View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Creative Repository of Electro-Communications

修　士　論　文　の　和　文　要　旨

研究科・専攻	大学院　情報理工学研究科　情報・通信工学専攻　博士前期課程		
氏　名	PHAM VU PHONG	学籍番号	1331089
論文題目	A Hybrid Instantaneous Recovery Route Design Scheme Using Different Coding-Aware Scenarios		

要　旨

ネットワーク上のサービスの進化と通信量の増加に従い、経済的で高信頼な経路の設計が求められている。本研究では、ネットワーク上の単一のリンク故障に対して、瞬時に復旧可能で、かつ，リソースを効率的に利用する経路設計法を扱う。

１＋１プロテクションは単一のリンク故障に対する瞬間復旧の代表的な手法である。このプロテクションでは同じデータが同時に独立の二つの経路へ送信されている。一つの経路上にシングルリンク故障が発生した時に着ノードで、もう一方の経路にスイッチすることによりデータが瞬時に復旧することが可能となる。この技術では必要な資源が少なくとも二倍以上必要となる。一方、ネットワーク符号化は中継ノードに到着データを符号化する技術がある。以前の研究で、この符号化の技術を用いて１＋１プロテクションの瞬間復旧機能を保ちながら必要な資源を削減する方式として，TS (traffic splitting)と 2SD (2 sources common destination)というシナリオが報告されている。

本研究ではネットワーク上のすべて発着ノードのペアに対する１＋１プロテクションを提供するハイブリッド経路設計法を提案する。この設計法は２段階のフェーズから構成される。第１フェーズでは、TS と 2SD の選択肢の中から、それぞれの発着ノードペアに対して適切なプロテクションシナリオを選択する。第２フェーズでは、第１フェーズで得られた結果からシナリオの組み合わせが符号化可能な共通経路を抽出し、ネットワークコストが低減されるように最適な組み合わせを探索する。提案したハイブリッド経路設計法と、従来方法のＴＳと２ＳＤとの性能を比較した結果、提案方法は，従来方法と比較して５％の資源を削減ができることを示す。

A Hybrid Instantaneous Recovery Route Design Scheme Using Different Coding-Aware Scenarios

VU PHONG **PHAM**

1331089

A DISSERTATION PRESENTED TO THE
DEPARTMENT OF COMMUNICATION ENGINEERING AND INFORMATICS
IN CANDIDACY FOR THE MASTER'S DEGREE

RECOMMENDED FOR ACCEPTANCE BY THE
DEPARTMENT OF COMMUNICATION ENGINEERING AND INFORMATICS

ADVISOR: EIJI **OKI**, professor
ADVISOR: NAOTO **KISHI**, professor

JANUARY 30, 2015

Contents

概要 iv

Abstract v

Acknowledgments vi

Chapter 1. Introduction 1

1.1. Routing 1

1.2. Link failure protection 1

1.3. Network coding 2

Chapter 2. Network coding based protection 3

2.1. Instantaneous recovery by 1+1 protection 3

2.2. Network coding aware 1+1 protection 3

2.3. Network coding aware traffic splitting based protection 4

Chapter 3. Hybrid instantaneous recovery route design scheme 6

3.1. Protection scenarios selection in hybrid protection scheme 6

3.2. Coding gain 9

3.3. Largest effective gain first policy 10

Chapter 4. Multiple coding scenario 11

4.1. Network coding between two protection scenarios 11

4.2. Network coding between two protection scenarios in hybrid protection scheme 11

4.3. Policy for selecting two scenario pairs in multiple network coding scenarios 16

Chapter 5. Performance evaluation for hybrid protection scheme 18

5.1. Simulation Model 18

5.2. Evaluation for hybrid protection scheme 19

Chapter 6. Performance evaluation for multiple coding based protection scenario 21

Chapter 7. Conclusion 23

Publications 24

Bibliography 25

概要

ネットワーク上のサービスの進化と通信量の増加に従い、経済的で高信頼な経路の設計が求められている。本研究では、ネットワーク上の単一のリンク故障に対して、瞬時に復旧可能で、かつ，リソースを効率的に利用する経路設計法を扱う。

１＋１プロテクションは単一のリンク故障に対する瞬間復旧の代表的な手法である。このプロテクションでは同じデータが同時に独立の二つの経路へ送信されている。一つの経路上にシングルリンク故障が発生した時に着ノードで、もう一方の経路にスイッチすることによりデータが瞬時に復旧することが可能となる。この技術では必要な資源が少なくとも二倍以上必要となる。一方、ネットワーク符号化は中継ノードに到着データを符号化する技術がある。以前の研究で、この符号化の技術を用いて１＋１プロテクションの瞬間復旧機能を保ちながら必要な資源を削減する方式として，TS (traffic splitting) と 2SD (2 sources common destination) というシナリオが報告されている。

本研究ではネットワーク上のすべて発着ノードのペアに対する１＋１プロテクションを提供するハイブリッド経路設計法を提案する。この設計法は２段階のフェーズから構成される。第１フェーズでは、TS と 2SD の選択肢の中から、それぞれの発着ノードペアに対して適切なプロテクションシナリオを選択する。第２フェーズでは、第１フェーズで得られた結果からシナリオの組み合わせが符号化可能な共通経路を抽出し、ネットワークコストが低減されるように最適な組み合わせを探索する。提案したハイブリッド経路設計法と、従来方法のＴＳと２ＳＤとの性能を比較した結果、提案方法は，従来方法と比較して５％の資源を削減ができることを示す。

Vu Phong Pham
January 2015

Abstract

With the development of service in Internet and the rapid increasing of data traffic on network, low cost and high reliability are the challenge task of route design technique. In this research, protection against network failure while considering the efficient resource utilization is discussed.

1 + 1 protection is a typical protection provide instantaneous recovery against link failure scheme. In this protection, data are sent along two disjoint paths from source node to destination nodes. When single link failure happens on one path, data can be recovered instantaneously by switching to the remaining path at destination node. The drawback of this protection technique is at least double of required resource are needed. Network coding (NC) is an technique in which intermediate node can encoded incoming packet together to reduce the traffic on the outgoing links. In previous studies, NC has been used with 1 + 1 protection to reduce the protection resource while maintaining the instantaneous recovery ability of 1 + 1 protection. NC aware traffic splitting based 1 + 1 protection scenario (TS) and NC aware two source common destination (2SD) scenario are two well-known scenarios of this protection technique.

This research proposes a hybrid scheme for instantaneous recovery 1+1 protection route design for all possible source-destination pairs in a network. This work have two stage, the first is we provide a hybrid scheme in which TS and 2SD are intelligently selected to protect all possible source destination pairs. The second, for each scenario that multiple source have common destination in which TS and 2SD are intelligently used, we apply NC on the common path of scenario pairs which are selected on the first stage. We compare the total costs of all the working and protection paths obtained by the proposed scheme, the TS scenario, and the 2SD scenario. Numerical results observe that the proposed scheme achieves more 5% resource saving than the TS or 2SD scenario in our examined networks.

Acknowledgments

I would like to express my deepest gratitude to my advisor Eiji OKI, professor at the University of Electro-Communications for his invaluable guidance and advices and providing me with an comfortable working atmosphere to do the research. Also, my gratitude goes to my sub-advisor Naoto KISHI, professor at the University of Electro-Communications for his guidance.

I would like to acknowledge all the advices, guidance and patience from Mr. Abu Hena Al Muktadir in helping to conduct my research. And I would also like to thank all lab members for their cooperation, encouragement, and making a great international working environment.

I also would like to express my gratitude to Sagawa Foreign Students' Scholarship Foundation for the supporting by providing the scholarship, which help me concentrate on my research.

Finally, I would like to thank all of my friends for their encouragement. And my great appreciate to my parents and family members for the support and encouragement they give.

CHAPTER 1

Introduction

1.1. Routing

Routing process is the process that packet is forwarded in hop-to-hop along the path from source to destination. This mean that intermediate node, which is known as router, is responsible for forwarding data packet to adjacent router based on the destination. In packet delivery, buffer space of router, bandwidth of link, transmission error, packet switching are factors that affect the efficient of packet transferring. By switching incoming packets to appropriate outgoing links at intermediate node, the performance of packet delivery can be improved. The information of routing table is used in deciding the next hop for incoming packets. In order to provide network with specific properties such as minimum transferring cost, recovery against link failure, a routing algorithm that determine the most appropriate next hop are desired.

1.2. Link failure protection

In communication networks, robustness is a desired property, because links in such networks carry a large amount of data. Hence, an efficient protection technique that can recover the data and services affected by link failure is needed. Protection techniques can classified as proactive (or pre-planned) protection and reactive (or on-demand) protection [**1**].

. Dedicated backup path protection (DBPP) and shared backup path protection (SBPP) are typical pre-planned protection techniques. 1:N protection is a SBPP technique in which N active paths share one path for sending recovery data when path failure is detected. 1+1 protection is a DBPP technique, where data are send simultaneously along both active path and protection path. 1+1 protection technique provides instantaneous recovery, but it requires at least double network resource.

1.3. Network coding

Network coding is a packet encoding technique, where data from various sources are encoded at some intermediate node and sent through the outgoing link of that node. By modifying the incoming data at intermediate node, network coding can increase the network throughput. Recent research reveal that network coding technique has been used with the dedicated protection technique for reducing backup resource requirement [**2**], [**3**]. In Fig. 1.1 the multicast of source nodes $S1, S2$ to destination nodes $D1, D2$ shared common links $M1 - M2$. By applying network coding at intermediate node $M1$, the throughput of link $M1 - M2$ are increased.

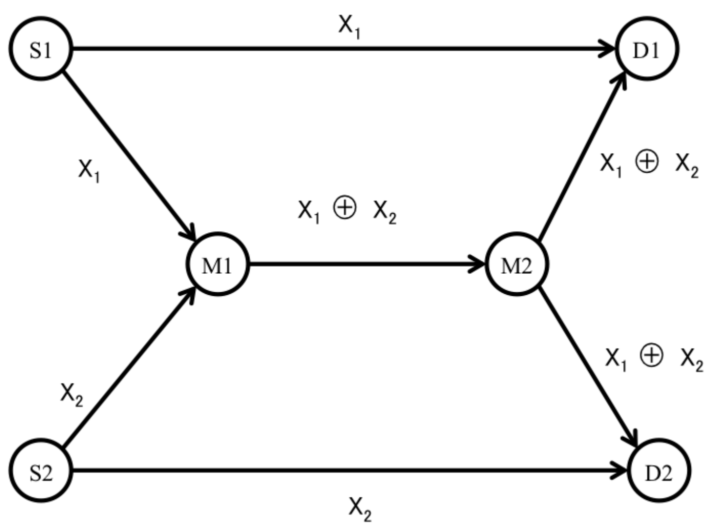


FIGURE 1.1. Network coding in

.

CHAPTER 2

Network coding based protection

2.1. Instantaneous recovery by 1+1 protection

1 + 1 protection is a proactive dedicated path protection technique, where data are sent simultaneously along two link disjoint active and protection paths. Instantaneous recovery from failure is the protection with no loss of data due to any failure. In 1+1 protection, 100% of data can be recovered by switching the working path to the backup path at the destination node when a link failure is detected as in Fig. 2.1. 1+1 protection technique provides instantaneous recovery, in which the recovery action is achieved *only at the destination node*. However, it requires at least double network resource.

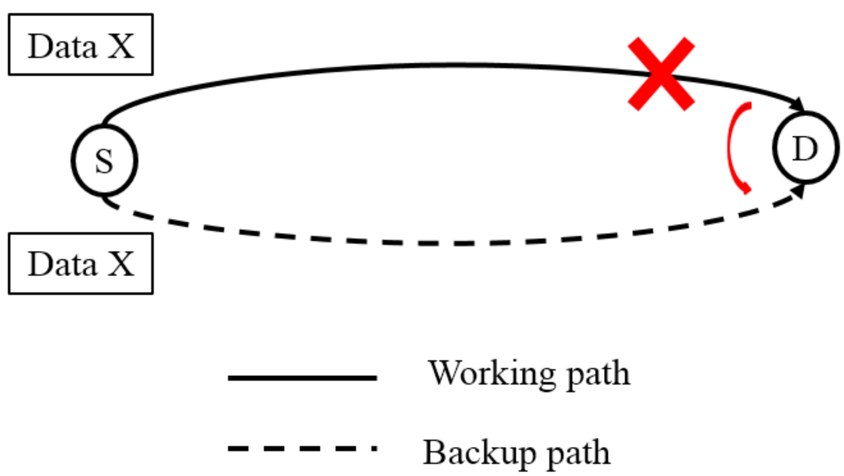


FIGURE 2.1. Conventional 1+1 protection.

2.2. Network coding aware 1+1 protection

Coding aware 1+1 protection techniques presented in [**4, 5**] reduces the backup resource requirement for conventional 1+1 protection. In the 2SD (two sources and a common destination) scenario, coding can be performed at some intermediate node [**4**] (known as network coding [**6**]).

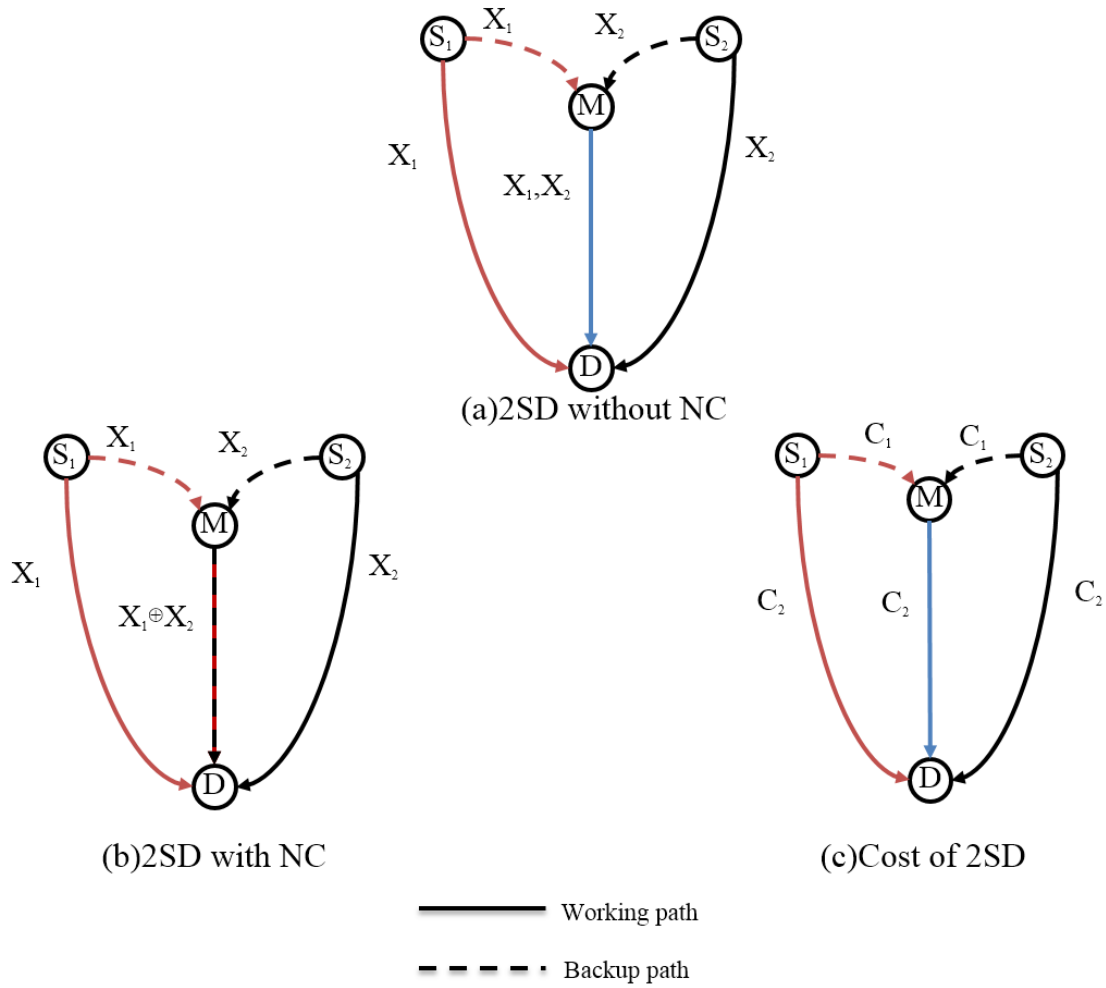


FIGURE 2.2. Cost reduction of 2SD scenario.

Theoretically, up to 25% of resource saving is possible by introducing NC with 1+1 protection in the 2SD scenario. In Fig. 2.2, let c_1, c_2 be the cost of links $S_1 - M$ and $S_2 - M$ and c_2 be the cost of other links. For conventional 1+1 protection in this scenario, the total cost is $4c_2 + 2c_1$. When network coding is employed, link $M - D$ is used only once, and the total required cost is reduced to $3c_2 + 2c_1$. Thus, $\frac{c_2}{4c_2+2c_1} \times 100\%$ of resource saving is achieved.

2.3. Network coding aware traffic splitting based protection

In the TS (traffic splitting) scenario [**5, 7**], coding is performed at the source node with split data. Assume that there is an unit traffic demand between the source and destination in Fig. 2.3(b). This demand is split into K equal parts. Bandwidth demand on each of the

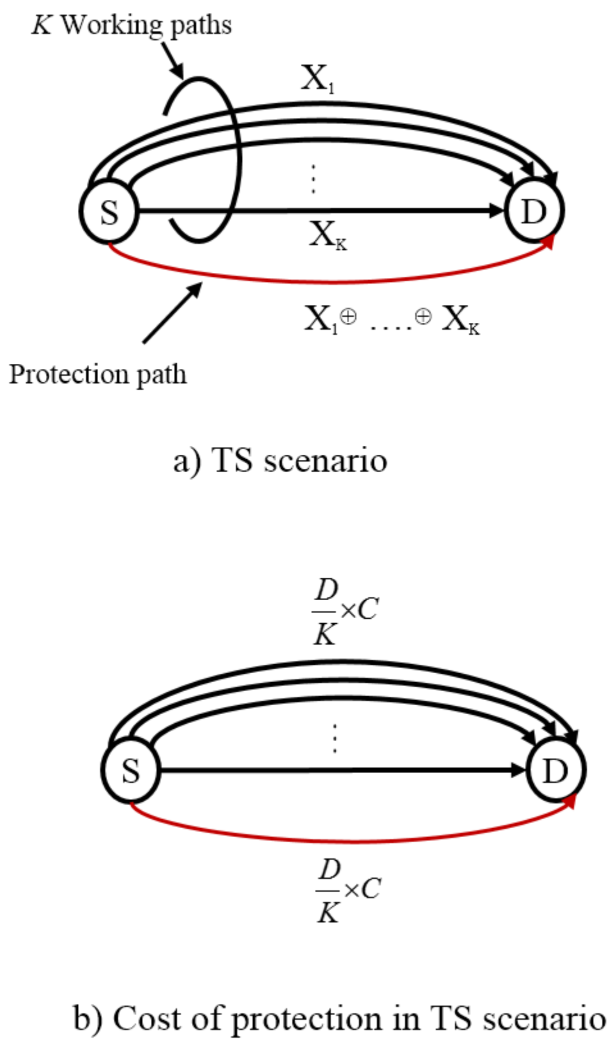


FIGURE 2.3. Cost reduction of TS scenario.

used disjoint paths is $\frac{1}{K}$. For conventional 1+1 protection, the total required bandwidth on two disjoint paths is two. With splitting, this total cost becomes $\frac{K+1}{K}$. Thus, the bandwidth saving, with respect to conventional 1+1 protection bandwidth requirement, is $\frac{2-\frac{K+1}{K}}{2} \times 100\%$. If K becomes large, the bandwidth saving approaches to about 50%.

CHAPTER 3

Hybrid instantaneous recovery route design scheme

3.1. Protection scenarios selection in hybrid protection scheme

We consider a network with N nodes and L undirected links. The proposed scheme is described in the following.

- Step 1: Divide the given traffic matrix into N scenarios, where in each scenario a common destination node has demands from k sources ($2 \leq k \leq N-1$). For each of these N scenarios, initialize $k = N-1$, and perform step 2.
- Step 2: Select two sources out of k sources at a time according to the largest effective gain first policy, which is explained in section 3.1.
  - Step 2.1: For the selected pair compute the total costs of working and protection paths obtained by using the $2SD$ scenario and the TS scenario. Select the scenario that provides the minimum total cost.
  - Step 2.2: Assign routing to the selected two sources (having a common destination) according the selected scenario. Update k as $k = k-2$, which is the remaining number of source nodes.
  - Step 2.3: Select the next two sources from the remaining sources, and assign routing according to steps 3.1-3.2.
  - Step 2.4: Repeat steps 3.1-3.3 until $k-2$ equals 1 or 0. When only 1 source is left, 1+1 protection with TS scenario is applied for that pair.
- Step 3: The scheme stops.

In order to illustrate the scheme, we consider the scenarios that 4 sources common destination as in Fig. 3.1. Here, $1, 2, 3, 4$ are four source nodes which send data to common destination node D. Each source send one traffic unit data to destination node. In this case, the cost for carrying one unit traffic data along one link is 1.

In Fig. 3.1, the conventional $1+1$ protection was used to protect traffic from 4 source to destination node. Here, the total cost when applying conventional $1+1$ protection is 16.

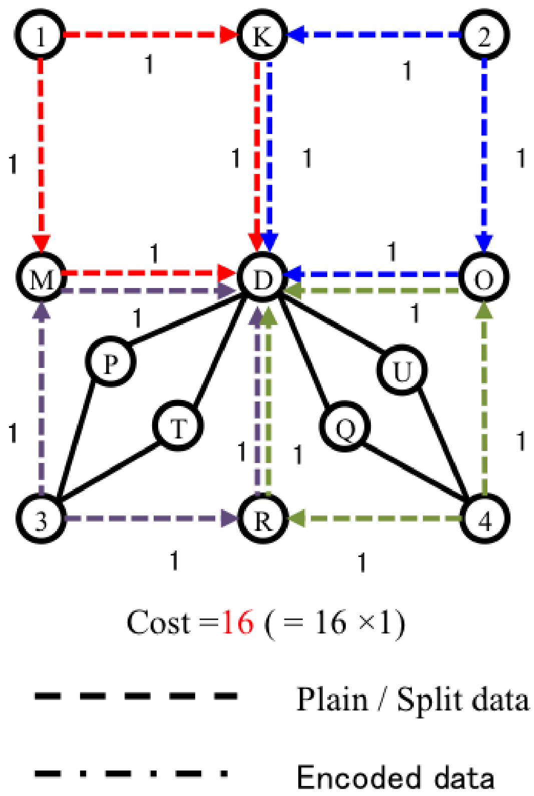


FIGURE 3.1. Conventional 1+1 protection on

In Fig. 3.1, $K-D$, $M-D$, $O-D$, $R-D$ are the common paths of source node pairs $(1,2)$, $(2,4)$, $(3,4)$, $(1,3)$, respectively. The destination node can satisfy the condition of 2SD, so that network coding can be applied at intermediate node M, K, O, R to save the resource along common paths of these source node pairs. In the scenario, multiple source nodes common destination, the total cost varies on the selection of source node pairs for using 2SD scenarios. Fig. 3.2 is the combination of source node provide highest resource saving where the total cost is 14.

According to Fig. 3.3, from source node $1, 2, 3, 4$ to destination there are 2, 2, 4, 4 number of disjoint path. Since the cost of TS scenarios are independent to others, the total cost become 13.28.

In Fig. 3.2 and Fig. 3.3, TS and 2SD scenarios can be applied for source node pairs $(3,4)$ and TS scenarios saving more resource than 2SD scenarios for this source node pair. Based on this fact, the 2SD, and TS are selected to apply for source node pairs $(1,2)$ and $(3,4)$,

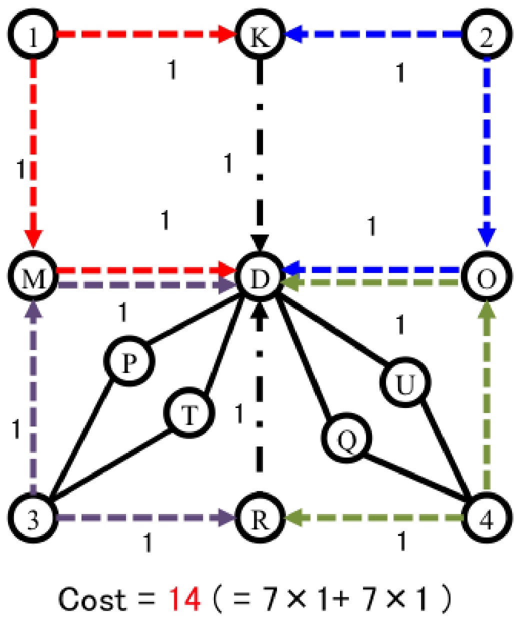


FIGURE 3.2. 4 sources common destination

respectively, as in Fig. 3.4. This illustration show that more resource can be saved when using appropriate protection technique for each source destination pairs in route design.

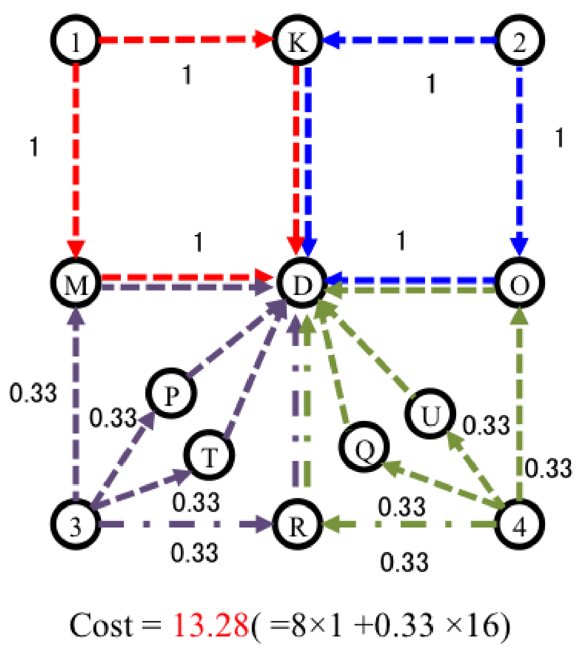


FIGURE 3.3. Applying 2SD in 4 sources common destination

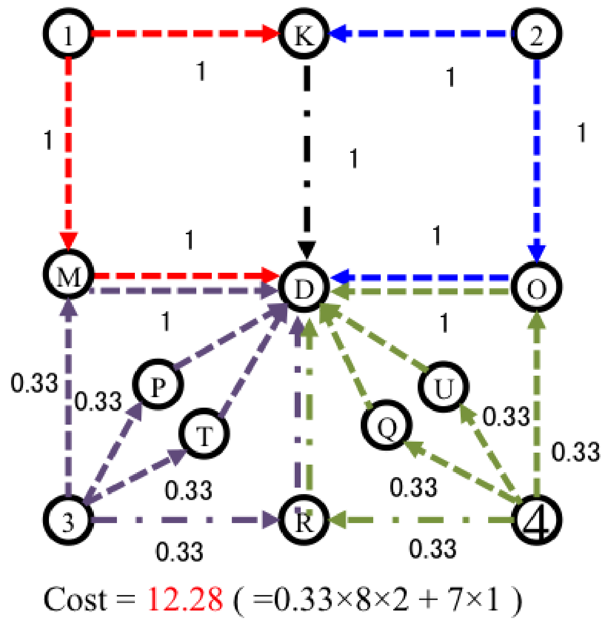


FIGURE 3.4. Network coding in

3.2. Coding gain

We describe the largest effective gain first policy to select two sources out of k sources, after defining some notations in the following.

Let φ be the set of source nodes having a common destination, where $s_i \in \varphi, i = 1, 2, \cdots, k$, where $k \geq 2$. A combination of two sources, s_i and s_j, out of k sources, is expressed by $(s_i, s_j) \in \Theta_2, (i < j)$, where Θ_2 is a set of (s_i, s_j). Θ_2 includes $\binom{k}{2}$ combinations of two sources, i.e., pairs.

Coding gain, $\mathcal{G}_C(s_i, s_j)$, indicates how much network resources is saved in 1+1 protection by using the 2SD scenario, consisting of (s_i, s_j) and a common destination. Let us assume that $\mathcal{C}_C(s_i, s_j)$ indicates the cost of employing 1+1 protection with the 2SD scenario for (s_i, s_j), and $\mathcal{C}_{NO\_C}(s_i, s_j)$ indicates the same cost without the 2SD scenario. $\mathcal{G}_C(s_i, s_j)$ is defined by,

$$\mathcal{G}_C(s_i, s_j) = \max\left\{\frac{\mathcal{C}_{NO\_C}(s_i, s_j) - \mathcal{C}_C(s_i, s_j)}{\mathcal{C}_{NO\_C}(s_i, s_j)}, 0\right\}. \tag{3.1}$$

Equation (3.1) states that, if the cost with coding is smaller than that without coding, we achieve some positive gain. Otherwise there is no gain and the solution without using the 2SD scenario is adapted.

Let $\rho_2(s_i, s_j)$, which is called an effective gain for 2SD, be the product of the coding gain and bandwidth demand for (s_i, s_j). $\rho_2(s_i, s_j)$, is expressed by,

$$\rho_2(s_i, s_j) = \mathcal{G}_C(s_i, s_j) \times \min(\omega_{s_i d}, \omega_{s_j d}), \tag{3.2}$$

where $\omega_{s_i d}$ and $\omega_{s_j d}$ are the traffic demands of source nodes s_i and s_j to common destination node d, respectively.

3.3. Largest effective gain first policy

- Step 1: For all $(s_i, s_j) \in \Theta_2$, compute $\rho_2(s_i, s_j)$.
- Step 2: REPEAT
  - Step 2.1: Select $(s_i, s_j) \in \Theta_2$ with the highest $\rho_2(s_i, s_j)$.
  - Step 2.2: Remove (s_i, s_j) and all other pairs including either s_i or s_j from Θ_2.

  UNTIL Θ_2 is empty.

At the end we select a set of $\lfloor \frac{k}{2} \rfloor$ pairs with the highest effective gain in each of the case, where $\lfloor x \rfloor$ demotes the largest integer not greater than x. The number of times to compute $\rho_2(s_i, s_j)$ is expressed as $W_2(k)$, which is given by,

$$W_2(k) = \begin{cases} \frac{k(k-1)}{2}, & \text{if } k \text{ is even} \\ \frac{k(k-1)(k-2)}{2}, & \text{if } k \text{ is odd.} \end{cases} \tag{3.3}$$

When we select a pair at a time, this policy has the computational complexity of $O(k^2)$ when k is even, and $O(k^3)$ when k is odd.

CHAPTER 4

Multiple coding scenario

4.1. Network coding between two protection scenarios

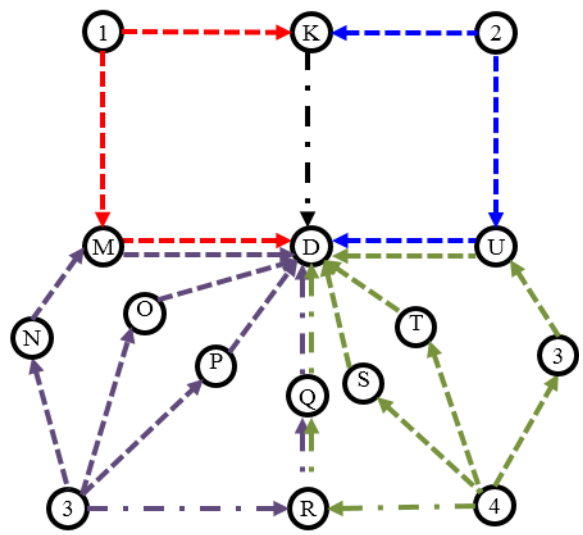


FIGURE 4.1. 4 sources common destination scenario

In this section, we explain about the the mechanism for applying NC to combine two scenarios which have common path. In Section 3.1, the protection scenarios for all source-destination pairs in network are selected based on the total path cost from sources to common destination as in Fig. 4.1. In Fig. 4.1, 4 sources$1, 2, 3$ and 4 have common destination D, 2SD scenario is used for source node pairs $1, 2$ and TS scenario is used for source node 3,4. Here, $M - D$, $R - S - D$, $U - D$ are the common path of two scenarios in protection scenario pairs. Applying NC at intermediate node M, R, D, resource can be saved on the common path.

4.2. Network coding between two protection scenarios in hybrid protection scheme

In network coding for two scenarios, there are three case of combination of two scenario which are TS-TS, 2SD-2SD, 2SD-TS. In applying network coding in the common path of two scenarios, the ability of data recovery at destination node when single link failure happened must be guaranteed. In the following, we discuss about the condition for encoding data on the common path of two scenarios.

We denote the parameter of TS and 2SD as follow:

- k : the number of common paths of two scenarios.
- m, n: the total number of disjoint path of each scenarios.
- l: the number of the common paths on which data from different scenarios are not encoded together.

4.2.1. 2SD-2SD case.

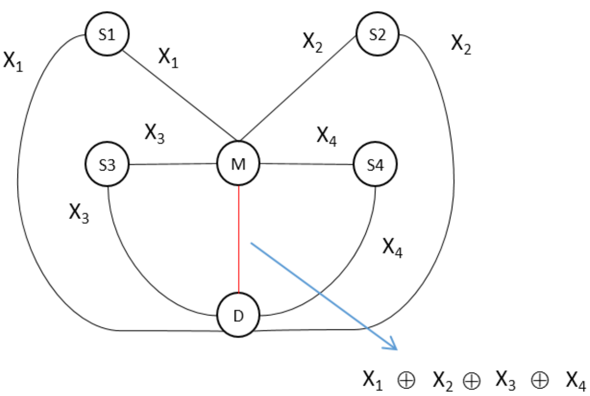
Fig. 4.2 show the case where two 2SD scenarios have common path. In Fig. 4.2 a), $(S1, S2), (S3, S4)$ are source node pairs of common destination D that employ 2SD for link protection. $M - D$ is the common path of this scenario pair. In this case $k = 1$, $m = n = 3$, if network coding is applied at intermediate node M as in the figure ($l = 0$), resource can be save along the $M - D$ path. For example, if link $S3 - D$ fails, destination node can recover data X_3 by decoding from X_1, X_2, X_4, $X_1 \bigoplus X_2 \bigoplus X_3 \bigoplus X_4$.

The number of disjoint path in 2SD scenario is 3 so that any 2SD scenarios pairs have maximum 3 paths in common. In other word, the maximum value of k is 3. Fig. 4.2 a) k is 1, network coding can be applied on the common link and Fig. 4.2 b) k is 2, node $S3$ and N can be candidate for applying network coding. If network coding is applied at node M, the data that reach destination D are X_1, X_3, $X_1 \bigoplus X_2 \bigoplus X_3 \bigoplus X_4$, X_4. In case link $S3 - D$ fails, all data can not be recover from $X_1 \bigoplus X_2 \bigoplus X_3 \bigoplus X_4$, X_4.

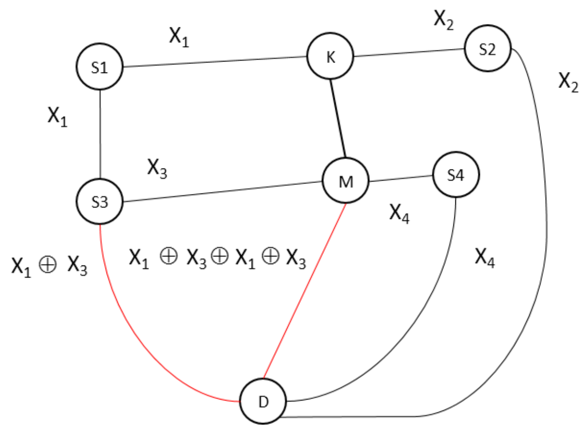
The condition for applying network coding can be decide base on the relation between k and l:

The number of data from 4 source of two scenario is

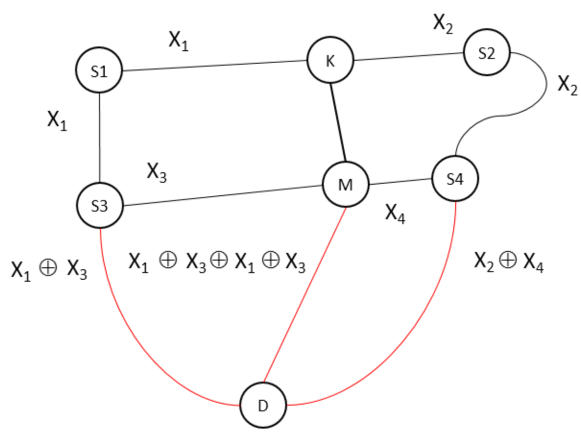
$$m + n = 2 + 2 = 4 \tag{4.1}$$



(a) 1 common path



(b) 2 common paths



(c) 3 common paths

FIGURE 4.2. Common path of 2SD scenario pair

. In $k > 1$ common paths of two scenarios $l \leq k$ do not apply network coding, then the number of data reach destination node is

$$m + n - k + l = 4 - k + l \tag{4.2}$$

Since the common paths of two scenario carry at least two kind of data from two scenario, when single link happen at least two data can not reach destination node. Then, the highest number of data will reach the destination in case of single link fail on common path of two scenarios is :

$$m + n - k + l - 2 = 2 - k + l \tag{4.3}$$

The condition for decoding original data is that the number of data arriving at destination node is greater or equal to the number of total original data from two scenarios

$$2 - k + l \geq 2$$
$$\Leftrightarrow l \geq k \tag{4.4}$$

while $l \leq k$ then l must equal to k. When k is greater than 1, network coding can not be applied on the common paths.

4.2.2. TS-TS case.

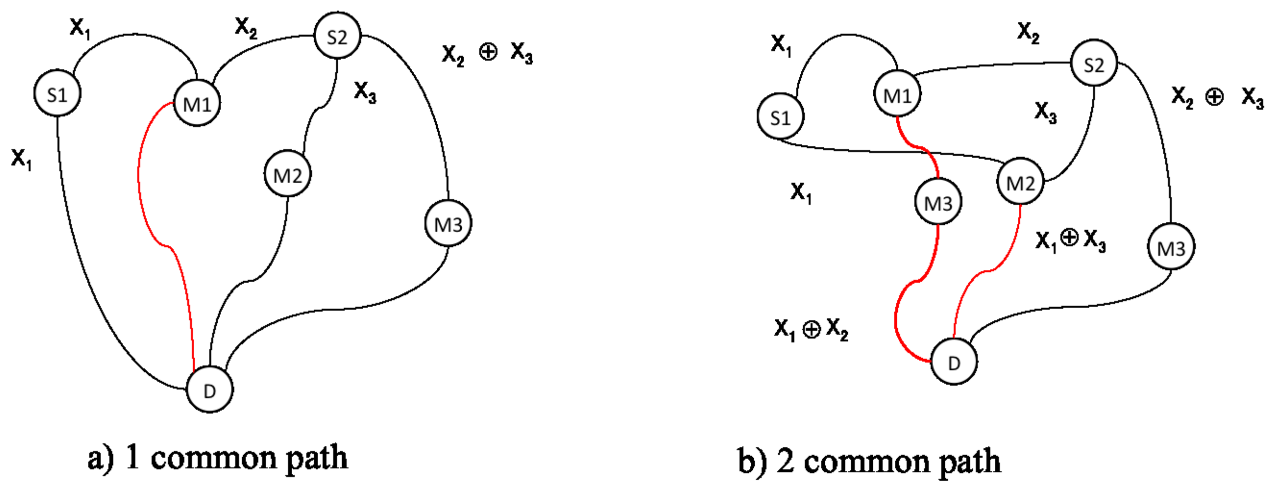


FIGURE 4.3. Common path of TS scenario pair

Fig. 4.3 show the case where two TS scenarios have common paths. Fig. 4.3 a), the number of disjoint path from two sources $S1$, $S2$ to common destination D is $m = 3$, $n = 2$, respectively. $M1 - D$ is the common path of two scenarios which carry encoded data $X_1 \bigoplus X_2$ of two scenario. Arriving data at destination node D are X_1, $X_1 \bigoplus X_2$, X_3, $X_2 \bigoplus X_3$. Assuming that single link $S1 - D$ fails, original data X_1 can be recover form $X_1 \bigoplus X_2$, X_3 ,$X_2 \bigoplus X_3$. Fig. 4.3 b), two TS have 2 path in common. If network coding is applied at intermediate node $M1$, $M2$, original data can not decoded at common destination node D.

Two TS scenarios have the number of disjoint path to common destination is m, n, respectively. Here, there are $m - 1$, $n - 1$ original data are sent from source to common destination. The number of arriving data at destination node is $m + n - k + l$, where $k > 1$

is the number of common path of two scenario, $l \leq k$ is the number of path do not encoded data from two sources. The condition that guarantee all original data from two sources can be decoded at destination node is

$$\begin{aligned} m + n - k + l - 2 &\geq m + n - 2 \\ \Leftrightarrow l &\geq k \end{aligned} \tag{4.5}$$

While $l \leq k$ then l must equal to k. On other word, when two TS scenarios have more than one paths in common, network coding can not be applied for guaranteeing the data recovery ability prevent single link failure.

4.2.3. Network coding between two protection scenarios.

Fig. 4.4 are three case that TS and 2SD have scenarios in common. In Fig. 4.4 (a), three source nodes $S1$, $S2$, $S3$ have common destination D, where source node ($S1$,$S2$) is the source node pair of 2SD scenarios and $S3$ is the source node of TS scenario. $M2 - D$ is the common path of two scenarios which carry encoded data $X_2 \bigoplus X_3$. Here, when single link such as $S1 - D$ fails, the arriving data destination node are $X_1 \bigoplus X_2$, $X_2 \bigoplus X_3$, X_4, $X_3 \bigoplus X_4$. In this case, the original data can be decoded based on the arriving data. In Fig. 4.4 (b) and (c), when network coding is applied at intermediate node to encode data from two scenario on the common paths, only encoded data arrived since that original data can not be achieved.

The number of disjoint path of 2SD and TS scenarios are 3, n, respectively. Therefore, the maximum number of common paths of two scenarios are 3. Since data in TS scenario are split into $n-1$ part, the number of original data of two scenarios is $(n-1)+2 = n+1$. The number of data from two scenario arrived at destination node when network coding is not applied on l common paths among $k \geq 1$ one is $n + 2 - k + l$. The condition for applying network coding on the coming path while guaranteeing the ability of single link failure prevention is

$$\begin{aligned} n + 3 - k + l - 2 &\geq n + 1 \\ \Leftrightarrow l &\geq k \end{aligned} \tag{4.6}$$

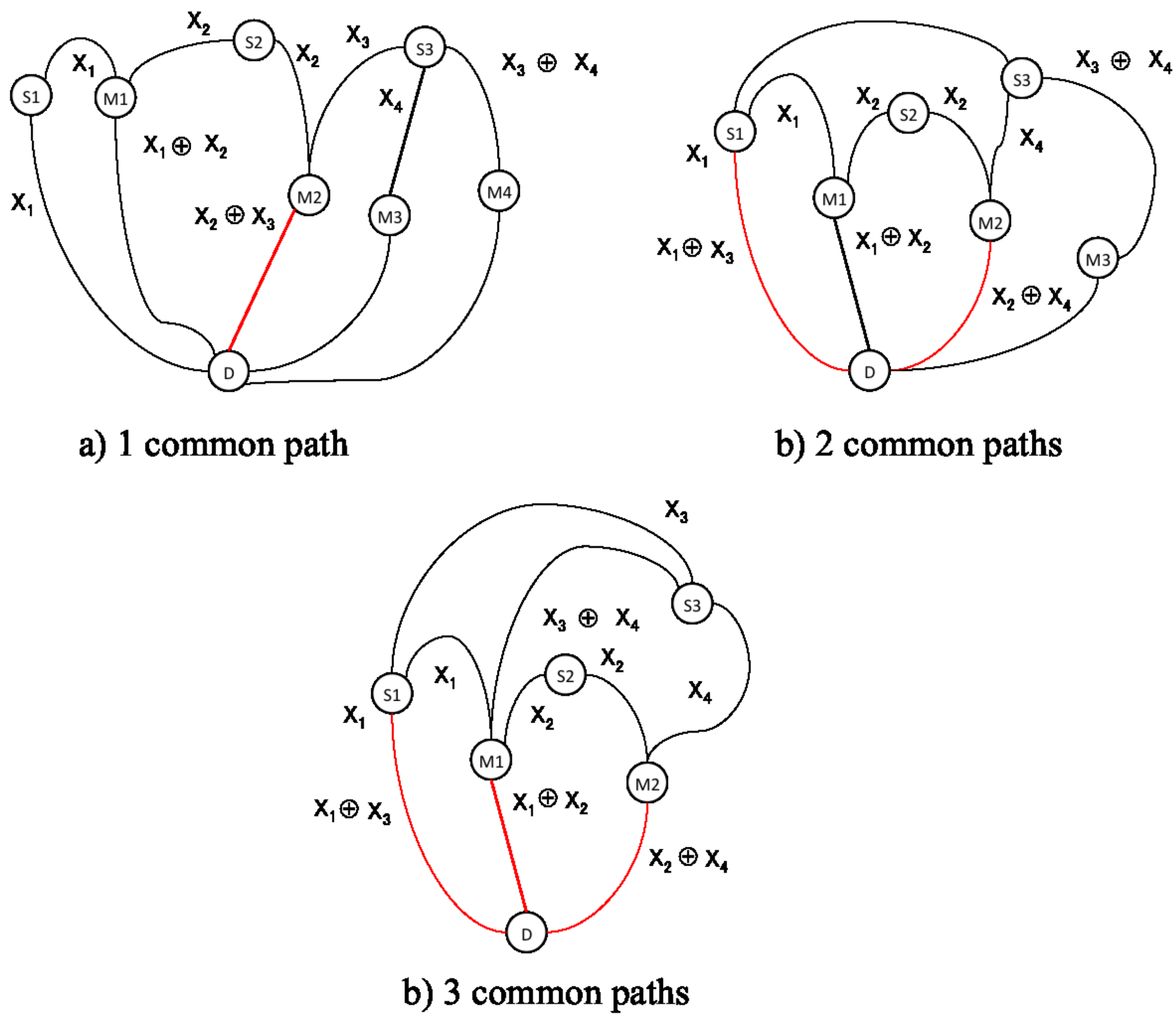


FIGURE 4.4. Common path of 2SD and TS spair

While $l \leq k$, then the ability of recovery from single link failure at destination node are not guaranteed when network coding is applied on the common paths of two scenarios in case the number of commons path is greater than 1.

4.3. Policy for selecting two scenario pairs in multiple network coding scenarios

In Sec 4.2, the condition for applying network coding for three combination of two protection scenarios has been discuss. Network coding can be applied to save more resource while guaranteeing the ability of data recovery at destination node when single link failure happen if and only if the number of common path of two scenarios is 1.

In route design for the scenario in which multiple source nodes have common destination, there are number of different ways to select scenario pairs. The issue need to be consider is that which combination set of scenario should be selected to achieve more resource saving. Since choosing the pair for applying network coding is affected to the total resource saving of the scenarios, we propose the policy for choosing the set of pairs of two scenarios.

Let $\mathcal{D}(sc_{ij}, s_i)$ is the traffic demand from scenario s_i on the common link of two scenarios i, j and $\mathcal{G}_{NC(sc_{ij})}$ is the gain when applying network coding for 2 scenarios i, j. The network coding gain on the common link can be defined by:

$$\mathcal{G}_{NC(sc_{ij})} = 1 - \min\left\{\frac{\mathcal{D}(sc_{ij}, s_i)}{\mathcal{D}(sc_{ij}, s_i) + \mathcal{D}(sc_{ij}, s_j)}, \frac{\mathcal{D}(sc_{ij}, s_j)}{\mathcal{D}(sc_{ij}, s_i) + \mathcal{D}(sc_{ij}, s_j)}\right\} \tag{4.7}$$

Based on the network coding gain, the combination of scenarios pair can be selected as follow:

- Step 1: Generate the set of source node set of all combination of scenario pairs and compute the network coding gain $\mathcal{G}_{NC(sc_{ij})}$ for all scenario pairs.
- Step 2: Select the set that have the maximum $\mathcal{G}_{NC(sc_{ij})}$.
- Step 3: Eliminate all the set of source node, which have the common source with the selected set at step 2.
- Step 4: Repeat step 2

CHAPTER 5

Performance evaluation for hybrid protection scheme

5.1. Simulation Model

Our evaluation uses networks 1, 2, 3, and 4 in Fig. 5.1, known as synthetic network [2], COST 239 network [1], Indian network [6], and Japan photonic network (JPN 25) [8], respectively. The traffic demands for all possible source-destination pairs are set equal.

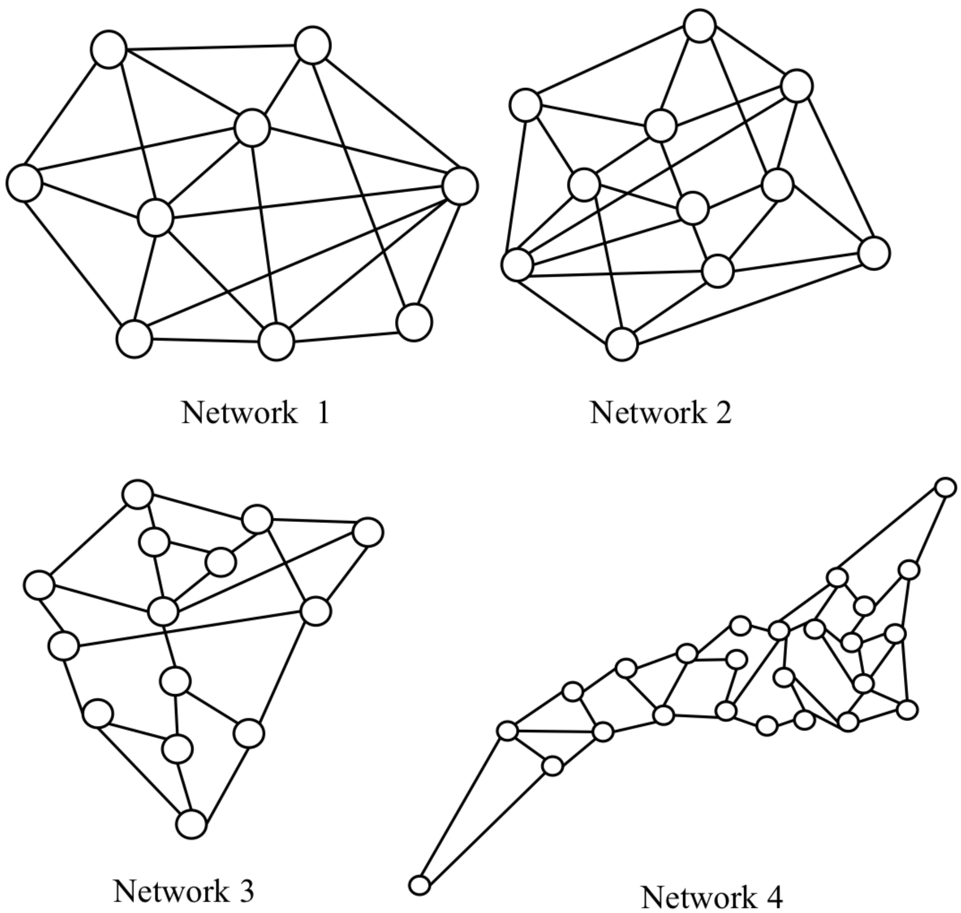


FIGURE 5.1. Examined networks, where A_C indicates average node connectivity.

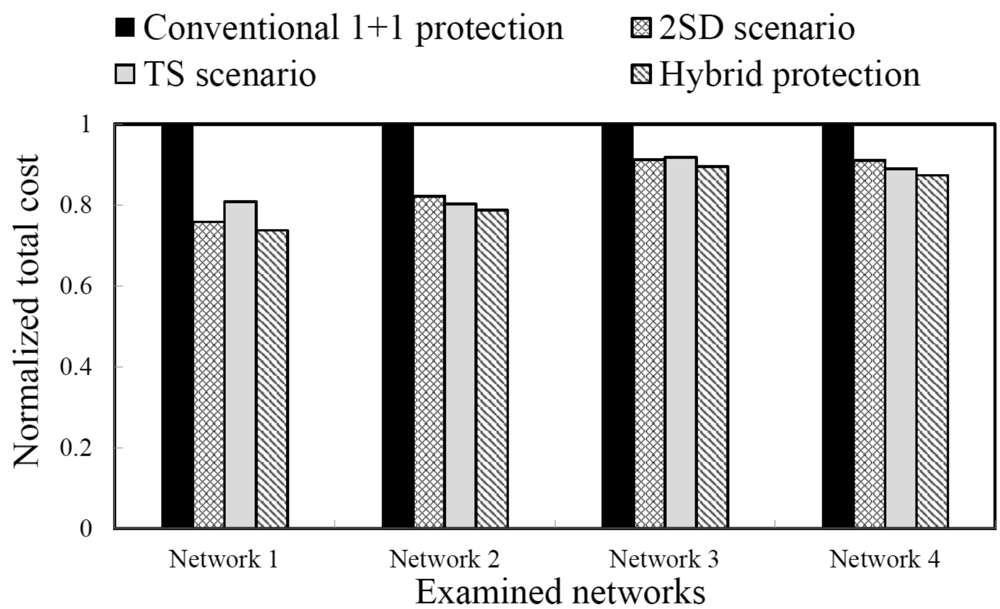


FIGURE 5.2. Comparison of total routing cost.

5.2. Evaluation for hybrid protection scheme

Fig. 5.2 observes that the proposed scheme achieves more resource saving than each applied individual protection scheme. In networks 1 and 2, the proposed scheme achieves 2.1% more resource saving than the most efficient scenario between TS and 2SD, and 1.6% for networks 3 and 4. The average network connectivity of networks 1 and 2 is higher than that of networks 3 and 4. In our evaluation, the proposed scheme can saves more resources in the network with higher connectivity. The reason is as follows. 2SD requires that both common destination and transit nodes have the network connectivity with three or more and some specified routes be disjoint [**4**]. TS requires that both source and destination nodes have the network connectivity with three or more and all the routes be disjoint [**5**]. Additionally, to make each scenario applicable, its cost with coding must be less than that without coding. The larger the network connectivity is, the higher the possibility for finding more cost-effective routes satisfying the disjoint condition is. When the network connectivity is low, there is less chance that both 2SD and TS are applicable since the above required conditions may not be satisfied. In this case, since our option to take the better scenario out of the two is limited, the resource saving is limited.

We discuss the impacts of computation time and implementation of the proposed scheme, compared to that of individual scenario.

As to the computation time, in the proposed scheme, for each pair both TS and 2SD scenarios are evaluated. Therefore, the computation time of the proposed scheme is at most twice than that of the longer scenario of the two, while the order of the computation time in terms of the numbers of nodes and links are the same as that of individual scenario. As the proposed scheme is used for route design in a planning phase, the double increase of computation time is acceptable for a network designer unless the increase of computation time violates the time constraint in the planning phase. The proposed scheme gives a network designer an option to achieve 1.6-2.1% resource saving, which leads to reducing the capital expenditure, at the cost of the double increase of computation time.

Second, we consider the implementation impact of the proposed scheme on the encoding and decoding functions. In both 2SD and TS, each node is required to have encoding and decoding functions. Encoding is performed at intermediate and source nodes in 2SD and TS, respectively. Decoding is performed at a destination node in both 2SD and TS. In the proposed scheme, each node is also required to have encoding and decoding functions in the same way of both 2SD and TS. Therefore, the implementation complexity of the proposed scheme in terms of encoding and decoding functions is the same as that of each individual scenario.

CHAPTER 6

Performance evaluation for multiple coding based protection scenario

In the evaluation of the multiple coding based protection scenarios, we used 2, 3, and 4 in Fig. 5.1. The traffic demands for all possible source-destination pairs are set equal. We calculated the total path cost of implementing proposed protection scheme. We compared the total path cost of proposed scheme, TS and 2SD scenario to the total cost of applying individually conventional 1+1 protection.

According to the result in Fig. 6.1, the proposed scheme can reduce 5% resource more than the higher efficient one between TS and 2SD. The proposed scheme achieved the highest resource reduction on network 4. Based on the node average degree and number of links in Table 6.1, network 3 and network 4 have almost the same average node degree and the number of link of network 4 is higher than network 2 and 3. When the number of links become higher, our proposed scheme have more chance to reduce the resource on the common links of two scenarios.

Table 6.1. Average node degree and number of links of examined networks

	Network 1	Network 2	Network 3	Network 4
Average Node Degree	4.67	4.73	3.43	3.44
Number of Links	20	24	23	42

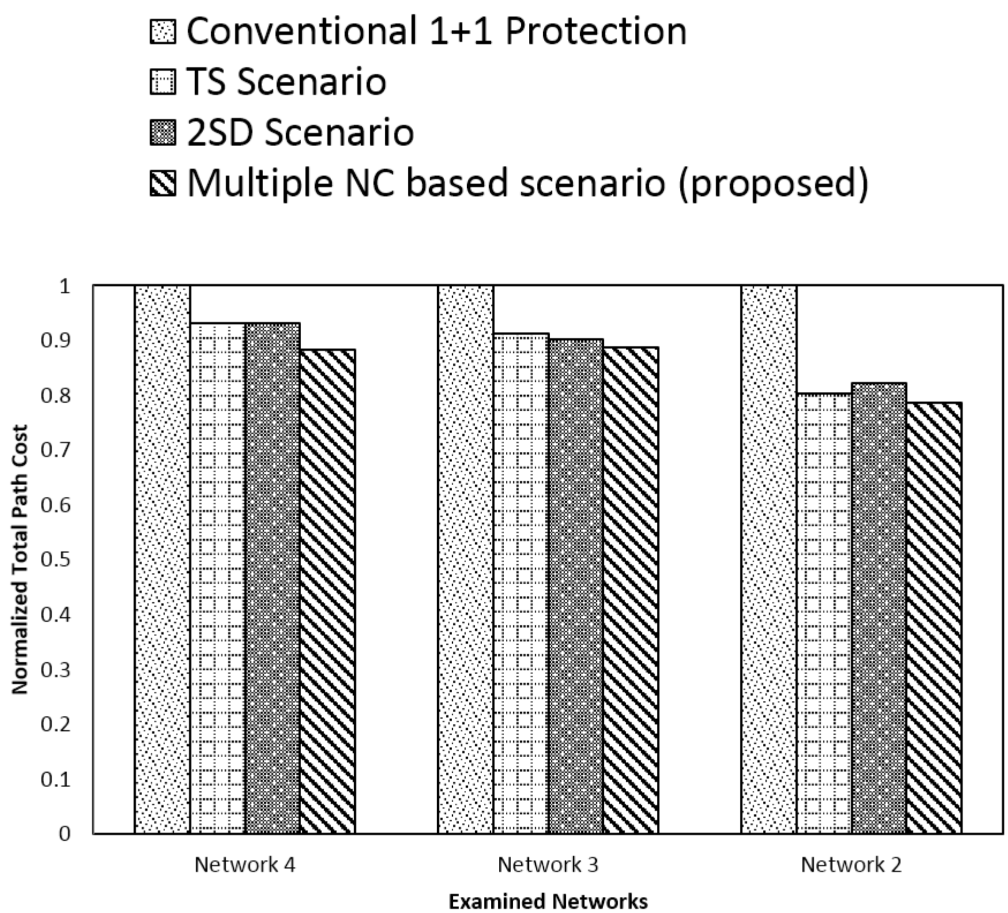


FIGURE 6.1. Comparison of total routing cost.

CHAPTER 7

Conclusion

The objective of this research is to reduce the cost of the protection technique while maintaining the instantaneous recovery ability. This research was done in two parts. First, we consider using two scenarios, TS and 2SD, intelligently to enhanced the resource saving. Second, we extended to reduce more resource by considering network coding on the common paths of two scenarios while maintaining the ability of instantaneous recovery from single link failure.

The resource saving of proposed scheme varies on the average node degree and number of links of the topology. It works more efficiently when the have more chance to take the balance of using of two scenarios and more chance to combine two scenario together.

Publications

Letter Publications

- P.V.Pham, A. H. A. Muktadir, and E. Oki, "A Hybrid Instantaneous Recovery Route Design Scheme with Two Different Coding Aware Scenarios," *IEICE Communications Express*, 2015.
- A.H.A. Muktadir, P.V. Pham, and E. Oki, "A Mathematical Model for Network Coding Aware Optimum Routing in 1+1 Protection for Instantaneous Recovery with Relaxing Destination's Node Degree Constraint,'' IEICE Commun. Express, vol. 2, no. 12, pp. 512-517, Dec. 2013.

Conference Proceeding Publications

- P.V.Pham, A. H. A. Muktadir, and E. Oki, "A Hybrid Scheme for Instantaneous Recovery Route Design with Two Different Coding Aware Scenarios," *IEEE International Conference on Network Infrastructure and Digital Content (IC-NIDC 2014)*, Sept. 2014.
- P.V.Pham, A. H. A. Muktadir, and E. Oki, "A Mathematical Model for Network Coding Aware Optimal Routing in 1+1 Protection for Destination's Node Degree >= 2," *IEEE 18th OptoElectronics and Communications Conference (OECC/PS 2013)*, Jul. 2013.
- P.V.Pham, A. H. A. Muktadir, and E. Oki, "Performance of Hybrid Instantaneous Recovery Route Design Scheme with Two Different Coding-Aware Scenarios in Japan Photonic Networks," *Japan Photonic Network design contest*, Nov. 2014.

Bibliography

[1] B. Mukherjee, "Optical WMD Networks," Springer, 2006.

[2] A.E. Karmal, "1+N Network Protection for Mesh Networks: NC-Based Protection Using p-Cycles," IEEE/ACM Transactions vol. 18, pp. 67-80, Aug. 2010.

[3] A.E. Karmal and O. Al-Kofahi, "Efficient and Agile 1+N Protection," IEEE Transactions on Communications vol. 59, pp.169-180, Jan. 2011.

[4] A. H. A. Muktadir and E. Oki, "Optimum Route Design in 1+1 Protection with Network Coding for Instantaneous Recovery," IEICE Trans. Commun., vol. E97-B, no. 1, pp. 87-104, Jan. 2014.

[5] A. A. Jose, A. H. A. Muktadir, and E. Oki, "Network Coding Aware Instantaneous Recovery Scheme Based On Optimal Traffic Splitting," IEICE Commun. Express vol. 1, no. 1, pp. 28-32, Jun. 2012.

[6] R. Ahlswede, N. Cai, S. R. Li, and R. W. Yeung, "Network Information Flow," IEEE Trans. Inf. Theory, vol. 46, no. 4, pp. 1204-1216, Jul. 2000.

[7] A. H. A. Muktadir and E. Oki, "A Heuristic Routing Algorithm with Erasure Correcting Code Based Instantaneous Recovery Technique," in Proc. IEEE ICC 2014 Conf., pp. 1149-1153, Sydney, Australia, 10 - 14 Jun., 2014.

[8] A. H. A. Muktadir and E. Oki, "A Heuristic Routing Algorithm for Network Coding Aware 1+1 Protection Route Design for Instantaneous Recovery,in Proc. 15^{th} IEEE HPSR Conf., pp. 84-89, Vancouver, British Columbia, Canada 1-4 Jul., 2014.

[9] B. C. Chatterjee, N. Sarma, and P. P. Sahu, "Priority Based Routing and Wavelength Assignment With Traffic Grooming for Optical Networks," IEEE/OSA J. Opt. Commun. Netw., Vol. 4, Issue 6, pp. 480-489, 2012.

[10] P. V. Phong, A. H. A. Muktadir and E. Oki, "A Hybrid Scheme for Instantaneous Recovery Route Design with Two Different Coding Aware Scenarios," in Proc. IEEE Int. Conf. on Network Infrastructure and Digital Content (IC-NIDC 2014), Beijing, China, 19-21 Sep., 2014.