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GreenTouch GreenMeter Core Network Power Consumption Models and Results

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***Abstract*— This paper summarizes the energy efficiency improvement obtained by implementing a number of techniques in the core network investigated by the GreenTouch consortium. These techniques include the use of improved components with lower power consumption, mixed line rates (MLR), energy efficient routing, sleep and physical topology optimization. We consider an example continental network topology, NSFNET, to evaluate the total power consumption of a 2010 network and a 2020 network. The 2020 network results are based on traffic projections, the reductions in the equipment power consumption expected by 2020 and a range of energy saving measures considered by GreenTouch as outlined above. The projections of the 2020 equipment power consumption are based on two scenarios: a business as usual (BAU) scenario and a Green Touch (GT) (i.e. BAU+GT) scenario. The results show that the 2020 BAU scenario improves the network energy efficiency by a factor of 4.8x compared to the 2010 network as a result of the reduction in the network equipment power consumption. Considering the 2020 BAU+GT network where the equipment power consumption is reduced by a factor of 27x compared to the 2010 network, and where sleep, MLR and network topology are jointly optimized, a total improvement in energy efficiency of 64x is obtained.**

I. INTRODUCTION

With the continuously growing popularity of data intensive applications and the increasing number of devices connected to the Internet, the total Internet traffic is growing exponentially. One of the main challenges faced by next-generation networks is serving this increasing traffic demand while maintaining sustainability and enhancing the profit margins through lower energy usage. Today the power consumption of networks is a significant contributor to the total power demand in many developed countries. For example, in the winter of 2007, British Telecom became the largest single power consumer in the UK accounting for 0.7% of the total UK's power consumption [1]. Driven by the economic, environmental and societal impact, significant academic and industrial research effort has been focused recently on reducing the power consumption of communication networks.

GreenTouch is an international research consortium, formed in 2010, embracing a broad spectrum of organizations playing essential roles in the technology breakthroughs in network energy efficiency including equipment providers, operators, research institutes and academic organizations. GreenTouch was launched to pursue the ambitious goal of bridging the gap between traffic growth and network energy efficiency by developing network architectures and technologies to improve the network energy efficiency by a factor of 1000 compared to 2010 levels, with wireless networks having to achieve the highest savings followed by access networks and finally core networks. A roadmap demonstrating theses architectures and technologies will be delivered by 2015. The research areas investigated by GreenTouch include wireline access, mobile communications, switching and routing, optical networking, and services, applications and trends.

After three years from launching GreenTouch, a white paper was published to discuss the outcomes of a comprehensive research study called the "GreenMeter" [2] that summarizes the overall impact and the overall energy efficiency obtained from implementing a range of technologies, architectures, devices and protocols developed by GreenTouch.

In this paper we give the technical background, assumptions, models and detailed results of the core networks architectures and techniques considered in the GreenMeter study. We introduce our traffic growth and distribution studies, the improvements expected in components power consumption and the architecture improvements which include sleep and low energy state modes [3], mixed line rates (MLR) [4], [5] and physical topology optimization [6].

The total power consumption is evaluated considering a 2010 network and a 2020 network. For the 2010 network we consider the traffic in 2010 along with the most energy-efficient commercially available equipment in 2010. The 2020 network is based on projections of the traffic in 2020 [7]-[9] and the reductions in the equipment power consumption by 2020. The projections of the 2020 equipment power consumption are based on two scenarios: a business as usual (BAU) scenario and BAU+GT scenario [10] where the technical advances achieved by the GreenTouch Consortium will accelerate the reduction in equipment power consumption.

The reminder of this paper is organized as follows: In Section II we introduce the optimization models for the different energy efficiency techniques evaluated in the paper. In Section III we discuss the network traffic demand and equipment power consumption for the 2010 and 2020 networks. Section IV presents the optimization results of the 2010 and 2020 networks. Section V outlines the main conclusions.

II. MILP MODELS FOR ENERGY-EFFICIENT IP OVER WDM NETWORKS WITH ENERGY EFFICIENT: MLR, ROUTING, SLEEP AND TOPOLOGY DESIGN

In this section we introduce the different Mixed Integer Linear Programming (MILP) models built to support the energy-efficient approaches considered in this paper.

A. MILP Model for Mixed Line Rate IP over WDM Networks

Optical networks with mixed line rates (MLRs) have been proposed [4], [5] as a flexible architecture choice to efficiently support a heterogeneous range of applications in the core network. MLR reduces the bandwidth wastage and can as a result save energy. Furthermore, given that the power consumption of transponders is not directly proportional to the data rate, MLR uses the optimum combination of transponders that minimizes the power needed to serve a given demand. In this paper we evaluate the energy savings obtained by introducing the MLR architecture to IP over WDM networks.

Before introducing the MILP for MLR IP over WDM networks, we introduce the parameters defined by the model:

i and *j*	Denote end points of a virtual link in the IP layer,
s and *d*	Denote source and destination of a traffic demand,
m and *n*	Denote end points of a physical link in the optical layer,
L_{mn}	The length of the physical link between nodes *m* and *n,*
T	Set of time points,
R	set of possible rates
S	Distance between neighbouring EDFAs,
N	Set of nodes,
Np_i	The set of neighbour nodes of node *i* in the optical layer,
W	The number of wavelengths in a fibre,
B_r	The capacity of a wavelength of line rate *r,*
λ^{sdt}	Traffic demand between source *s* and destination *d* at time *t,*
EA_{mn}	The number of EDFAs on physical link (*m, n*). Typically $EA_{mn} = \lfloor L_{mn}/S - 1 \rfloor + 2$, where *S* is the distance between two neighbouring EDFAs [11],
EG_{mnr}	The number of regenerators for a wavelength of line rate *r* on physical link (*m, n*). Typically $EG_{mn} = \lfloor L_{mn}/RG_r - 1 \rfloor$, where $RG_r$is the reach of a transponder of line rate r,
PR_r	Power consumption of a router port of line rate *r*,
PT_r	Power consumption of a transponder of line rate *r*,
PE	Power consumption of an EDFA,
RG_r	Power consumption of a regenerator of line rate *r*,
PO	Power consumption of the optical switch,
PMD	Power consumption of a multi/demultiplexer.

The model also defines the following variables:

C_{ijrt}	The number of wavelength channels of line rate *r* in the virtual link (*i, j*) at time *t,*
ω_{mnrt}	The number of wavelength channels of line rate *r* in the physical link (*m, n*) at time *t,*
W_{mnrt}^{ij}	The number of wavelength channels of line rate *r* in the virtual link (*i, j*) that traverse physical link (*m, n*) at time *t*.
DM_i	The number of multi/demultiplexers in node *i,*
NO_i	The number of optical switches in node *i,*
λ_{ijt}^{sd}	The traffic flow from node *s* to node *d* that traverses the virtual link (*i, j*) at time *t,*
f_{mnt}	The number of fibres on physical link (*m, n*) at time *t*.

Under the non-bypass approach, the total network power consumption is composed of:

1) The power consumption of router ports at time *t*

$$\sum_{m \in N} \sum_{n \in Np_m} \sum_{r \in R} PR_r \cdot \omega_{mnrt} \tag{1}$$

2) The power consumption of transponders at time *t*

$$\sum_{m \in N} \sum_{n \in Np_m} \sum_{r \in R} PT_r \cdot \omega_{mnrt} \tag{2}$$

3) The power consumption of EDFAs at time *t*

$$\sum_{m \in N} \sum_{n \in Np_m} \left(PE \cdot EA_{mn} \cdot f_{mnt} \right) \tag{3}$$

4) The power consumption of regenerators at time *t*

$$\sum_{m \in N} \sum_{n \in Np_m} \sum_{r \in R} \left(PG \cdot EG_{mnrt} \cdot \omega_{mnrt} \right) \tag{4}$$

5) The power consumption of optical switches at time *t*

$$\sum_{i \in N} PO \cdot NO_i \tag{5}$$

6) The power consumption of multiplexers and demultiplexer at time *t*

$$\sum_{i \in N} PMD \cdot DM_i \tag{6}$$

The MILP model is defined as follows:

Objective: minimize

$$\sum_{t \in T} \Bigg(\sum_{m \in N} \sum_{n \in Np_m} \sum_{r \in R} PR_r \cdot \omega_{mnrt} + \sum_{m \in N} \sum_{n \in Np_m} \sum_{r \in R} PT_r \cdot \omega_{mnrt} + \sum_{m \in N} \sum_{n \in Np_m} (PE \cdot EA_{mn} \cdot f_{mnt}) + \sum_{m \in N} \sum_{n \in Np_m} \sum_{r \in R} (PG \cdot EG_{mnrt} \cdot \omega_{mnrt}) + \sum_{i \in N} PO \cdot NO_i + \sum_{i \in N} PMD \cdot DM_i \Bigg) \tag{7}$$

Subject to:

1) *Flow conservation constraint in the IP layer:*

$$\sum_{j \in N: i \neq j} \lambda_{ijt}^{sd} - \sum_{j \in N: i \neq j} \lambda_{jit}^{sd} = \begin{cases} \lambda^{sdt} & if\ i = s \\ -\lambda^{sdt} & if\ i = d \\ 0 & otherwise \end{cases}$$

$$\forall t \in T, \forall s, d, i \in N: s \neq d \tag{8}$$

Constraint (8) represents the flow conservation constraint in the IP layer. It ensures that in all nodes the total outgoing traffic is equal to the total incoming traffic except for the source and the destination nodes. It also ensures that traffic flows can be split and transmitted through multiple flow paths in the IP layer.

2) *Virtual link capacity constraint:*

$$\sum_{s \in N} \sum_{d \in N: s \neq d} \lambda_{ijt}^{sd} \leq \sum_{r \in R} B_r \cdot C_{ijrt}$$

$$\forall t \in T, \forall i, j \in N: i \neq j \tag{9}$$

Constraint (9) ensures that the summation of all traffic flows through a virtual link does not exceed its capacity.

3) *Flow conservation constraint in the optical layer:*

$$\sum_{n \in Np_m} W_{mnrt}^{ij} - \sum_{n \in Np_m} W_{nmrt}^{ij} = \begin{cases} C_{ijrt} & if\ m = i \\ -C_{ijrt} & if\ m = j \\ 0 & otherwise \end{cases}$$

$$\forall\ t \in T, r \in R, \forall\ i, j, m \in N: i \neq j \tag{10}$$

Constraint (10) represents the flow conservation constraint in the optical layer. It represents the fact that in all nodes the total outgoing wavelengths of a virtual link should be equal to the total incoming wavelengths except for the source and the destination nodes of the virtual link.

4) *Physical link capacity constraints:*

$$\sum_{i\in N}\sum_{j\in N:i\neq j}\sum_{r\in R} W_{mnrt}^{ij} \leq W \cdot f_{mnt} \quad \forall t\in T, \forall m\in N, n\in Np_m \tag{11}$$

$$\sum_{i\in N}\sum_{j\in N:i\neq j} W_{mnrt}^{ij} = \omega_{mnrt} \quad \forall t\in T, r\in R, \forall m\in N, n\in Np_m \tag{12}$$

Constraints (11) and (12) represent the physical link capacity constraints. Constraint (11) ensures that the total number of wavelength channels in virtual links traversing a physical link does not exceed the maximum capacity of fibres in the physical link. Constraint (12) ensures that the number of wavelength channels in virtual links traversing a physical link is equal to the number of wavelengths in that physical link.

The model can be extended to represent the bypass approach by redefining the power consumption of IP ports at time *t* as follows:

$$\sum_{i\in N}\sum_{j\in N:i\neq j}\sum_{r\in R} PR_r \cdot C_{ijrt} \tag{13}$$

Therefore the network objective function (to be minimized) becomes:

$$\sum_{t\in T}\Bigg(\sum_{m\in N}\sum_{n\in Np_m}\sum_{r\in R} PR_r\cdot C_{ijrt} + \sum_{m\in N}\sum_{n\in Np_m}\sum_{r\in R} PT_r\cdot\omega_{mnrt} + \sum_{m\in N}\sum_{n\in Np_m}(PE\cdot EA_{mn}\cdot f_{mnt}) + \sum_{m\in N}\sum_{n\in Np_m}\sum_{r\in R}(PG\cdot EG_{mnrt}\cdot\omega_{mnrt}) + \sum_{i\in N} PO\cdot NO_i + \sum_{i\in N} PMD\cdot DM_i\Bigg) \tag{14}$$

Note that this model is general, therefore the single line rate model can be obtained by assigning a single rate to the set *R*.

B. *MILP Model for Energy Efficient Physical Topology Design for IP over WDM Networks*

A number of the major operators and equipment manufacturers are currently interested in the physical topology design of core networks, [6], [11], [12]. Previous research on physical topology design has concentrated on improving the quality of service (QoS) and reducing the cost of networks [13], [14]. In this paper, energy-efficient physical topology design for IP over WDM networks is investigated [6].

We consider a scenario where the node locations are given (for example city locations) and in addition to optimizing the virtual topology, the model optimizes the deployment of the physical links connecting these nodes so that the total network power consumption is minimized [6].

In addition to the parameters defined in Section II.A, the energy-efficient physical topology defines the following parameters:

$Ndgr$ Minimum nodal degree, (this can be used to ensure for example that nodes do not become isolated after a single or multiple link failures).

$Nlink$ Total number of links,

NF Maximum number of fibres on one physical link,

In addition to the variables in Section II.A, the following variable is also defined:

$link_{mn}$ If there is a physical link between nodes *m* and *n*, $link_{mn} = 1$, otherwise $link_{mn} = 0$,

The total network power consumption of the energy-efficient physical topology under the bypass approach is similar to the total network power consumption given by Equation (14). However, with physical topology optimization m,n, the end points of a physical link, are both defined in set N, i.e. all nodes in the network, so the model can select to deploy a physical link between any node pair. Therefore the objective function becomes:

Objective: minimize

$$\sum_{t\in T}\Bigg(\sum_{m\in N}\sum_{n\in N}\sum_{r\in R} PR_r\cdot\omega_{mnrt} + \sum_{m\in N}\sum_{n\in N}\sum_{r\in R} PT_r\cdot\omega_{mnrt} + \sum_{m\in N}\sum_{n\in N}(PE\cdot EA_{mn}\cdot f_{mnt}) + \sum_{m\in N}\sum_{n\in N}\sum_{r\in R}(PG\cdot EG_{mnrt}\cdot\omega_{mnrt}) + \sum_{i\in N} PO\cdot NO_i + \sum_{i\in N} PMD\cdot DM_i\Bigg) \tag{15}$$

Subject to:

constraints (8)-(12), and the following constraints:

1) *Physical link capacity constraints:*

$$\sum_{i\in N}\sum_{j\in N:i\neq j} W_{mnt}^{ij} \leq W\cdot NF\cdot link_{mn} \quad \forall t\in T, \forall m\in N, n\in N: m\neq n \tag{16}$$

Constraint (16) ensures that the total number of wavelength channels in virtual links traversing a physical link does not exceed the maximum capacity of fibres in the physical link if the physical link exists.

2) *Nodal degree limit constraint:*

$$\sum_{n\in N:n\neq m} link_{mn} \geq Ndgr \qquad \forall m\in N \tag{17}$$

Constraint (17) gives the minimum nodal degree. Note that a limit on the minimum nodal degree is needed to ensure connectivity i.e. the node is not isolated from the network (even after a number of link failures).

3) *Number of links constraint:*

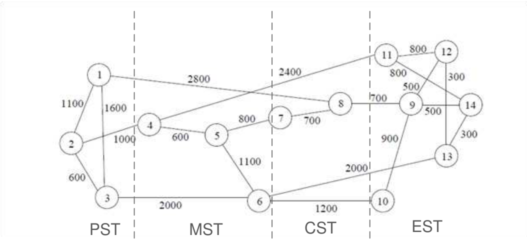
$$\sum_{m\in N}\sum_{n\in N:n\neq m} link_{mn} = 2\cdot Nlink \tag{18}$$

Constraint (18) ensures that the total number of links in the network does not exceed the limit on the number of links. This allows network designers to select a maximum number of links to be deployed and request that the traffic is served under this constraint. This constraint can be removed to allow MILP to select the best number of links to be deployed and the way they are deployed to minimize power consumption.

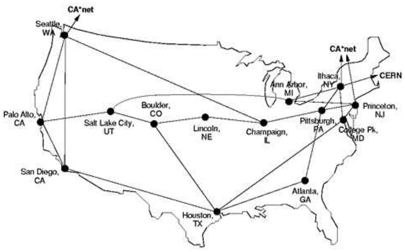
III. NETWORK TRAFFIC DEMAND AND EQUIPMENT POWER CONSUMPTION

The NSFNET network, depicted in Figure 1, is considered and the impact of the different energy saving techniques is evaluated over this network. We have more recently carried out similar evaluations over other networks including AT&T network, BT

EU network and Telecom Italia network and consistent results were observed. The NSFNET network consists of 14 nodes and 21 bidirectional links. Figure 1.a shows the physical distances between nodes. As the NFSNET network covers the US, different parts of the network fall in different time zones, i.e., nodes experience different levels of traffic demand at any given point in time. There are four time zones, Eastern Standard Time (EST), Central Standard Time (CST), Mountain Standard Time (MST) and Pacific Standard Time (PST). There is an hour time difference between each time zone and the next, we use EST as the reference time. Note that time zones dictate habits and therefore network utilization and traffic demands in our case.



(a) Physical distances between nodes (km)



(b)Cities in which the nodes are located

Figure 1. The NSFNet network architecture

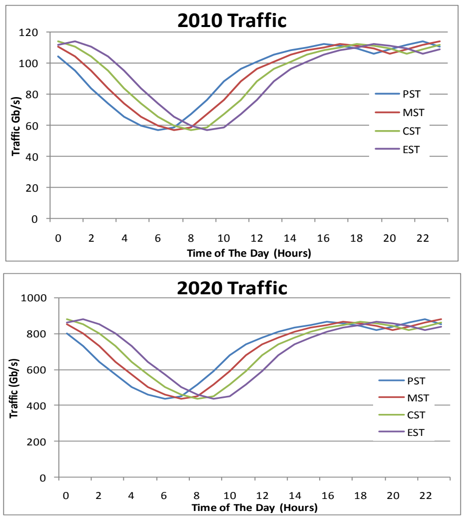


Figure2. Average traffic demand in different time zones

Figure 2 shows the NSFNET total traffic at different times of the day for 2010 and 2020 [7]-[9]. The NSFNET network contains five data centres located at nodes 2, 3, 6, 8, and 10. The traffic between node pairs is based on a gravity traffic model where the traffic demand between a node pair is proportional to the product of the populations of the nodes and inversely proportional to the distance between them. The projection for 2020 traffic shows an increase by a factor 7.7 compared to 2010 traffic.

Table I shows the equipment power consumption of the 2010 network and 2020 network [10]. The 2010 equipment represents the best (from power consumption point of view) commercially deployed equipment in 2010 (a limited 2010 deployment is sufficient) that is able to perform the desired function. The router ports power consumption is quoted at 40 Gb/s and includes the share of the aggregate power (switching matrix, router processor, power module and other power consuming elements of the router including fans and their controllers) portioned to the 40Gb/s port. The projections of the 2020 network equipment power consumption are based on two models: Business As Usual (BAU) model, where a 12% annual reduction in electronics power consumption is taken into account (Moore's law), and BAU+GT model where the technical advances achieved by the GreenTouch Consortium accelerate the reduction in equipment power consumption beyond BAU. As a result in this case two additional factors reduce the power consumption of routers, transponders and regenerators. A 1.5x factor attributed to the use of optical interconnects developed in the GreenTouch Silicon Photonic Interconnects and Single-Chip Linecard (SCORPION) project [15] and 5x due to better system design in a range of projects, for example SCORPION (for routers) [15] and HalfMoon (for transponders and regenerators) [16]. The 1.5x and 5x factors are multiplicative in the case of these 3 components (routers, transponders and regenerators). In 2020 the optical switches power consumption is reduced by 10x through the GreenTouch SwiTching And tRansmission (STAR) project [17]. The reduction in EDFAs power consumption in Table I is a result of work in the GreenTouch Service Energy Aware Sustainable Optical Networks (SEASON) project [18]. Power reduction as a result of sleep and the optimum use of mixed line rates is achieved as a result of work in the GreenTouch OPtimum End-to-end Resource Allocation (OPERA) project [3], [5]. Finally topology optimization and the resultant reduction in power consumption is a contribution by the GreenTouch STAR project [6]. There are a range of other GreenTouch energy reduction measures that will be included in future. These include energy saving as a result of conserving power in protection paths when these are not used (OPERA), optimum content caching and data centres locations and content placement and replacement (OPERA and SEASON), and network function virtualization (OPERA).

The 2020 BAU projections show a reduction in the power consumption of router ports, transponders and regenerators by a factor of 3.6 (12% annual reduction due to Moore's law). For the 2020 BAU+GT projections, the routers, transponders and regenerators power consumption is reduced by a factor of 27x compared to the 2010 network. We assume a linear increase in power consumption for 100 Gb/s and 400 Gb/s router ports compared to the 40 Gb/s router port. This is a conservative estimate as the power consumption has so far increased below the linear trend as the data rate has increased in these components.

TABLE I. POWER CONSUMPTION OF NETWORK EQUIPMENT AND REACH OF TRANSPONDERS [10], (POWER USAGE EFFECTIVENESS (PUE) OF 2 AND 1.5 IN 2010 AND 2020 RESPECTIVELY)

Device	Power Consumption 2010	Power Consumption 2020 (BAU)	Power Consumption 2020 (BAU+GT)
Router port	440 W	123W	16 W
Transponder 40Gb/s	148 W Reach: 2500 km	41W Reach: 2500 km	5.5 W Reach: 2500 km
Transponder 100Gb/s	Not widely deployed in the field	48 W Reach: 2000 km	6.4W Reach: 2000 km
Transponder 400 Gb/s	Not deployed in the field	54 W Reach: 150 km	7.2 W Reach: 150 km
Regenerator 40Gb/s	222 W	61.5W	8.25 W
Regenerator 100Gb/s	Not widely deployed in the field	72 W	9.6 W
Regenerator 400 Gb/s	Not deployed in the field	81 W	10.8 W
EDFA	52 W	18 W	12.5 W
Optical switch	85 W	85 W	8.5 W
Multiplexer/Demutiplexer	0 W	0 W	0 W

IV. MILP MODELS RESULTS

In Figure 3 - Figure 8, the total network power consumption of the cases considered is broken down into its parts showing the power consumption of the different network components, namely the contribution of routers, transponders, EDFAs, optical switches and regenerators to the total power. For the different figures the major contribution to the total power consumption is due to routers followed by transponders.

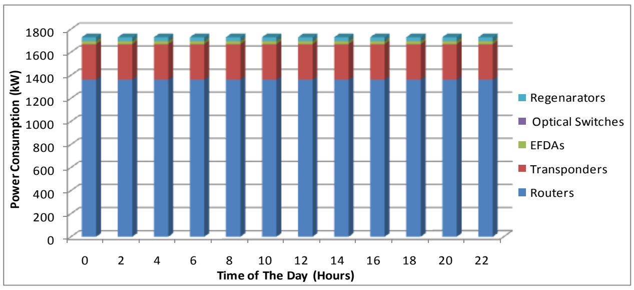


Figure 3. The Power consumption of the original NSFNET topology, 2010 components power consumption, 40 Gb/s, non-bypass

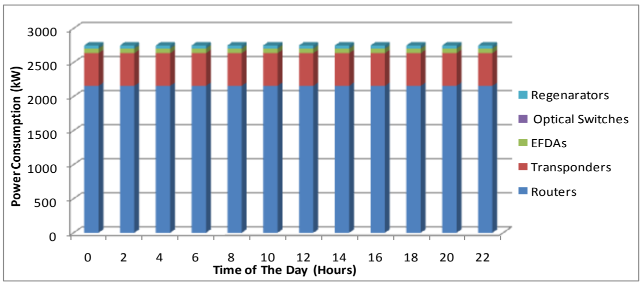


Figure 4. The Power consumption of the original NSFNET topology, 2020 BAU components power consumption, 40 Gb/s, non-bypass

Figure 3 shows the reference case, the power consumption of the NSFNET network under 2010 traffic, 2010 components power consumption and 2010 design where the network is dimensioned for maximum traffic and the components do not adapt their capacity / power usage as traffic varies, hence the flat trend of Figure 3. Figure 4 shows the situation in 2020 under BAU where the traffic grows, the equipment power consumption is reduced by Moore's law factor (3.6x), but there is no adaptation with traffic variation.

In Figure 5 under 2020 traffic, 2020 BAU component power consumption and where unused router ports, transponders and regenerators are put into sleep and the bypass approach is used (here router ports at intermediate nodes are bypassed using the optical layer), the power consumption is reduced and the power used follows the traffic variation throughout the day.

Implementing MLR with sleep, bypass, 2020 traffic, 2020 BAU components power consumption and with the optimum (power wise) combination of 3 line rates, 40 Gb/s, 100 Gb/s and 400 Gb/s, results in a further reduction in the network power consumption (Figure 6). The additional reduction in Figure 6 beyond the power consumption levels in Figure 5 is mainly associated with the optimum selection of transponders in MLR. While the power consumption of router ports linearly increases as the line rate increases, the increase in the power consumption of transponders is not linear as seen in Table I. Note that if router ports were to have power consumption that increases below the linear trend in a similar way to transponders (see Table I), then router ports can be incorporated into the MLR optimization and further power reduction can be obtained. The total power consumption of regenerators increases when higher data rates are used as the 100 Gb/s and 400 Gb/s transponders have a shorter reach and therefore more regenerators are used.

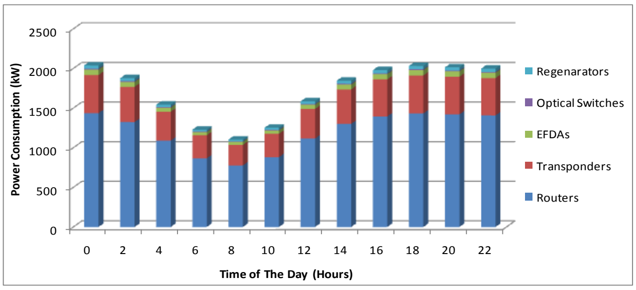


Figure 5. The Power consumption of the original NSFNET topology, 2020 BAU components power consumption, 40 Gb/s, bypass, sleep

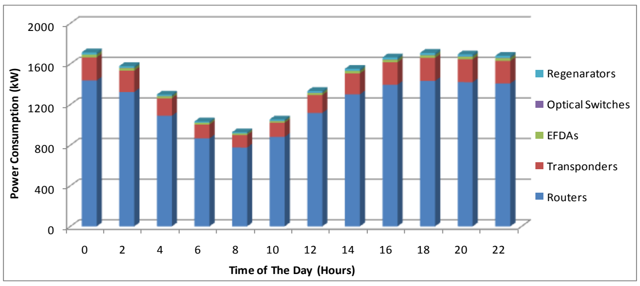


Figure 6. The Power consumption of the original NSFNET topology, 2020 BAU components power consumption, MLR, bypass, sleep

Figure 7 shows the optimal topology obtained from the energy efficient physical topology optimization. The optimal topology was obtained with no constraint (limit) on the number of links in the network and considering a $Ndgr = 2$ to ensure that nodes are not totally disconnected from the network in case of a single link failure. The optimal topology has 60 links and an average nodal degree of 8.6. In our previous results [5], when no limit on the number of links was set, the optimum topology was a full mesh. However, the results in this paper consider MLR with higher per wavelength data rates that have a shorter reach together with the actual physical distances between nodes (longer in Figure 1a compared to [5]) and therefore regenerators are needed. As the power consumption of a regenerator is higher than the power consumption of a transponder, it becomes more energy-efficient for traffic flows to go through intermediate nodes but using optical bypass, (a transponder is still used at each intermediate node in this case), instead of travelling through a direct link where one or more regenerators are used. Figure 8 shows the power consumption of the optimized topology.

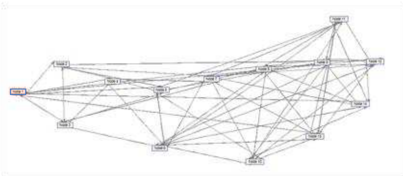


Figure 7. The optimized NSFNET topology, 2020 BAU components power consumption, MLR, bypass, sleep

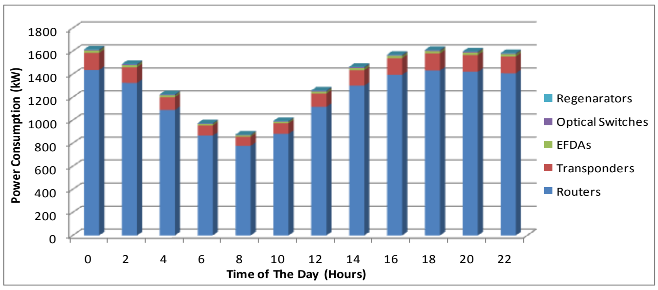


Figure 8. The Power consumption of the optimized NSFNET topology, 2020 BAU components power consumption, MLR, bypass, sleep

Figure 9-Figure 11 show the power consumption of the 2020 BAU+GT network under the different energy saving approaches. Similar trends to those of the 2020 BAU are observed and optimizing the physical topology has resulted in very similar topologies to the 2020 BAU topologies. However the total power consumption is significantly reduced as the equipment power consumption is reduced. Furthermore, we have defined the 2020 BAU network as one where the power consumption of the equipment is as shown in Table I under BAU and where routing employs the non-bypass approach and the physical topology is not optimized, namely the results in Figure 4. As such improvements which result from topology optimization, sleep and mixed line rates are attributed to BAU+GT. The previous results in Figure 5 – Figure 8 were however presented to allow flexibility in defining 2020 BAU, for example sleep may be included in 2020 BAU.

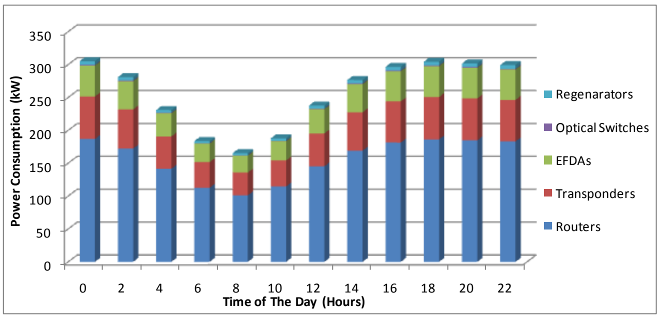


Figure 9. The Power consumption of the original NSFNET topology, 2020 BAU+GT components power consumption, 40 Gb/s, bypass, sleep

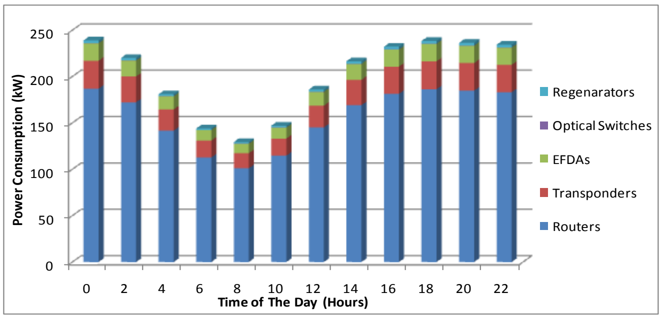


Figure 10. The Power consumption of the original NSFNET topology, 2020 BAU+GT components power consumption, MLR, bypass, sleep

Figure 12 shows the energy efficiency of the 2020 network with BAU components power consumption under the different MILP models. For comparison, we consider the 2010 network with 40 Gb/s line rate under the non-bypass approach, Figure 3 results, as the reference case. The energy efficiency of 9792 kbps/W for this case is equivalent to 102 nJ/b which seems reasonable given each router port in 2010 is 440 W/40 Gb/s = 11 nJ/b, and each transponder is 148 W/40 Gb/s = 3.7 nJ/b. A typical path in the network has a source node, a destination node and two intermediate nodes on average in NSFNET. This calls for 4 ports (a bit less on average) and 3 transponders, i.e. 44 nJ/b + 11 nJ/b = 55 nJ/b. A PUE=2 results in 110 nJ/b, which is higher than the result above; however the average number of hops is typically smaller, but this is a useful check.

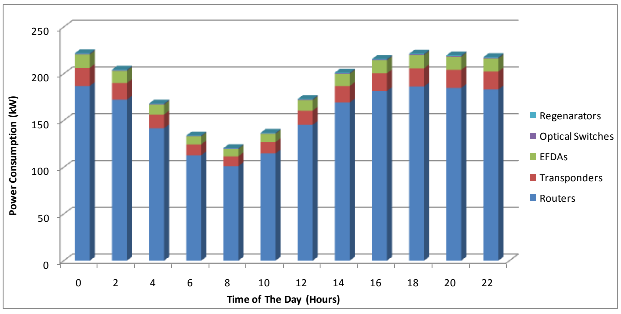
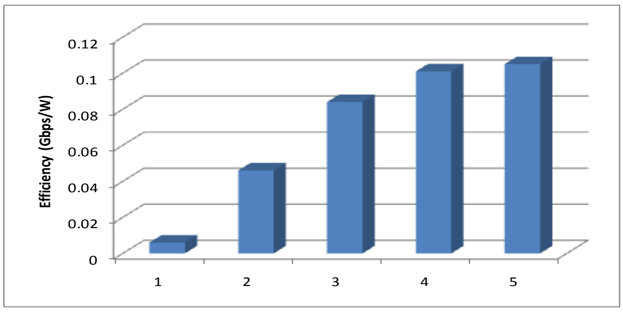
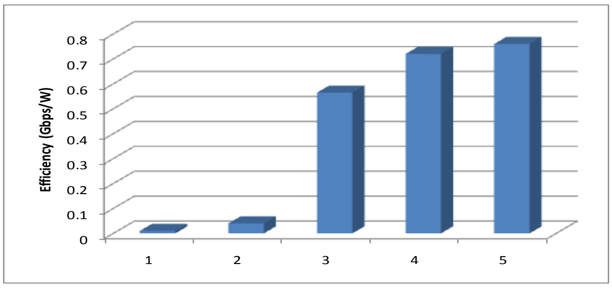


Figure 11. The Power consumption of the optimized NSFNET topology, 2020 BAU+GT components power consumption, MLR, bypass, sleep



1 Original NSFNET topology, 2010 components power consumption, 40 Gb/s, non-bypass
2 Original NSFNET topology, 2020 BAU components power consumption, 40 Gb/s, non-bypass
3 Original NSFNET topology, 2020 BAU components power consumption, sleep, 40 Gb/s
4 Original NSFNET topology, 2020 BAU components power consumption, sleep, MLR
5 Optimized NSFNET topology, 2020 BAU components power consumption, sleep, MLR

Figure 12. The energy efficiency of the network with 2020 BAU components power consumption under different energy saving techniques



1 Original NSFNET topology, 2010 components power consumption, 40 Gb/s, non-bypass
2 Original NSFNET topology, 2020 BAU components power consumption, 40 Gb/s, non-bypass
3 Original NSFNET topology, 2020 BAU+GT components power consumption, sleep, 40 Gb/s
4 Original NSFNET topology, 2020 BAU+GT components power consumption, sleep, MLR
5 Optimized NSFNET topology, 2020 BAU+GT components power consumption, sleep, MLR

Figure 13. The energy efficiency of the network with 2020 BAU+GT components power consumption under different energy saving techniques

In the 2020 BAU network, the most power consuming equipment (router ports, transponder and regenerators) has a power consumption lower by a factor of 3.6 compared to 2010 and the PUE is reduced from PUE=2 in 2010 to PUE=1.5, i.e. reduced by a factor of 1.33. Therefore the 2020 BAU network is expected to be 3.6×1.33=4.79 times better than the 2010 network which is consistent with the MILP model results shown in Figure 12.

Optimizing the 2020 BAU network so that it saves energy through the use of the bypass approach (coupled with MILP optimized routing) and sleep improved the power consumption by an additional factor of 1.78x. Introducing the bypass approach by itself achieved an improvement by a factor of 1.45x. This improvement is consistent with the improvement obtained by bypass in [3], [11] and [19]. The introduction of sleep achieved an improvement of 1.23x which is consistent with the traffic variation with time of day in Figure 2. Note that sleep can result in up to 50% saving if half of the day has low utilization. However, if users continue to consume traffic well into the night (movies for example) or in core networks that span several time zones that result in smoothed traffic peaks and troughs; there will be little point in pursuing “power follows load” in hardware in the core as the load will be almost flat.

MLR has resulted in an improvement by a factor of 1.2x which is around the typical improvement obtained by a MLR network compared to a 40 Gb/s network [4], [5].

The improvement obtained by physical topology optimization is limited to 1.1x. However, it is estimated (using the MILP in [6] and electronic aggregation/de-aggregation nodes at the head ends) that this improvement can be increased up to 5x if a full mesh is deployed to serve nodes with symmetric traffic. This 5x improvement is the subject of ongoing work. The traffic considered in this work is attributed to population size in a given node and as a result the nodes (cities) produce varying amounts of traffic. Currently operators divide a large city into multiple nodes, so that each node in the network serves a comparable population size. For example BT translates London into 4 nodes, leading to a full mesh among the 8 inner core nodes in the BT network [20]. Such additional refinements in topology design can lead to further energy saving as outlined above. In addition with a full mesh and hence a direct route to each destination, the reliance on IP routing can be reduced in the core with the potential of up to 20x power saving as a result of the combined measures outlined [6].

TABLE II. SUMMARY OF MILP MODELS RESULTS

	2010	2020 (BAU)	2020 (GT)
T_Core TByte/year	66779122	514457280	514457280
E_Core GWh/year	15.16	24.01	1.23
Efficiency (kbps/W)	9792	47442.65	627865.09
Improvement	1	4.84	64.12

Figure 13 shows the improvement in energy efficiency in the 2020 BAU+GT network where the router ports, transponders and regenerators power consumption is reduced by a factor of 27x compared to the 2010 network. Optimizing (MILP) the 2020 BAU+GT network by jointly considering bypass, sleep, MLR and topology optimization resulted in a total improvement in the core network by a factor of 27×1.78×1.2×1.1= 64x. Table II shows a summary of the MILP models results. As work on the GreenTouch technologies continues, we can expect these values to change with the development and greater understanding of new technologies and their potential applications. For example, an active topic of discussion is the use of data compression. Further evolution in compression algorithms for video and data can be expected to save bandwidth by 2020. A GreenTouch analysis [2] showed that this also aids overall network energy efficiency despite the extra energy required for compression. It is, however, debatable whether better compression by new algorithms can be performed at the application layer and can therefore be assumed for all content before it enters the network, or whether additional compression functions can be embedded in the network to make up for content that is compressed with legacy technology and not with the latest and most efficient algorithms. We have investigated the potential use of compression in the network and it provides an additional efficiency gain that would yield an overall energy efficiency improvement in the core network of up to 95x.

TABLE III. SUMMARY OF SCALED MILP MODELS RESULTS

	2010	2020 (BAU)	2020 (GT)
T_Core TByte/year	133558244	1028914560	1028914560
E_Core GWh/year	363.72	578.33	29.52
Efficiency (kbps/W)	816	3953.55	52321.92
Improvement	1	4.84	64.12

In Table III the traffic and energy of Table II are scaled by a number of factors to consider the following:

1. To convert North America results to a Group 1 Nations result: Multiply traffic and power by factor of 2, which is a factor that has been determined by GreenTouch based on studies in its Services, Policies, & Standards (SPS) Working Group and operators surveys.
2. To account for over provisioning for QoS: Multiply the power consumption by a factor of 3 both in 2010 and 2020. Note that we are not introducing here any GT measure in 2020 that can help reduce overprovisioning. The factor 3 for overprovisioning is typical for 2010 operators’ networks [7], [8].

3. To take into account protection: Multiply the power by a factor of 2 in 2010 and 2020. This corresponds to 1+1 protection in both cases and also does not assume any GT measure in 2020 to reduce power usage due to protection (eg. Protection resources sleep). Shared protection in addition to 1+1 protection will result in a factor less than 2, but as both the 2010 and 2020 results are scaled by this factor, our core energy efficiency results are not affected, however the total core network power consumption is affected, which affects the energy efficiency of connections that span the core and wireless or the core and wired access for example. We are interested in the core network in this paper however.
4. To account for vendor redundancy: Multiply the equipment power consumption by a factor of 2 in 2010 and 2020. Vendor redundancy is expected to remain a requirement in 2020.

Note that these factors do not affect the energy efficiency improvements, however it is important to identify the appropriate value of the total energy used in the core as this affects the end-to-end network energy efficiency as discussed.

V. CONCLUSIONS AND DISCUSSION

In this paper, the energy efficiency of core networks has been evaluated in 2010 and 2020 where in the latter case consideration is given to different energy saving techniques including lower component power consumption, the use of mixed line rates (MLR), sleep, optimum routing and physical topology optimization. The NSFNET topology is considered as an example of a continental network topology. We evaluated the total power consumption considering a 2010 network and a 2020 network. The projections of the 2020 equipment power consumption are based on two scenarios: a business as usual (BAU) scenario and a BAU plus GreenTouch BAU+GT scenario resulting from the technical advances achieved by the GreenTouch Consortium. MILP optimization models were developed in each case which allowed the improvements to be determined accurately when a range of measures are deployed simultaneously. The results show that the 2020 BAU network has achieved an energy efficiency improvement by a factor of 4.8x compared to the 2010 network. Further improvement can be attributed to the 2020 BAU network if measures such as sleep, MLR and topology optimization are considered. Considering the joint optimization of sleep, MLR and topology, the 2020 BAU+GT network achieved a total improvement in core network energy efficiency by a factor of 64x. Here the router ports, transponders and regenerators power consumption is reduced by a factor of 27x compared to the 2010 network due to GreenTouch improvements. We considered a number of factors to scale the network power consumption and traffic demand, including a factor to convert North America results to a Group 1 Nations result, and factors for overprovisioning, protection and vendor redundancy.

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