Receiving failure	*X*5	Screen fails
*M*3	Power system fails	*X*6	Battery I fails
*X*1	Microphone fails	*X*7	Battery II fails
*X*2	Baseband fails		

As shown in Fig. 2(b) and Table 2, nodes *X*2 (baseband fails) and *X*3 (antenna fails) are the common failures of nodes *M*1 (transmitting failure) and *M*2 (receiving failure). There are two batteries (*X*6, *X*7) for the power system (*M*3), i.e., *M*3 is the AND of nodes *X*6 and *X*7.

For the OR nodes in this DBN (*M*1, *M*2, *T*), the algorithm to calculate the CPT of OR nodes with *i* parent nodes can be proposed in Algorithm 1.

Algorithm 1 CPT for OR gate with *i* parent nodes

```
Input: $i \leftarrow$ the number of parent nodes
        CPT $\leftarrow$ zeros([2, $2^i$])
        for $P_1 \leftarrow$ 1 to 2
            for $P_2 \leftarrow ((P_1-1)\times 2+1) : P_1\times 2$
            ...
                for $P_i \leftarrow ((P_{i-1}-1)\times 2+1) : P_{i-1}\times 2$
$h = \min[P_1, P_2-(P_1-1)\times 2, \cdots, P_i-(P_{i-1}-1)\times 2]$
                CPT$([h, P_i]) = 1$
                end for
            ...
            end for
        end for
Output CPT
```

Typically, the reliability of node power system *T* can be obtained as

$$R_T(t) = P(T=2) = R_{M3}(t)\prod_{i=1}^{5} R_{Xi}(t) \tag{5}$$

where $R_{Xi}(t)$ is the reliability of node *Xi* (*i*=1, 2, ⋯, 5); $R_{M3}(t)$ represents the reliability of the power system *M*3.

3.3 Network reliability analysis

Wireless communication network reliability analysis [28−30] needs to consider the reliability of each device and radio propagation. However, these two events follow temporal and non-temporal failure distributions. For this problem, a solution of CTBN formalism with a 2-state CPT is proposed. As shown in Fig. 3, a simple wireless communication network is provided, where station I connects to station II via a certain frequency. The DBN of this communication mission is constructed. As shown in Fig. 4, nodes *A* and *B* represent the temporal failure events of corresponding stations, while node *W* represents the non-temporal failure event of radio propagation. As one of these three node fails, node *T* fails, i.e., node *T* is the OR gate of nodes *A*, *B*, and *W*. The MPTs & CPTs are also provided in Fig. 4.

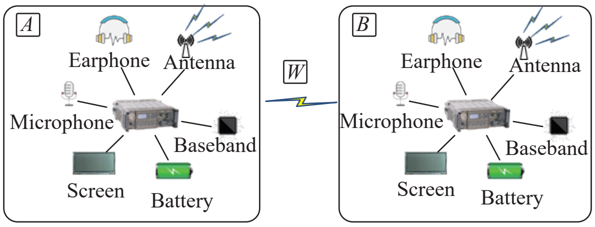
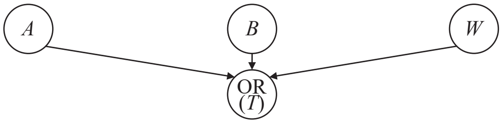


Fig. 3 Wireless communication network

A	1	2	*B*	1	2	*W*	1	2
P	$F_A(t)$	$R_A(t)$	*P*	$F_B(t)$	$R_B(t)$	*P*	F_W	R_W



A		1				2			
B		1		2		1		2	
W		1	2	1	2	1	2	1	2
T	1	1	1	1	1	1	1	1	0
	2	0	0	0	0	0	0	0	1

Fig. 4 DBN for network in Fig. 3

4. Case study

In this section, an application example of a wireless communication network is provided. As shown in Fig. 5, this network consists of five nodes (*A*, *B*, *C*, *D*, and *E*). The mission of node *A* connecting node *D* needs to pass through corresponding communication stations and radio bands. Node *A* has three communication stations (*A*1, *A*2, and *A*3), stations *A*1 and *A*2 are working in parallel while station *A*3 is the cold spare station of them. *W*2 is the cold spare band of band *W*1 which these stations work on. Node *B* has two communication stations (*B*1 and *B*2), station *B*1 is responsible for connecting node *A* while station *B*2 connects node *C* via band *W*3. Node *C* has three stations (*C*1, *C*2, and *C*3) which connect nodes *B*, *D*, and *E* respectively. In node *D*, *D*2 is cold spare station of station *D*1.

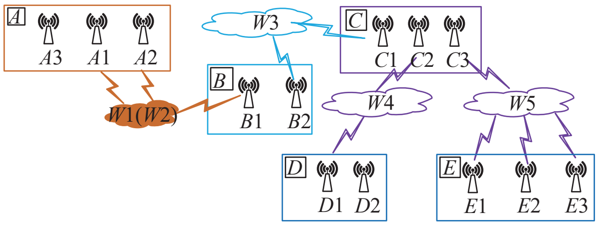


Fig. 5 Wireless communication network topology

The DBN of communication between nodes *A* and *D* is constructed and shown in Fig. 6.

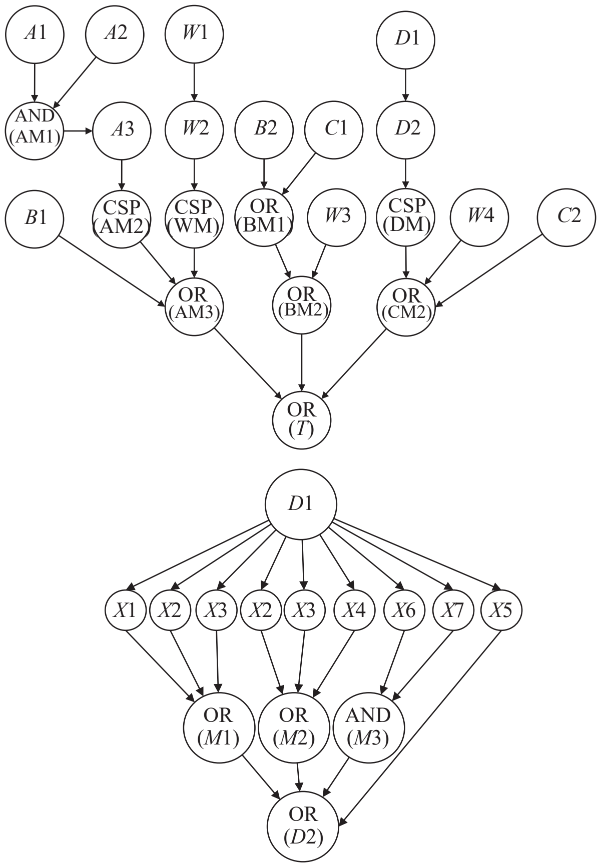
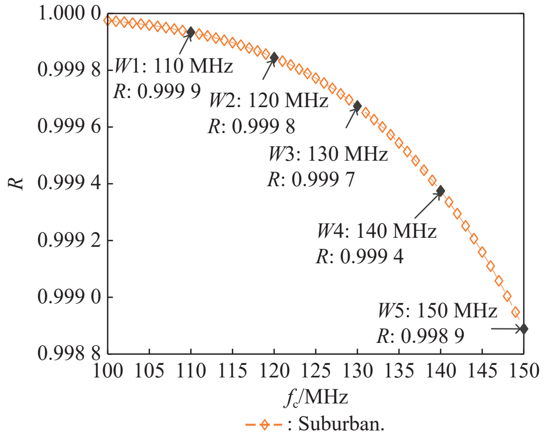
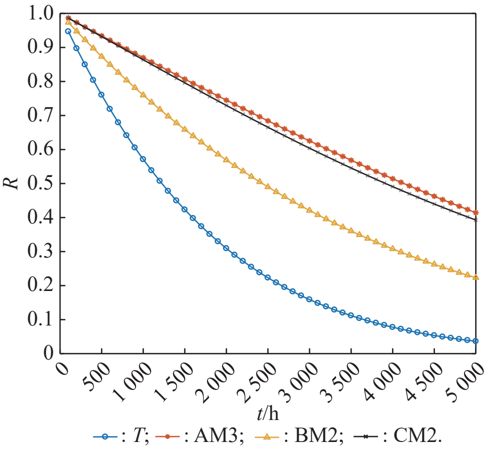


Fig. 6 DBN for a wireless communication network in Fig. 5

There are three types of logic gates in this DBN including AND, OR, and cold spare (CSP) gates, among them three CSP nodes (*A*3, *W*2, *D*2) are included. Although the three nodes are all CSP nodes but not the same, nodes *D*2 and *A*3 represent spare communication stations which are temporal events, according to the DBN in Fig. 7, when these stations are in a dormant state, their base events are also in a dormant state. For instance, the DBN of nodes *D*1 to *D*2 will change to the structure shown in Fig. 6. The CPTs of nodes *X*1−*X*7 can be modeled as Table 3. The failure distributions of these nodes all follow the exponential distribution and λ_i is the hazard rate of node *Xi* (i=1,2,$\cdots$,7) listed in Table 4. $f_{D1}(t_{D1})$ is the PDF of failure time while t_{D1} is the failure time of node *D*1.



(a) Communication frequency



(b) Communication mission between each node

Fig. 7 Reliability curves

Table 3 CPT of node *W*1

*D*1		1	2
Xi(i=1, 2, $\cdots$, 7)	1	$1-\dfrac{\mathrm{e}^{-\lambda_i t}\int_0^t f_{D1}(t_{D1})\mathrm{e}^{\lambda_i t_{D1}}\mathrm{d}t_{D1}}{\int_0^t f_{D1}(t_{D1})\mathrm{d}t_{D1}}$	0
	2	$\dfrac{\mathrm{e}^{-\lambda_i t}\int_0^t f_{D1}(t_{D1})\mathrm{e}^{\lambda_i t_{D1}}\mathrm{d}t_{D1}}{\int_0^t f_{D1}(t_{D1})\mathrm{d}t_{D1}}$	1

Table 4 Hazard rate of node *Xi* (i=1,2,⋯,7)

Number	Device	λ	Number	Device	λ
$X1$	Microphone	0.000 04	$X5$	Screen	0.000 01
$X2$	Baseband	0.000 02	$X6$	Battery I	0.000 067
$X3$	Antenna	0.000 023	$X7$	Battery II	0.000 067
$X4$	Earphone	0.000 04			

Node $W2$ represents the failure of spare communication frequency, which is a non-temporal event. The CPT of node $W1$ can be calculated through Table 5. The reliability of each communication frequency under the suburban scenario is shown in Fig. 7(a) [12].

Table 5 CPT of node *W*1

$W2$	$W1$	
	1	2
1	F_{W2}	F_{W2}
2	R_{W2}	R_{W2}

As shown in Fig. 6, four nodes in this DBN represent different communication missions, i.e., T (node A connects node D), AM3 (node A connects node B), BM2 (node B connects node C), and CM2 (node C connects node D). Based on the reliabilities of communication devices and radio propagation, the reliability of communication between each node can be calculated through Algorithm 2, where the states of these four nodes are both equal to 2.

Algorithm 2 Algorithm for DBN in Fig. 6

```
Input:
    $N \leftarrow$ number of nodes
    dag($N$,$N$) $\leftarrow$ adjacent matrix for DBN
    state number of each node $\leftarrow 2 * \text{ones}(1, N)$
for $i \leftarrow$ 1 to 50 do
    $t \leftarrow i * 100$
    bnet.CPD$\{N\}$ $\leftarrow$Probability Table for each node;
    define inference engine;
    $R \leftarrow$ marginal probabilities of T(2), AM3(2), BM2(2), M2(2);
end for
Output $R(t)$
```

Based on Algorithm 2 and BNT toolbox for Matlab [24], the communication reliability of each node in this network can be calculated as shown in Fig. 7(b). This methodology can comprehensively analyze the posterior probability of query nodes, which can be applied to marginal probability evaluation of each communication mission in this network.

5. Conclusions

This paper proposes a generalized CTBN with a 2-state CPT and derives the algorithms for logic gates including AND, OR, and WSP gates in DBN. Subsequently, reliability analysis methodologies for radio propagation, communication devices, and networks are presented. Moreover, a case study of reliability analysis for a wireless communication network is accomplished via this method. Overall, some conclusions are listed as follows.

(i) For the WSP gate, this generalized CTBN with a 2-state CPT can get the same closed-form solution of marginal probability as traditional CTBN. Furthermore, combined with the BNT toolbox for Matlab, reliability of such a wireless communication network with temporal and non-temporal events can be analyzed sufficiently.

(ii) A novel DBN structure for a wireless communication network is proposed. Simultaneously, different communication missions between each node are considered, and the posterior probability for these nodes can be analyzed directly through this DBN.

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Biographies

YANG Shunqi was born in 1982. He received his bachelor's and M.S. degrees in mechanical engineering from the University of Electronic Science and Technology of China, Chengdu, China, in 2007 and 2010, respectively. He is pursuing his Ph.D. degree in the School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan, China. His research interests include system reliability analysis and prognostic and health management.

E-mail: shunqiyang@foxmail.com

ZENG Ying was born in 1994. He received his M.S. and Ph.D. degrees in mechanical engineering from University of Electronic Science and Technology of China, Chengdu, China, in 2019 and 2023, respectively. He is a post doctor at University of Electronic Science and Technology of China. His research interests include reliability analysis of electronics and prognostics health management for electronics.

E-mail: zengying@uestc.edu.cn

LI Xiang was born in 1989. He received his M.S. degree from China University of Petroleum-Beijing in 2012. He is a Ph.D. at the School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China. His research interests include system reliability analysis and prognostics health management.

E-mail: lixiang@std.uestc.edu.cn

LI Yanfeng was born in 1981. He received his Ph.D. degree in mechatronics engineering from the University of Electronic Science and Technology of China, Chengdu, China, in 2013. He is currently a professor with the School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China. His research interests include reliability modeling and analysis of complex systems, dynamic fault tree analysis, and Bayesian networks modeling and probabilistic inference.

E-mail: yanfengli@uestc.edu.cn

HUANG Hongzhong was born in 1963. He is a full professor of mechanical engineering with the School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China, Chengdu, China. He is also the Director of the Center for System Reliability and Safety, University of Electronic Science and Technology of China. He has held visiting appointments at several universities in the USA, Canada, and Asia. His research interests include reliability engineering, optimization design, fuzzy sets theory, and product development.

E-mail: hzhuang@uestc.edu.cn