On the Energy Efficiency of Mixed-Line-Rate Networks

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Abstract: We present an approach to evaluate energy efficiency of mixed-line-rate (MLR) optical networks. A comparative study of energy efficiency of MLR and single-line-rate (SLR) networks shows that MLR is more energy efficient than SLR networks.

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1 Introduction

The Internet is continuously transforming our lifestyle, increasing productivity, and supporting economic developments across the world. Consequently, Internet traffic continues to grow overwhelmingly, and the energy usage of Internet infrastructures and devices is also growing rapidly. It is estimated that power consumption of the Internet is around 4% of the total energy consumption in broadband-enabled countries, and backbone network infrastructures (i.e., routers, transmission systems, optical switches, ROADMs, etc.) consume approximately 12% of total Internet energy consumption (estimated to increase to 20% in 2020) [1]. Carbon footprint of the Internet is dominated by its energy consumption, so an obvious way to reduce carbon emission is to design "green" (energy-efficient) network infrastructures. Until recently, telecom researchers mainly focused on designing networks with optimized resources (e.g., bandwidth, cost, etc.). With the increasing energy demand of the Internet, it is now imperative to satisfy another design objective - energy efficiency.

As the Internet continues of grow, demands of bandwidth in the Internet are becoming more heterogeneous. Existing optical backbone networks support 10-40 Gbps line rate, and demands for higher bandwidth are growing. Recently, a major social networking site claimed that it could use 100 Gbps line rate right now if available [2]. Hence, future optical backbone networks will be required to support mixed line rates (MLR) (e.g., 10/40/100 Gbps). MLR networks provide versatility in provisioning bandwidth demand since low-data-rate requests can be multiplexed into high-capacity wavelengths, and direct lightpath can be set on high-capacity wavelengths for high-data-rate requests [3].

However, due to bit-error-rate (BER) constraints, maximum transmission distance of an optical signal reduces with increase of bit rate. High-data-rate transmission also consumes more energy compared to low-data-rate transmissions. Hence, in a MLR network, a tradeoff exists between capacity and energy consumption. High-data-rate wavelengths increase the capacity and energy consumption of the network at the same time. Therefore, while designing a MLR network, we need to find the optimum number of wavelengths at different data rates to support a given set of traffic demands and minimize the networkwide energy consumption.

In this paper, we present a mathematical model to determine the energy efficiency of a MLR optical network. We compare the energy consumption of both MLR and SLR networks using our model. Our results indicate that a MLR network performs better than the SLR networks by reducing the networkwide energy consumption.

2 Energy Cost Evaluation

Here, we state the problem of evaluating the energy efficiency of a MLR network, a special version of which considering a single rate can model a SLR network. We consider a transparent optical network with no wavelength conversion and different reach for different line rates. During variable indexing, we use the following rules: m and n index the nodes in the physical topology of the network, i and j index the nodes in the virtual lightpath topology, and s and d index source and destination nodes of a traffic demand. To describe the model, we introduce some notations for the parameters and variables as follows.

- $G(V,E)$: Physical topology consisting of node set V and link set E. At each node, a router is connected to an optical switch with long-reach interfaces.
- l_{ijk}: lightpath between a node pair (i,j) at rate r_k.
- α_{ijk}: denotes whether a lightpath l_{ijk} is feasible or not based on an acceptable BER.
- L_{mn}: length of fiber span between nodes m and n.
- P_{mn}: set of lightpaths through physical link (m,n).
- F_{mn}: variable denoting number of fibers on a physical link (m,n).
- $X_{ijk\lambda}$: variable denoting the number of lightpaths on virtual link (i,j) at rate r_k over wavelength λ.
- $R = r_1, r_2, ..., r_k$: set of available channel rates.
- E_{r_k}: energy cost of a transponder with rate r_k.
- E_a: energy cost of an in-line amplifier.
- E_p: energy cost of electronic processing (per Gbps).
- W: maximum number of wavelengths supported on a link, $\lambda \in \{1, 2, ..., W\}$.
- $T = [\Lambda_{sd}]$: forecasted traffic matrix with aggregate demand Λ_{sd} between a (s,d) pair.
- A_{mn}: number of amplifiers on a fiber on link (m,n).
- f_{ij}^{sd}: variable denoting traffic from source s to destination d on virtual link (i,j).
- Z_j: variable expressing the amount of data carried by lightpaths which are terminated at node j.

The objective of the problem is to find the energy efficiency of a MLR network, and can be written as:

$$minimize \sum_{\lambda} \sum_{ij} \sum_{k} X_{ijk\lambda}.E_{r_k} + \sum_{mn} A_{mn}.F_{mn}.E_a + \sum_{j} Z_j.E_p \qquad (1)$$

subject to the following constraints:

$$\sum_{\lambda}\sum_{k} r_k.X_{ijk\lambda}.\alpha_{ijk\lambda} \geq \sum_{sd} f_{ij}^{sd} \quad \forall(i,j) \qquad (2)$$

$$\sum_{(i,j)\in P_{mn}}\sum_{k} X_{ijk\lambda}.\alpha_{ijk\lambda} \leq F_{mn} \quad \forall(m,n),\forall\lambda \qquad (3)$$

$$\textstyle\sum_i f_{ij}^{sd} - \sum_i f_{ij}^{sd} = \begin{cases} \Lambda_{sd}, if \ s=j \\ -\Lambda_{sd}, if \ d=j \\ 0, otherwise \end{cases} \qquad (4)$$

$$\forall i, \forall(s,d)$$

$$Z_j = \sum_{sd}\sum_{i} f_{ij}^{sd} \quad \forall i \neq s, \forall j \neq d \qquad (5)$$

The mathematical formulation of the problem turns out to be a mixed integer linear program (MILP). The objective function (Eqn. (1)) minimizes the energy consumption of the MLR network. The first term in Eqn. (1) computes the total energy consumption of WDM transponders required to support the traffic demands. The second term calculates the energy consumption of all the in-line amplifiers in the network. If we are given the span distance L (e.g., 80 km) between two neighboring amplifiers (EDFA), the number of in-line amplifiers for a fiber link (m,n) is given by $A_{mn} = \lceil L_{mn}/L - 1 \rceil + 2$ where 2 is used to count pre- and post-amplifiers [4]. Obviously, the longer the link, the more the number of amplifiers needed. F_{mn} quantifies the number of fibers needed to carry the traffic demands as we may need multiple fibers on a link in case of low-bit-rate networks. However, we can easily downgrade the formulation for single-fiber networks by forcing the value of F_{mn} to 1. The third term in Eqn. (1) captures the total energy cost for electronic processing at each intermediate node for all the traffic demands. We account here specifically the traffic that is electronically processed in intermediate nodes along multi-hop lightpath routes, and we disregard the electronic processing of traffic at source and destination nodes since this contribution is constant under all the scenarios.

In the constraints, $\alpha_{ijk\lambda}$ determines whether the lightpath $X_{ijk\lambda}$ between nodes i and j, of rate r_k and on wavelength λ, is feasible based on the BER threshold. These $\alpha_{ijk\lambda}$ values are calculated offline for each possible physical route. The physical routes are determined by Dijkstra's shortest-path algorithm. In Eqns. (2) and (3), the multiplication of $X_{ijk\lambda}$ and $\alpha_{ijk\lambda}$ ensures that only feasible lightpaths are present in the solution. Equation (2) is the capacity constraint which limits the traffic demands routed over a lightpath by its capacity. Equation (3) is the wavelength-continuity constraint which ensures that, on a physical link with multiple fibers, there should not be more than one lightpath on the same wavelength, i.e., there is no color clash. Equation (4) is the flow conservation constraint which captures the fact that, in all nodes of the network, total outgoing traffic should be equal to total incoming traffic except for source and destination nodes. If an end-to-end traffic flow from i to j is routed using two lightpaths (i,k) and (k,j), then at node k, electronic processing of that flow is required. Equation (5) calculates the aggregated traffic flow at each node which needs electronic processing. We can generate the formulation for a SLR network by enforcing a single value for r_k in the MILP model.

3 Illustrative Numerical Examples and Discussion

Here, we present illustrative results obtained by MILP for both MLR and SLR networks. For solving the MILP, we use ILOG CPLEX software on a Intel Core 2 Duo machine with 4 Gigabyte RAM. Our network topology is NSFNet (Fig. 1). We use the traffic demand matrix as in [3]. The base traffic demands sum up to 1 Tbps, and can be multiplied with different load factors.

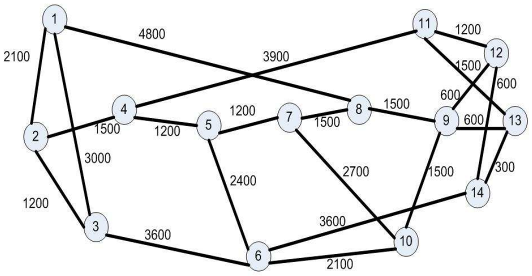
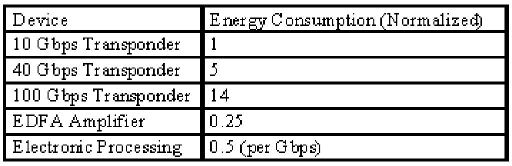


Fig. 1. NSFNet topology (link lengths in km).



Device	Energy Consumption (Normalized)
10 Gbps Transponder	1
40 Gbps Transponder	5
100 Gbps Transponder	14
EDFA Amplifier	0.25
Electronic Processing	0.5 (per Gbps)

Fig. 2. Energy consumption of network devices.

Energy costs are given in Fig. 2 (collected from various sources such as [4], others are not cited due to space limits) and are normalized to a 10 Gbps transponder's energy cost (35 W). We note that high-data-rate transponders have "volume penalty", i.e., energy cost of capacity scales more than linearly as capacity increases. For illustration purposes, we use energy cost values of Fig. 2. However, our model is general and can take any energy cost values.

Estimating the energy cost for electronic processing of traffic at an intermediate node is trickier. In an intermediate node, depending on interconnection between optical switch and router, this energy cost will vary. If we consider that the router is connected through long-reach interfaces to the optical switch, the electronic-processing power consumption depends on the processing cost (energy consumption of O-E, electronic processing, and E-O) at router.

Here, we do not consider electronic processing cost at each end node of a traffic demand. To calculate BER constraints, we use optical duobinary modulation scheme which gives less complexity among advanced modulation formats [3]. The BER threshold is set at B $= 10^{-3}$. At most, 16 fibers can be multiplexed in each fiber, and there is no limit on number of fibers at each link.

Figure 3 evaluates the total power consumption of SLR (link rates are either 10 Gbps, 40 Gbps, or 100 Gbps) and MLR networks. In [3], the authors have demonstrated that MLR can minimize network cost. Our

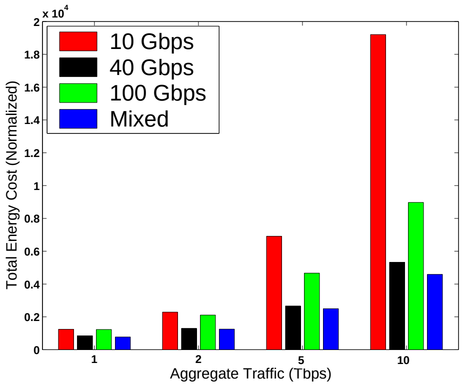


Fig. 3. Total energy cost.

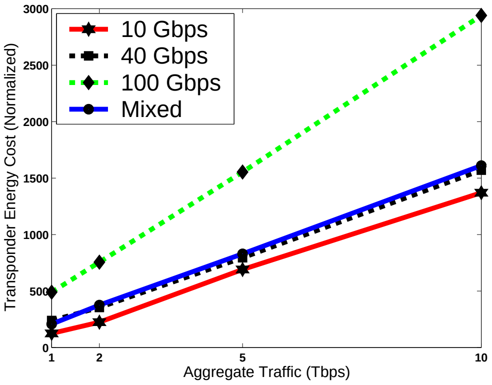


Fig. 4. Transponder energy cost.

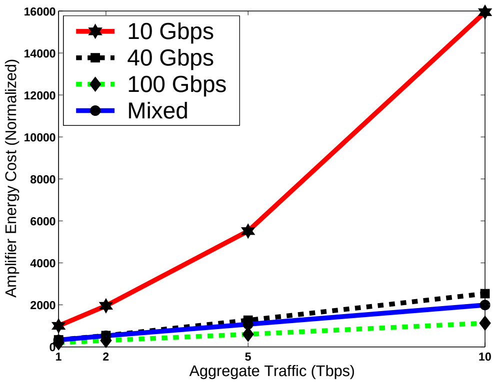


Fig. 5. Amplifier energy cost.

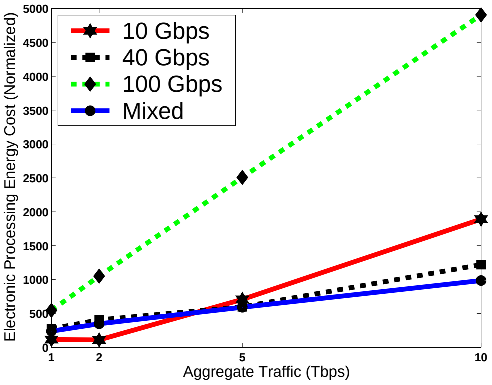


Fig. 6. Electronic processing energy cost.

model, on the other hand, minimizes the energy cost of network devices (transponders, amplifiers, etc.) and shows that a MLR network also consumes less energy compared to SLR networks. Figures 4, 5, and 6 present the distribution of power consumption in different network devices. Power consumed by transponders is very high in a 100 Gbps SLR network due to "volume penalty" in energy costs.

Figure 4 shows that 10 Gbps SLR network consumes the minimum transponder energy. But this advantage is offset by other energy costs of 10 Gbps SLR network. In fact, Fig. 5 shows that, for 10 Gbps SLR network, amplifier energy cost is very high, and it constitutes the major portion of total energy consumption. This is due to the fact that we need to deploy more fibers to support the traffic demand in 10 Gbps SLR network. Even if high-data-rate transponders have "volume penalty", our model estimates that energy cost is minimized if we use high-data-rate transponders because this allows us to deploy fewer fibers which relevantly contribute to the energy cost of the network. Figure 6 shows the energy cost of electronic processing. As anticipated, 100 Gbps SLR network requires more electronic processing as signals at 100 Gbps can not travel longer distance. For higher traffic demands, 10 Gbps SLR network requires more electronic processing as it requires to set up more lightpaths to carry higher traffic load.

It is worth noting that, in SLR networks, there is a close relation between Capital Expenditure (CapEx)-minimized and energy-minimized design [4]: it turns out that energy-minimized design is also CapEx-minimized. In MLR networks, we can consider two CapEx models: (a) CapEx of only transponders, and (b) CapEx of transponders and deployed fibers. If we consider model (a), energy-minimized MLR network will not be CapEx-minimized since "volume penalty" applies for high-bit-rate transponders. However, for model (b), energy-minimized MLR networks will also be CapEx-minimized. If energy costs for high-data-rate transponders would exhibit "volume discount" in future, energy and CapEx-minimized design will also be similar for model (a).

4 Conclusion

We have investigated the energy cost of MLR and SLR networks. We have developed a mathematical model and applied it on a case-study network with realistic energy cost parameters. We found that an MLR network consumes less energy compared to SLR networks.

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