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Entropy-Based Reliability Evaluation Model for Network Data

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Abstract

Reliability is very important in wireless network since large number of wireless standards are widely used in our daily life. The network flow ratio and workload will increase significantly as well. It is observed that network manager is not able to ensure the reliability of the network even if the network connection is smooth. This paper proposes a network reliability evaluation model using factorization approach for the small and medium-sized wireless communication network. The factorization approach is a decomposition of an object into a product of other objects or factors, which when multiplied together give the original for example a number a polynomial or a matrix. With the model, the solution algorithms are proposed to work out the corresponding defined objectives. Experiments show that, the proposed model outperforms the ergodic method which uses large number of loops to obtain the network reliability. From the experiment, when $p_c = 0.9$ *and* $p_m = 0.1$ *as well as* $p_c = 0.9$ *and* $p_m = 0.01$*, it could be find that there are six transmission lines which are with the maximum reliability.*

Keywords: *Factorization Approach, Network Reliability, Evaluation Model*

1. Introduction

Reliability is very important in wireless network since large number of wireless standards are widely used in our daily life. The first study on network reliability was carried out by Mr. Lee in 1955 to investigate the reliability on telecom exchange network [1]. Due to the defects of the network devices, the total transmission capacity will be greatly reduced, resulting in network congestions [2-3]. The network will be crashed with large area that vast cost will be caused. As the development of computer science and technology, the scale and users of the network is sharply increasing. The network flow ratio and workload will increase significantly as well. It is observed that network manager is not able to ensure the reliability of the network even if the network connection is smooth [4]. The network congestion or delay can cause the reduction of network performance and some functionalities of the network will be out of work.

The reliability of a network is defined as “under certain situations, the capacity of executing the functions in the network given the limited time” [5]. The possibility of reliability is termed as reliability degree. That means under the condition it reflects the possibility of inefficient operations. The calculation of network reliability has been confirmed as NP hard [6]. Thus, it is challenging to figure out a method to work out the network reliability. Two types of network reliability calculation approach are widely used. They are accurate algorithm and approximation algorithm. The accurate algorithm is mainly used for calculating the reliability under small and medium-sized network which has special topology [7-9]. The accurate algorithm includes status enumeration method, inclusion-exclusion principle, factorization approach, *etc.* The approximation algorithm includes upper and low boundary approach, simulation method, *etc.*

This paper proposes a network reliability evaluation model using factorization approach for the small and medium-sized wireless communication network. The factorization approach is a decomposition of an object into a product of other objects or

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factors, which when multiplied together give the original for example a number a polynomial or a matrix [10]. The aim of factoring is usually to reduce something to “basic building blocks”, such as numbers to prime numbers, or polynomials to irreducible polynomials [11]. Factoring integers is covered by the fundamental theorem of arithmetic and factoring polynomials by the fundamental theorem of algebra. The opposite of polynomial factorization is expansion, the multiplying together of polynomial factors to an “expanded” polynomial, written as just a sum of terms. Integer factorization for large integers appears to be a difficult problem [12]. There is no known method to carry it out quickly. Its complexity is the basis of the assumed security of some public key cryptography algorithms, such as RSA [13].

The organization of this paper is as follows. Section 2 reports on the factorization approach principle. Section 3 illustrates the evaluation model based on the factorization approach. Section 4 discusses the experiments and analysis. Section 5 concludes this paper by giving the contributions and future research directions.

2. Factorization Principle

Factorization approach principle for calculating the network reliability is based on some rules to decompose the whole network into two sub-networks. With the sub-networks, the decomposition will be carried out until all the sub-networks cannot be decomposed. Through the iterations, the network reliability could be achieved. The factorization approach is based on the linkage working status and network inefficiency. If the linkage works properly, the network linkage will be contracted. Two nodes in a link will be contracted into one node. If the link is out of work, the link will be removed. The two nodes will keep in the network. The reliability of a network based on the factorization could be expressed as:

$$R = p_e R_{G_{+e}} + (1 - p_e) R_{G_{-e}}$$

Where, e presents a link in the network. p_e is the working possibility of the link network. $R_{G_{+e}}$ is the reliability of contracted link e. $R_{G_{-e}}$ is the reliability of removing the link e.

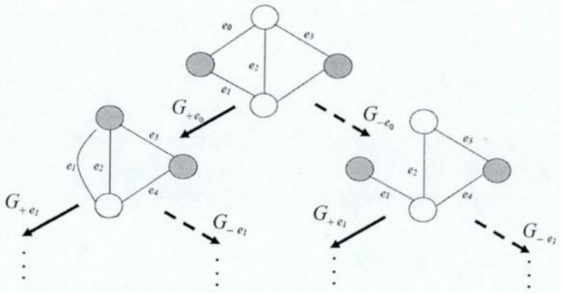


Figure 1. Factorization Approach-based Reliability Principle

As shown in Figure 1, the principle of factorization-based reliability is demonstrated. G_{+e} presents the contracted the link e. The solid arrow shows the generated sub-network. G_{-e} is the removed link e. The dotted arrow shows such a generated sub-network. It could be observed that, the principle of factorization follows a tree view for extending the process. When there are m links in the network, the whole tree will have m layers with maximum leaves amount 2^m. It is found that the complexity of the calculation process is $O(2^m)$. Thus, as the increasing of link quantity in a network, the calculation cost of the reliability will crease coefficiently. Thus, the principle should be improved due to the large scale of the network. Additionally, the nodes in the network may be out of service. In this case, the reliability of a network will be more complex.

In the real-life practical network, the nodes will be out of work. In order to solve this, the factorization approach uses the space decomposition to convert the status space into three sets: acceptable set A, nonacceptable sets N, and unspecified sets U. If the required data could be sent from the source node to the destination, the network status is acceptable set A. Each unspecified status includes acceptable and nonacceptable status. That means U will be deposited much smaller A, N, and U. Thus, the reliability of the whole network is the sum of the possibility of all A.

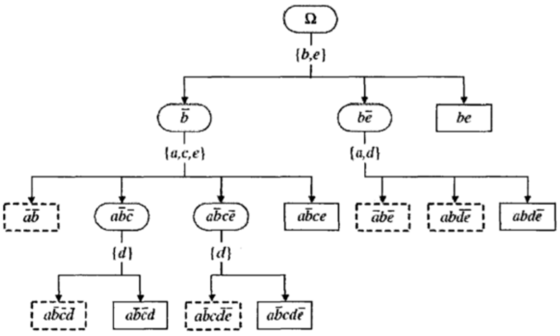
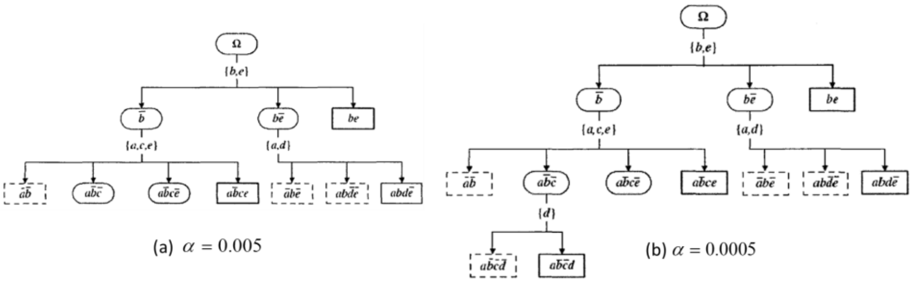


Figure 2. Status Space Decomposition

3. Network Reliability Model based on Factorization Principle

This section presents a model for evaluating the network reliability based on the factorization approach. The maximum data stream is used for working out the network status of success sending the data. A status space decomposition approach (as shown in Figure 2), is adopted in the model to evaluate the network reliability accurately. Four items are used in this model. They are reliable route, acceptable status, nonacceptable status, and unspecified status.



(a) $\alpha = 0.005$ (b) $\alpha = 0.0005$

Figure 3. Network Reliability Evaluation based on Factorization Principle

Figure 2, shows the decomposition method. Ω is the nonacceptable status. The possibility of Ω is used for working out the upper and low boundary value. Each boundary $\bar{a}$, $\bar{b}$,…has the possibility. For example, in the Figure 1, the corresponding possibilities of $\bar{b}$, $b\bar{e}$, $a\bar{b}\bar{c}$, and $a\bar{b}c\bar{e}$ are 1, 0.05, 0.0095 (0.95×0.01), 0.002125 ($0.85\times0.05\times0.05$), and 0.00040375 ($0.85\times0.05\times0.95\times0.01$). Using the upper and low boundary for the network reliability, the possibilities of Ω is less than $\alpha = 0.005$ and $\alpha = 0.0005$. The following Figure 2, presents the principle of the proposed method which uses the status space decomposition approach to work out the network reliability.

From Figure 3, the calculation complexity and accuracy are improved. Figure 3 (a), shows with the $\alpha = 0.005$, the layer will be three with the status of Ω is unspecified. The second layer has two unspecified statuses: $\bar{b}$, and $b\bar{e}$. be is the acceptable status. Thus, the unspecified statuses are decomposed. $\bar{b}$ then has four status nonacceptable $\bar{a}\bar{b}$, two unspecified statuses: $a\bar{b}\bar{c}$ and $a\bar{b}c\bar{e}$, as well as an acceptable status $a\bar{b}ce$. $\{b,e\},\{a,c,e\},\{a,d\}$ are reliable path from the network. It is observed that, with the smaller α, the status space will be decomposed with more layers.

4. Network Reliability Evaluation Model

Based on the principle, the network reliability evaluation model could be established. The key elements in the network could be modeled such as nodes, links, and paths' relations. Let (N, A, S, T) is a multi-source multi-sink multi-state network (MMMN). N is the set of nodes, $A = \{\mathrm{a}_i \mid \mathrm{i} = 1, 2, ..., \mathrm{n}\}$ presents the set of links. $\mathrm{len} = \{\mathrm{L}_i \mid \mathrm{i} = 1, 2, ..., n\}$ indicates the length of each link. $S = \{\mathrm{s}_j \mid \mathrm{j} = 1, 2, ...\alpha\} \subset \mathrm{N}$ is the set of source node. $\mathrm{T} = \{\mathrm{t}_k \mid \mathrm{k} = 1, 2, ..., \beta\} \subset \mathrm{N}$ is the set of destination nodes. Let P_{jkv} presents the no. v minimum path (MP) of link of s_j and t_k, $v = 1, 2, ...m_{jk}$. d_{jk} denotes the data transmission of s_j to t_k via P_{jkv}.

Let $L = \{l_s \mid \mathrm{s} = 1, 2, ..., \mathrm{n}_L\}$ presents a set which contains n_L transmission path which could be selected. c_s is the configuration cost of l_s unit length. $h_s(w)$ is the no w capacity in l_s, $w = 1, 2, ..., M_k$. Where M_k is the total quantity of capacity status of l_s. $h_k(M_k)$ presents the maximum capacity value of l_s. Let $B = (b_1, b_2 ..., b_n)$ denotes the configuration of a transmission line, if the transmission line l_s is assigned to link a_i, $i = 1, 2, ..., n$, $b_i = k$. Let $C(B)$ presents a transmission line configuration B's cost, $C(B)$ should meet:

$$C(B) = \sum_{i=1}^{n} (c_{b_i} \times len_i) \le C_{TH} \tag{1}$$

Where $c_{b_i} \times len_i$ is the generated configuration cost of l_{b_i} assigned to a_i. Let x_i presents the current capacity, $X = (x_1, x_2, ..., x_n)$ is the status vector of the network capacity. f_{uvj} is the flow ratio via P_{uvj}. For a transmission line configuration B, the total flow ratio ff_i should be less than the maximum capacity of a_i. Additionally, the flow ratio via P_{uvj} will be less than the maximum capacity of the path, then:

$$ff_i = \sum_{u=1}^{\alpha} \sum_{v=1}^{\beta} \sum_{j=1}^{m_{uv}} \{ f_{uvj} | a_i \in P_{uvj} \} \le h_{b_i}(M_{b_i}), i = 1, 2, ..., n \tag{2}$$

$f_{uvj} \le \min\{h_{b_i}(M_{b_i}) \mid a_i \in P_{uvj}\}, u = 1, 2, ..., \alpha$, $v = 1, 2, ..., \beta$, $j = 1, 2, ..., m_{uv}$. Where $h_{b_i}(M_{b_i})$ denotes the maximum value capacity of a_i under the transmission configuration B. $\min\{h_{b_i}(M_{b_i}) \mid a_i \in P_{uvj}\}$ is the maximum capacity value of B. As s_u sends the data

d_{uv} to t_v via P_{uvj}. The total flow ratio between s_u and t_v should be equal to d_{uv}. That means from the network:

$$\sum_{j=1}^{m_{uv}} f_{uvj} = d_{uv} \tag{3}$$

If there is a $w \in 1, 2, ..., M_{b_i}$ meets $h_{b_i}(w-1) < ff_i \le h_{b_i}(w)$, then we can get $x_i = h_{b_i}(w)$. Where $h_{b_i}(w)$ is the minimum capacity with the flow ratio requirement of l_{b_i}. Then the network capacity status vector is $X = (x_1, x_2, ..., x_n)$. Let $X_{uv} = (x_{uv1}, ..., x_{uvi}, ..., x_{uvn})$ denotes the network capacity status vector of the link P_{uvj}. Since the capacity status not belonged to P_{uvj} has not effects on $u-v$ reliability degree. If $a_i \in P_{uvj}$, $x_{uvi} = x_i$; otherwise, $x_{uvi} = 0$. Assume there are total q_{uv} of X_{uv} which meet the requirements, X_{uv}^1, X_{uv}^2, …, $X_{uv}^{q_{uv}}$ presents the vectors. For $\forall X_{uv}$ meets $X_{uv} \ge X_{uv}^k$, $k = 1, 2, ..., q_{uv}$. Under the X_{uv} status, the data in d_{uv} could be transferred successfully via P_{uvj}. Where $X_{uv} \ge X_{uv}^k$ means $(x_{uv1}, ..., x_{uvi}, ..., x_{uvn}) \ge (x_{uv1}^k, ..., x_{uvi}^k, ..., x_{uvn}^k)$. Thus, the network reliability could be calculated from the possibility of the associated status vector of the network capacity which meets the required condition. Let $\mathrm{Re}_{uv}(B)$ presents the data of d_{uv} under the transmission line configuration B with the reliability degree of s_u to t_v. $\mathrm{Re}_{uv}(B)$, $u = 1, 2, ..., \alpha$, $v = 1, 2, ..., \beta$ could be obtained from:

$$\mathrm{Re}_{uv}(B) = pr(\{X_{uv} \ge X_{uv}^1\} \cup \{X_{uv} \ge X_{uv}^2\} \cup ... \cup \{X_{uv} \ge X_{uv}^{q_{uv}}\}) \tag{4}$$

Based on the factorization principle, the reliability evaluation model aims to find the optimal Pareto solution under network cost constrains. Thus the reliability could be maximum $\mathrm{Re}(B) = (\mathrm{Re}_{11}(B), ..., \mathrm{Re}_{1\beta}(B), ..., \mathrm{Re}_{\alpha\beta}(B))$. The model is presented as:

$$\max \mathrm{Re}(B) = (\mathrm{Re}_{11}(B), ..., \mathrm{Re}_{1\beta}(B), ..., \mathrm{Re}_{\alpha\beta}(B)) \tag{5}$$

$$B = (b_1, b_2, ..., b_i, ..., b_n)$$

s.t.

$$b_i = k, k \in \{1, 2, ..., n_L\}, i = 1, 2, ..., n \tag{6}$$

$$b_i \ne b_j, i \ne j \tag{7}$$

$$\sum_{i=1}^{n} (c_{b_i} \times len_i) \le C_{TH} \tag{8}$$

Where, B is the decision variable. $\mathrm{Re}(B)$ is the objective function. n is the dimensions of the decision variable. $\max \mathrm{Re}(B) = (\mathrm{Re}_{11}(B), ..., \mathrm{Re}_{1\beta}(B), ..., \mathrm{Re}_{\alpha\beta}(B))$ will maximizes $\mathrm{Re}_{uv}(B)$ and $u = 1, 2, ..., \alpha$, $v = 1, 2, ..., \beta$. The constraints indicate that each link only requires one transmission line.

5. Solution Algorithm

In order to calculate the network reliability, the network capacity status vector could be figured out. X with the suitable lower boundary point could be used for evaluating the network reliability under certain possibility. Let define a vector operator, it could be expressed as follows:

$$Y \geq X : (y_1, y_2, ..., y_n) \geq (x_1, x_2, ..., x_n) \tag{9}$$

Where $y_i > x_i$, $i = 1, 2, ...n$.

Let n_ψ presents the total quantity of the suitable X, $\psi_{\min}$ stores the set of X_{LBP}. $K = \{1, 2, ..., n_\psi\}$ and I present the set of qualified X and coefficient of $non - X_{LBP}$. J stores the coefficient set of X_{LBP}. The solution algorithm includes the following procedures:

Algorithm 1. X_{LBP} generation

```
Function $\psi_{\min} = LBP(X_1, X_2, ..., X_{n_\psi})$
{
    $I = \varnothing$, $J = \varnothing$;
    for $i = 1$ to $n_\psi$ with $i \notin I$ do
        for $j = i + 1$ to $n_\psi$ with $j \notin I$ do
            if $X_i \geq X_j$ then
                $I = I \cup \{i\}$;
            else
                $I = I \cup \{j\}$;
            end if
            $j = j + 1$;
        end for
        $i = i + 1$;
    end for
    $J = K - I$;
    $\psi_{\min} = \{X_{J(1)}, X_{J(2)}, ..., X_{J(len(J))}\}$;
}
```

Algorithms 2. RSDP

Assume there are h_v $X_{LBP}S$, Re could be calculated by:

$$\mathrm{Re} = \Pr\{\bigcup_{v=1}^{h_v} \{X|X \geq X_{LBP_v}\}\} \tag{10}$$

$\Pr\{X \geq X_{LBP_v}\}$ could be calculated by:

$$\Pr\{X \geq X_{LBP_v}\} = \Pr\{x_1 \geq x_{LBP_{v1}}\} \times \{x_2 \geq x_{LBP_{v2}}\} \ldots \times \{x_n \geq x_{LBP_{vn}}\} \tag{11}$$

Based on the algorithm definition, RSDP could be established:

```
Function $\mathrm{Re} = RSDP(X_{LBP_1}, X_{LBP_2}, \ldots, X_{LBP_{h_v}})$
{
    For $i = 1$ to $h_v$ do
        if $i == 1$ then
            $\mathrm{Re} = \Pr\{X \geq X_{LBP_i}\}$;
        else
            $re_1 = \Pr\{X \geq X_{LBP_i}\}$;
            if $i == 2$ then
                $re_2 = \Pr\{X \geq (X_{LBP_1} \oplus X_{LBP_i}\}$;
            else
                for $j = 1$ to $i-1$ do
                    $X_{LBP_{ji}} = X_{LBP_j} \oplus X_{LBP_i}$;
                end for
                $\psi_{\min_{ji}} = LBP(X_{LBP_{1i}}, X_{LBP_{2i}}, \ldots, X_{LBP_{(i-1)i}})$;
                $re_2 = RSDP(\psi_{\min_{ji}})$;
            end if
        end if
        $\mathrm{Re} = \mathrm{Re} + re_1 + re_2$;
    end for
}
```

6. Simulations and Discussions

This section reports the simulations using Matlab. The experimental environment is with the CPU 2.6GHz and 2GB RAM. For a network as shown in Figure 3, there are 5 nodes in the network.

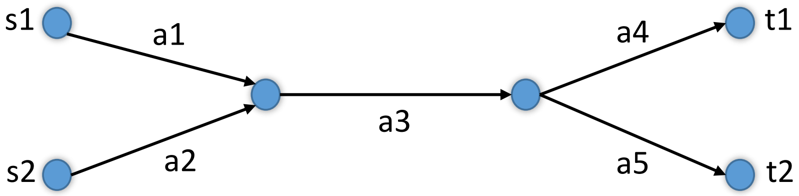


Figure 3. An Example of Network

In Figure 3, there are 5 transmission lines which could be selected to the link. Assume that, the cost of each one kilometers with specific amount. Table 1, indicates the capacity status and associated possibility distribution.

Table 1. Capacity Status and Distribution

l_k	Cost (USD/KM)	Capacity (Gbps)				
		0	1	2	3	4
1	85	0.01	0	0.08	0	0.92
2	75	0.03	0	0.05	0.9	0
3	67	0.05	0	0	0.91	0.02
4	88	0.02	0	0.02	0.92	0.95
5	78	0.02	0	0.08	0.95	0.01

For connecting the s_1 and t_1, the path is $P_{11}=\{a_1,a_3,a_4\}$. While the path $P_{12}=\{a_1,a_3,a_5\}$ is for connecting s_1 and t_2. $P_{21}=\{a_2,a_3,a_4\}$ is to connect s_2 and t_1. $P_{22}=\{a_2,a_3,a_5\}$ is for connecting s_2 and t_2. Link lengths in this experiment are 45, 49, 38, 88, and 50. The parameters for the model are as follows: $d_{uv}=1Gb$, $u=1,2$ and $v=1,2$. $C_{TH}=2400$ USD.

Table 2 gives the experimental results with the proposed model. With certain p_c and p_m, the network reliability $s-t$ could be influenced by the optimal configuration of the transmission lines.

Table 2. Experimental Results

p_c	p_m	Optimal Configuration	$s-t$ Reliability	CPU (s)
0.95	0.1	(1, 2, 4, 3, 5)	(0.89, 0.93, 0.87, 0.91)	19.36
		(1, 2, 4, 5, 3)	(0.93, 0.89, 0.91, 0.88)	
		(2, 5, 4, 3, 1)	(0.88, 0.91, 0.89, 0.93)	
		(5, 1, 4, 2, 3)	(0.89, 0.91, 0.89, 0.91)	
		(1, 5, 4, 3, 2)	(0.90, 0.93, 0.88, 0.91)	
0.95	0.01	(1, 2, 4, 3, 5)	(0.89, 0.91, 0.89, 0.91)	17.47
		(1, 5, 4, 2, 3)	(0.91, 0.87, 0.91, 0.89)	

		(1, 5, 4, 3, 2)	(0.89, 0.91, 0.90, 0.91)	
		(2, 1, 4, 3, 5)	(0.87, 0.91, 0.89, 0.92)	
		(5, 3, 4, 2, 1)	(0.91, 0.93, 0.87, 0.91)	
0.85	0.1	(1, 2, 4, 5, 3)	(0.93, 0.89, 0.91, 0.88)	18.03
		(1, 3, 4, 2, 5)	(0.91, 0.93, 0.88, 0.89)	
		(2, 1, 4, 3, 5)	(0.87, 0.91, 0.90, 0.93)	
		(5, 1, 4, 3, 2)	(0.90, 0.91, 0.90, 0.90)	
		(5, 1, 4, 2, 3)	(0.91, 0.93, 0.91, 0.91)	

From the above table, when $p_c = 0.9$ and $p_m = 0.1$ as well as $p_c = 0.9$ and $p_m = 0.01$, it could be find that there are six transmission lines which are with the maximum reliability. When $p_c = 0.8$ and $p_m = 0.1$, five transmission lines configuration could be observed that the reliabilities of $s-t$ are maximum. Emerging the configurations of the transmission lines with different p_c and p_m. Total six reliability values could be obtained for the $s-t$.

Table 3. Results from Ergodic Method

Optimal Configuration	$s-t$ Reliability	CPU (s)
(1, 2, 4, 3, 5)	(0.85, 0.92, 0.81, 0.83)	41.98
(1, 2, 4, 5, 3)	(0.93, 0.82, 0.84, 0.81)	
(1, 3, 4, 2, 5)	(0.81, 0.82, 0.88, 0.83)	
(1, 5, 4, 2, 3)	(0.85, 0.91, 0.87, 0.85)	
(1, 5, 4, 3, 2)	(0.85, 0.82, 0.81, 0.86)	
(2, 1, 4, 3, 5)	(0.85, 0.90, 0.91, 0.88)	

The proposed approach is compared with the ergodic method whose results are shown in Table 3. It could be found that, the proposed approach outperforms the ergodic method in terms of $s-t$ reliability and CPU. Firstly, the reliability could be greatly improved by the proposed model since different transmission lines will generate same x_{LBP_s} that will influence the configurations. The proposed approach identifies them by using the $\psi_{\min_{ji}}$ to manage the set elements. Secondly, the CPU time costs have been largely reduced since the ergodic methods are based on lots of loops for scanning each nodes. While the proposed approach targets the limited sets so that the discrete capacity status could be closely related to the possibilities with finding the qualified transmission configuration. Thus, the calculation time will be reduced.

7. Summary

This paper introduces a network reliability evaluation model which uses factorization approach for decomposing the network into different sub-networks so that the reliability could be evaluated by the possibilities of each transmission lines. With the model, the solution algorithms are proposed to work out the corresponding defined

$\psi_{\min} = LBP(X_1, X_2, ..., X_{n_\psi})$ and $\mathrm{Re} = RSDP(X_{LBP_1}, X_{LBP_2}, ..., X_{LBP_{h_V}})$. Experiments show that, the proposed model outperforms the ergodic method which uses large number of loops to obtain the network reliability.

Further research directions will be investigated so as to improve this model. First of all, the time constrains are not considered in this model. In real-life practice, the transmission time will large influence the network reliability. Thus, it will be investigated in the near future. Secondly, the proposed model will be realized in a system for practical applications after large number of testing by using the real data from different types of networks.

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