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An Optimal Design Framework for 1 + 1 Routing and Network Coding Assignment Problem in WDM Optical Networks

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ABSTRACT Network coding (NC) features a new perspective for leveraging network performances as more efficient resources utilization could be achieved. In recent years, the application of NC to the realms of failure recovery in optical networks has been receiving growing attention and indeed, combining the near-instantaneous recovery of dedicated protection and improved capacity efficiency enabled by NC constitutes an important research trend in optical protection. In order to maximize the benefits empowered by NC, a critical problem on routing of traffic demands, selecting demands for encoding and determining the respective coding node and coding links has to be optimally addressed. The problem becomes even more challenging if multiple traffic demands are considered at once and the traffic is non-equal. In addressing those issues, for the first time, we present a novel unified framework for augmenting 1 + 1 dedicated protection against single link failures with a practical network coding scheme based on XOR operation for both equal and non-equal traffic scenarios. In line with this framework, a mathematical model in the form of integer linear programming for optimal routing and network coding assignment to minimize the path cost is presented. Numerical results based on evaluating the model on realistic topologies and all-to-one traffic setting highlight the cost advantages of our proposed NC-assisted protection scheme compared to traditional counterparts.

INDEX TERMS Routing, network coding, dedicated protection, optical networks, integer linear programming, network optimization.

I. INTRODUCTION

The "data storm" era is undoubtedly booming with the increasing connectivity of everything, known as Internet of things, and the proliferation of bandwidth-intensive applications such as high-definition on-line video, cloud computing services. According to a recent report from Cisco [1], the global IP traffic is forecasted to increase nearly threefold over the next 5 years, and will have increased nearly 100-fold from 2005 to 2020. Overall, IP traffic will grow at a compound annual growth rate (CAGR) of 22% in the timespan from 2015 to 2020. Clearly, such explosive growths in network traffic are posing serious challenges for transport networks to improve their capacity efficiency in order to meet the traffic requirements. Besides, as there is increased large amount of information (i.e., multi Terabit) being carried over optical transport networks and the businesses are essentially reliant on the continuity and robustness of information flows, securing the network against failures has become indispensable [2]–[4].

In designing protection schemes, the central issue for consideration is the compromise between redundant capacity and recovery speed. Although there are several innovative protection schemes, dedicated optical protection (1 + 1) remains widely implemented in backbone networks to provide the necessary resilience and (near-) instantaneous recovery against single link failures with remarkably simple operation [2], [5], [6]. Its simplicity is based on the fact that there are two copies of the same data being sent from the source to the destination on disjoint routes and as soon as the receiver detects any unsatisfactory signal quality on the primary path, it can rapidly switch over to the alternative path for receiving the data. While this protection scheme offers unparalleled recovery speed, it comes at a cost of inefficacious capacity utilization as the large amount of sparse resources are generally required, typically doubling the capacity requirements.

Originally coined in [7], network coding (NC) in which the data is manipulated inside the network has become a promising technique to increase throughput, reduce delay and improve robustness. In recent years, the NC techniques have been actively introduced to the realms of failure recovery in optical networks to provide both near-instantaneous recovery and capacity efficiency [8]–[12]. The foundation of research on NC combined with protections is based on the idea that intermediate network nodes are capable of processing a set of signals such that a destination receives linear combinations of signals over disjoint paths. The combination has to be satisfied that if one signal is lost due to a failure, it can be recovered almost immediately from the other received signals. By doing so, better capacity utilization could be attained while the advantage of rapid recovery speed is maintained [12]–[15].

Being considered as the major research trend in optical protection, there have been considerable amount of works in literature addressing the use of NC for enhancing survivable optical networks, collectively referred as network coding-based protection [8]–[10], [12]. In improving the classical shared protection 1:N, the authors in [16], [17] proposed 1+N network coding protection in combination with p-cycles strategy. The p-cycles were used to protect multiple bidirectional link-disjoint connections, which are also link disjoint from the p-cycle links. In the same framework, the research in [18] addressed the efficient implementation of 1+N protection with network coding by using a tree shaped minimum cost protection circuit. This work also introduced an integer linear programming formulation to evaluate the protection cost of using this technique and compared it to the cost of conventional 1 + 1 protection. By transforming the node failure problem to the multiple link failures cases, NC was successfully applied for enhancing node failure protection schemes in [19]. The research work from [20] investigated protection of multi-domain networks by adopting network coding in combination with 1 + 1 protection and dual homing and it was shown that this technique could enable the network to survive under any node or link failure in each subdomain. In [21], NC technique was demonstrated to reduce resource utilization in bandwidth-intensive 1 + 1 protection with the help of a network model with two sources and a common destination node. This work nevertheless considered only conventional shortest path and load-balanced routing algorithms and thus, had a shortage of non-optimal solutions. In addressing this problem, the authors from [22] proposed mathematical formulations in the form of integer quadratic programming to achieve optimum routes for maximizing resource saving with the NC effect considering various two sources and a common receiver scenarios. Instead of limiting to considering two demands with shared destination at once, the research effort in [23] addressed the optimization problem considering arbitrarily multiple demands. This work, however, was restricted to assumption that all traffic demands are equal. In the same context of 1 + 1 protection with NC, [24] extended the network coding scenarios to take into account the case of multiple sources and common destination and proposed an efficient heuristic for finding the near-optimal coding-aware routing. However, the works did not provide mathematical models for optimum routing and network coding selection among demands and still limited to the case of equal traffic. Traffic splitting in addition to network coding was addressed in [25], [26] for improving the robustness efficiency. Network coding in all-optical networks was also examined from both algorithmic and infrastructure perspectives in [27]. More recently, the network coding techniques were also investigated in the context of elastic optical networks for improving the network efficiency with pioneering works from [11], [28], [29].

Our work is centered on the application of a practical coding scheme based on XOR operation for leveraging the 1 + 1 dedicated protection against singe link failures in wavelength division multiplexing (WDM) optical networks. The motivation for adopting XOR coding operation is based on the fact that this coding scheme has been backed by increasing experimental works [30]–[32] and the current technologies could enable XOR operation at line speed for transmission above 10 Gbps and up to 100 Gbps with different modulation formats [30]–[32]. In this scope, this paper goes beyond the existing in literature by providing a novel unified framework for augmenting the 1 + 1 protection with XOR network coding addressing both equal and non-equal traffic cases. A new problem called routing and network coding assignment (RNCA) is introduced as the extension of the traditional 1 + 1 routing. In order to harness the benefits empowered by NC, a novel mathematical model in the form of integer linear programming for optimal routing and network coding assignment problem to minimize the path cost is presented. Numerical results based on evaluating the model on realistic topologies and all-to-one traffic setting highlight the cost advantages of our proposed NC-assisted protection solutions compared to traditional counterparts.

The rest of this paper is organized as follows. Section II presents in detail on how XOR coding is exploited for better resource utilization in 1 + 1 protection taking into account different traffic scenarios. In Sec. III, the problem of finding optimum routing and determining optimal network coding selection among traffic demands with the objective of minimizing the path cost is presented and formulated as integer linear programming models. Section. IV is dedicated to provide extensive simulation results on realistic topologies to draw a comparison between the NC-assisted 1 + 1 protection solution and conventional 1 + 1 case. Finally, the Sec. V is left for conclusion.

II. XOR NETWORK CODING FOR EFFICIENT 1 + 1 PROTECTION

This section details how the NC is used in leveraging the 1 + 1 protection for both the equal and non-equal traffic cases. We focus on a practical coding scheme based on XOR as it could be realized by optical logic and indeed, there has been significant experimental works for realizing this coding operation [30]–[32]. The metric for comparison is the path cost in which the cost is evaluated by summing up on all

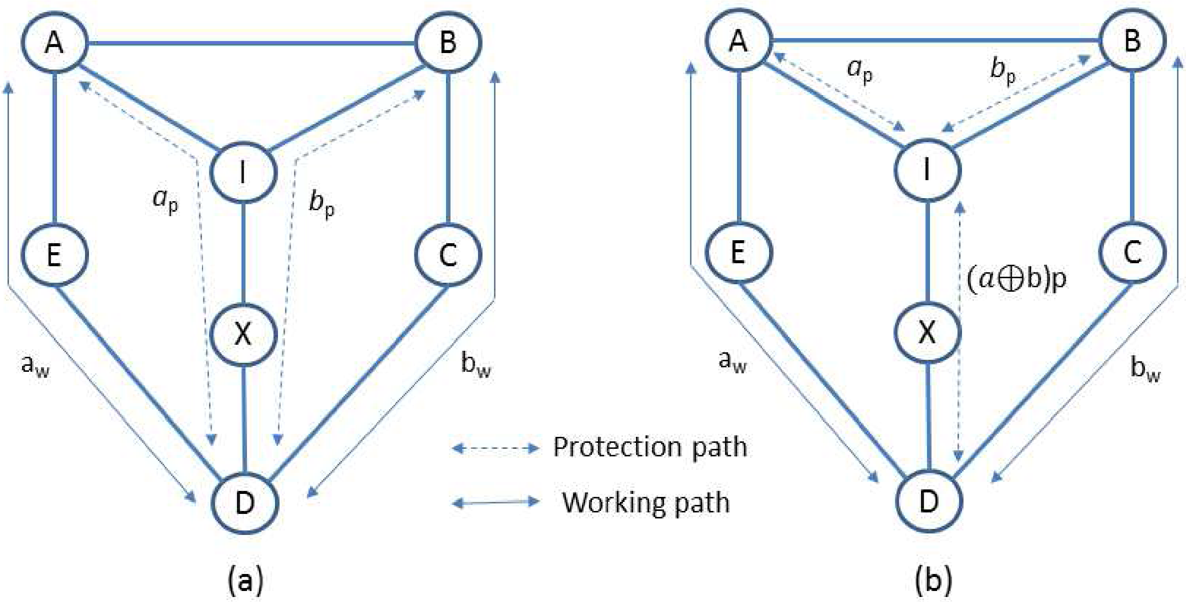

FIGURE 1. Network coding for 1 + 1 protection in equal traffic case.

routed links. The cost of routing one traffic unit over a link is a constant c.

A. EQUAL TRAFFIC CASE

Assuming that there are two dedicated protection connections, a and b, originated from node A and node B respectively and ended at common node D. Without loss of generality, we assume that those two connections require the same amount of *one* traffic unit. Provisioning those connections in traditional case 1 + 1 protection, as depicted in Fig. 1a, requires finding pair of link-disjoint routes for each connection and allocating necessary capacity on routed links. The cost of doing so is therefore $5c$ for connection a (i.e., $2c$) for the working route and $3c$ for the protection route) and similarly $5c$ for connection b. If the network coding is applied, better resource efficiency could be achieved. Figure 1b illustrates the network coding-assisted solution. At node I, the protecting signals a_p and b_p are combined so that a single signal occupying one traffic unit, represented by $(a \oplus b)_p$ is sent from node I to destination node D. This solution, taking into account both demand a and b, requires a cost of $4c$ for the working and more importantly, reduces the protection cost to $4c$. Compared to the classical case, the NC-based solution brings about a saving of 20%. It is important to notice that that saving is achieved on the condition that the coding is only performed on protecting signals while leaving the working signals intact. If any single link failure occurs on the primary paths, the destination node still receives two remaining signals which allows it to reconstruct the lost signal by XOR operation. Following equations explain the recovery operations for both connection a and b

$$b = a_w \oplus (a \oplus b)_p \tag{1}$$
$$a = b_w \oplus (a \oplus b)_p) \tag{2}$$

B. NON-EQUAL TRAFFIC CASE

In the case of unequal traffic, considering that connection a requests *three* units while connection b demands *one* unit. We assume that the single routing policy is enforced for the entire traffic of each connection and focus on the case that the XOR operation is performed on two flows having the same amount of traffic and the output is simply a mixing of those two flows that occupies exactly the same bandwidth as one of those two input flows. Using this XOR scheme, there are two options for mixing a and b. The first option is that the flow with smaller traffic, b, is padded with idle traffic so that the overall traffic is equal to the larger flow a while the second option is to encode only on the smaller part of those two flows, b in this case, and leave the remaining part of larger flow, $a - b$, untouched. We opt for the latter option since the XOR is executed only on a smaller amount of traffic and thus, it is likely to be more cost-effective.

It is assumed that the traffic from node A could be split into a^1 and a^2 where a^1 is *one* traffic unit which is equal to b while a^2 is *two* traffic units. If network coding is applied at node I, the part of protecting signals for connection a, a_p^1 is coded with protecting signal b_p to produce the encoded signal $(a^1 + b)_p$ which occupies one capacity unit while the remaining part of protecting signal for connection a, a^2 remains intact and all are sent from node I to node D. In case of any singe link failure on the working routes, each connection could be easily recovered by the following operations:

$$b = a_w^1 \oplus (a^1 \oplus b)_p \tag{3}$$
$$a = a_p^2 + (b_w \oplus (a^1 \oplus b)_p) \tag{4}$$

In term of cost, it is straightforward to verify that the classical 1 + 1 approach is $20c$ while the NC-assisted one is $18c$. The amount of cost saving is therefore 10% in this

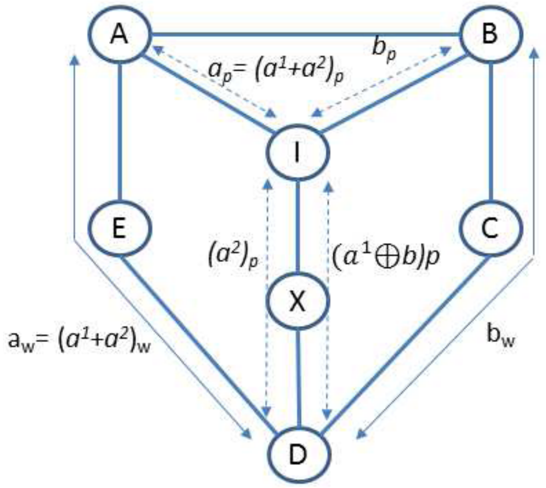

FIGURE 2. Network coding for 1 + 1 protection in non-equal traffic case.

case. Compared to the case of equal traffic, the non-equal traffic exhibits lower gain. This is due to the fact that the relative amount of encoded traffic is lower when there is a un-match in terms of traffic between coded demands.

III. A MATHEMATICAL MODEL FOR OPTIMAL DESIGN OF NC-ASSISTED 1 + 1 PROTECTION

The saving in the aforementioned example in Sec. II is clearly dependent on the underlying physical topology, the nature of demands and routing together with the location of network coding nodes. In this section, we develop a unified mathematical model that could minimize the path cost, or alternatively maximizing the impact of network coding. The model takes inputs of physical topology, set of requested traffic demands and determines optimal routing of demands including both the working and protection, the optimal coding pairs of demands and respective coding nodes and coding links. We refer to that problem as *Routing and Network Coding Assignment (RNCA)* and indeed, the problem is the extension of the traditional 1 + 1 routing as the dimension on network coding among demands is taken into account. The link capacity is assumed to be unconstrained as all the demands are supported and the objective is focused on minimizing the path cost. Without loss of generality, we assume that the cost of routing a single traffic unit over one link is a constant and equals to 1.

A. MATHEMATICAL MODEL FOR THE ROUTING AND NETWORK CODING ASSIGNMENT

Given Information:

- $G(V, E)$: Physical network topology with $|V|$ nodes and $|E|$ links. Each link $e \in E$ has its beginning node $s(e)$ and its ending node $r(e)$.
- D: Set of traffic demand, indexed by d. Each demand d has its origin $s(d)$ and destination $r(d)$ respectively and request t_d traffic unit.

Variables:

- $x_e^d(y_e^d) \in \{0, 1\}$: equals to 1 if link e is used for working (protection) path of demand d, 0 otherwise.
- $z_e^{d,v} \in \{0, 1\}$: equals to 1 if demand d is coded at node v and link e belongs to the coding path, 0 otherwise
- $\theta_v^d \in \{0, 1\}$: equals to 1 if demand d is coded at node v, 0 otherwise
- $f_{d_1}^{d_2} \in \{0, 1\}$: equals to 1 if demand d_1 is coded with demand d_2, 0 otherwise

Objective in Equal Traffic Case ($t_d = t$ for $d \in D$)

$$Minimize \sum_{d\in D}\sum_{e\in E}(x_e^d + y_e^d - \sum_{v\in V}\frac{z_e^{d,v}}{2}) \times t \quad (5)$$

Objective in Non-equal Traffic Case

$$Minimize \sum_{d_1\in D}\sum_{e\in E}(x_e^{d_1} + y_e^{d_1}) \times t_{d_1}$$
$$\sum_{d_1\in D}\sum_{e\in E}\sum_{v\in V}\frac{z_e^{d_1,v} \times \sum_{d_2\in D} f_{d_1}^{d_2} \times min(t_{d_1}, t_{d_2})}{2} \quad (6)$$

subject to the following constraints:

$$\sum_{e\in E:v\equiv s(e)} x_e^d(y_e^d) - \sum_{e\in E:v\equiv r(e)} x_e^d(y_e^d) = \begin{cases} 1 & \text{if } v \equiv s(d) \\ -1 & \text{if } v \equiv r(d) \\ 0 & otherwise \end{cases} \quad \forall d \in D, \quad \forall v \in V \quad (7)$$

$$x_e^d + y_e^d \leq 1 \quad \forall d \in D,\ \forall e \in E \quad (8)$$

$$\sum_{v\in V}\theta_v^d \leq 1 \quad and\ \theta_v^d = 0 \quad \text{if } v \equiv r(d) \quad \forall d \in D \quad (9)$$

$$\sum_{d_2\in D} f_{d_1}^{d_2} \leq 1 \quad \forall d_1 \in D \quad (10)$$

$$f_{d_1}^{d_1} + \sum_{d_2\in D:r(d_2)\neq r(d_1)} f_{d_2}^{d_1} = 0 \quad \forall d_1 \in D \quad (11)$$

$$f_{d_1}^{d_2} = f_{d_2}^{d_1} \quad \forall d_1, d_2 \in D \quad (12)$$

$$\sum_{v\in V} z_e^{d_1,v} \leq \sum_{d_2\in D} f_{d_1}^{d_2} \quad \forall d_1 \in D,\ \forall e \in E \quad (13)$$

$$\sum_{d_2\in D} f_{d_1}^{d_2} = \sum_{v\in V}\theta_v^{d_1} \quad \forall d_1 \in D \quad (14)$$

$$x_e^{d_1} + x_e^{d_2} + f_{d_1}^{d_2} \leq 2 \quad \forall d_1,\ d_2 \in D,\ \forall e \in E \quad (15)$$

$$x_e^{d_1} + y_e^{d_2} + f_{d_1}^{d_2} \leq 2 \quad \forall d_1,\ d_2 \in D,\ \forall e \in E \quad (16)$$

$$\theta_v^{d_1} - \theta_v^{d_2} + f_{d_1}^{d_2} \leq 1 \quad \forall d_1,\ d_2 \in D,\ \forall v \in V \quad (17)$$

$$\theta_v^{d_2} - \theta_v^{d_1} + f_{d_1}^{d_2} \leq 1 \quad \forall d_1,\ d_2 \in D,\ \forall v \in V \quad (18)$$

$$z_e^{d,v} \leq y_e^d \quad \forall d \in D,\ \forall v \in V,\ \forall e \in E \quad (19)$$

$$\sum_{e\in E:i\equiv s(e)} z_e^{d,v} - \sum_{e\in E:i\equiv r(e)} z_e^{d,v}$$

TABLE 1. Model complexity comparison.

Problem	Number of Variables	Number of Constraints
1+1 Routing	$O(\|D\|\|E\|)$	$O(\|D\|(\|E\|+\|V\|)$
1+1 Routing and Network Coding Assignment (Equal Traffic)	$O(\|D\|\|E\|\|V\|)$	$O(\|D\|^2(\|E\|+\|V\|)+\|D\|\|V\|\|E\|)$
1+1 Routing and Network Coding Assignment (Non-equal Traffic)	$O(\|D\|^2\|V\|\|E\|)$	$O(\|D\|^2\|V\|\|E\|)$

$$= \begin{cases} \theta_v^d & \text{if } i \equiv v \\ -\theta_v^d & \text{if } i \equiv r(d) \\ 0 & \text{otherwise} \end{cases}$$
$$\forall d \in D, \quad \forall v \in V, \; \forall i \in V \tag{20}$$

The objective of minimizing the path cost is shown in Eq. 5 for the equal traffic case while the non-equal case is more complicated with the quadratic term as in Eq. 6. Constraint in Eq. 7 is about the flow conservation of working and protection route for all demands. The link-disjointness condition between working and backup route is formulated in Eq. 8. Constraint expressed by Eq. 9 says that each demand has at most one coding node and the coding node could not be at the destination. The requirement that each demand is coded with at most one demand whose destination are common is indicated by Eqs. 10, 11, and 12. Constraints formulated by Eqs. 13, 14 are for coherence purpose, i.e., each coded demand has a corresponding coding node and coding links. Constraints given by Eqs. 15, 16 are to guarantee that if two demands are coded together, their working routes have to be link-disjoint and the working route of first demand also has to be link-disjoint with the protection route of second demand. This is to ensure the recovery capabilities under any single link failures. Constraints 17 and 18 imply that if two demands are coded together, they must have the same coding node. The coding links, if any, have to be on the protection path are expressed by Eq. 19. The coding flow conservation constraint is guaranteed by Eq. 20.

B. LINEARIZED MODEL FOR THE NON-EQUAL TRAFFIC CASE

To derive a unified and simplified mathematical model as integer linear programming that could work with a generic traffic, we transform the non-linear objective in the non-equal traffic case into a linear one. In order to do so, we adopt a standard practice that was introduced in [33] for linearizing quadratic expression. Specifically, auxiliary variables and constraints have to be introduced to replace the non-linear expression.

We denote a new integer variable $u_{d_2,e}^{d_1,v} \in \{0, 1\}$ defined by the following equation:

$$u_{d_2,e}^{d_1,v} = z_e^{d_1,v} \times f_{d_1}^{d_2} \tag{21}$$

and re-write the objective in Eq. 6 into a linearized form:

$$Minimize \sum_{d_1 \in D} \sum_{e \in E} (x_e^{d_1} + y_e^{d_1}) \times t_{d_1}$$
$$- \sum_{d_1 \in D} \sum_{d_2 \in D} \sum_{e \in E} \sum_{v \in V} \frac{u_{d_2,e}^{d_1,v} \times min(t_{d_1}, t_{d_2})}{2} \tag{22}$$

New auxiliary linear constraints are added as the consequences of linearizing process:

$$u_{d_2,e}^{d_1,v} \le z_e^{d_1,v} \quad \forall d_1 \in D, \; \forall d_2 \in D, \; \forall v \in V, \; \forall e \in E \tag{23}$$
$$u_{d_2,e}^{d_1,v} \le f_{d_1}^{d_2} \quad \forall d_1 \in D, \; \forall d_2 \in D, \; \forall v \in V, \; \forall e \in E \tag{24}$$
$$u_{d_2,e}^{d_1,v} \ge z_e^{d_1,v} + f_{d_1}^{d_2} - 1 \quad \forall d_1 \in D, \; \forall d_2 \in D, \; \forall v \in V, \; \forall e \in E \tag{25}$$

C. MODEL COMPLEXITY

The mathematical model for optimal routing and network coding assignment problem in WDM optical networks with 1 + 1 protection leveraged by XOR network coding is computationally more difficult than the conventional 1 + 1 routing. This is due to the proliferation of variables and constraints associated with the new dimension on network coding selection including the determination of pair of demands for encoding, the respective coding node and coding links. In the case of non-equal traffic, the model's complexity is increased by an order of magnitude as the consequence of linearizing process and thus, new variables and constraints have to be added. Table 1 shows the model complexity evaluation as the function of network size and traffic demands of three design, namely, the conventional 1 + 1 routing, the 1 + 1 routing and network coding assignment in both the equal and non-equal traffic setting. Generally, the proposed models for 1 + 1 RNCA is more complex than the conventional 1 + 1 routing by one order of magnitude in the equal traffic case and two orders of magnitude in the non-equal traffic scenario.

IV. NUMERICAL RESULTS AND DISCUSSIONS

This section presents extensive numerical results drawing on the path cost comparison of the NC-based protection approach and conventional 1 + 1 dedicated path protection. Both the survivable network design models, NC-based approach and traditional 1 + 1 scheme, based on integer linear programming formulation are solved by CPLEX with academic version [34]. In order to expedite the running time, the optimal solution from conventional 1 + 1 case is fed into NC-based models as the warm-start solution.

We make use of two topologies for experiment, namely, COST239 (11 nodes, 52 links) as in Fig. 3 and CompuServe (11 nodes, 28 links) as in Fig. 4. Table 2 highlights the main characteristics of both topologies. To investigate all the coding opportunities among demands ending at the common receiving node, the traffic is considered to be all-to-one where one destination node is designated and there are the traffic requests from remaining nodes in the network to that designated destination node. The experiment is performed on

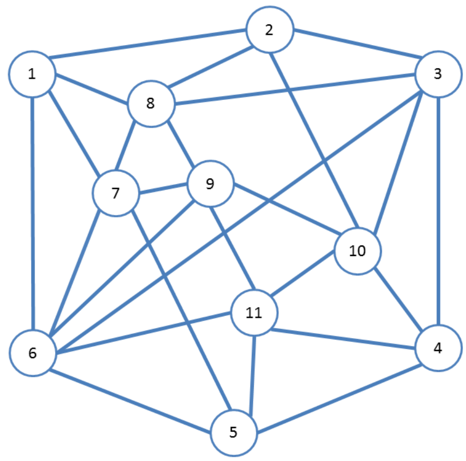

FIGURE 3. COST239: 11 nodes, 52 links.

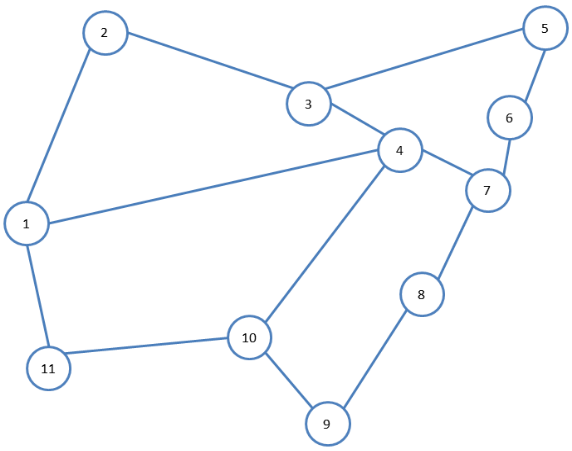

FIGURE 4. CompuServe: 11 nodes, 28 links.

TABLE 2. Topology characteristic.

Parameters	COST239	CompuServe
Nodes	11	11
Links	26x2	14x2
Average nodal degree	4.72	2.55
Min nodal degree	4	2
Max nodal degree	6	4
Node degree types	{4, 5, 6}	{2, 3, 4}

work station computers armed with X5670 Intel Xeon and 32GB RAM. All the results are optimally obtained. In the most demanding cases (non-equal traffic), the running time is still practical within roughly 4 hours.

The first set of result is focused on the equal traffic case where all the demands are one traffic unit. Table 3 shows the path cost comparison between classical 1 + 1 approach and the NC-based one for both two topologies and at all destination node degree types. Since the network coding for 1+1 protection is only applicable to destination nodes whose degree are at least three, we thus present the results for node degree 3 and 4 of CompuServe topology. The result of

TABLE 3. Path cost comparison for equal traffic.

Topology	Node	1+1 Naive	1+1 with NC	Gain
COST239	Degree 4	38.60	31.60	18.13 %
	Degree 5	37.20	30.40	18.28 %
	Degree 6	35.00	29.00	17.14 %
CompuServe	Degree 3	55.25	48.50	12.22%
	Degree 4	45.00	40.00	11.11%

each destination node degree type is averaged over all nodes having the same degree. It is clearly shown that applying NC brings up encouraging cost improvements. Specifically, the cost gain for COST239 topology is more than 17% for all node degree types while the gain from CompuServe one is more than 11%. The improvement is almost comparable for all node degree types. On a sparser topology, CompuServe, the path cost is higher than COST239 for both 1 + 1 and NC-assisted 1 + 1 schemes. This is due to the less connected nature of the topology and thus, the longer paths are generally required for routing the traffic. Besides, the cost gain is lower than in COST239 topology. This could be explained by the fact that in CompuServe, there are less nodes that are code-able and thus, coding paths have less choices to be routed through, resulting in less efficient resource utilization improvement.

It is important to note that such gain is achieved on the condition of optimum routing and network coding selections. Table 4 and 5 show the full results from our simulation at node degree 4 (node 4 in CompuServe topology) and node degree 6 (node 6 in COST239 topology). The results include the optimal working route (W-route), protection route (P-route) for each demand, the coding information including the coding node and coding links for each coded demand. Noted that there are five coding operations for CompuServe topology and they occur all at node degree 3 (i.e., node 1, 3, 7 and 10)

Next, we turn the attention to the unequal traffic case. For evaluation, the traffic demands are assumed to be randomly selected either single traffic unit or double traffic unit. The result for each node degree type is averaged over all nodes of the same type and over four traffic instances. Table 6 presents the cost comparison and respective gain of two protection approaches, namely 1+1 Naive and 1+1 with NC. Compared to the equal traffic case, the path cost increases for both two protection schemes as the consequence of increasing the traffic demands. Besides, there is slightly decrease in the cost gain. Being averaged over all node degree types, the improvement for COST239 is 15.58% while there is 10.95% for CompuServe topology. The decrease in cost gain is expected as there are unequal traffic demands and thus, some coding between demands have to occur at un-matched traffic, lowering the coding benefits.

V. CONCLUSION

In this paper, we proposed a novel unified framework for applying a practical network coding scheme based on XOR operation to leverage the traditional 1 + 1 dedicated

TABLE 4. Routing and coding information at destination node 6 of cost239 topology.

Demand	W-route	P-route	Coding node	Coding links	Coded with Demand
$1 \to 6$	(1-6)	(1-7-6)	7	(7-6)	$8 \to 6$
$2 \to 6$	(2-1-6)	(2-3-6)	3	(3-6)	$10 \to 6$
$3 \to 6$	(3-6)	(3-4-11-6)	4	(4-11-6)	$4 \to 6$
$4 \to 6$	(4-5-6)	(4-11-6)	4	(4-11-6)	$3 \to 6$
$5 \to 6$	(5-6)	(5-11-6)	11	(11-6)	$9 \to 6$
$7 \to 6$	(7-6)	(7-9-6)	9	(9-6)	$11 \to 6$
$8 \to 6$	(8-3-6)	(8-7-6)	7	(7-6)	$1 \to 6$
$9 \to 6$	(9-6)	(9-11-6)	11	(11-6)	$5 \to 6$
$10 \to 6$	(10-9-6)	(10-3-6)	3	(3-6)	$2 \to 6$
$11 \to 6$	(11-6)	(11-9-6)	9	(9-6)	$7 \to 6$

TABLE 5. Routing and coding information at destination node 4 of compuserve topology.

Demand	W-route	P-route	Coding node	Coding links	Coded with Demand
$1 \to 4$	(1-11-10-4)	(1-4)	1	(1-4)	$3 \to 4$
$2 \to 4$	(2-1-4)	(2-3-4)	3	(3-4)	$5 \to 4$
$3 \to 4$	(3-4)	(3-2-1-4)	1	(1-4)	$1 \to 4$
$5 \to 4$	(5-6-7-4)	(5-3-4)	3	(3-4)	$2 \to 4$
$6 \to 4$	(6-5-3-4)	(6-7-4)	7	(7-4)	$7 \to 4$
$7 \to 4$	(7-8-9-10-4)	(7-4)	7	(7-4)	$6 \to 4$
$8 \to 4$	(8-7-4)	(8-9-10-4)	10	(10-4)	$11 \to 4$
$9 \to 4$	(9-8-7-4)	(9-10-4)	10	(10-4)	$10 \to 4$
$10 \to 4$	(10-11-1-4)	(10-4)	10	(10-4)	$9 \to 4$
$11 \to 4$	(11-1-4)	(11-10-4)	10	(10-4)	$8 \to 4$

TABLE 6. Path cost comparison for non-equal traffic.

Topology	Node	1+1 Naive	1+1 with NC	Gain
COST239	Degree 4	56.60	47.65	15.81 %
	Degree 5	54.95	46.20	15.92%
	Degree 6	55.00	46.75	15.00%
CompuServe	Degree 3	87.38	77.56	11.24 %
	Degree 4	65.75	58.75	10.65 %

protection. The proposed network coding-based protection scheme combined protection flows of two demands in favorable conditions while leaving the working signals remain intact, featuring near-immediate recovery and capacity-efficient capabilities. Our framework had the merit of being applicable to generalized traffic scenarios considering multiple (equal/non-equal) traffic demands at once. In this framework, we introduced a new problem, called 1 + 1 routing and network coding assignment, taking into account the dimension on network coding for better resource utilizations. In order to maximize the benefits empowered by network coding, a mathematical model in the form of integer linear programming for optimizing RNCA problem in both equal and non-equal traffic scenarios was formulated. We performed extensive simulation on realistic topologies to draw a comparison between NC-assisted $1+1$ protection and the conventional $1+1$ one. Numerical results highlighted the efficient use of network coding for enhancing cost efficiency when more than 17% cost improvement was observed in the case of equal traffic while in the non-equal traffic, the cost gain was slightly lower with up to roughly 15% in our studied cases. The results also suggested that more densely connected topologies and equal traffic cases would be more profited from applying network coding.

As network coding is seen as the new dimension for improving the network efficiency, further works are planned to uncover the practicability and potentialities of network coding in different optical network architectures. Future works therefore include the extension of our proposal to translucent and transparent architectures in which the issue of wavelength/spectrum assignment has to be taken into account. Besides, the impact on cost issue and energy efficiency of integrating network coding to optical nodes deserves more investigations and could be a promising research direction.

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