Reliability Measurement in A Multi-path Transmission Network Using SMP-BP Algorithm

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Xiaoling Li (✉), Xinwei Zhou
Nanchang University Gongqing College, Jiangxi, China
6699114749@sina.com

Abstract—Data security is very important in the multi-path transmission networks (MTN). Efficient data security measurement in MTN is crucial so as to ensure the reliability of data transmission. To this end, this paper presents an improved algorithm using single-single minimal path based back-up path (SSMP-BP), which is designed to ensure the data transmission when the second path is out of work. From the simulation study, the proposed algorithm has the better network reliability compared with existing double minimal path based backup path (DMP-BP) approach. It could be found that, the proposed algorithm uses less back-up paths compared with DMP-BP so that less network resources like nodes are achieved.

Keywords—Data Security, Multi-path Transmission, Network, SMPBP, Algorithm, Efficiency

1 Introduction

Data security is very important in the network where the cloud-based communications and transmissions could be conducted [1]. When carrying out the data transmission, the time for a group of channels or paths without any crossover is less than the time spent on a single path. Multi-path transmission network (MTN) has been widely used in our daily life such as mobile ad hoc networks, cloud-based applications and multi-protocol label switch networks [2-4]. However, MTN is easily influenced by the errors or network fault, which will greatly impact the efficient data transferring and even a system break-down will be happened sometimes.

Efficient data security measurement in the MTN is one of the most significant research areas. It is necessary to measure the efficient data transmission so that the network could be more reliable [5]. One typical approach is using back-up path for ensuring the data security. Data could be transferred in parallel through k paths which are not crossover. That means there is no same links for any two paths. A back-up paths with k possible routes were used for ensuring the efficient data transmission [6]. If there are some faults, the back-up paths could be used. It is with significant to use multiple alternative paths through a network, which can yield a variety of benefits such as fault tolerance, increased bandwidth, or improved security.

Table 1. A list of symbols is presented in the following in this paper.

k	Number of paths in the network
P_i	A path in the network
P_{bi}	A back-up path in the network
G	A multi-path transmission network (MTN)
N	A set of nodes
A	A set of linkages
L	A set of time delay
C	A set of cost for transmission
M_i	Maximum value of $a_i \in A$
x_i	Current capacity of $a_i \in A$
m	Total number of minimal path
P_e	A set of minimal path
n_e	Total number of linkages
s	The start node
t	The end node
d	The data from s to t
d_e	Data quantity
$\bar{d}_e$	Upper boundary of d_e
$F(d_e,P_e)$	Total cost
$T(d_e,P_e)$	Transmission time
T	Time
$P_r()$	Reliability
$\varsigma,\lambda,o,k,\omega,u$	Index
I,K,J	Index set

Assume that there are *k* paths $(P_1, P_2, ..., P_i, ..., P_j, ..., P_k)$ in the network. If one of them P_i is out of service, the back-up path P_{bi} could be used. The current working route will be $(P_1, P_2, ...P_{i-1}, P_{bi}, P_{i+1}..P_j, ..., P_k)$. When another path P_j $j = 1, 2, ..., i-1, b_1, j+1, ..., k$ is out of work, based on the P_{bi}, another back-up path will be selected $(P_1, P_2, ...P_{i-1}, P_{bi}, P_{i+1}..P_{j-1}, P_{bj}, P_{j+1}..., P_k)$. In some cases, the working path will be out of service instantly one following another [7], the back-up path P_{bq} will be selected based on the previous $P_{b(q-1)}$. In this way, the data security could be ensured. However, how to measure the efficiency of data security under the multi-path transmission system needs to be further studied.

Some research has been done for the measurement of the reliability. For example, a single minimal path based back-up path (SMP-BP) algorithm was proposed for this purpose [8-10]. SMP-BP uses two individual paths as a working couple where the minimal paths without cross as back-up paths. It supports end-to-end path-based connection restoration in SPR (Shortest Path Restoration), PIR (Partial Information Restoration) and CIR (Complete Information Restoration) networks. If there are any errors, the back-up paths will be triggered [11]. A new path or route will be established with the functions of back-up path in the network.

The shortest path problem usually uses graphs including undirected, directed or mixed models to consider different objective functions such as minimized costs or time. However, some sharing of back-up paths is possible while using the aggregated service bandwidth on each link. It was reported that it is reasonable to increase backup path sharing using aggregated information as with PIR [12]. Low Cost an S-Disjoint (LCSD) paths algorithm is based on a SRLG disjoint active and backup paths for network protection that can be used to avoid the risk sharing with active path [13, 14]. More precisely, a route for the backup path to minimize the joint path failure probability between the primary and the backup paths will be determined. To demonstrate the feasibility of that, extensive evaluations under both single and double link failure models have been carried out in terms of robustness.

In this paper, an improved algorithm using single-single minimal path based back-up path (SSMP-BP) was introduced. SSMP-BP is designed to ensure the data transmission when the second path is out of work. The proposed algorithm uses two non-crossing paths as working routes one of which is non-crossing with the working path. That will be regarded as the back-up. When there are some working path fails, the back-up path will be evoked. A new working path will be created. Thus, there are two paths in the network which can transmit the data at the same time. This algorithm improves the back-up path selection through the non-crossing paths so that the reliability of transmission could be enhanced.

The rest of this paper is organized as follows. Section 2 gives the problem description. Section 3 presents how to use the proposed algorithm to measure the data efficiency. Section 4 gives a simulation case which compares the DMP-BP, SMP-BP, and SSMP-BP. Section 5 concludes this paper.

2 Problem Description

Let $G=(N,A,L,C)$ denotes a MTN, N is a set of nodes, $A=\{a_i \mid i=1,2,..,n\}$ refers to a set of linkages for connecting the nodes. $L=\{l_i \mid i=1,2,..,n\}$ indicates a set of time delay. In $C=\{c_i \mid i=1,2,..,n\}$, a_i means the no. i linkage. l_i is the transmission delay. c_i denotes the cost of the transmission. M_i is used to present the maximum value of a_i. x_i means the current capacity of a_i. $X=(x_1,x_2,...,x_n)$ is a vector showing the status of network capacity. Let m denotes the total number of minimal path (MP). $P_e = \{a_{e1}, a_{e2}, ..., a_{eq}, a_{en_e},\}$ refers to no. e MP $e = 1, 2, ..., m$. n_e is the total number of linkages. a_{eq} is the no. q linkage in P_e $q = 1, 2, ..., n_e$. Let s and t represent the start and end nodes, d means the data from s to t, d_e means the data quantity allocated to P_e. $\overline{d}_e$ is the upper boundary of d_e. B and T shows the cost and time constrains respectively.

Some assumptions are made in this paper as follows:

- Every node will not be out of service.
- The capacity for each path/link follows random distribution and they are strictly independent.
- Each path couple contains two non-cross routes.
- The total input flow is equal to the output flow.

Based on the assumptions, let $F(d_e, P_e)$ presents the total cost and $T(d_e, P_e)$ is the transmission time. The calculation of $F(d_e, P_e)$ and $T(d_e, P_e)$ will be based on [15], where (d_e, c_{eq}) is the cost of data passing a_{eq}. $\min_{1 \le q \le n_e} x_{eq}$ is the capacity under the vector X of the network status.

$$F(d_e, P_e) = \sum_{q=1}^{n_e} (d_e g c_{eq}) \tag{1}$$

$$T(d_e, P_e) = \sum_{q=1}^{n_e} l_{eq} + \left\lceil \frac{d_e}{\min_{1 \le q \le n_e} x_{eq}} \right\rceil \tag{2}$$

If the data from unit d pass λ ($\lambda \ge 2$) paths which are not cross over, d could be divided into $(d_1, d_2, ..., d_\varsigma, ..., d_\lambda)$. The total transferring cost could be calculated by:

$$F(d, (P_1, P_2, ...P_\varsigma, P_\lambda)) = \sum_{\varsigma=1}^{\lambda} F(d_\varsigma, P_\varsigma) \tag{3}$$

Where $d = \sum_{\varsigma=1}^{\lambda} d_\varsigma$, $d_\varsigma \le \overline{d_\varsigma}$. d_ς is a non-negative integer and $\overline{d_\varsigma}$ is the maximum data allocated to $P_\varsigma = \{a_{\varsigma 1}, ..., a_{\varsigma\omega}, ..., a_{\varsigma n_\varsigma}\}$.

$$\overline{d_\varsigma} \leq (T - \sum_{\omega=1}^{n_\varsigma} l_{\varsigma\omega}) g \left\lfloor \min_{1 \leq \omega \leq n_\varsigma} M_{\varsigma\omega} \right\rfloor \tag{4}$$

Thus, we can get:

$$T(d_\varsigma, P_\varsigma) \leq T \tag{5}$$

$$F(d, (P_1, P_2, ... P_\varsigma, P_\lambda)) \leq F(d_e, P_e) \tag{6}$$

In the multi-path network environment, Internet packet traffic keeps growing as the number of applications and services as well as their bandwidth requirements explode. It then becomes necessary to ensure that network throughput is maximized. In this problem description, dynamic multi-path routing is considered to improve network reliability. Multi-path routing is important for throughput, reliability and security. In multi-path routing, improvements in performance are achieved by utilizing more than one feasible path for more effective network resource utilization. Various research on multipath routing have addressed network redundancy, congestion, and QoS issues using the sensor data at each outgoing network link [11]. The real-time status will be captured by the sensors deployed in the network nodes such as routers, extenders, servers, etc. The time differences could be calculated by the sending and receiving time at different network nodes. For example, one data package DP is sent out by router A in time T_1 through Internet (TCP/IP). After several time, router B receives the DP at T_2. The cost of transferring the data could be calculated by $(T_2 - T_1) \times C_u$. C_u is the unit cost considering the transmission channel.

3 Proposed SSMP-BP Algorithm

3.1 SMP-BP algorithm

Define (P_b, P_o) and (P_k) $(b, o, k = 1, 2, ..., m, b \neq o \neq k)$ represent the working and back-up paths, the reliability could be calculated by:

$$P_{r_{SMP-BP}}(S \mid P_b P_o, P_k) = P_r(\overline{P_b}) P_r(S \mid P_o P_k) + P_r(\overline{P_o}) P_r(S \mid P_b P_k) \tag{7}$$

The first part $P_r(\overline{P_b}) P_r(S \mid P_o P_k)$ considers possibility of working path that could be in failure and the second part $P_r(\overline{P_o}) P_r(S \mid P_b P_k)$ considers the possibility of back-up path which could be working after the failure of current working path so that the total reliability of the network could be optimized. P_r is the probability of failure at node r at the condition of current working path failure $P_r(\overline{P_b})$ and back-up path working $P_r(\overline{P_o})$. And $S \mid P_o P_k$ is the conditional probability of the survival of current working path when it is failed.

Assume that at least one of the path will be out of service, then $P_r(\overline{P_w})$ will be

$$P_r(\overline{P_w}) = (1 - \prod_{r:a_r \in P_\omega} P_r(x_r \geq 1)) \tag{8}$$

The low boundary of the capacity vector $(d,T,B,MP)-LBPs$ will be considered under the time and cost constraints. The measurement of $P_r(S \mid P_i P_j)$ and $P_r(S \mid P_k)$ will be based on $(d,T,B,(p_i,p_j))-LBPs$ and $(d,T,B,(P_k))-LBP$. Let $P_i = \{a_{i1},...,a_{i\alpha},...,a_{in_i}\}$, $P_j = \{a_{j1},...,a_{j\beta},...,a_{jn_j}\}$, XX and $XX_{\min}$ are used for keeping the vector candidates $(d,T,B,(p_i,p_j))-LBPs$. Set I and K are used for keeping the indexes of $non-(d,T,B,(p_i,p_j))-LBPs$ and $(d,T,B,(p_i,p_j))-LBPs$. J is used to keep the index of $(d,T,B,(p_i,p_j))-LBPs$. Let h_v denotes the total number of $(d,T,B,(p_i,p_j))-LBPs$ in J, then, $(d,T,B,(p_i,p_j))-X_v$ is the status vector of a network capacity. $P_r(S \mid P_i P_j)$ could be expressed as follows:

$$P_r(S \mid P_i P_j) = P_r\{\bigcup_{v=1}^{h_v} B_v\} \tag{9}$$

Where $B_v = \{X \mid X \geq X_v\}$.

3.2 SMP-BP characteristics

SMP-BP has some characteristics, which are defined as follows.

- The prerequisite of the successful data transferring event for a single path (P_k) is the maximum capacity should not be less than required capacity $\overline{d_k} \geq d$.
- The prerequisite of the successful data transferring event for two paths (P_i, P_j) is the sum of both maximum capacity should not be less than the required capacity, $\overline{d_i} + \overline{d_j} \geq d$.

Data could be transmitted through two ways: single or two path, by comparing the network reliability $P_r(S \mid P_f)$ and $P_r(S \mid P_f P_g)$, some conclusions could be made: $P_r(S \mid P_f P_g) \geq P_r(S \mid P_f)$.

If one path is out of service, we can get

$P_{r_{SMP-BP}}(S \mid P_b P_o, P_k) \geq P_{r_{DMP-BP}}(S \mid P_b P_o, P_i P_j)$,

$b, o, k, i, j = 1, 2, ..., m; b \neq o \neq k,\ b \neq o \neq i \neq j$. That means the reliability of SMP-BP is better than DMP-BP because SMP-BP uses less back-up paths achieving the more efficient data transmission so as to save the network resources.

3.3 SSMP-BP model

Let P_k and P_{kk} present two back-up paths. $< P_k, P_{kk} >$ reveals the orders of these two paths. If the second path is out of service, the reliability could be measured by:

$$P_{r_{SSMP-BP}}(S \mid P_b P_o, < P_k, P_{kk} >) = P_r(\overline{P_b})[P_r(\overline{P_o})P_r(S \mid P_k P_{kk}) + P_r(\overline{P_k})P_r(S \mid P_o P_{kk})]$$
$$+P_r(\overline{P_o})[P_r(\overline{P_b})P_r(S \mid P_k P_{kk}) + P_r(\overline{P_k})P_r(S \mid P_b P_{kk})]$$
$$= 2P_r(\overline{P_b})P_r(\overline{P_o})P_r(S \mid P_k P_{kk}) + P_r(\overline{P_k})P_{r_{SMP-BP}}(S \mid P_b P_O, P_{kk}) \quad (10)$$

Formula (10) considers two back-up paths in the network system. $P_r(\overline{P_b})$ is the probability of network failure of current working path. $P_r(\overline{P_o})P_r(S \mid P_k P_{kk})$ is the working probability of the first back-up path and $P_r(\overline{P_k})P_r(S \mid P_o P_{kk})$ represents the second one which has the probability for replacing the first one. $P_r(\overline{P_o})$ indicates the probability of failure of any back-up path since two back-up paths are considered. $P_r(\overline{P_b})P_r(S \mid P_k P_{kk}) + P_r(\overline{P_k})P_r(S \mid P_b P_{kk})$ is the alternative back-up path selection if one of them is failed.

Under this case, if the back-up path couple is (P_k, P_{kk}), based on the DMP-BP approach, the network reliability is:

$$P'_{r_{DMP-BP}}(S \mid P_b P_o, P_k P_{kk}) = P_r(\overline{P_b})P_r(\overline{P_o})P_r(S \mid P_k P_{kk}) \quad (11)$$

Based on (10) and (11), it could be observed that under the failure of second back-up path,

$$P_{r_{SSMP-BP}}(S \mid P_b P_o, < P_k, P_{kk} >) \geq P'_{r_{DMP-BP}}(S \mid P_b P_o, P_k P_{kk}),$$

$b, o, k, kk = 1, 2, ..., m;\ b \neq o \neq k \neq kk$.

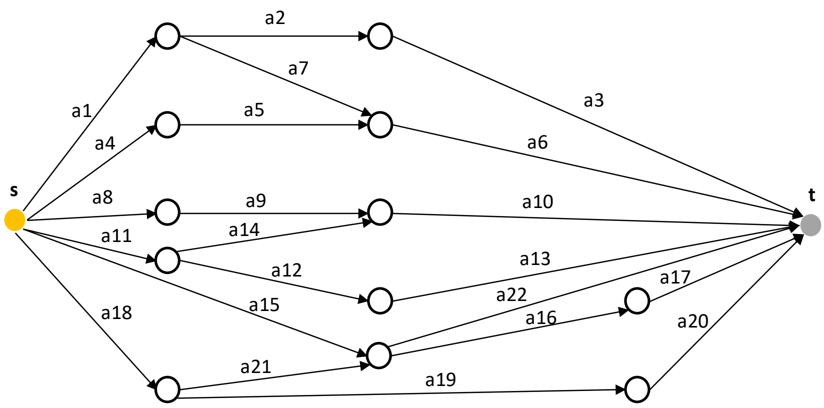

Fig. 1. A multi-path transmission network

4 Simulation Study

This section reports on a simulation study based on the following network structure as shown in Fig. 1. Some parameters are set as follows so that the proposed model could be evaluated by comparing with other approaches. $d = 200$, $T = 13$, $B = 2000$. Assume the working paths couples are $P_1 = (a_1, a_2, a_3)$ and $P_2 = (a_4, a_5, a_6)$. From Figure 1, the paths with non-crossing relation with P_1 and P_2 are $P_3 = (a_8, a_9, a_{10})$, $P_4 = (a_{11}, a_{12}, a_{13})$, $P_5 = (a_{15}, a_{16}, a_{17})$, $P_6 = (a_{18}, a_{19}, a_{20})$, $P_7 = (a_{10}, a_{11}, a_{14})$, $P_8 = (a_{15}, a_{22})$, $P_9 = (a_{18}, a_{21}, a_{22})$ and $P_{10} = (a_{16}, a_{17}, a_{18}, a_{21})$.

The data is from [16], in DMP-MP algorithm, when the working path is (P_1, P_2), the reliability for the back-up path is listed in Table 1.

Table 2. Reliability list

i, j	$P_r(S \mid P_iP_j)$	i, j	$P_r(S \mid P_iP_j)$	i, j	$P_r(S \mid P_iP_j)$	i, j	$P_r(S \mid P_iP_j)$
3,4	0.78	3,10	0.40	4,10	0.70	6,8	0.55
3,5	0.77	4,5	0.89	5,6,	0.78	7,8	0
3,6	0.70	4,6	0.79	5,7	0.71	7,9	0
3,8	0.52	4,8	0.72	5,9	0.61	7,10	0
3,9	0.47	4,9	0.65	6,7	0.61	8,10	0

The maximum value from Table 1 is $P_r(S \mid P_4P_5)$=0.89. Thus, (P_4, P_5) is the best back-up path couple. In this simulation study, we use it as the back-up path and the comparison of SSMP-BP and DMP-BP approaches is conducted.

Let P_4 present the back-up path in SSMP-BP, there are two path failure events with the out of service from P_1 and P_2. When P_1 fails, P_4 will be triggered to replace P_1 for sending the data with the help from P_2. In this situation, (200,13,2000, (P_2, P_4))- $LBPs$: X_1 and X_7 will be occurred twice. $P_r(S \mid P_2P_4) = 0.71$. When P_2 fails, (200,13,2000, (P_1, P_4))- $LBPs$: X_1, X_7, X_{14} and X_{21} will be occurred four times. $P_r(S \mid P_1P_4) = 0.89$.

Under the constraints of T and B, for the data transmission through (P_1), there is one (200,13,2000, (P_1))- LBP: $X_{LBP} = (50, 50, 40, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0)$. Thus, we can get $P_r(S \mid P_1) = 0.58$. Since $\overline{d_2} = 120 \le d$, then $P_r(S \mid P_2) = 0$, according to Equation (8), we can get $P_r(\overline{P_1}) = 0.14$ and $P_r(\overline{P_2}) = 0.14$. Based on the Equation (7) and (10), we can get the following results under path failure case using P_4 as a back-up path:

$$P_{r_{DMP-BP}}(S \mid P_1P_2, P_4P_5) = P_r(\overline{P_1})P_r(S \mid P_2) + P_r(\overline{P_2})P_r(S \mid P_1) = 0.14 \times 0 + 0.14 \times 0.58 = 0.08$$

$$P_{r_{SSMP-BP}}(S \mid P_1P_2, P_4) = P_r(\overline{P_1})P_r(S \mid P_2P_4) + P_r(\overline{P_2})P_r(S \mid P_1P_4) = 0.14 \times 0.71 + 0.14 \times 0.89 = 0.23$$

$$P_{r_{SSMP-BP}}(S \mid P_1P_2, P_4) - P_{r_{DMP-BP}}(S \mid P_1P_2, P_4P_5) = 0.15$$

Similarly, if we use P_5 as the back-up path, we can get:

$$P_r(S \mid P_1P_5) = 0.88, \; P_r(S \mid P_2P_5) = 0.70$$

$$P_{r_{SSMP-BP}}(S \mid P_1P_2, P_5) = P_r(\overline{P_1})P_r(S \mid P_2P_5) + P_r(\overline{P_2})P_r(S \mid P_1P_5) = 0.14 \times 0.70 + 0.14 \times 0.88 = 0.23$$

$$P_{r_{SSMP-BP}}(S \mid P_1P_2, P_5) - P_{r_{DMP-BP}}(S \mid P_1P_2, P_4P_5) = 0.15$$

It could be concluded that, using P_4, P_5 as the back-up paths, the network efficiency or reliability could be improved by 0.14 (14%). Using the proposed algorithm, under the failure of the second path, since P_4 is serving as a working path, the possibility is P_1, P_2 or P_4. According to the rule that data should be transmitted by non-crossing paths, the following paths will be available P_3, P_5, P_6, P_8, P_9 and P_{10}. When the main path is (P_1, P_2), the first and second back-up paths are P_4 and P_{kk} respectively. Based on equation (10), $P_{r_{SSMP-BP}}(S \mid P_1P_2, < P_4, P_{kk} >) = 2P_r(\overline{P_1})P_r(\overline{P_2})$ $P_r(S \mid P_4P_{kk}) + P_r(\overline{P}_4)P_{r_{SMP-BP}}(S \mid P_1P_2, P_{kk})$. Thus, we can get the results from Table 2.

Table 3. Reliability list

P_{kk}	$P_r(S \mid P_1P_{kk})$	$P_r(S \mid P_2P_{kk})$	$P_r(S \mid P_4P_{kk})$	$P_{r_{SSMP-BP}}(S \mid P_1P_2, < P_4, P_{kk} >)$
P_3	0.78	0.51	0.78	0.06
P_5	0.88	0.70	0.89	0.07
P_6	0.78	0.52	0.79	0.06
P_8	0.68	0	0.72	0.04
P_9	0.67	0	0.65	0.04
P_{10}	0.58	0	0.70	0.04

From Table 2, it could be observed that $P_r(\overline{P_4})$=0.14. Due to the maximum value of $P_{r_{SSMP-BP}}(S \mid P_1P_2, < P_4, P_5 >) = 0.07$ when $kk = 3,5,6,8,9,10$, P_5 is selected to be the second back-up path. Thus, the first and second back-up paths will be P_4 and P_5. The network reliability will be $P_{r_{SSMP-BP}}(S \mid P_1P_2, < P_4, P_5 >) = 0.07$. When the back-up path couple is (P_4, P_5), when the path couple is out of service, using CMP-BP algorithm, the reliability is $P_{r'_{DMP-BP}}(S \mid P_1P_2, P_4P_5) = 0.02$. While, using the proposed algorithm, we can get:

$$P_{r_{SSMP-BP}}(S \mid P_1P_2, < P_4, P_5 >) - P_{r'_{DMP-BP}}(S \mid P_1P_2, P_4P_5) = 0.05$$

That implies when the second path is failed, the network reliability will be increased by 0.05 (5%) using the proposed algorithm if P_4 and P_5 are used as the back-up paths. For the small scale network, traverse algorithms could be used for finding out the best back-up paths [17, 18]. However, for intermediate or large scale networks, these algorithms are not able to work properly [19]. The proposed SSMP-BP approach could be extended to a network with $u(u \geq 2)$ paths. If there are some working paths $(P_1, P_2, ..., P_i, ..., P_u)$, P_τ is the back-up path, where P_τ and P_i are non-crossing paths $i = 1,2,...,u$. Based on the proposed approach, the network reliability could be calculated by:

$$
\begin{aligned}
P_{r_G}(S \mid P_1P_2 \dots P_u, P_\tau) &= P_r(\overline{P_1})P_r(S \mid P_2 \dots P_u, P_\tau) \\
&+ P_r(\overline{P_2})P_r(S \mid P_1P_3 \dots P_u, P_\tau) + \dots \\
&+ P_r(\overline{P_u})P_r(S \mid P_1P_2 \dots P_{u-1}, P_\tau)
\end{aligned}
$$

5 Conclusion

This paper introduces a SMP-BP algorithm to improve the network reliability under the situation of one transmission path failure. SMP-BP uses two non-crossing paths as working routes. And one path which is non-crossing with the working path will be used as the back-up. When a working path fails, the back-up path will be evoked and a new working path will be created with another working path. Thus, there are two paths in the network which can transmit the data at the same time. From the simulation study, the proposed algorithm has a better network reliability compared with existing DMP-BP approach. It could be found that, the proposed algorithm uses less back-up paths compared with DMP-BP so that less network resources like nodes are achieved.

Future research directions will be carried out in the following aspects. Firstly, the network disturbances are ignored in this research. Some disturbances such as power failure could be considered so that some probability theory could be integrated into this algorithm. Secondly, simulation study is only conducted. A testing scenario will be created in the future to evaluate the feasibility and practicality of this proposed algorithm.

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8 Authors

Xiaoling Li is an Associate Professor and Senior Engineer in the Nanchang University Gongqing College, Jiujiang, Jiangxi, China. Her research interests include data security measurement and computer networks. She has published several papers in international journals and conferences.

Xinwei Zhou is an Lecturer and Engineer in Computer Network from the Nanchang University Gongqing College, Jiujiang, Jiangxi,China. His research focuses on computer networks and network reliability. He has published several papers in international journals and conferences.

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