Examining the Cost Efficiency of Future Heterogeneous Optical Networks

Filippos Balasis [1], Sugang Xu [1], and Yoshiaki Tanaka [1, 2]
[1] Global Information and Telecommunication Institute, Waseda University, Tokyo, Japan
[2] Department of Communications and Computer Engineering, Waseda University, Tokyo, Japan
fbalasis@akane.waseda.jp, xusugang@m.ieice.org, ytanaka@waseda.jp

Abstract— **Orthogonal Frequency Division Multiplexing (OFDM) promises to provide the necessary boost in the core networks' capacity along with the required flexibility in order to cope with the Internet's vastly heterogeneous traffic. At the same time, wavelength division multiplexing (WDM) technology remains a cost-effective and reliable solution especially for long-haul transmission. Due to the high implementation cost of optical OFDM transmission technology it is expected that OFDM transponders will co-exist with conventional WDM ones. In this paper, we provide an ILP formulation that minimizes the cost of such hybrid architecture and then a comparison is made with a pure OFDM-based elastic optical network (EON) and a mixed line rate (MLR) WDM optical network.**

Keywords— **Optical Network, Elastic, OFDM, Bandwidth Variable Transponders, Cost Efficiency, Optimization, ILP**

I. INTRODUCTION

Bandwidth demanding services like 4k video streaming and cloud computing along with fibre-to-the-home connections of 1Gbps have already become a reality. The need for higher capacity in optical core networks has reached unprecedented levels and 10Gbps optical transponders are rapidly being replaced by 40Gbps and 100Gbps ones. However, increasing the data rate and spectral efficiency is only one aspect of the problem. Flexibility in terms of bandwidth and spectrum allocation with varying optical reach is going to be the most sought after feature in future optical networks. Currently, mixed line rate (MLR) optical networks that use the ITU fixed grid of 50GHz is the only commercially available solution but with limited flexibility. The upcoming advent of flex-grid OFDM-based elastic optical network (EON) though is expected to change that. In OFDM transmission, contrary to single-carrier modulation schemes of conventional WDM transponders, multiple contiguous sub-carriers are used. The occupied spectral width of each sub-carrier, known as frequency slot, is standardized by ITU at 12.5GHz. The number of the subcarriers as well as the data rate of each sub-carrier can be adjustable and therefore, flexibility in the spectrum allocation and the supported optical reaches is much higher than those of WDM transmission. These transponders that utilize OFDM transmission are often called in literature as bandwidth variable transponders [1].

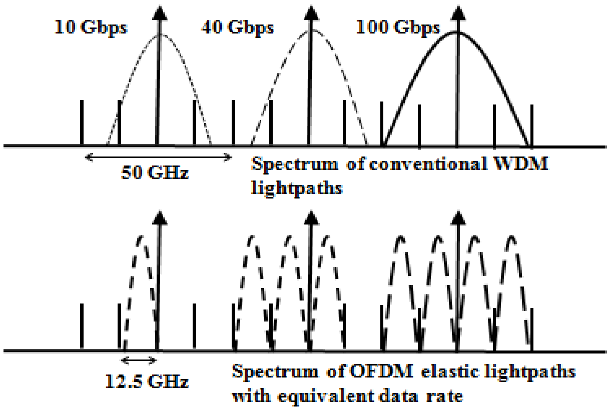

Fig. 1. Elastic optical network offers greater flexibility and greater efficiency in spectrum allocation comparing to a MLR WDM network.

Nevertheless, the cost of BVTs and the correspondent flex-grid switching modules is expected to be significantly higher than that of already available WDM ones. A telecommunication vendor will rightfully be concerned about the implementation cost and this is why the transition to a fully flex-grid architecture is expected to be slow. For this matter, there are several published works that concern the cost and energy efficiency of an elastic optical network and how it compares to a fixed grid WDM architecture. In [2] the authors provide a spectrum and energy efficiency comparison between single line rate (SLR) WDM, MLR WDM and OFDM-based EON architectures and estimate the break-even cost of flexible transponders. In [3] the authors use heuristic algorithms and actual electricity price models that minimize the cost and the energy consumption of the above mentioned architectures. In [4] the authors compare, in terms of equipment cost and energy consumption, a flex-grid and a fixed grid SLR optical network on three different topologies and conclude that the scale of the network and its average link length is a factor that should be taken into consideration.

Nevertheless, to the best of our knowledge, the scenario of a hybrid optical network architecture that combines fixed grid WDM and flex-grid bandwidth variable transponders has not been investigated and this is what separates our present work from the earlier ones. Simulations and field trials have shown that co-propagation of WDM and OFDM elastic lightpaths is possible [5]-[7] and once OFDM-based BVT become widely available, it is more than probable that the optical network providers are willing to use them along with the already implemented WDM transponders. In this paper, we compare in terms of equipment cost and energy consumption three different network architectures: i) a hybrid OFDM-WDM one, ii) a pure OFDM-based elastic one, and (iii) a MLR WDM one. Integer linear programming (ILP) is used in order to find the optimal solution in each case. Due to space limitation, only the ILP model of the hybrid OFDM-WDM architecture, which is the general and most complex case, is provided in the following section. Our proposed model is based on [8] but is heavily modified in order to contain both OFDM and WDM lightpaths. The ILP models of the other architectures are actually cut-down and simpler cases of the former one and can be derived by omitting several variables and constraints.

II. Network Assumptions and ILP Model

In order to make the ILP model easily understood it is necessary to explain the assumed conditions in the network. Regarding the hybrid OFDM-WDM architecture, each bandwidth request between a pair of network nodes can be broken down to WDM and elastic lightpaths. For example, if the bandwidth request is 500Gbps the connection can be served from an elastic lightpath of 300Gbps plus two WDM lightpaths of 100Gbps or five WDM lightpaths of 100Gbps. However, should an elastic lightpath is used it must be unique for each pair of nodes and the number of occupied frequency slots must be contiguous so that they form a super-channel. On the other hand, WDM lightpaths do not have to use contiguous wavelengths or the same route and the WDM transponders are assumed to be spectrally tuned in the same way as in a fixed grid network with a 50GHz step.

Furthermore, all lightpaths share the same available spectrum and the optical cross-connect (OXC) nodes are equipped with switching granularity of 12.5GHz that can easily support WDM lightpaths by adjusting the switching filter to four slots of 12.5GHz. Since the cost and the energy consumption of the transponders is much higher than that of other optical network equipment, such as optical amplifiers and switches [2][4], we omit from the objective function the cost contribution and the power usage of the latter. Finally, for the sake of reducing computational time, a list of k-shortest paths is pre-computed for each pair of nodes and given as input parameters to the model. The ILP model is shown as the following:

Input Parameters

G = (V, E)	Physical topology of the network with node set V and link set E.
Λ_{sd}	Matrix with the bandwidth demands for all pair of nodes s and d.
F	Maximum number of supported frequency slots in each link.
W	Maximum number of supported wavelengths in each link, $W = F$ div 4.
K	Maximum number of supported subcarriers in an OFDM transponder.
B	The number of required vacant frequency slots between two lightpaths (guardband).
P	Set of all k-shortest paths in the network's topology.
P_{sd}	Set of all k-shortest paths between nodes s and d. $P_{sd} \subseteq P$.
D_p	Parameter equal to the maximum supported data rate per subcarrier for a given path p.
E_p	Parameter equal to the energy consumption per subcarrier of an elastic lightpath for a given path p.
$E_{\mathrm{WDM},r}$	Parameter equal to the energy consumption of a WDM lightpath with data rate r.
$\alpha_{p,ij}$	Boolean parameter that is equal to 1 if path $p \in P$ traverses link $(i, j) \in E$.
$b_{p,r}$	Boolean parameter that is equal to 1 if data rate r is possible with a WDM lightpath in $p \in P$.
C_{OFDM}	Normalized cost of a set of OFDM transponders.
$C_{\mathrm{WDM,r}}$	Normalized cost of a WDM transponder with data rate r.

Variables

X_p	Boolean variable that is equal to 1 if path p is used by an elastic lightpath.
$f_{s,d}$	Integer variable that is equal to the starting frequency slot of the elastic lightpath that serves the connection (s, d).
$m_{p,s,d}$	Integer variable that is equal to the number of contiguous frequency slots of the elastic lightpath that serves the connection (s, d) on path $p \in P_{sd}$.
$z_{sd,s'd'}$	Boolean variable that equals to 1 if the starting frequency of the elastic lightpath of connection (s, d) is greater than the starting frequency of connection (s', d').
$h_{sd,w}$	Boolean variable that equals to 1 if the starting frequency of the elastic lightpath of connection (s, d) is spectrally higher than wavelength w.
$l_{sd,w}$	Boolean variable that equals to 1 if the starting frequency of connection (s, d) is overlapping or is spectrally lower than wavelength w.
$Y_{p,w,r}$	Boolean variable that is equal to 1 if path p is used by a WDM lightpath in wavelength w and data rate r.
B_p	Integer variable that denotes the number of used OFDM transponders in path p.
$U_{w,l}$	Boolean variable that equals to 1 if wavelength w in link $l \in L$ is used by a WDM lightpath.

Objective

Minimize:

$$C = \sum_{p\in P} 2\cdot B_p \cdot C_{\mathrm{OFDM}} + \sum_{p\in P}\sum_{w}^{W}\sum_{r}^{R} 2\cdot Y_{pwr}\cdot C_{\mathrm{WDM},r} \qquad (1)$$

Constraints

Requested bandwidth constraint:

$$\sum_{p\in P_{sd}} m_{p,sd}\cdot D_p + \sum_{p\in P_{sd}}\sum_{w}^{W}\sum_{r}^{R} r\cdot Y_{pwr} \geq \Lambda_{sd} \qquad (2)$$

$$K\cdot B_p \geq m_{p,s,d} \qquad (3)$$

$$m_{p,s,d} \leq X_p\cdot F \qquad (4)$$

for all pairs (s, d).

Spectrum ordering constraints:

$$z_{sd,s'd'} + z_{s'd',sd} = 1 \qquad (5)$$

$$f_{sd} - f_{s'd'} < F\cdot z_{sd,s'd'} \qquad (6)$$

$$f_{s'd'} - f_{sd} < F\cdot z_{s'd',sd} \qquad (7)$$

for all commodities (s, d) and (s', d') that have $p\in P_{sd}$ and $p'\in P_{s'd'}$, with p and p' sharing at least one common link. The above constraints ensure that variables $z_{sd,s'd'}$ and $z_{s'd'',sd}$ are equal to 1 and 0 respectively if $f_{sd} > f_{s'd'}$ and vice versa.

$$f_{sd} - 4\cdot w \leq h_{sd,w}\cdot(F-4) \qquad (8)$$

$$4\cdot w - f_{sd} \leq l_{sd,w}\cdot(F-1) \qquad (9)$$

$$h_{sd,w} + l_{sd,w} = 1 \qquad (10)$$

for all commodities (s, d) and $w\in W$. Constraints (8)-(10) ensure that that variables $h_{sd,w}$ and $l_{sd,w}$ are equal to 1 and 0 respectively if $f_{sd} > 4\cdot w$ and equal to 0 and 1 respectively if $f_{sd} \leq 4\cdot w$.

Single path routing constraint for elastic lightpaths:

$$\sum_{p\in P_{sd}} X_p \leq 1 \qquad (11)$$

for all pairs (s,d).

Spectrum continuity and non-overlapping constraints:

$$f_{sd} + m_{p,s,d} + B - f_{s'd'} \leq (3 - X_p - X_{p'} - z_{s'd',sd})\cdot F \qquad (12)$$

$$f_{s'd'} + m_{p',s',d'} + B - f_{sd} \leq (3 - X_p - X_{p'} - z_{sd,s'd'})\cdot F \qquad (13)$$

for all commodities (s, d) and (s', d') that have $p\in P_{sd}$ and $p'\in P_{s'd'}$, with p and p' sharing at least one common link. The above constraints ensure that two elastic lightpaths that share at least one link cannot use the same frequency slots.

$$f_{sd} + m_{p,s,d} + B - 4\cdot(w-1) \leq (3 - X_p - U_{w,l} - l_{sd,w})\cdot F \qquad (14)$$

$$4\cdot w + B - f_{sd} \leq (3 - X_p - U_{w,l} - h_{sd,w})\cdot F \qquad (15)$$

for all $w\in W$, $l\in L$ and pairs (s,d) that have at least one $p\in P_{sd}$ that uses link l.

$$\sum_{p\in P}\sum_{r}^{R} a_{p,l}\cdot b_{pr}\cdot Y_{pwr} \leq 1 \qquad (16)$$

$$\sum_{p\in P}\sum_{r}^{R} a_{p,l}\cdot b_{pr}\cdot Y_{pwr} = U_{w,l} \qquad (17)$$

for all $w\in W$ and $l\in L$. Constraints (14)-(17) ensure that a WDM lightpath cannot be spectrally overlapped with another lightpath, WDM or elastic one.

III. CASE STUDY AND SIMULATION RESULTS

For the cost comparison, the NSFNET topology with 14 nodes and 21 bidirectional links was used. The length of the links was downsized so that the network can be transparent with no need for 3R regeneration. Each fibre link is assumed to support 40 wavelengths of 50GHz or equivalently, 160 frequency slots of 12.5GHz. The normalized cost and respective optical reach of each transponder are shown in Table 1. It can be noticed that the cost of the OFDM transponder remains the same regardless of the transmission rate since the transponder itself can adjust the data rate and optical reach by changing its modulation scheme. It is also assumed that maximum number of sub-carriers an OFDM

TABLE 1 PARAMETERS IN THE SIMULATION

Type of transponder	Normalized cost C	Optical reach (km)
WDM 10Gbps	1	3200
WDM 40Gbps	2	2000
WDM 100Gbps	4	1000
OFDM 3Gbps per subcarrier (BPSK)	6	3000
OFDM 12.5Gbps per subcarrier (QPSK)	6	1500
OFDM 30Gbps per subcarrier (8QAM)	6	700

transponder can transmit is ten, and the guard-band is equal to one frequency slot. IBM ILOG CPLEX 12.6 was chosen as the ILP solver. For every simulation cycle, the total traffic load is constant and equal to 15Tbps. However, what changes in each cycle is the way the traffic load is distributed across the whole network topology and this is indicated by the average length of the lightpaths.

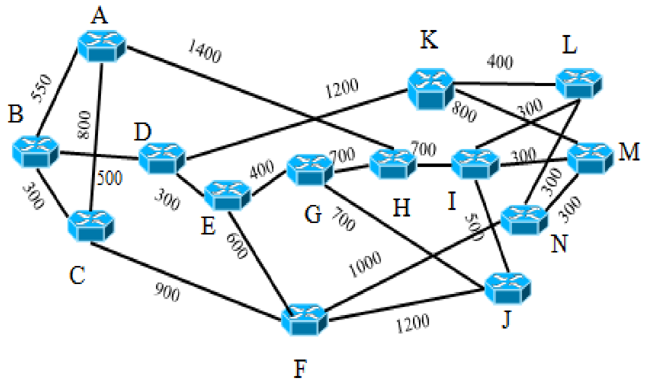

Fig. 2. The topology that was used in simulation. The length of each link is in km.

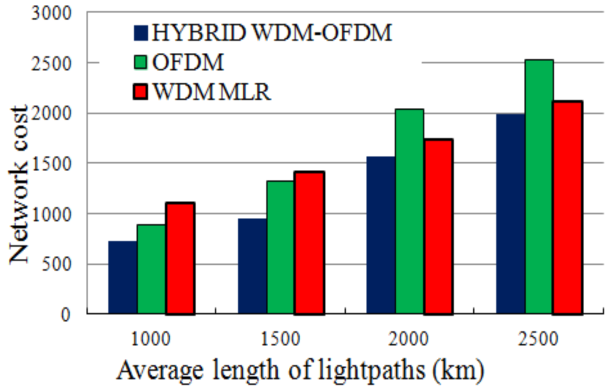

Fig. 3. Total cost of employed transponders for each network architecture.

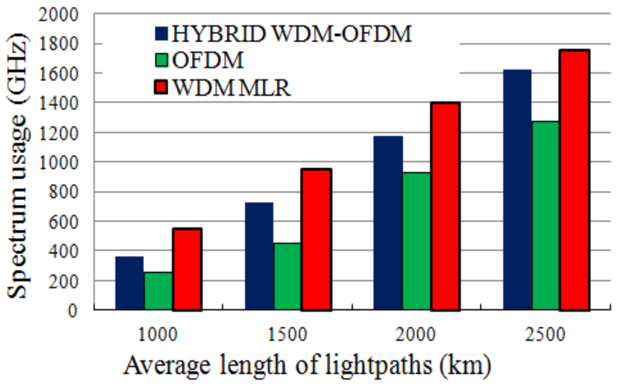

Fig. 4. The correspondent spectrum usage of each architecture.

The results are shown in Figs. 3 and 4. Figure 4 shows how the total network cost scales while the average length of the lightpaths is increasing. The result shows that in every case the hybrid architecture has the cost advantage. When the connections are mostly served by short distance lightpaths more OFDM transponders with high data rate sub-carriers can be employed and thus, the cost of the hybrid network is closely followed by the cost of EON.

On the other hand, when the average lightpath length increases so does the number of WDM transponders and the EON architecture becomes the least cost-effective solution. With regard to the spectrum usage, EON proved to be more efficient one, as shown in Fig. 4.

IV. CONCLUSION

In this paper, an ILP formulation that minimizes the cost of a hybrid OFDM-WDM optical network was presented. In addition, based on this ILP model, a cost comparison was made with a OFDM EON and a MLR WDM optical network. Results showed that the hybrid architecture offers the highest cost-efficiency among the three and a spectrum usage that is always more efficient than that of MLR WDM optical network.

REFERENCES

[1] N. Sambo, et al., “Next generation sliceable bandwidth variable transponders,” IEEE Communications Magazine, vol. 53, no. 2, pp. 163 - 171, Feb 2015.

[2] E. Palkopoulou, M. Angelou, D. Klonidis, K. Christodoulopoulos, A. Klekamp, F. Buchali, E. Varvarigos, and I. Tomkos, “Quantifying spectrum, cost, and energy efficiency in fixed-grid and flex-grid networks,” IEEE/OSA Journal of Optical Communications and Networking, vol.4, no. 11, pp. B42 - B51, Nov. 2012.

[3] P. Papanikolaou, P. Soumplis, K. Manousakis, G. Papadimitriou, G. Ellinas, K. Christodoulopoulos, and E. Varvarigos, “Minimizing Energy and Cost in Fixed-Grid and Flex-Grid Networks,” IEEE/OSA Journal of Optical Communications and Networking, vol.7, no. 4, pp. 337 - 351, April 2015.

[4] N. Yoshikane and T. Tsuritani, “Comparative study of network cost and power consumption between a 100-Gb/s-based single-line-rate network and a 100-G&400-Gb/s-based flexible-bitrate network in three different network topologies,” IEICE Transactions on Communications, vol. E97-B, no. 7, pp. 1295 - 1302, July 2014.

[5] A. Pagano, E. Riccardi, M. Bertolini, V. Farelli, and T. V. D. Velde, “400 Gb/s real-time trial using rate-adaptive transponders for next-generation flexible-grid networks,” IEEE/OSA Journal of Optical Communications and Networking, vol. 7, no. 1, pp. A52 - A58, Jan. 2015.

[6] K. Tanaka and S. Norimatsu, “Transmission performance of WDM/OFDM hybrid systems over optical fibers,” Electronics and Communications in Japan, Part 1, vol. 90, no. 10, Oct. 2007.

[7] S. Chandrasekhar, X. Liu, P. J. Winzer, T. H. Lotz, C. J. Youn, Y. H. Kwon, and E. S. Nam, “Demonstration of 3×341-Gb/s PDM-OFDM-256 iterative polar modulation signals over 495 km of a field-deployed WDM system,” Journal of Lightwave Technology, vol. 33, no. 3, pp. 625 - 630, Feb. 2015.

[8] K. Christodoulopoulos, I. Tomkos, and E.A. Varvarigos, “Elastic bandwidth allocation in flexible OFDM-based optical networks,” Journal of Lightwave Technology, vol. 29, no. 9, pp. 1354 -1366, May 2011.