Power-Efficiency Comparison of Spectrum-Efficient Optical Networks

Sridhar Iyer

Abstract—**With steady traffic volume growth in the core networks, it is predicted that the future optical network communication will be constrained mainly by the power consumption. Hence, for future internet sustainability, it will be a mandate to ensure power-efficiency in the optical networks. Two paradigms known to support both, the traffic heterogeneity and high bandwidth requests are the: (i) next generation flexible (or elastic) orthogonal frequency division multiplexing (OFDM) based networks which provide flexible bandwidth allocation per wavelength, and (ii) currently deployed mixed-line-rate (MLR) based networks which provision the co-existence of 10/40/100 Gbps on varied wavelengths within the same fiber. In this work, the power-efficiency of an OFDM, and a MLR based network has been compared for which, a mixed integer linear program (MILP) model has been formulated considering deterministic traffic between every network source-destination pair. The simulation results show that in regard to power-efficiency, the OFDM based network outperforms the MLR based network.**

Keywords—**Elastic optical networks, mixed line rate optical networks, MILP, power-efficiency, spectrum-efficiency.**

I. INTRODUCTION

For satisfying request(s) of the various heterogeneous services having different applications and varied bandwidth requirements, the legacy 10 Gbps optical transport networks have been upgraded to the 40 and/or 100Gbps networks via the adoption of a mixed line rate (MLR) strategy [1]. MLR networks are spectrum-efficient as they provision the co-existence of 10/40/100 Gbps on varied wavelengths within the same fiber, and further, decrease the overall transmission cost owing to volume discount of the high bit-rate transponders [2]. However, the MLR based networks follow the ITU-T defined fixed-grid which necessitates the admission of all the channels within a fixed 50 GHz channel spacing [2], which may (i) not be adequate for high speed channels, and (ii) under-utilize spectrum for low bit-rate requests. Hence, for pursuing technologies for future networks, flexi-grid systems need to be adopted which can adjust the bandwidth utilization as per the demands, and also provision long transmission range (TR) and high spectral-efficiency (SE) [3, 4].

Recent studies have identified Orthogonal Frequency-Division Multiplexing (OFDM) as the technology to enable the flexi-grid system based networks [5, 6]. In OFDM, several orthogonal carriers (individual carrier is referred to as a subcarrier) are modulated and the composite signal is then carried over an individual wavelength, via a fiber, and further, many such wavelengths are multiplexed within the fiber. Further, in an OFDM based flexi-grid network (i) the ITU-T defined standardized granularity of 12.5 GHz [6] is followed, (ii) on the basis of requirement(s), wider channels are created by combining the spectrum units (also called as slots), and (ii) use of multiple subcarriers ensures that the wavelength capacity can be zoned into finer granularities, hence provisioning increased flexibility in capacity allocation to the heterogeneous demands. Such elastic networks make use of the flexible transceivers (referred to as Bandwidth Variable Transponders (BVTs) in this study) which allows many demand serving options by making a decision on the modulation format, bit-rate, and/or spectrum, and making a choice which provides adequate TR performance. Hence, any BVT with a cost c, r Gbps of transmission rate tuning, and using the spectrum slot(s) of bandwidth b and guardband g, leads to p amount of power consumed in order to transmit with a satisfactory quality of transmission (QoT), for l km of distance [7].

Further, compared to MLR networks, in OFDM based networks, based on the various scenarios, the overall power incurred is different, which can be explained as follows: let there occur a 100 Gbps demand between two nodes *a*-*b* of the network. To satisfy such a demand, there may exist(s) multiple paths which are connected via the fiber links between the two network nodes *a*-*b*. Also, it may occur that the demand (i) is set up using a transparent (i.e., an all-optical channel (wavelength)) resulting in minimum network cost, or (ii) at the increased load values, owing to the signal reach constraint (which restricts high bit-rate signal(s) to traverse only a short distance before the regeneration requirement), there is no end-to-end transparent route, and hence, between the multiple channels, the demand will require splitting up. Further, the used channels may traverse via the same or through different fibers, and therefore, varied overall network power will be incurred. Hence, in the complete network with many requests, and the (i) wavelength-continuity constraint, (ii) capacity constraint, and (iii) maximum subcarrier constraint [3, 4], the optimization problem of minimizing

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power consumption is challenging.

In this work, we compare the power efficiency of OFDM and MLR based networks. We propose and formulate a mixed integer linear program (MILP) model that minimizes power consumption of a specific network with *a-priori* traffic requests. The traffic is assumed to be deterministic (static) specified by a traffic matrix containing forecasted mean traffic between various source-destination (*s-d*) pairs. It must be noted that for the comparisons, we have not considered the single line rate (SLR) based networks, as existing studies have already established that under most traffic load values, the MLR networks are power-efficient compared to the SLR networks [2, 8, 9].

Rest of the paper is structured as follows: In Section II, we detail the problem formulation and the power model used in the study. Section III presents and discusses the various obtained simulation results. Finally, in Section IV, we conclude the study.

II. Problem Formulation

A. MILP Model

In this sub-section we detail the developed MILP mathematical model for power-optimization in an OFDM-based optical network, which is as follows:

Input parameters:

$G(V,E)$: Network topology comprising of a set of *V* nodes and a set of *E* links;

$T=\left[\Lambda_{s-d}\right]$: Matrix consisting of the traffic having the total Gbps requests of Λ_{s-d} between an *s-d* pair;

R: Rate for an individual subcarrier;

C_{TP}: Transponder power cost (fixed);

C_S: Individual subcarrier cost (fixed);

C_A: In-line amplifier cost;

A_{mn}: On a fiber, the amplifier numbers over the link with nodes *m* and *n*. For a span distance *L* = 80 km between adjacent amplifiers (EDFAs), the amount of EDFAs for the link of a fiber is given as $A_{m\,n}=\left[L_{mn}/L-1\right]+2$; where,

L_{mn} denotes length of span of the fiber between *m* and *n*.

C_p: Power cost of electronic processing (per Gbps) cost i.e., cost of Optical-Electrical-Optical (OEO) conversion.

W: Maximum amount(s) of the wavelength(s) on a link $\lambda\in\{\ 1,\ 2,....W\}$;

l_{mn}: Link (physical) between *m* and *n*;

P_{mn}: Lightpath(s) set passing through the link l_{mn}.

Variables:

$L_{i\,j\,\lambda}$: Variable (binary) referring to lightpath(s) number(s) over wavelength λ over link *i*- *j*;

$T_{i\,j}^{s\,d}$: Variable (integer) referring to the traffic volume from *s* to *d* routed over link *i*- *j*.

OF_{mn}: Variable (integer) referring to the number of optical fibers over a physical link (*m, n*).

D_j: Variable (integer) which denotes the data amount that is carried by the lightpaths ending at node *j*.

$S_{i\,j\,\lambda}^{k}$: Variable (binary) denoting whether k^{th} subcarrier in wavelength λ is utilized over the path between nodes *i*- *j*.

Problem formulation:

Minimize overall network power which is mathematically given as follows:

$$\sum_{\lambda}\sum_{i\,j}\sum_{k}S_{i\,j\,\lambda}^{k}\cdot C_s+\sum_{\lambda}\sum_{i\,j}T_{ij\lambda}\cdot C_{TP}+\sum_{m,n}C_A\cdot A_{m\,n}\cdot OF_{mn} +\sum_{j}D_j\cdot C_p \quad . (1)$$

The objective function in (1) consists of power due to the (i) BVTs, which in turn consists of a variable and a fixed power consumption (detailed in sub-section *2.2*), (ii) fiber amplifiers in the network, and (ii) electronic processing used for setting up the multi-hop connections. Further, the objective function in (1) is constrained by

(i) the capacity constraint requiring the amount of subcarriers which are set up over the total wavelengths on a path to support the flow of aggregate traffic on that route, given as

$$R\sum_{\lambda}\sum_{k}S_{i\,j\,\lambda}^{k}\geq\sum_{s,d}T_{i\,j}^{s\,d}\quad\forall(i,j)\quad , \qquad (2)$$

$$\sum_{\lambda}\sum_{k}S_{i\,j\,\lambda}^{k}\leq\quad W\quad\forall(i,j,k)\quad , \qquad (3)$$

(i) the constraint to avoid wavelength clash, given as

$$\sum_{i,j\in P_{mn}}X_{i\,j\,\lambda}\leq OF_{mn}\quad\forall(m,n),\forall\lambda\quad , \qquad (4)$$

(ii) the conservation of traffic flow on each path, given as

$$\sum_{i}T_{i\,j}^{s\,d}-\sum_{i}T_{j\,i}^{s\,d}=\begin{cases}\Lambda_{sd} & for\ s=j\\ -\Lambda_{sd} & for\ d=j\\ 0 & otherwise\end{cases}\quad\forall(i,j)\forall(s,d)\quad , (5)$$

(iii) the total of flows ending at node *j* i.e., sum traffic at every node requiring electronic processing, given as

$$E_j=\sum_{s,d}\sum_{i}T_{i\,j}^{s\,d}\quad\forall i\neq s,\forall j\neq d\quad , \qquad (6)$$

(iv) the constraints which signify whether, at least, there occurs utilization of one subcarrier for specific path *i-j* and wavelength λ, which results in lightpath liting up for that specific path-wavelength combination, given as

$$L_{i\,j\lambda}\quad\geq\quad\frac{\sum_k S_{i\,j\lambda}^{k}}{M}\quad\forall i,j,\lambda\quad , \qquad (7)$$

$$L_{i\,j\lambda}\quad\leq\quad S_{i\,j\lambda}^{k}\quad\forall i,j,\lambda\quad . \qquad (8)$$

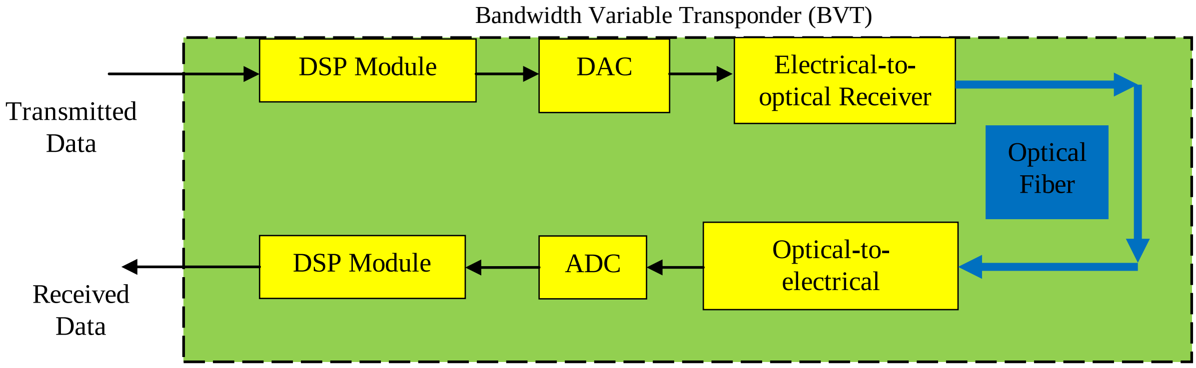

Fig.1. Architecture of a Bandwidth Variable Transponder.

B. Power Model

In our study, as shown in (1), the BVT power model consists of a (i) variable (dynamic) part, depending on the subcarrier(s) number(s) allocated for every lightpath, and (ii) fixed (static) part, accounting for power of the transponder.

Further, fixed part of the BVT is the major power consumer, whereas, variable part of the BVT alters with the accommodation of flexible bandwidth when various subcarrier(s) number(s) are modulated at the appropriate level(s). The BVT model of our study, shown in Fig. 1, consists of (i) two digital signal processing (DSP) modules, (ii) one digital-to-analog (DAC) module, (iii) one analog-to-digital convertors (ADC) module, and (iv) optical transmitters and receivers i.e., optical-to-electrical (transmitters) and electrical-to-optical (receivers) modules.

According to the studies in [10-13], the power consumed by BVTs supporting a maximum bandwidth of 100 Gbps can be gauged by utilizing the power consumption values of the following modules: (i) DSP: approximately 50-70 W, (ii) DAC/ADC, and (iii) optical transmitters and receivers. From the studies in [10, 11], the variable power consumption of a BVT is: 180 mW/Gbps of the bandwidth, approximately. Hence, as per the combined figures from [10-13], the aggregate power consumed by a BVT supporting a maximum bandwidth of 100 Gbps is approximately in the 120-140 W range. Further, the power consumed by the 10/40/100 Gbps transponders is 40 W, 100 W, and 210 W [14-16], respectively.

In our simulations, we have compared the MLR and OFDM based networks with a BVT power consumption which is fixed, and is given by the following equation

$$P_{BVT} = P_{DSP} + P_{ADC} + P_{DAC}\,, \qquad (9)$$

Hence, from (9), we obtain the BVT power consumption with fixed values of 120 W, 140 W, and 160 W. Further, we also use a value of 192 W which is chosen so that the aggregate network power consumption can be compared for the case when, a 100 Gbps transponder and a BVT with utmost 100 Gbps bandwidth, incur the same power consumption. The aforementioned implies that power consumption of the BVT for the operation at 100 Gbps is $[(192)\times(180\,mW\times100)]=210\,W$. The normalized consumed power values are hence summarized in Table I.

TABLE I NORMALIZED POWER COST OF VARIOUS COMPONENTS.

Component	**Normalized Power Cost**			
	10 Gbps	**40 Gbps**	**100 Gbps**	**OFDM**
Transponder	1	2.7	5.8	M + 0.005*x*, where M = 3.5,3.8, 4.1, 5.3 *x* = bandwidth in Gbps
Amplifier	0.25 per fiber [8]			
OEO Processing	0.5*x*, where *x* = bandwidth in Gbps [8]			

It must be noted that the power consumption values of BVTs are as per the recently available data, and also, to the best of our knowledge, BVTs for long distance optical communication are not yet commercialized. Hence, in our study, we assume a BVT with utmost power consumption, which at full load, provisions the same power consumption as a single carrier transponder at the same bandwidth. The aforementioned assumption exploits the ability of BVT's power consumption adjustment with bandwidth, which corresponds to the variable part of the consumed power. Therefore, as an example, to support a demand of 40 Gbps, (i) as a worst case scenario, a 100 Gbps BVT as per our values has $[5.3+(0.005\times40)]=5.5\,units$ of normalized power consumption (see Table 1), whereas (ii) for the case of a single carrier, a 100 Gbps transponder incurs $5.5\,units$. We intend to capture the aforementioned particular scenario in our study.

III. SIMULATION RESULTS AND DISCUSSION

The formulated MILP is solved for the NSFnet backbone network topology shown in Fig. 2 and its corresponding traffic demand matrix shown in Table II [1]. To model traffic loads with higher values, the base traffic matrix mentioned Table II is scaled by appropriate constant values.

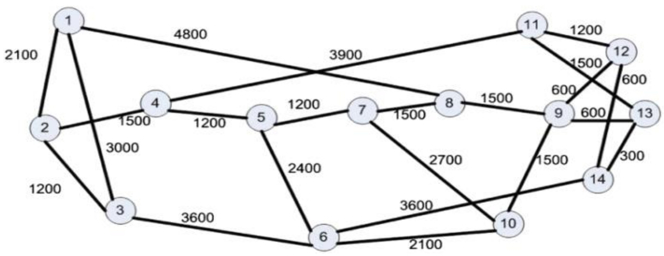

Fig.2. NSFNet topology (link lengths in km).

TABLE II TRAFFIC MATRIX FOR NSFNET NETWORK (EACH ENTRY IN GBPS).

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0	2	1	1	1	4	1	1	2	1	1	1	1	1
2	2	0	2	1	8	2	1	5	3	5	1	5	1	4
3	1	2	0	2	3	2	11	20	5	2	1	1	1	2
4	1	1	2	0	1	1	2	1	2	2	1	2	1	2
5	1	8	3	1	0	3	3	7	3	3	1	5	2	5
6	4	2	2	1	3	0	2	1	2	2	1	1	1	2
7	1	1	11	2	3	2	0	9	4	20	1	8	1	4
8	1	5	20	1	7	1	9	0	27	7	2	3	2	4
9	2	3	5	2	3	2	4	27	0	75	2	9	3	1
10	1	5	2	2	3	2	20	7	75	0	1	1	2	1
11	1	1	1	1	1	1	1	2	2	1	0	2	1	61
12	1	5	1	2	5	1	8	3	9	1	2	0	1	81
13	1	1	1	1	2	1	1	2	3	2	1	1	0	2
14	1	4	2	2	5	2	4	4	1	1	61	81	2	0

The number of available wavelengths (*W*) is assumed to be 16 wavelengths per link, and 16-QAM modulation format is assumed for every subcarrier. The OEO (electronic) processing and EDFAs power consumptions are as specified in [8]. From the study in [17], it is known that with an overhead of less than 10% for the cyclic prefix, at 100 Gbps rate of data, the least size of FFT corresponds to 2048. Hence, with assumption of the use of a standard single-mode fiber (SSMF) and a 1000 km tolerance for chromatic dispersion, a 3.9 ns length of cyclic prefix is used in the simulations so as to achieve a 10 % symbol overhead comprising of overheads such as, training symbol, FEC, Ethernet, and phase-noise compensation. For the MLR based fixed-grid network, we use the MILP formulation from [8] to minimize the power consumption. Further, compared to a similar bandwidth OFDM signal, for the MLR based network, each 10/40/100 Gbps transponder has the same TR. For conducting the simulations, we have used the ILOG CPLEX on an Intel Core 2 Duo machine which has a 2.0 GHz processor with 4 GB memory and the Ubuntu operating system, with which, each run of the MILP takes approximately 1-2 hours.

Fig. 3 compares the normalized power cost for an OFDM and a MLR based network. It can be seen from the figure that for various load values, an OFDM based network is highly power efficient compared to a MLR based network. It is also seen that for high values of traffic load, compared to the MLR based network, the saving(s) in power increases for an OFDM based network since the spectral resources are less over-provisioned.

In Fig. 4, for various BVT(s) and MLR transponder power consumption values, the variation of aggregate normalized power cost with the traffic load is shown. It can be seen from the figure that, with the BVT fixed power costs till 160 W, for all traffic loads, OFDM is more power efficient compared to MLR. However, when BVT fixed power consumption is 192 W (i.e., when the OFDM BVT and the MLR transponder power consumptions are similar for a bandwidth of 100 Gbps), and the traffic load(s) is low (i.e. for 5 and 10 Tbps), OFDM based network is seen to be power inefficient compared to the MLR based network. However, as the traffic load increases, OFDM based network demonstrates more power efficiency even for similar maximum power consumption of the OFDM BVT and the MLR transponder.

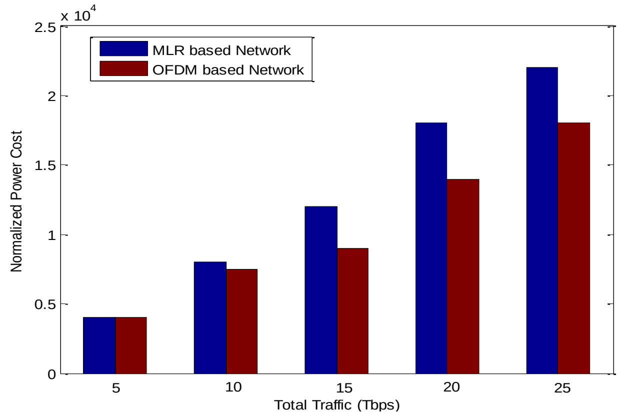

Fig.3. Comparison of normalized power cost for an OFDM and a MLR based network.

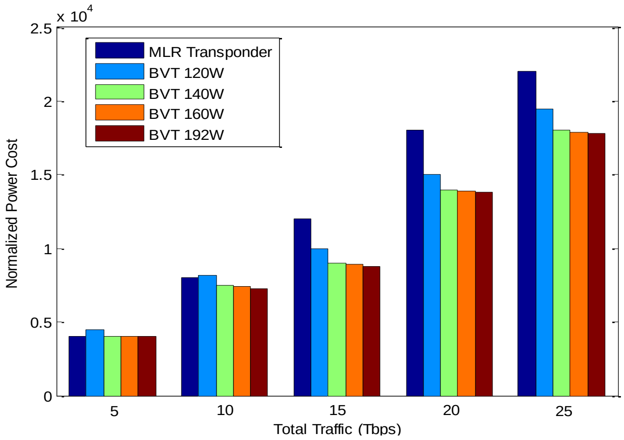

Fig.4. Aggregate normalized power cost versus transponder power consumption for an OFDM and a MLR based network.

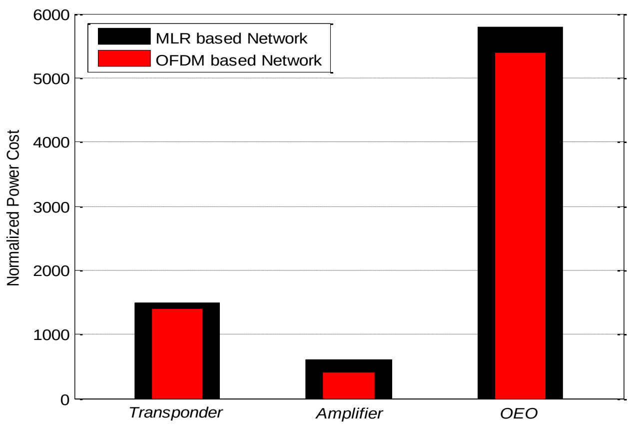

Fig.5. Normalized power cost for various components in an OFDM and a MLR based network for 20 Tbps traffic load.

In Fig. 5, we show the power consumed by various components when the total network traffic is 20 Tbps. From the figure it is seen the maximum network cost is incurred owing to the intermediate nodes of the *s–d* connections, whose establishment occurs over many i.e., multiple-hop lightpath(s) path(s), which requires OEO conversion (i.e. electronic processing). Also, compared to an MLR based network, owing to the higher spectral efficiency of OFDM based networks, the per fiber bandwidth packing is highly efficient, and hence, less power is exhausted on the BVTs and the EDFAs.

IV. Conclusion

In the current work, we conducted a power-efficiency comparison of an OFDM and a MLR based network for which, we formulated a MILP model with a specific mean traffic for every network source-destination pair. The simulation results show that in regard to power-efficiency, OFDM based network outperforms MLR based network.

It must be noted that the related planning problems using the MILPs are NP-hard, and hence, searching for the absolute optimums is time consuming. However, as an initial investigation, our primary focus in the current study has been to compare the power-efficiency in OFDM and MLR based networks. However, as a future work, we will aim to develop and use heuristic algorithms for power-efficiency comparison in fixed- and flexi-grid networks.

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