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Energy Efficient Survivable IP over WDM Networks with Network Coding

Mohamed Musa, Taisir Elgorashi, and Jaafar Elmirghani

***Abstract*—In this work we investigate the use of network coding in 1+1 survivable IP over WDM networks by encoding the protection paths of multiple flow with each other at intermediate nodes. We study the energy efficiency of this scheme through MILP, and a heuristic with five operating options. We evaluate the MILP and the heuristics on typical and regular network topologies. Our results show that implementing network coding can produce savings up to 37% on the ring topology and 23% considering typical topologies. We also study the impact of varying the demand volumes on the network coding performance.**

Keywords*—*Energy Efficiency; IP/WDM; MILP model; Network coding.

I. INTRODUCTION

PROVIDING resilience against failures has become an integral part of the network planning process, and efficient schemes to do so, that also reduce capital and operational cost, have therefore been constantly sought out. The central issue in designing protection schemes is the compromise between redundant capacity and recovery speed [1]. In practice, dedicated protection (1+1) is widely implemented in backbone networks to provide instantaneous recovery against single link failures with remarkable simplicity. This simplicity is due to the fact that there are two live connections between the source and destination, and the destination is simply equipped with decision circuitry to select the stronger (in terms of received power) of the two paths. This approach, nevertheless, has inherent limitations as a large amount of spare capacity is required, typically doubling the resources [1]. Typical protection schemes that provide high network availability in addition to the 1+1 include 1:N and M:N protection. To reduce the resource requirement of the 1+1, the 1:N protection scheme has been proposed where N connections share a single dedicated protection path to be used by any path that suffers link failure. Assuming that only one of the N paths fails at a time, and under normal circumstances, the single shared protection path carries low priority traffic that is pre-empted when failure happens. For example, a 1:2 scheme enables two paths to share a single protection path, where the protection link is set to idle state or carries low priority traffic until a failure occurs. The 1:1 protection scheme is a special case of the 1:N scheme where N=1. The main difference between the 1+1 and the 1:1 protection schemes, is that the traffic in the 1+1 is continuously routed through both paths, while in the 1:1 the traffic is bridged only when a failure occurs, and therefore 1+1 does not allow the protection paths to carry any extra traffic. Another difference is that the 1:1 scheme is a revertive protection scheme where the traffic reverts back to the working path after recovering from failure, while the 1+1 is a non revertive protection scheme, where the traffic does not switch back when the network is restored [1].

In recent years, the application of network coding to failure recovery in optical network has been noted and increasingly studied, collectively known as network coding based protection [2]. Indeed, this marks a major departure from traditional research in optical protection as it can potentially achieve both rapid recovery and capacity improvement, challenging the well-known trade-off of trading speed of recovery for capacity, efficiency or vice versa. The ability of network coding to reduce the overall traffic in the network, and therefore improve the network throughput, provides a motivation for using network coding to achieve energy efficiency by requiring less operating resources than the conventional approach.

Protection and network coding appear to be a good match as the multiple paths to the same destination requirement of protection acts as a ripe environment for network coding to improve network efficiency. In [3] the authors provided a $1+N$ network coding protection scheme, and through integer linear programmes and simulation they showed that significant cost savings over the $1+1$ approach can be achieved. Network coding was proposed in [4] and [5] as a technique to improve protection in $1+N$ protection schemes that employ p-cycles. The p-cycle are used to protect multiple bidirectional link-disjoint connections, which are also link disjoint from the p-cycle links. In [6], network coding is used to provide protection against node failures by reducing the problem to a problem of multiple link failures as a consequence of the node failure. In [7] it is shown that for networks with multiple subdomains, network coding can be used to enable the network to survive any node or link failure in each subdomain. The study of $1+1$ protection schemes with network coding was reported in [8], through an integer non linear programme. This study is limited however, to equal traffic demands between different sources, provides results that are considerably lower than those achievable through network coding, and constrains the network coding only to nodes with degree greater than or equals to 3. Our work is different in that it focuses on the widely implemented 1+1 protection scheme where it provides optimal and thorough solutions to protection with network coding focusing on improving the energy efficiency of the network.

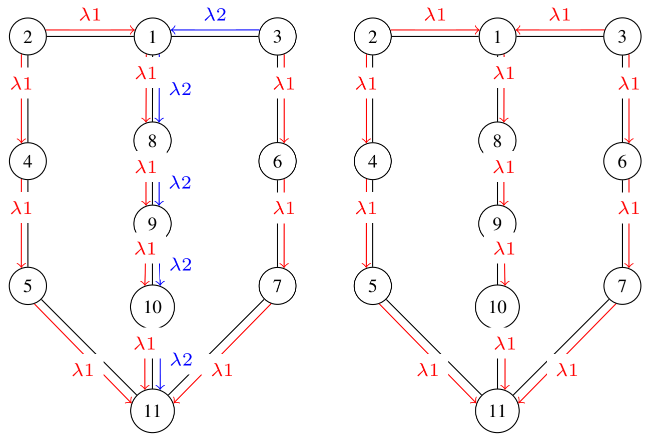
There has been an extensive research effort to improve energy efficiency in core networks. Good and thorough surveys and approaches are presented in [9], [10]. In addition to the energy efficiency techniques for Wavelength Division Multiplexing core networks, the authors in [11] investigated power savings in multi-granular optical transport network, and in [12] the energy efficiency of IP over WDM networks with robust and integrated grooming is addressed. In our previous work we investigated the energy efficiency in core networks considering renewable energy sources [13], core networks with data centers [14], physical topology design [15], distributed clouds [16], future high definition TV [17], P2P content distribution [18] and virtual network embedding [19]. We introduced network coding for energy efficient IP over WDM networks in [20] and [21], by encoding bidirectional flows using an XOR operation, and presented a thorough study of the use of network coding to improve the energy efficiency in core networks in unicast settings [22]. While the previous work focused on addressing the optimum architecture, design and operation of the network, this work attempts to introduce energy efficiency improvements by employing a novel routing approach using network coding for survivable nonbypass IP over WDM networks. An in depth study is presented with numerical results based on MILP models and heuristics to demonstrate the energy efficiency improvements.

The remainder of this paper is organized as follows: Section II reviews the concept of network coding in IP/WDM networks. In Section III we model the survivable IP over WDM networks with network coding using mixed integer linear programming (MILP). The heuristics are described in section IV, and the model and heuristic results and their analysis are given in Section V. In Section VI we study regular topologies and in Section VII we study the impact traffic variation. Finally the paper is concluded in Section VIII.

II. $1+1$ PROTECTION WITH NETWORK CODING

Figure 1 shows a comparison between the conventional (Fig. 1.a) and the network coded (Fig. 1.b) 1+1 protection scheme in an arbitrary topology. Consider two connections representing two demands a and b having the source destination pairs $(2, 11)$ and $(3, 11)$, respectively. This setting represents the case where two sources (i.e. 2 and 3) have different flows transmitted to the same destination (i.e. 11). With traditional dedicated protection, the cost is two distinct wavelengths for the whole network (e.g. $\lambda 1$ and $\lambda 2$) and a total of sixteen wavelength-links. With the utilisation of an XOR coder at node 1, new opportunities arise. The protection path of demand $(2, 11)$ and demand $(3, 11)$ on the same wavelength $\lambda 1$ are combined at node 1 such that one signal represented by $a \oplus b$ is transmitted on wavelength $\lambda 1$ from node 1 to node 11 passing through nodes $8, 9$ and 10. Only a coding operation is needed at node 1 and a single decoding operation is needed at the destination (i.e. node 11), leaving the remaining intermediate nodes of the shared protection path to route the encoded flows. It is noted that under any single link failure on primary paths, the destination still receives the two remaining signals which allow it to reconstruct the lost signal by performing an all-optical XOR operation (e.g., a $\oplus$ (a $\oplus$ b) = b). This NC-based solution simply requires one distinct wavelength for the whole network (i.e. $\lambda 1$) and 12 wavelength-links where each of the 12 links uses a single wavelength to route demands. The conventional approach requires two distinct wavelengths (i.e. $\lambda 1$ and $\lambda 2$), and a total of 16 wavelengths in links. This corresponds to a 50% saving in the total number of distinct wavelengths and 25% saving in the total number of wavelength-links in the network. Protection resources in the conventional case require 10 wavelength-links compared to only 6 in the coded case which leads to 40% saving in protection resources. This additional throughput comes with the same survivability benefits of the $1+1$ protection scheme. The drawback is the coding delay at encoding nodes (i.e. coding at node 1 and decoding at node 11).

The savings in the aforementioned example depend on the underlying topology, the nature of demands and routes, and the location of network coding points. Our solution to the problem determines the routes, and network coding points for demands in the network given a certain topology and traffic demands.



(a) (b)

Fig. 1: Example of using network coding for protection

This example highlights the promise of network-coding-based protection in optical networks and it is clear that by properly performing a coding operation among appropriate demands, better resource utilisation can be achieved. Note that because the scheme uses a very simple coding technique, where for a given topology the two network encodable paths can be optimally determined and encoded using a simple xor operation, the encoding delay will have a negligible incremental contribution on the pre-existing processing operations in the conventional approaches. Note that core networks currently use forward error correction codes (FEC) which are significantly more complex than the proposed xor operation [23] and these FEC coding and decoding operations in core networks introduce negligible delay [24].

III. MILP MODEL

In this section we develop an MILP model to minimise the total power consumption of survivable IP over WDM network with 1+1 protection employing network coding. The model optimises the working and protection routes each demand takes, and the number and location of coding operations, for a given network topology and demands matrix. Figure 2 shows the components used in an IP over WDM network

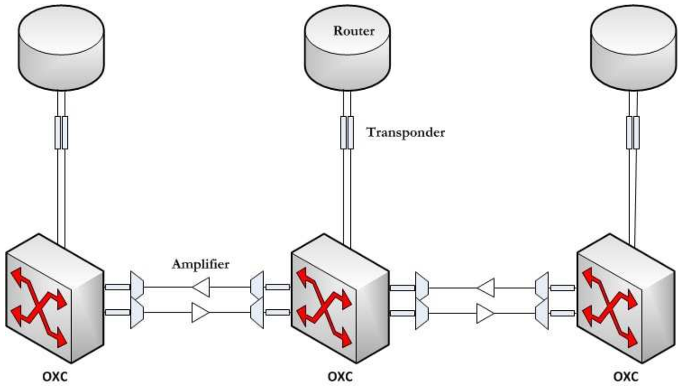


Fig. 2: The architecture of IP over WDM networks

(3 nodes are shown for simplicity). IP routers are connected to optical cross-connects that provide the switching in the optical layer and connect to the optical fiber links. A pair of multiplexers/demultiplexers is used to provide the wavelength multiplexing and demultiplexing. The transponders provide OEO processing for full wavelength conversion at each switching node. Erbium doped fiber amplifiers (EDFAs) are utilized to enable long distance optical transmission. The Traffic is routed according the nonbypass approach where it passes through the IP layer at all intermediate nodes. Tables I, II, and III show the lists of sets, parameters, and variables defined in the MILP model, respectively.

Below are the lists of sets, parameters and variables defined in the MILP model:

TABLE I: List of the sets used in the MILP model

Set	description
$\mathcal{N}$	Set of the network nodes
$\mathcal{N}_m$	Set of the neighbouring nodes to node m

TABLE II: List of the parameters used in the MILP model

parameter	description
V^d	The volume of demand d in Gbps
$src(d)$	The source node of demand d
$dst(d)$	The destination node of demand d
p_p	The power consumption of a router port
p_t	The power consumption of a transponder
p_e	The power consumption of an EDFA
B	The capacity of a wavelength in Gbps
W	Number of wavelengths per fibre
p_{xor}	The power used by a network coding/decoding operation

TABLE III: List of the variables used in the MILP model

variable	description
P_T	The total power of the network
x^d_{mn}	Binary variable, $x^d_{mn} = 1$ if the working path of demand d is routed over link (m,n), and $x^d_{mn} = 0$ otherwise.
y^d_{mn}	Binary variable, $y^d_{mn} = 1$ if the protection path of demand d is routed over link (m,n), and $y^d_{mn} = 0$ otherwise.
$b^{d_1}_{d_2}$	Binary variable, $b^{d_1}_{d_2} = 1$ if demand d_1 is encoded with demand d_2, and $b^{d_1}_{d_2} = 0$ otherwise
$h^{d_1}_{d_2}$	The number of shared links between the demand d_1 and d_2
$\beta^{d_1 d_2}_{mn}$	Binary variable, $\beta^{d_1 d_2}_{mn} = 1$ if demand d_1 is encoded with demand d_2 on link (m,n), and $\beta^{d_1 d_2}_{mn} = 0$ otherwise
A_{mn}	The number of EDFAs in a physical link (m,n). Typically $A_{mn} = \lfloor L_{mn}/S - 1 \rfloor$, where S is the distance between two neighbouring EDFAs.
f_{mn}	The number of fibres on physical link (m,n)

The MILP model is defined as follows:

Objective: minimise the total power of the network:

$$
\begin{aligned}
P_T = {} & \frac{p_p + p_t}{B} \sum_{m \in \mathcal{N}} \sum_{n \in \mathcal{N}_m} \sum_{d \in D} V^d \left(x^d_{mn} + y^d_{mn} \right) \\
& - \frac{p_p + p_t}{B} \sum_{m \in \mathcal{N}} \sum_{n \in \mathcal{N}_m} \sum_{d_1, d_2 \in D} \min(V^{d_1}, V^{d_2}) \frac{\beta^{d_1 d_2}_{mn}}{2} \\
& + 2 p_{xor} \sum_{d_1, d_2 \in D} \frac{b^{d_1}_{d_2}}{2} + p_e \sum_{m \in N} \sum_{n \in \mathcal{N}_m} F_{mn} A_{mn} \qquad (1)
\end{aligned}
$$

The total power of the network is composed of the power consumption of the following components:

- $\frac{p_p+p_t}{B} \sum_{m \in \mathcal{N}} \sum_{n \in \mathcal{N}_m} \sum_{d \in D} V^d (x^d_{mn} + y^d_{mn})$ represents the total power consumption of router ports and transponders without network coding.
- $\frac{p_p+p_t}{B} \sum_{m \in \mathcal{N}} \sum_{n \in \mathcal{N}_m} \left(\sum_{d_1,d_2 \in D} \min(V^{d_1}, V^{d_2}) \frac{\beta^{d_1 d_2}_{mn}}{2} \right)$ represents the reduction in router ports and transponders resulting from sharing links facilitated by network coding. In the case of two unequal demand volumes, the larger volume is partitioned into two parts, the first has the size of the other demand and hence gets encoded with it, and the second is routed using conventional (non network coding) ports.
- $p_e \sum_{m \in \mathcal{N}} \sum_{n \in \mathcal{N}_m} F_{mn} A_{mn}$ represents the total power consumption of EDFAs.
- $2 p_{xor} \sum_{d_1,d_2 \in D} \frac{b^{d_1}_{d_2}}{2}$ represents the total power consumption of the xor operations at encoding and decoding nodes. The sum calculates the total number of encoded demands (division by 2 so a demand pair is not counted twice). The multiplication by a factor of 2 is because an encoding and a decoding operation are needed for each encoded demand pair.

Subject to:

$$\sum_{n\in\mathcal{N}_m} x^d_{mn} - \sum_{n\in\mathcal{N}_m} x^d_{nm} = \begin{cases} 1 & m = src(d) \\ -1 & m = dst(d) \\ 0 & otherwise \end{cases} \tag{2}$$

$$\forall d \in D, m \in N$$

$$\sum_{n\in\mathcal{N}_m} y^d_{mn} - \sum_{n\in\mathcal{N}_m} y^d_{nm} = \begin{cases} 1 & m = src(d) \\ -1 & m = dst(d) \\ 0 & otherwise \end{cases} \tag{3}$$

$$\forall d \in D, m \in \mathcal{N}$$

$$x^d_{mn} + y^d_{mn} \leq 1 \tag{4}$$

$$\forall d \in D, m \in \mathcal{N}, n \in \mathcal{N}_m$$

Constraints (2) and (3) represent the flow conservation constraints for the working and the protection paths, respectively, where the total incoming traffic equals the outgoing traffic for all nodes except the source and destination. They also impose single path routing behaviour for the working and protection paths. Constraint (4) ensures that the working and protection paths of each demand are link disjoint.

$$\sum_{d\in D} V_d(x^d_{mn}+y^d_{mn}) - \sum_{d_1,d_2\in D} \min(V_{d_1}, V_{d_2}) \frac{\beta^{d_1 d_2}_{mn}}{2} \leq WBf_{mn} \tag{5}$$

$$\forall m \in \mathcal{N}, n \in \mathcal{N}_m$$

Constraint (5) represents the capacity conservation constraint. It ensures that the sum of all the flows (in working or protection paths) minus the network coding reduction in a certain link is below the capacity of that link, given by the number of fibres and the capacity of each fibre. Note that here we consider partitioning which selects the minimum of the two flows if they differ in volume.

$$\beta^{d_1 d_2}_{mn} \leq y^{d_1}_{mn} \tag{6}$$

$$\forall d_1, d_2 \in D : d_1 \neq d_2, \forall m \in \mathcal{N}, n \in \mathcal{N}_m$$

Constraint (6) ensures that only the protection path of a demand gets encoded. The model sees the variables $y^{d_1}_{mn}$ and $x^{d_1}_{mn}$ as binary variables over a link (m, n) and hence does not distinguish between protection and working paths. This allows working and protection paths to be encoded, if the model finds it useful power wise, in four combinations i.e. w-w (working-working), w-p (working-protection), p-w (protection-working) and p-p (protection-protection).

$$\beta^{d_1 d_2}_{mn} = \beta^{d_2 d_1}_{mn} \tag{7}$$

$$\forall d_1, d_2 \in D : d_1 \neq d_2, \forall m \in \mathcal{N}, n \in \mathcal{N}_m$$

Constraint (7) ensures that if demand d_1 is encoded with demand d_2, demand d_2 is also encoded with d_1.

$$h^{d_1}_{d_2} = \sum_{m\in N} \sum_{n\in N_m} \beta^{d_1 d_2}_{mn} \tag{8}$$

$$\forall d_1, d_2 \in D : d_1 \neq d_2$$

Constraint (8) calculates the number of shared hops between two demands.

$$b^{d_1}_{d_2} \leq h^{d_1}_{d_2} \tag{9}$$

$$\forall d_1, d_2 \in D : d_1 \neq d_2$$

$$h^{d_1}_{d_2} \leq M b^{d_1}_{d_2} \tag{10}$$

$$\forall d_1, d_2 \in D : d_1 \neq d_2$$

Constraints (9) and (10) convert the shared hops variable $h^{d_1}_{d_2}$ into binary, and hence determine if demand d_1 is encodable with d_2. When there are no shared hops between the two demands, they can not be encoded (i.e. $b^{d_1}_{d_2} = 0$), and if at least there exists a shared hop, then potentially encoding can take place. As a demand can share hops with multiple demands, there is a potential for the variable $b^{d_1}_{d_2}$ to be set to 1 for each of the multiple potential demands.

$$\sum_{d_2\in D} b^d_{d_2} \leq 1. \tag{11}$$

$$\forall d \in D$$

Constraint (11) ensures that each demand $d \in D$ is not encoded with more than a single demand.

$$\beta^{d_1 d_2}_{mn} = 0 \tag{12}$$

$$\forall d_1, d_2 \in D : dst(d_1) \neq dst(d_2)$$

Constraint (12) ensures that only demands that share a single destination can be encoded.

The mixed integer linear programme for the conventional $1+1$ protection is provided as follows:

Objective: minimise the total power of the network:

$$P_T = (p_r + p_t) \sum_{m\in\mathcal{N}} \sum_{n\in\mathcal{N}_m} \sum_{d\in D} V^d \left(x^d_{mn} + y^d_{mn}\right) + \sum_{m\in N} \sum_{n\in N_m} p_e F_{mn} A_{mn} \tag{13}$$

Subject to:

$$\sum_{n\in\mathcal{N}_m} x^d_{mn} - \sum_{n\in\mathcal{N}_m} x^d_{nm} = \begin{cases} 1 & m = src(d) \\ -1 & m = dst(d) \\ 0 & otherwise \end{cases} \tag{14}$$

$$\forall d \in D, m \in N$$

$$\sum_{n\in\mathcal{N}_m} y^d_{mn} - \sum_{n\in\mathcal{N}_m} y^d_{nm} = \begin{cases} 1 & m = src(d) \\ -1 & m = dst(d) \\ 0 & otherwise \end{cases} \tag{15}$$

$$\forall d \in D, m \in \mathcal{N}$$

$$x^d_{mn} + y^d_{mn} \leq 1 \tag{16}$$

$$\forall d \in D, m \in \mathcal{N}, n \in \mathcal{N}_m$$

$$\sum_{d\in D} V^d(x^d_{mn}+y^d_{mn}) \leq WBf_{mn} \tag{17}$$

$$\forall m \in \mathcal{N}, n \in \mathcal{N}_m$$

Constraints (14) and (15) represent the flow conservation constraints for the working and protection paths respectively, where the total incoming traffic equals the outgoing traffic for all nodes except the source and destination nodes. While constraint (16) ensures that the working path and protection paths are link disjoint. Constraint (17) represents the capacity conservation constraint.

IV. HEURISTIC

In this section we develop a heuristic and use it to evaluate the performance of large networks that proved complex for the MILP. We provide a general case of the heuristic providing a real time solution, named Optimal Search Heuristic (OSH) (See Algorithm 1) and then we provide four special cases, where in each case the encoding of paths is unified across encodable demand pairs. It accounts for all the com- binations of encoding between the working and protection paths of the two demands, and is hence given the tags w-w, w-p, p-w, and p-p, where the (w) refers to the working path and (p) to the protection path. The OSH provides a fast running alternative to the MILP, by providing a polynomial time solution as compared to the exponential running time of the MILP model. The running times of the MILP and the heuristic on the computer used are provided in Section V.

Algorithm 1 Optimal Search Heuristic (OSH)

```
Input: $D$ demands, $N$ nodes and Topology
Prepare N arrays (Clusters), each of size $N - 1$.
for $d \in D$ do
    Add the demand to the cluster with the similar destination nodes
end for
Get working and protection paths for all demands ($i, j \in D$) using suurballe algorithm
for $i, j \in D$ do
    if $(i, j)$ in the same cluster then
        $weight(i, j)$ =Number of common links
    end if
end for
Perform the stable matching solution to each cluster
Calculate The Total power consumption of the network
```

The central approach of the heuristic is to implement the search on a much reduced search space. The heuristic is hence divided into four steps: The first is forming the encodable graph where demands are classified into clusters. The second step calculates the two link disjoint paths by using the Suurballe algorithm [25] which produces two link disjoint paths for each demand. In the third step the number of shared hops between each demand pair is calculated and the weighted encodable graph is formed. Finally, on the encodable graph, a stable matching solution is found that selects the demand pairs to be encoded and from that the total power consumption of the network is calculated. The details of each step is discussed in further detail below.

A. *Encodable graph formation*

The demands graph (complete graph) is reduced to the set of encodable demands, that satisfy the condition that limits encoding to be only between demands sharing the same destination and having different sources. This divides the complete graph into a set of complete N smaller graphs each of size $N-1$ nodes rather than a complete graph of the size N^2 nodes. The encodable graph for the example of a six node network (Figure 3) is shown in Figure 4.

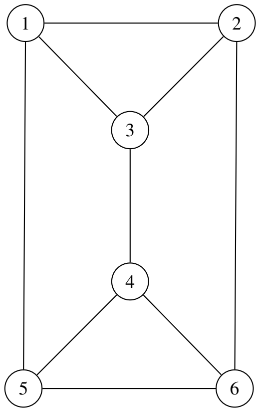


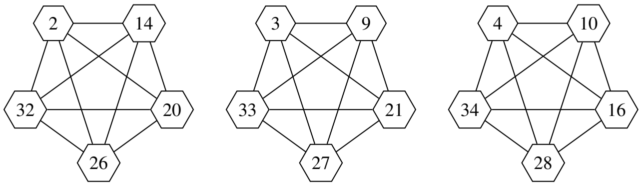
Fig. 3: Six nodes topology under consideration

In this six nodes example, each node has 5 possible destinations, and each node receives traffic from 5 possible sources. Therefore, if demands are clustered such that each cluster contains demands that share the same destination, then each cluster will have 5 demands as shown in Figure 4 (a)-(f). Each of the 5 demands in the cluster shares its destination with 4 other demands, hence Figure 4 (a)-(f) shows that each demand is linked (encodable) with 4 other demands.

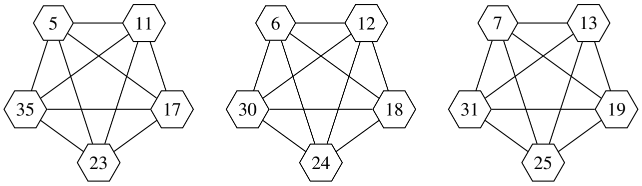
For 6 nodes, the 6x6 traffic matrix has 36 entries, which is reduced to 30 after removing demands from a node to itself (i.e. demands 1, 8, 15, 22, 29 and 36 in the traffic matrix), the remaining 30 demands, their clusters, and encodable graph links are as shown in Figure 4.

B. *Paths calculation*

For each source-destination demand, the working and protection paths are determined using suurballe's algorithm [25] which finds two disjoint paths connecting the source and destination nodes of a demand that also have the minimum total number of hops . The algorithm uses Dijkstra algorithm to find the first minimum hops path, and uses it again after changing the weights of the graph. As the result of the Suurbelle algorithm are two disjoint paths for each demand, where the shorter route is labelled as the working path and the longer as the protection path, hence we developed different combinations for encoding. We developed a general algorithm

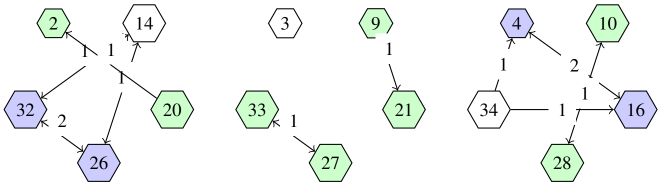


(a) Cluster-1 (b) Cluster-2 (c) Cluster-3

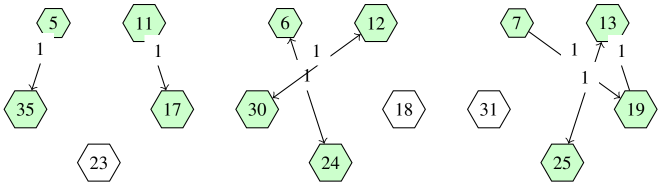


(d) Cluster-4 (e) Cluster-5 (f) Cluster-6

Fig. 4: The encodable graph where each node represents a demand for a six node topology



(a) Cluster-1 (b) Cluster-2 (c) Cluster-3



(d) Cluster-4 (e) Cluster-5 (f) Cluster-6

Fig. 5: The Weighted encodable graph

that finds the best path selection for encoding between the 4 combinations (working-working (w-w), working-protection (w-p), protection-working (p-w) and protection-protection(p-p)) for each demand. We label this the Optical Search Heuristic (OSH). We also created a more restricted version of the heuristic where the decision of which of the 4 combinations is used is unified for all encoded pairs. This means for the choice of encoding protection paths together, all encoded demands will have their protection paths encoded together pairwise. This makes the total number of heuristics equal to five.

C. Weighted encodable graph

The next step is forming the weighted encodable graph by assigning weights to the encodable graph. The weights represent the number of common links shared by the two encodable demands. This weight is a positive integer, that can take a value of zero, which represents no shared links. The total number of links in the graph is reduced by removing any link with a zero weight. This is shown for the six nodes network, in Figure 5.

Each link in the weighted encodable graph represents the number of shared hops between demands, and because there exists 4 possible path combinations between each pair of demands (i.e. w-w, w-p, p-w and p-p), therefore 4 links can exist between each demand pair in the weighted encodable graph. Four versions of the heuristic are generated by limiting all the links in the graph to a given path combination, therefore producing 4 weighted encodable graphs, each represents a heuristic. For example, in the network coding heuristic p-p, each demand pair in the weighted encodable graph is connected by a link with a weight that represents the number of shared hops between the protection paths of the two demands. The optimal search heuristic searches over all 4 parallel links between demands.

D. The Stable matching problem

Not all demands favour the demands that favour them in the encoding pair selection. For example, demand d_1 has the highest number of shared hops with d_2 which in turn prefers demand d_3. Ensuring fair pair selection given the preference criteria is essential to maximising the performance of the algorithm.

To select which demands to encode together, in each cluster, the links with the highest weights in the weighted encodable graph are selected first. If there exist multiple links with the same weight, the selection is done randomly which is implemented by progressing sequentially through the list of demands (demands in numeric order). The selected demands and their associated links are removed from the weighted encodable graph, since each demand should be encoded with one demand only. Encoded nodes (demands) and their associated links to all other nodes (demands) are also removed from the graph. This process is repeated until all links in the cluster are exhausted, and this process is repeated for all clusters. Then the total power consumption is calculated.

Figure 5 shows the different steps (as colors) in selecting the encoding pairs for the six node topology under consideration. The blue nodes are those selected (and deleted from the graph) first, which have the highest mutual preference (link weight=2). The green nodes come second, and so on. The graph weight search stops here for this example as the possible encodable node set is not large given the small network size. The remaining demands are not selected either because their possible encodable demands are already selected or because they do not have a link with another demand.

V. RESULTS

Due to the huge complexity of evaluating the MILP model for networks of large sizes (e.g. NSFNET topology with 14 nodes), we performed an evaluation for a 5 node topology (Figure 6) and benchmarked the heuristic results against the MILP model results. Then the heuristic is used to study the behaviour of larger network sizes. We performed the MILP optimisation using the AMPL/CPLEX software running on a High Performance Computing (HPC) cluster with 16 cores CPU and 256GB RAM, and ran the matlab heuristic on a normal PC with 8GB RAM and i5 core processor. A single run for a 6 nodes topology took the heuristic 3.55 seconds to finish while the MILP was manually stopped after 2 hours.

A. *Five nodes Topology*

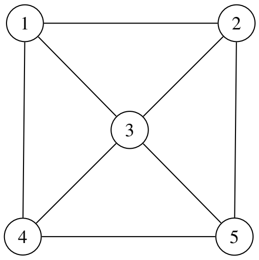


Fig. 6: Five nodes topology under consideration

We show the results of the MILP model and the various heuristics for the 5 node topology. We compare the results to the MILP model of the conventional protection approach under equal traffic demands and uniformly distributed random traffic demands evaluated in steps of 20Gbps starting from 20Gbps up to 200Gbps. The power consumption values are summarized in table IV.

Parameter	Value
Distance between neighbouring EDFAs	80 km
Number of wavelengths in a fibre (W)	16
Capacity of each wavelength (B)	40 Gbps
Power consumption or a normal port(Pp) [26]	1 kW
Power consumption of a coded port (Px)	1.1 kW
Power consumption of a transponder (Pt) [27]	73 W
Power consumption of an Optical Switch (PO) [28]	85 W
Power consumption of a MUX/DeMUX [29]	16 W
EDFAs power consumption (Pe) [30]	8 W
Power consumtion of the coding operation (p_{xor})	20 W

TABLE IV: Network Parameters

For the Equal demands case, the results in Figure 7 show a linear relationship between the power consumption and the demand volume, and this relationship applies to all of the heuristics and the MILP. The corresponding savings are shown in Figure 8. The optimum search heuristic is comparable to the MILP model with savings reaching 14%, while the heuristic version that encodes protection paths together approaches the MILP with savings of 13%.

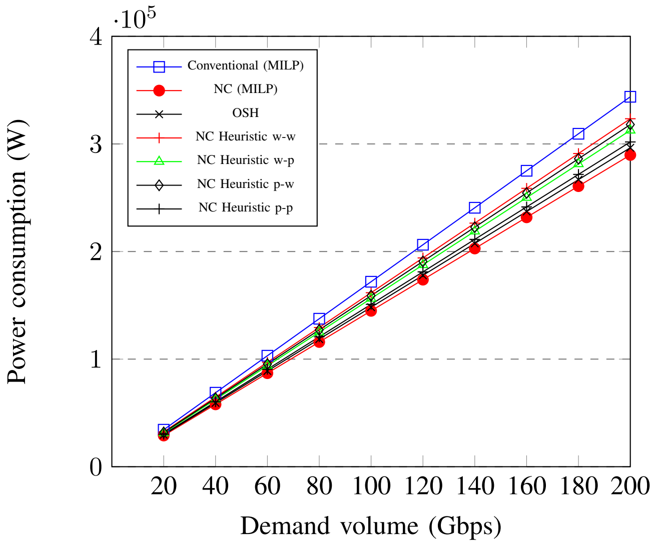


Fig. 7: Power consumption of the 5 node topology with equal demands

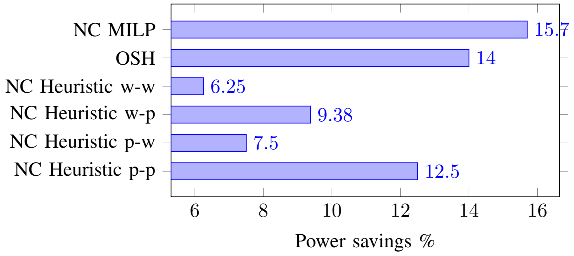


Fig. 8: Power savings of the various approaches with equal traffic for 5 nodes topology

Figures 9 and 10 show the power consumption and the corresponding power savings for the case of uniformly distributed random demands in the 5 nodes topology. The savings achieved by the different heuristics follow the same order as the case of equal demands, and the power savings are lower than those achieved under the equal demands case (8.8% compared to 14% when using OSH). The power consumption overall follows a linear function when the model is evaluated for a very high number of runs (current number of runs is 40). The reason behind this reduction in savings for the case of random demands as compared to equal demands is that demand partitioning (i.e. the larger flow is dividedd into two flows, one has the size of the other flow to encode with, and the other goes uncoded) is used and hence the minimum value between the 2 flows is encoded. The power saving added by network coding are maximised the closer the demands volumes get to each other, ultimately at equal demand values, the savings are maximum.

B. *Common Topologies*

We evaluated the performance of the heuristic on the NSFNET and the USNET topologies. The results are shown in Figure 11 and 12. We followed the same approach when

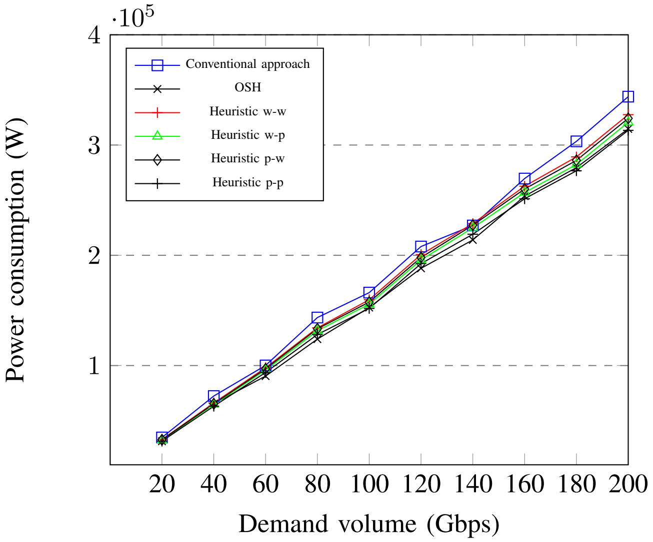


Fig. 9: Power consumption of the 5 node topology for random demands

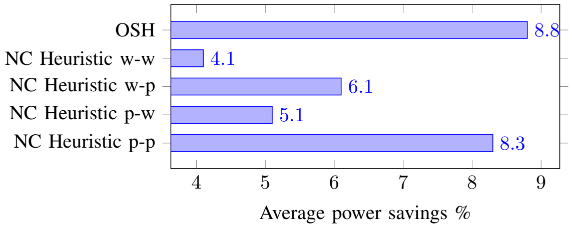


Fig. 10: Power savings of the various approaches with random demands for the 5 nodes topology

evaluating the results considering the demand variation as with the 5 nodes topology case. The figures show the same linear trend in power consumption as the average demand in the network grows, and show that the two networks provide comparable power savings of 23% and 21% for the NSFNET and the USNET topologies respectively, using OSH. Although the USNET has a higher average hop count than the NSFNET, the savings are slightly less. This is due to the topology as not every time a longer path is found a corresponding larger hop count is found. The figures also shows that the fourth network coding approach (Heuristic p-p) is the most energy efficient of the four cases after OSH.

VI. REGULAR TOPOLOGIES

In this section we study the behaviour of the proposed approach on regular topologies, namely the star, line, full mesh and the ring topologies.

The star topology does not show any savings with network coding due to the fact that the protection concept itself is not satisfied. Since each node is connected by a single link to the center of the star, no link disjoint paths for protection can be established. The line topology also is irrelevant as no protection path can be formed.

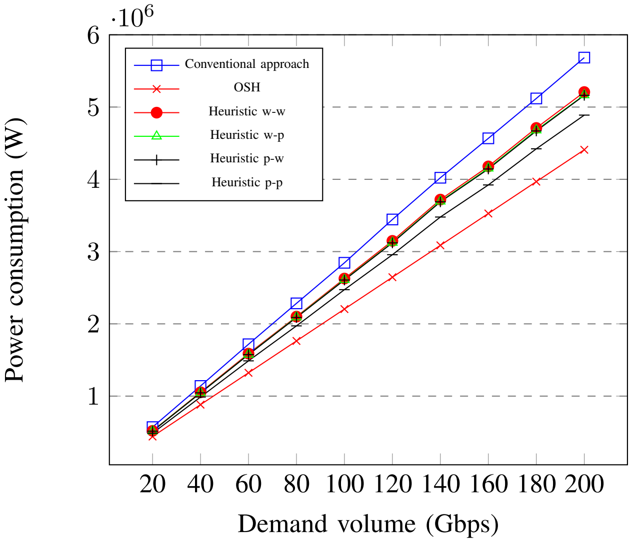


Fig. 11: Power consumption of the NSFNET topology

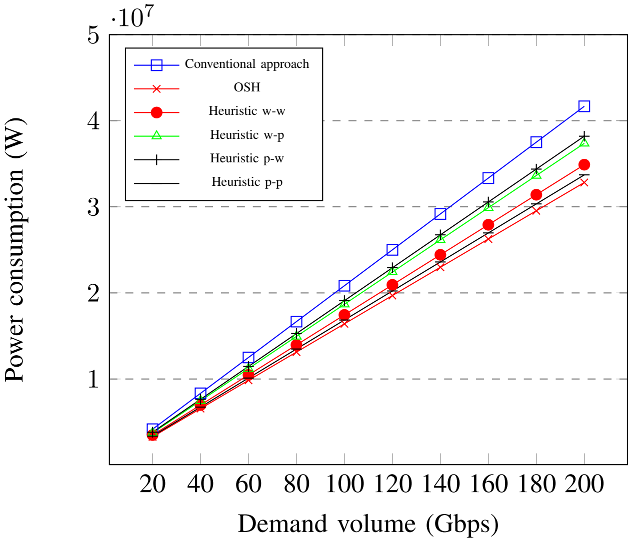


Fig. 12: Power consumption of the USNET topology

The power consumption values of the full mesh topology are shown in Figure 13 and the power savings in Figure 14. The savings can reach 15% considering the optimum search heuristic, and 10% when using the heuristic with encoding limited to protection paths. Encoding working flows together provides no improvements over the conventional approach because encoding is not possible in this case as all working paths have a single link from the source to the destination. The other two approaches where the protection path of one demand is encoded with the working path of the other, produce savings of 2%.

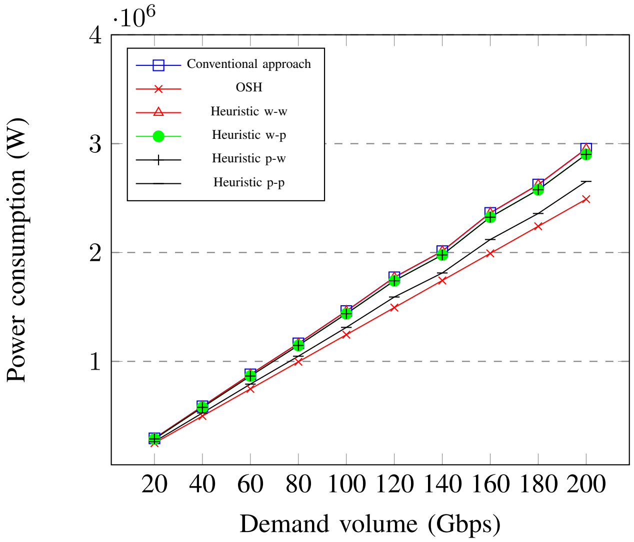


Fig. 13: Power consumption of the various approaches for a 14 node fullmesh topology

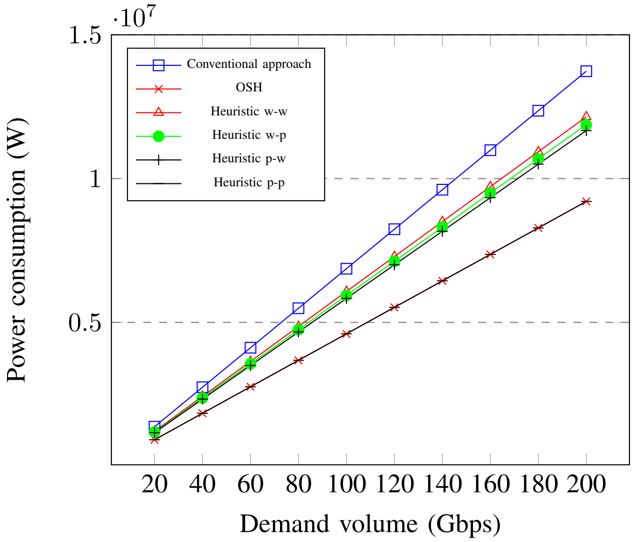


Fig. 15: Power consumption of the various approaches for a 14 node ring topology

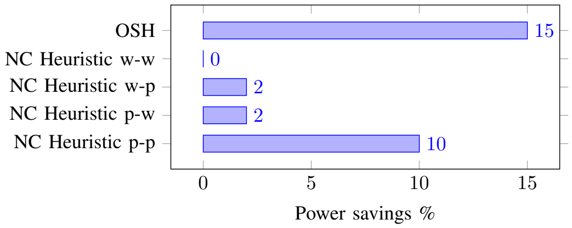


Fig. 14: Power savings of the various approaches with equal traffic for 14 node full mesh topology

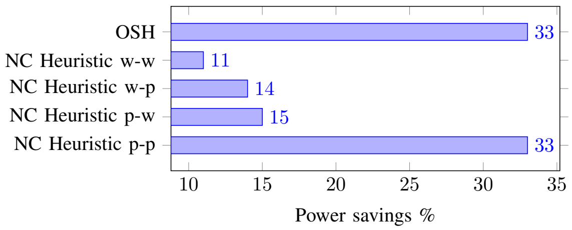


Fig. 16: Power savings of the various approaches with equal traffic for 14 node ring topology

For the Ring topology, the results are shown in Figure 15 and Figure 16 for a ring of 14 nodes. Encoding protection paths together produces savings of up to 33% while encoding working paths together produces 11% savings. This large difference is due to the fact that protection paths in the ring are considerably longer than working paths, and this difference increases as the ring size increases. The other two approaches of encoding the working path with protection paths produce savings of 14% and 15%. Savings of 33% can be achieved when the optimum search heuristic is used.

In Figure 17 we show a comparison of the power savings obtained in different topologies. The ring topology has the highest power savings followed by the NSFNET and the USNET topologies which are comparable. Smaller topologies produce low savings as the chance of finding multiple shared links is reduced.

VII. IMPACT OF TRAFFIC VARIATION

In this section, we study the impact of traffic variation. Assume the demands have an average value of V, we want to study the impact of the variation of individual demands around the average on the total power consumption of the network when network coding is implemented.

We study the impact of the volume of the traffic by varying the standard deviation of the uniform distribution. We study traffic demands with average values of 80 Gbps. The range is increased, starting from 0, representing equal demands volumes, increasing in steps of 10Gbps until 160Gbps which represents the largest range possible. The larger the range, the larger the probable difference between the volumes of the encoded demands, which due to partitioning, reduces the power saving potential compared to the equal demand case represented by the zero range.

Figure (18) shows the power consumption of the network using the various heuristics vs the normalised traffic standard deviation (i.e. the range of the distribution) in the NSFNET topology. Note that in the uniform distribution where samples are selected between two values (a, b), the range is $(b-a)$ and the standard deviation is $(\frac{1}{\sqrt{(12)}}b-a)$ which when normalized gives $(b-a)$. The figure clearly shows the linear relationship of the power savings to the standard deviation for all heuristic forms, having a maximum saving of 20% and a minimum

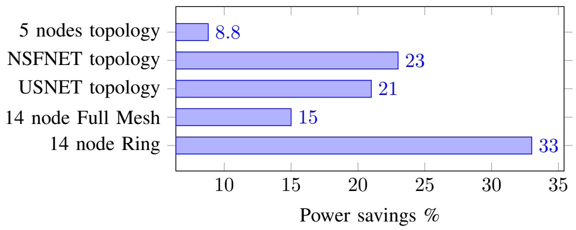


Fig. 17: Comparison of the power savings for different topologies

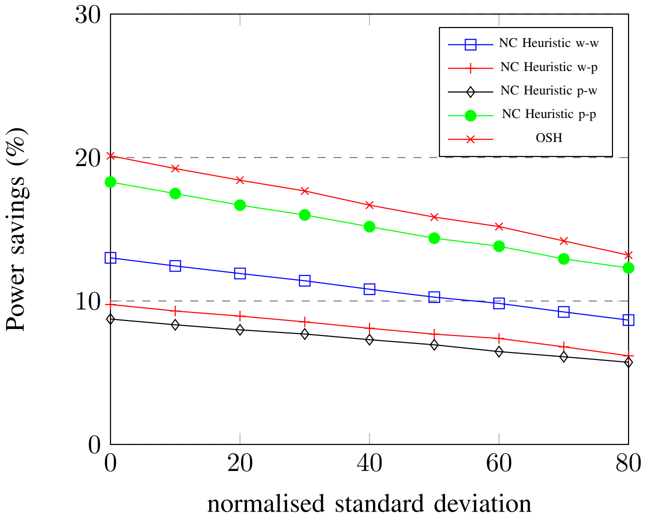


Fig. 18: Power savings of the various approaches for equal demands vs demand volume

saving of 13% for the OSH.

VIII. CONCLUSIONS

In this work, we introduced network coding to improve energy efficiency for survivable optical core networks employing $1+1$ protection. The idea is to provide the same reliability and instantaneous recovery provided by the $1+1$ protection but with a considerable reduction in the amount of protection resources by performing an XOR operation on routes for demands sharing the same destination and hence approaching the resource utilisation of the 1:2 protection scheme. The analysis is done using a MILP model and heuristics. The work considered the impact of topology on the energy efficiency of the approach, including small or common core networks, and regular topologies. The traffic impact is also studied, covering the demand size and demand size distribution. The heuristic is evaluated first considering the optimal selection of paths between each encoded pair and another 4 schemes covering the possibilities of encoding the two link disjoint paths of each demand with its pair, but unified for all demands. We showed that depending on the underlying topology, the decision of the encodable paths between demands has an impact on the savings. Power consumption savings up to 37% can be achieved on the ring topology, and 23% considering the NSFNET topology. These results demonstrate that network coding is an effective technique in reducing power consumption in protected optical networks. The network coded scheme is expected to introduce negligible incremental implementation cost and processing delay as compared to the conventional approach due to the simplicity of the xor operation compared for example to FEC, where the latter is routinely used now in core networks. Furthermore, the proposed NC approach maintains the same routing and protection path selection algorithm used in the conventional architecture. Future extensions include performing coding on multiple flows, using higher order codes, studying the problem of routing and wavelength assignment (RWA) with network coding in all optical networks, and performing an experimental implementation of the network coding scheme.

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