Energy Considerations in EoS-over-WDM Network Configuration

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Abstract—**Optical network nodes typically have to process varying traffic volumes and should therefore be configured optimally to service traffic at the lowest cost possible. We model an Ethernet-over-SONET/SDH-over-WDM network (to represent a metro optical network) and define the network cost incurred in terms of energy consumption and capital expenditure. We then propose an exact integer linear program to minimize either cost, with and without considering traffic survivability, in order to study the energy consumption of different network configurations. Our results for a realistic network show that capital expenditure optimization would result in a more future-proof network configuration, at only slightly higher energy consumption than the energy consumption optimization. When survivability is achieved by a 1+1 protected lightpath scheme, the network energy consumption is shown to be almost twice the energy consumed by a 1:1 protected lightpath scheme, due to the redundant use of line cards. We also study the effect of a single link addition to the network, which reduces the average shortest path length and increases the survivability of the network, at the expense of slightly higher network energy consumption.**

I. INTRODUCTION

The cost of setting up and running an optical network depends on its design and configuration. Network operators can reduce their capital expenditure by opting for network components with the lowest retail price, or operational expenditure by opting for network components with the least energy consumption. An improperly configured network will contribute to unnecessary high energy bills for the network operator, and poses environmental concerns due to the discharge of pollutants and greenhouse gases during energy generation. On the other hand, an efficiently configured network can serve its clients at minimal cost by efficiently placing suitable network components at the right nodes. Clearly, nodes with varying importance, e.g., with high traffic volumes due to their strategic location, should not be equally configured as other nodes. We refer to the cost of a network component in terms of its wattage and retail price. Simple and cheap network components generally consume little energy, but the limitation in supported capacity may affect the performance of the network.

Numerous publications [1]–[5] have focused on the energy efficiency of the core optical network, which may span a very large distance, covering even continents (although multi-layer multi-domain networks, e.g. see [6], have not been considered). The core optical network is typically implemented as an IP-over-WDM architecture using optical cross-connects (OXCs) as optical switches, with each node able to perform routing decisions using their IP router. Less focus had been given to the energy efficiency of the metro optical network, which may span up to hundreds of kilometers, covering a mid-size area or even a small country. There, routing decisions are performed by a dedicated network entity. In this paper, we consider the energy efficiency (or capital expenditure efficiency) of the metro optical network, based on the Ethernet-over-SONET/SDH(EoS)-over-WDM [7] architecture, with several types of Optical Add-Drop Multiplexers (OADMs) as optical switches.

The remainder of this paper is organized as follows. Section II explains the architecture of an EoS-over-WDM network. In Section III, we provide an ILP formulation to configure an optical network efficiently in terms of energy consumption or capital expenditure for serving its expected traffic. We use the energy consumption and retail price of several common network components as an input to the ILP. In Section IV, we present and discuss our results. We also study the effect of survivability on the network energy consumption. The effect of a single link addition to the network is studied in Section V. We conclude in Section VI.

II. EOS-OVER-WDM ARCHITECTURE

A. WDM Layer

The wavelength spectrum of an EoS-over-WDM network (illustrated in Fig. 1) can be divided into several wavebands, of several wavelengths each. Each waveband can be processed like a single wavelength to be added/dropped at the source/destination nodes or optically passed [4] through any intermediate nodes. According to Gerstel *et al.* [8], utilizing wavebands eases the wavelengths management and reduces the accumulating channel impairments (e.g., see [9]) of each wavelength along the traversed path, thus extending the reach of connections. Traffic is multiplexed/demultiplexed at the OADM of the source or destination nodes from electronic switches (ESs) connected to the client sites. We classify OADMs into three types, namely the modular OADM (MOADM), the serial OADM (SOADM), and the reconfigurable OADM (ROADM).

MOADMs can be configured with an optical supervisory channel (OSC) module, an amplifier, a group multi-

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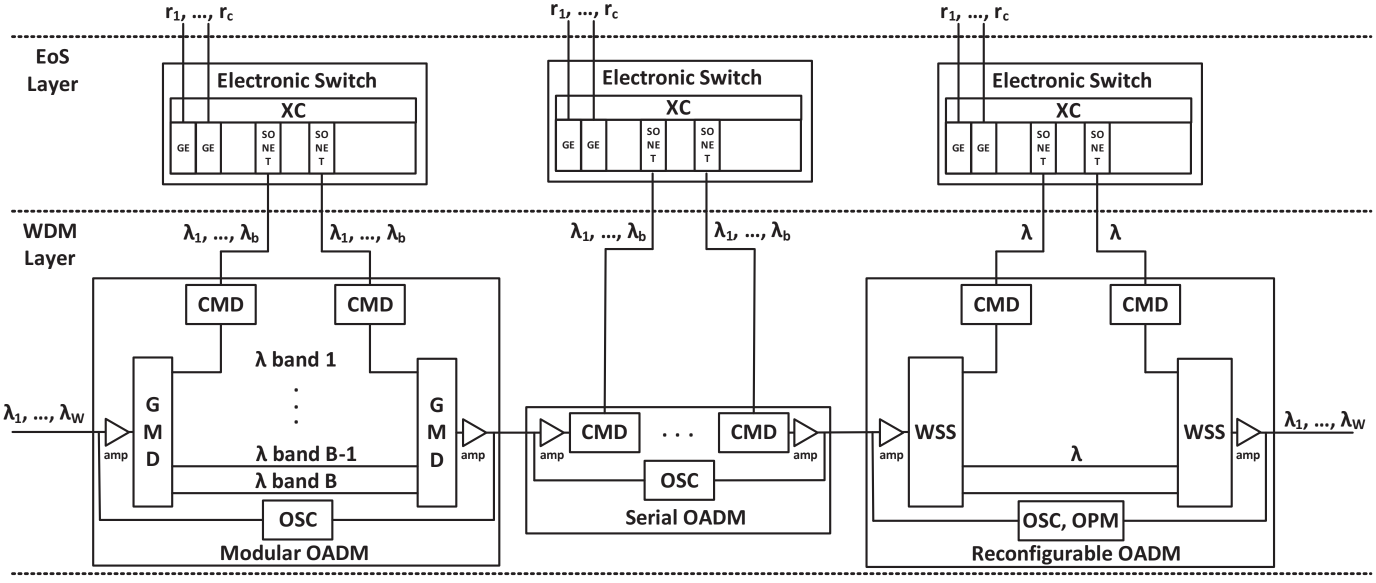


Fig. 1. An example of part of an EoS-over-WDM architecture.

plexer/demultiplexer (GMD), and a set of channel multiplexers/demultiplexers (CMDs) for each incident link. OSC uses an out-of-band wavelength for exchanging control and monitoring information between nodes. Amplifiers compensate attenuations, allowing longer reach connections. GMDs separate/combine the wavelength spectrum into/from several groups of wavebands, and multiplex/demultiplex the wavebands into/from an optical fiber. CMDs separate/combine individual wavebands into/from individual wavelengths, and multiplex/demultiplex the wavelengths into/from an optical fiber. We assume that two types of CMDs can be connected to a GMD, namely the CMD4 with four wavelength ports or the CMD8 with eight wavelength ports. For a band of eight wavelengths, the CMD4 can only utilize half of the wavelengths, while the CMD8 can utilize all eight wavelengths.

SOADMs can be configured with an OSC, an amplifier, and a set of CMDs for each incident link. SOADMs use cascaded CMD8s to add/drop traffic. We assume that up to three CMD8s can be put in series for each incident link, yielding 24 wavelength capacities. A SOADM is cheaper and smaller than a MOADM, though with lower capacity support. SOADMs are mostly used in nodes with low traffic volumes. Both MOADMs and SOADMs are not reconfigurable, where wavelengths to be added or dropped are planned beforehand [10], and adjustment will require manual intervention.

ROADMs can be configured with an OSC, an amplifier, a variable amplifier, a wavelength selective switch (WSS), and a set of CMDs for each incident link, and an optical power monitor (OPM) between each pair of WSSs. Variable amplifiers function similarly to an amplifier, except that their gain can be dynamically adjusted rather than being fixed. Although a ROADM is more expensive than a MOADM or a SOADM, WSSs allow automated adding, dropping or rerouting of any wavelength to any port while connecting up to nine nodes [11]. MOADMs and SOADMs can only connect up to two nodes. CMDs are still needed to multiplex/demultiplex wavelengths into/from fibers. We assume that two types of CMDs can be connected to the WSS, namely the CMD8 or the CMD44 with 44 wavelength ports. Apart from higher wavelength support, CMD44s are also passive, consuming no energy. However, a CMD44 is more expensive than a CMD8. OPMs and variable amplifiers are used for power equalization between WSSs.

B. *EoS Layer*

Electronic switches (ESs) encapsulates/de-capsulates Ethernet streams to/from SONET/SDH wavelengths by slots of card modules using the electronic cross-connect (XC) module. We assume that an ES has fourteen slots [12] available for card modules. Since two slots are used for the cross-connect (XC) modules, only twelve slots are available for card modules (SONET/SDH or Ethernet). Each CMD in the WDM layer is connected to a SONET/SDH card. We assume that two types of Ethernet card modules are used in the ESs, namely the 1·10GE and 4·GE card modules. A 1·10GE card module supports an OC-192 request, while a 4·GE card module supports up to four OC-24 requests. Requests can be unprotected, 1:1 protected or 1+1 protected. Protected connections utilize two link-disjoint dedicated paths, with the primary path transmitting data while the backup path is only activated [13] in case of the unavailability of the primary path. An unprotected connection or a 1:1 protected connection uses a single line card at both ends of the connection. 1+1 protected connections employ two line cards at both ends of the connection that transmit data simultaneously on both paths, protecting against the failure of a link or line card.

III. Design Optimization

A. Problem Formulation

We represent a network by an undirected graph $G = (\mathcal{N}, \mathcal{E})$ consisting of a set $\mathcal{N}$ of N nodes and a set $\mathcal{E}$ of E links of W wavelengths. A node from the set $\mathcal{N}$ is denoted by n, while a link from the set $\mathcal{E}$ between nodes u and v is denoted by (u, v). A request from the set $\mathcal{R}$ is denoted by the tuple $r = <s, d, c>$ where s is the source node, d is the destination node and c is the capacity. Given $\mathcal{R}$, the network configuration problem is to allocate suitable network components at each n such that all r are accommodated using minimal costs.

B. ILP Constants and Variables

$\mathcal{A}_{uv}$	is 1 if (u, v) exists; 0 else
D_n	number of links incident to node n
$C_1/C_2/C_{10}$	cost of an OSC/OPM/XC
C_3/C_4	cost of an amplifier/variable amplifier
C_5/C_6	cost of a GMD/WSS
$C_7/C_8/C_9$	cost of a CMD4/8/44
$C_{11}/C_{12}/C_{13}$	cost of a SONET/4·GE/10·GE card module
ε	tiebreaker cost
$x_{n1}/x_{n2}/x_{n3}$	is 1 if n is a (M/S/R)OADM; 0 else
x_{n11}/x_{n12}	is 1 if a CMD4/8 is in MOADM n; 0 else
x_{n32}/x_{n33}	is 1 if a CMD8/44 is in ROADM n; 0 else
S_{n11}/S_{n12}	number of CMD4/8s in MOADM n
S_{n22}	number of CMD8s in SOADM n
S_{n32}/S_{n33}	number of CMD8/44s in ROADM n
S_{n4}	number of ESs at n
$S_{n41}/S_{n42}/S_{n43}$	number of SONET/4·GE/1·10GE card modules in ES n
Z_{n11}/Z_{n33}	number of wavelengths added or dropped by CMD4/CMD44 at (M/R)OADM n
$Z_{n12}/Z_{n22}/Z_{n32}$	number of wavelengths added or dropped by CMD8 at (M/S/R)OADM n
T_{n1}/T_{n2}	number of OC-24/OC-192 connections added or dropped at n
T_{n3}	number of wavelengths optically passed at n
P_{ruv}/B_{ruv}	is 1 if the primary/backup path of r uses (u, v); 0 else

C. ILP formulation

Minimize:

$$\begin{aligned}
&\sum_{n\in\mathcal{N}} D_n\Big(x_{n1}(C_1 + C_3 + C_5) + x_{n2}(C_1 + C_3)\Big)\\
&+ \sum_{n\in\mathcal{N}} D_n x_{n3}\Big(C_1 + C_2\frac{D_n - 1}{2} + C_3 + C_4 + C_6\Big)\\
&+ \sum_{n\in\mathcal{N}} D_n\Big(C_7 S_{n11} + C_8(S_{n12} + S_{n22} + S_{n32})\Big)\\
&+ \sum_{n\in\mathcal{N}} \Big(C_9 S_{n33} + C_{10} S_{n4} + C_{11} S_{n41}\Big)\\
&+ \sum_{n\in\mathcal{N}} \Big(C_{12} S_{n42} + C_{13} S_{n43} + \varepsilon T_{n3}\Big)
\end{aligned} \tag{1}$$

Configuration Constraints:

$$x_{n1} + x_{n2} + x_{n3} = 1 \qquad \forall n \in \mathcal{N} \tag{2}$$
$$x_{n11} + x_{n12} \le 2x_{n1} \qquad \forall n \in \mathcal{N} \tag{3}$$
$$x_{n32} + x_{n33} \le 2x_{n3} \qquad \forall n \in \mathcal{N} \tag{4}$$
$$S_{n11} + S_{n12} \le 9x_{n1} \qquad \forall n \in \mathcal{N} \tag{5}$$
$$S_{n22} \le 3x_{n2} \qquad \forall n \in \mathcal{N} \tag{6}$$
$$S_{n32} + S_{n33} \le 9x_{n32} + 2x_{n33} \qquad \forall n \in \mathcal{N} \tag{7}$$
$$S_{n41} + S_{n42} + S_{n43} \le 12S_{n4} \qquad \forall n \in \mathcal{N} \tag{8}$$
$$Z_{n11} \le 4S_{n11} \qquad \forall n \in \mathcal{N} \tag{9}$$
$$Z_{n12}+Z_{n22}+Z_{n32} \le 8(S_{n12}+S_{n22}+S_{n32}) \qquad \forall n \in \mathcal{N} \tag{10}$$
$$Z_{n33} \le 44S_{n33} \qquad \forall n \in \mathcal{N} \tag{11}$$
$$2T_{n1} \le 4S_{n42} \qquad \forall n \in \mathcal{N} \tag{12}$$
$$2T_{n2} = S_{n43} \qquad \forall n \in \mathcal{N} \tag{13}$$
$$S_{n41} = S_{n11} + S_{n12} + S_{n22} + S_{n32} + S_{n33} \qquad \forall n \in \mathcal{N} \tag{14}$$

Connection Request Constraints:

$$Z_{n11}+Z_{n12}+Z_{n22}+Z_{n32}+Z_{n33}=T_{n1}+T_{n2}\ \forall n \in \mathcal{N} \tag{15}$$
$$T_{n1} = \sum_{r\in\mathcal{R}} 1\ \forall n \in \mathcal{N} : (n = s \text{ or } d)\ \&\ c = \text{OC-24} \tag{16}$$
$$T_{n2} = \sum_{r\in\mathcal{R}} 1\ \forall n \in \mathcal{N} : (n = s \text{ or } d)\ \&\ c = \text{OC-192} \tag{17}$$
$$T_{n3} = \sum_{r\in\mathcal{R}}\sum_{v\in\mathcal{N}} (P_{rnv} + B_{rnv})\ \forall n \in \mathcal{N} : n \ne s \tag{18}$$
$$\sum_{u\in\mathcal{N}} P_{ruk} = \sum_{v\in\mathcal{N}} P_{rkv}\ \forall r \in \mathcal{R}, k \in \mathcal{N} : k \ne s \text{ or } d \tag{19}$$
$$\sum_{u\in\mathcal{N}} B_{ruk} = \sum_{v\in\mathcal{N}} B_{rkv}\ \forall r \in \mathcal{R}, k \in \mathcal{N} : k \ne s \text{ or } d \tag{20}$$
$$\sum_{u\in\mathcal{N}} P_{rud} = \sum_{v\in\mathcal{N}} P_{rsv} = \sum_{u\in\mathcal{N}} B_{rud} = \sum_{v\in\mathcal{N}} B_{rsv} = 1\ \forall r \in \mathcal{R} \tag{21}$$
$$\sum_{u\in\mathcal{N}} P_{rdu} = \sum_{v\in\mathcal{N}} P_{rvs} = \sum_{u\in\mathcal{N}} B_{rdu} = \sum_{v\in\mathcal{N}} B_{rvs} = 0\ \forall r \in \mathcal{R} \tag{22}$$
$$P_{ruv} + P_{rvu} + B_{ruv} + B_{rvu} \le 1\ \forall r \in \mathcal{R}, (u, v) \in \mathcal{E} \tag{23}$$
$$\sum_{r\in\mathcal{R}} (P_{ruv} + B_{ruv}) \le A_{uv} W\ \forall (u, v) \in \mathcal{E} \tag{24}$$

Our ILP formulation can be used for energy consumption minimization by using wattage of network components as the cost C, or capital expenditure minimization by using the retail price of network components as the cost C. The costs incurred by network components are taken from Table I. The actual cost may be higher since we do not consider the cost of chassis, cooling, conditioning, software or deployment. We assume that sub-components are compatible with each other, regardless of vendors and model variants. The listed costs merely serve as a benchmark of the sub-components, since costs do differ according to vendors, model variants and time of purchase. Since the ILP objective is to minimize the network cost, and not to allocate traffic over the shortest (in hops) paths, traffic may be assigned to a longer path, if the cost of using the longer path is equal to the cost of the shortest path. Hence, we add

TABLE I
NETWORK COMPONENTS COSTS.

Network Component	Sub Component	ILP Notation	Wattage (W)	Source	Retail Price (USD)	Source
MOADM	OSC	$C1$	45	[14]	5,638	[15]
	amplifier	$C3$	35	[11]	11,813	[15]
	GMD	$C5$	45	[14]	34,390	[16]
	CMD4	$C7$	15	[17]	14,795	[15]
	CMD8	$C8$	20	[17]	21,728	[15]
SOADM	OSC	$C1$	45	[14]	5,638	[15]
	amplifier	$C3$	35	[11]	11,813	[15]
	CMD8	$C8$	20	[17]	21,728	[15]
ROADM	OSC	$C1$	45	[14]	5,638	[15]
	OPM	$C2$	70	[11]	21,773	[15]
	amplifier	$C3$	35	[11]	11,813	[15]
	variable amplifier	$C4$	50	[11]	16,484	[15]
	WSS	$C6$	126	[5]	115,500	[15]
	CMD8	$C8$	20	[17]	21,728	[15]
	CMD44	$C9$	0	[18]	32,450	[15]
ES	XC	$C10$	70	[19]	41,250	[15]
	SONET card module	$C11$	18	[20]	16,830	[15]
	4·GE card module	$C12$	28	[5]	8,195	[15]
	1·10GE card module	$C13$	38	[5]	14,685	[15]

a small routing-dependent cost $\varepsilon = 0.00001$ as a tiebreaker when the network component costs for both paths are equal.

Configuration constraints ensure that enough network components are available at each node. A node can be a MOADM, a SOADM, or a ROADM (Eq. 2). A MOADM can be inserted with up to nine filters (Eq. 5) from any mix of CMD4 and CMD8 (Eq. 3), for each incident link. A SOADM can be inserted with up to three CMD8 filters (Eq. 6), for each incident link. A ROADM can be inserted with up to nine CMD8 filters, or two CMD44 filters (Eq. 7), or any mix of them (Eq. 4), for each incident link. An ES can be inserted with up to twelve card modules (Eq. 8). Enough filters should be available at nodes (Eqs. 9-11). Eqs. 12-13 ensure that connections are serviced by card modules with the appropriate capacity (change $2T_{n1}$ to T_{n1} and $2T_{n2}$ to T_{n2} for unprotected and 1:1 protected connections). Enough SONET card modules should be available at nodes (Eq. 14).

Connection request constraints ensure flow conservation. All requests must be serviced (Eq. 15). The number of OC-24/OC-192 connections added/dropped at n is checked by Eq. 16 and Eq. 17. The number of wavelengths optically passed at n is checked by Eq. 18 (omit B_{rnv} for unprotected connections). Eqs. 19-20 ensure that any connection entering an intermediate node should exit it (omit Eq. 20 for unprotected connections). Eqs. 21-22 ensure that paths start from the source node and end at the destination node (omit $B_{rud}, B_{rsv}, B_{rdu}$ and B_{rvs} for unprotected connections). Eq. 23 assumes that the links are unidirectional and protection is achieved via link-disjoint paths (omit B_{ruv} and B_{rvu} for unprotected connections). Eq. 24 ensures that paths are routed through viable links (omit B_{ruv} for unprotected connections).

IV. ANALYSIS

We used the IBM ILOG/CPLEX software to solve the ILP formulation. We studied a network topology with 22 nodes and 28 links as illustrated in Fig. 2 (without the dotted lines), which represents the SURFnet network [21] in The Netherlands. The average number of incident links of network nodes is 2.55. The wavelength spectrum of the network is divided into nine wavebands of eight wavelengths each. We assume that each link can support up to 88 wavelengths. Hence, the maximum number of usable wavelengths is 72 per link, with the exception of links connecting two ROADMs, which may support all 88 wavelengths. Nodes with number of incident links higher than two are predefined as ROADMs. Each request is generated with a random source and destination node, and of either OC-24 or OC-192 capacity according to the distribution 4:1. Connections are assumed to have infinite holding time. All simulation results are averaged over a thousand runs.

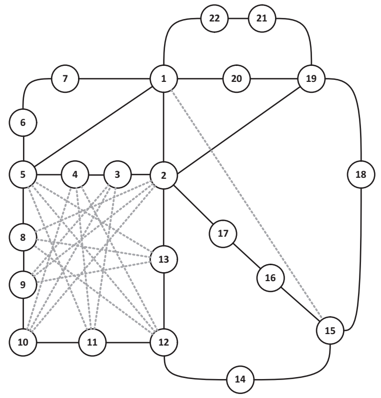
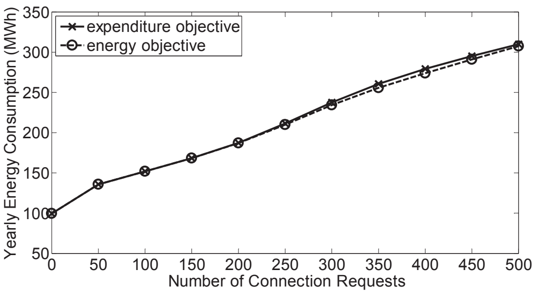
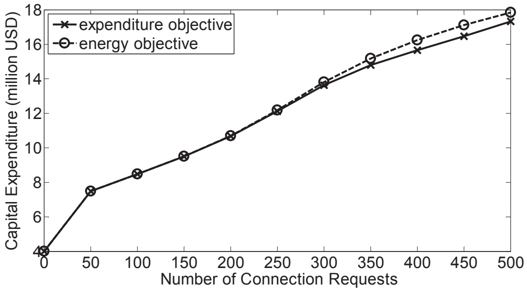


Fig. 2. Network topology (dotted lines are candidate links, see Section V).

As illustrated in Fig. 3, the energy objective would save up to 5.4MWh yearly compared to the expenditure objective, while the expenditure objective would save up to 0.65 million USD compared to the energy objective. Both objectives perform similarly at low traffic volumes. The maximum deviation of the average values in Fig. 3a at 95% confidence interval is 0.1692MWh, and 0.0112 million USD for Fig. 3b. The network costs increase almost linearly with the increase in traffic since the network costs are dominated by the number

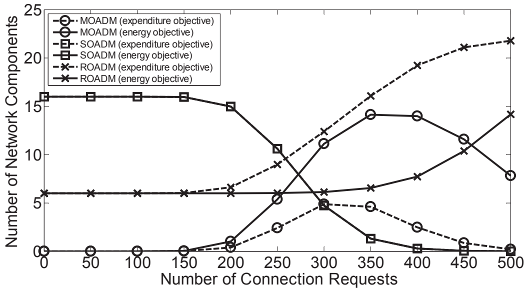


(a) Energy consumption

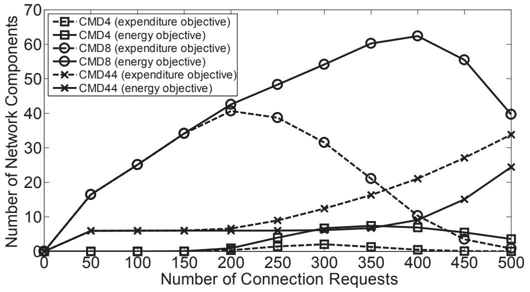


(b) Capital expenditure

Fig. 3. Average network costs for unprotected connections.



(a) Optical switch



(b) Channel Multiplexer/Demultiplexer

Fig. 4. Average number of network components.

of card modules used in ESs, which increases linearly with the increase of requests.

We refer to Fig. 4 to differentiate between the network components selection of both objectives. The maximum deviation of the average values in Fig. 4a at 95% confidence interval is 0.0967, and 0.5135 for Fig. 4b. Although a CMD44 is passive, while CMD4 and CMD8 are not, the high cost of all other network components in ROADM (e.g., WSS and OPM) prevents CMD44 from being the optimal choice for both objectives at low traffic. More ROADMs are selected by the expenditure objective than the energy objective at medium and high traffic volumes. Using ROADMs brings flexibility to the network, which can be more future-proof since ROADMs can switch traffic without restriction on colour and direction. At low traffic volumes, SOADMs utilizing CMD8 are preferred for both objectives due to its low cost, at the trade-off of lower capacity. As the traffic volume increases, using SOADMs is no longer a viable option and MOADMs utilizing either CMD4 or CMD8 are used instead. The cost associated to network components plays a vital role to their selection in both objectives. For example, the expenditure objective would ignore ROADMs completely if the retail price of a WSS were to increase two-fold, and ignore MOADMs completely if the retail price of a WSS were to be cut in half. In the considered scenario, we believe that the increased flexibility and capital expenditure savings gained by the expenditure objective outweigh the energy savings from the energy objective.

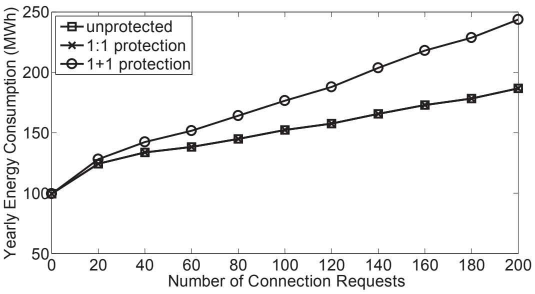


Fig. 5. Average energy consumption per protection scheme.

From Fig. 5, the 1+1 protection scheme that uses redundant line cards has the highest network energy consumption for all traffic volumes, since line cards are the major energy consumers in the network. The maximum deviation of the average values in Fig. 5 at 95% confidence interval is 0.1067 MWh. Since unprotected and 1:1 protected requests use the same amount of line cards, the energy consumption did not differ much. 1:1 protected connections will succumb to the failure of line cards while 1+1 protected connections will not.

V. NETWORK AUGMENTATION

Optical networks are not static, and will continuously grow to cater for the ever-increasing number of clients. The network capacity can then be improved by adding more network components, or by adding more network links to reduce the distance traversed by connections. We employ a pre-selection strategy [22] to maximize the positive effects of the link addition. We ensure that an added link conserves the ring design, and the initial shortest path between the nodes is more than three hops, as illustrated by the dotted lines in Fig. 2. A traffic request with a long shortest path might be able to traverse the new link for a shorter path. For example, by adding a link between nodes 2 and 10 in Fig. 2, the average shortest

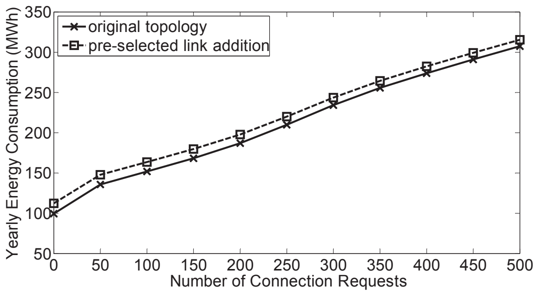


Fig. 6. Average energy consumption before and after a single link addition.

path length of the network can be lowered from 3.1 hops to 2.9 hops. Fewer nodes would be traversed by traffic, relaxing the capacity requirements (and consequently network costs) of nodes that would otherwise be traversed.

However, link addition requires new network components at the nodes, which increase their energy consumption, and counteracts the energy savings gained due to lower network average shortest paths, as illustrated in Fig. 6. The maximum deviation of the average values in Fig. 6 at 95% confidence interval is 0.1408 MWh. When a link is added between two ROADMs, an extra WSS is needed at both ends. When a link is added between two MOADMs or SOADMs, they need to be replaced with ROADMs. When the link addition is carefully done, we believe that the trade-off of a little increase in the energy consumption is justified, because apart from lower shortest path, link addition also increases the network availability [23], which is also an important criterion in the network design. For example, by adding a link between nodes 2 and 10 of the network in Fig. 2, the network algebraic connectivity [24] is increased from 0.29 to 0.33. Higher algebraic connectivity implies that the network is better protected against the failure of nodes or links.

VI. CONCLUSION

We have laid out a model of an Ethernet-over-SONET/SDH-over-WDM network, complete with the details on the energy consumption and retail price of its network components. Using the model, we have proposed an exact ILP formulation to optimize the network configuration in terms of energy consumption or capital expenditure minimization. Our results indicate that, for the considered network, although energy savings could be achieved by opting for the energy objective, the expenditure objective would yield a more future-proof network configuration with only a slight increase in energy consumption. Hence, it is important to consider different optimization strategies in configuring a network. We have also showed that utilizing 1+1 protection would consume almost twice the energy of using unprotected or 1+1 protection. The network survivability could also be improved by selectively adding a link to the network at the expense of slightly higher network energy consumption. Our ILP formulation can also be used to configure Carrier Ethernet-over-WDM networks by using the appropriate cost values.

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