Bounds on GreenTouch GreenMeter Network Energy Efficiency

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***Abstract*—In this paper, we validate the energy efficiency improvements in core networks obtained through mixed integer linear programming (MILP) optimization models as part of the GreenMeter study carried out by the GreenTouch consortium by developing closed form expressions and bounds for the power consumption of core networks. We consider nonbypass, bypass, mixed line rates, and physical topology optimization energy efficiency schemes. In addition to validating the optimization model results by setting bounds on the power consumption, these bounds can predict network performance at operating conditions highly complex for the MILP models. The derivation of a single bound that includes all the measures proved intractable and therefore each measure is evaluated separately.**

***Index Terms*—Energy Efficiency, IP/WDM, MILP model, Greentouch, GreenMeter.**

I. Introduction

THERE has been a growing demand for advanced energy efficient schemes in the wake of the exponential growth of Internet traffic resulting from the popularity of data intensive applications and the widespread use of Internet connected devices. To tackle this, the GreenTouch consortium was formed with the ambitious endeavor to cut energy consumption levels in mobile access, fixed access and core networks in the year 2020 by a factor of 1000 compared to 2010 levels.

In the white papers in [1], [2], the Greentouch consortium published the results of a thorough study on implementing a set of technologies and solution for an end-to-end energy reduction in mobile access, fixed access and core networks and is referred to as the GreenMeter. The core networks category considered multiple layer solutions and the results are summarized in [3] combining the individual solutions. The solutions include the bypass approach, the mixed line rates, physical network topology optimization, the optimization of distributed clouds for content distribution, and virtualization of network equipment. In [4] the bypass approach, where the traffic bypasses electrical conversion at the intermediate nodes to which the traffic is not destined, is considered, as well putting idle components into sleep mode and placing protection resources into a low power state mode when not utilized. In [5] and [6] the mixed line rate is investigated where links with different speeds are assigned, adapting to the variability in network and demands. Optimizing the physical network topology has proven also to yield considerable energy savings as shown in [7]. In [8]–[10], the content distribution problem in the core network considering data centres as well as peer to peer traffic was thoroughly investigated and the connection of virtually allocated data centre resources over virtually connected network has been studied in [11]. The same optimization techniques have been used in [12] for greening big data networks, and in [13] for energy efficient data centres with dis-aggregated servers.

In [3] we produced a collective mixed integer linear programming optimization model incorporating the mentioned energy efficiency schemes, and evaluated the collective mixed integer linear programming (MILP) model over the AT&T topology. In this paper we extend our work by developing bounds on the power consumption of core networks for the non-bypass, bypass, mixed line rate and topology optimization scenarios to verify the energy savings of these schemes individually obtained through MILP optimization models and to provide simple analytic bounds and closed form expressions that can be used to obtain results for individual measures or a set of measures. These formulas are valuable as they give insights and predictions where the MILP struggles at different scenarios and network conditions, such as big network sizes. The derivation of a single bound that includes all the measures proved intractable. We have developed similar bounds for the network coding enabled energy efficient survivable core networks in [14] and [15].

The remainder of this paper is organized as follows: In Section II, we present the analytic bounds for the IP over WDM network under non-bypass and sleep mode, followed by the bypass case under sleep mode in Section III. In Section IV we develop the bounds for the mixed line rate and energy efficient protection and in Section V we develop the bounds for the topology optimization scenario. The paper is finally concluded in Section VI.

II. Bounds on Power Consumption of Core Networks Under Non-bypass and Sleep Mode Measures

Here we develop upper and lower bounds for the IP over WDM power consumption under the non-bypass approach considering sleep, energy efficient and inefficient protection and random and equal traffic demands. In the energy efficient

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protection scheme, protection resources are switched off when idle as opposed to the energy inefficient protection where they are left active even when idle.

Let N be the set of IP/WDM nodes and N_m be the set of neighboring nodes of node m. There are W wavelengths per fiber and each wavelength supports a data rate B. Between each node pair (m, n) exists a number of EDFAs denoted as $A_{m,n}$, a number of regenerators denoted as $G_{m,n}$ and a number of optical fibres referred to as $F_{m,n}$. The average number of EDFAs and regenerators in the network is A and G respectively.

Let p_r, p_t, p_f, p_x, p_g and p_s be the power consumption of a router port, a transponder, an EDFA, a multiplexer/demultiplexer, an optical regenerator and an optical switch respectively.

For a given traffic demand $L^{s,d}$ between a node pair (s, d), the network assigns a path with a total hop count of $h^{s,d}$. $\bar{L}$ denotes the average traffic demand in the network and h is the average hop count of paths in the network. The result of routing all demands gives a total number of wavelengths of $\lambda_{m,n}$ on a physical link (m, n).

The total power consumption of the network under the non-bypass approach with sleep and energy efficient protection scheme is given as the sum of the following components:

1) The power consumption of router ports

$$= \eta_n \left(\sum_{s \in N} p_r Q_s + \sum_{m \in N, n \in N_m} p_r \lambda_{m,n} \right) \quad (1)$$

Where η_n is the IP/WDM power usage effectiveness and Q_s is the number of aggregation ports at node s. This can be rewritten as:

$$\eta_n \left(\frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} + \frac{p_r}{B} \sum_{s \in N, d \in N} L^{s,d} h^{s,d} \right) \quad (2)$$

where $h^{s,d}$ is the hop count of the path traversed by demand (s, d)

2) The power consumption of transponders

$$= \eta_n \sum_{m \in N} \sum_{n \in N_m} p_t \lambda_{m,n} \quad (3)$$

This can be rewritten as

$$\eta_n \frac{p_t}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} \quad (4)$$

3) The power consumption of EDFAs

$$\sum_{m \in N} \sum_{n \in N_m} p_f A_{m,n} F_{m,n} \quad (5)$$

This EFDFA power consumption is bounded by the following bounds:

$$\sum_{m \in N} \sum_{n \in N_m} p_f A_{m,n} F_{m,n} \geq \frac{p_f A_{(\min)}}{W} \sum_{m \in N} \sum_{n \in N_m} \lambda_{m,n} \quad (6)$$

$$\sum_{m \in N} \sum_{n \in N_m} p_f A_{m,n} F_{m,n} \leq \frac{p_f A_{(\max)}}{W} \sum_{m \in N} \sum_{n \in N_m} \lambda_{m,n} \quad (7)$$

where

$$A_{(\max)} = \max_{m,n \in N} A_{m,n} \quad (8)$$

$$A_{(\min)} = \min_{m,n \in N} A_{m,n} \quad (9)$$

are number of EDFAs associated with the links of maximum and the minimum distances, respectively.

4) The power consumption of regenerators

$$\sum_{m \in N} \sum_{n \in N_m} p_g G_{m,n} \lambda_{m,n} \quad (10)$$

The regenerators power consumption is bounded by the following bounds:

$$\sum_{m \in N} \sum_{n \in N_m} p_g G_{m,n} \lambda_{m,n} \geq p_g G_{(\min)} \sum_{m \in N} \sum_{n \in N_m} \lambda_{m,n} \quad (11)$$

$$\sum_{m \in N} \sum_{n \in N_m} p_g G_{m,n} \lambda_{m,n} \leq p_g G_{(\max)} \sum_{m \in N} \sum_{n \in N_m} \lambda_{m,n} \quad (12)$$

where

$$G_{(\max)} = \max_{m,n \in N} G_{m,n} \quad (13)$$

$$G_{(\min)} = \min_{m,n \in N} G_{m,n} \quad (14)$$

are the number of regenerators associated with the links of maximum and the minimum distances, respectively.

5) The power consumption of optical switches

$$\eta_n \sum_{s \in N} p_s = \eta_n N p_s \quad (15)$$

The total power consumption, after grouping terms and rearranging, is upper bounded by:

$$P \leq \eta_n \frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} + \frac{1}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} \Bigg(\eta_n p_r + \eta_n p_t + \frac{p_f A_{(\max)}}{W} + p_g G_{(\max)} \Bigg) + \eta_n N p_s \tag{16}$$

and lower bounded by:

$$P \geq \eta_n \frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} + \frac{1}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} \Bigg(\eta_n p_r + \eta_n p_t + \frac{p_f A_{(\min)}}{W} + p_g G_{(\min)} \Bigg) + \eta_n N p_s \tag{17}$$

Let:

$$Ec_{(\min)} = \frac{1}{B} \Bigg(\eta_n p_r + \eta_n p_t + \frac{p_f A_{(\min)}}{W} + p_g G_{(\min)} \Bigg) \tag{18}$$

represents the non-bypass lower energy consumption coefficient, and

$$Ec_{(\max)} = \frac{1}{B} \Bigg(\eta_n p_r + \eta_n p_t + \frac{p_f A_{(\max)}}{W} + p_g G_{(\max)} \Bigg) \tag{19}$$

represents the non-bypass higher energy consumption coefficient.

The total power consumption bounds can be given by:

$$P \geq \eta_n \frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} + Ec_{(\min)} \sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} + \eta_n N p_s \tag{20}$$

$$P \leq \eta_n \frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} + Ec_{(\max)} \sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} + \eta_n N p_s \tag{21}$$

For equal traffic demands, i.e.,:

$$L_{s,d} = \bar{L} \tag{22}$$

$$\forall s, d \in N, s \neq d \tag{23}$$

The total power consumption bounds are given as:

$$P \geq N(N-1)\bar{L} \left(\eta_n \frac{p_r}{B} + Ec_{(\min)} h \right) + \eta_n N p_s \tag{24}$$

$$P \leq N(N-1)\bar{L} \left(\eta_n \frac{p_r}{B} + Ec_{(\max)} h \right) + \eta_n N p_s \tag{25}$$

where the total number of demands in the network is $N(N-1)$ and h is the average hop count of the paths in the network, given as:

$$h = \frac{1}{N(N-1)} \sum_{s \in N} \sum_{\substack{d \in N \\ s \neq d}} h^{s,d} \tag{26}$$

Under equal traffic demands it suffices to consider the average hop count. Under unequal traffic demand two nodes representing two large cities may have larger traffic demand between them compared to two small cities. In this case it is important to consider the number of hops over which each traffic demand is routed. Therefore we introduce upper and lower bounds on the power consumption where all traffic is assumed to travel the maximum hop count $h_{(\max)}$ or the minimum hop count $h_{(\min)}$, respectively between each node pair. These bound are given as

$$P \geq \eta_n \frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} + \eta_n N p_s + Ec_{(\min)} h_{(\min)} \sum_{s \in N, d \in N} L^{s,d} \tag{27}$$

$$P \leq \eta_n \frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} + \eta_n N p_s + Ec_{(\max)} h_{(\max)} \sum_{s \in N, d \in N} L^{s,d} \tag{28}$$

Given that:

$$\bar{L} = \frac{1}{N(N-1)} \sum_{s \in N} \sum_{d \in N} L^{s,d} \tag{29}$$

The bounds can be simplified to:

$$P \geq N(N-1)\bar{L} \left(\eta_n \frac{p_r}{B} + Ec_{(\min)} h_{(\min)} \right) + \eta_n N p_s \tag{30}$$

$$P \leq N(N-1)\bar{L} \left(\eta_n \frac{p_r}{B} + Ec_{(\max)} h_{(\max)} \right) + \eta_n N p_s \tag{31}$$

Considering energy inefficient protection resources, i.e., provisioned resources are doubled, the total power consumption becomes bounded by:

$$P \geq 2N(N-1)\bar{L} \left(\eta_n \frac{p_r}{B} + Ec_{(\min)} h_{(\min)} \right) + \eta_n N p_s \tag{32}$$

$$P \leq 2N(N-1)\bar{L} \left(\eta_n \frac{p_r}{B} + Ec_{(\max)} h_{(\max)} \right) + \eta_n N p_s \tag{33}$$

It can be seen from Figure 1 that the MILP results are found to be much closer to the lower bound than the upper bound as most of the links in the AT&T network are comparable in length to the shortest link length and hence the number of EDFAs and regenerators are close to their minimum values. This makes the values generated by the lower bound represent a very good and quick approximation to the consumed power. The bounds in Figure 2 for unequal traffic additionally include the hop count component as shown in equation 30 and 31 where the maximum hop count and the minimum possible hop count are used for the

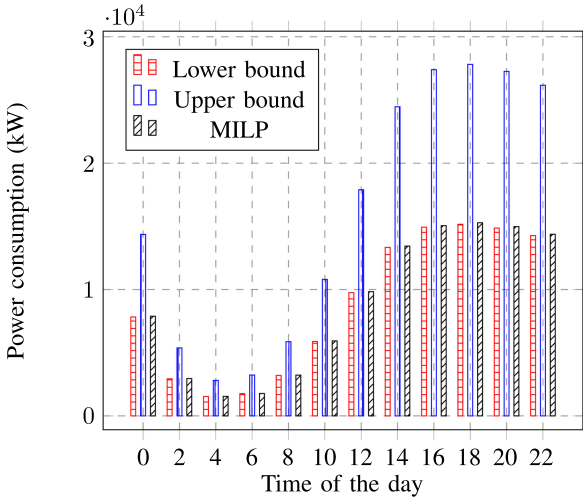


Fig. 1. Power Consumption with Bounds of the Original AT&T Topology, 2020 BAU+GT Components, 40 Gbps, Non-bypass, Sleep and Energy efficient Protection Considering Equal Traffic Demands.

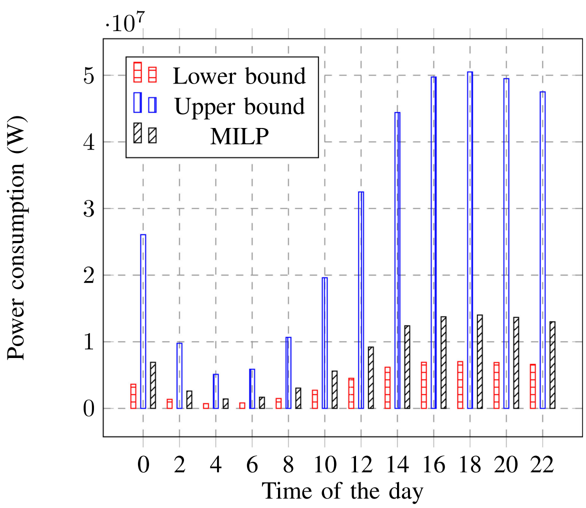


Fig. 2. Power Consumption and its bounds of the Original AT&T Topology, 2020 BAU+GT Components, 40 Gbps, bypass, Sleep and energy efficient Protection Considering Unequal Traffic Demands.

upper and lower bounds respectively. Therefore, the traffic plays a role in estimating where the power consumed lies between the two bounds. However, given that the average hop count of the AT&T topology is 2.65 and the maximum and minimum hop count are 5 and 1 respectively, and with the tendency of all paths to select the shortest possible paths, this makes the MILP results even closer to the lower bound.

III. Bounds on Power Consumption of Core Networks Under Bypass and Sleep Mode Measures

Here, similar to the non-bypass approach in Section II, we develop upper and lower bounds for the IP over WDM power consumption under the bypass approach considering sleep, energy efficient and inefficient protection and random and equal average traffic demands.

The bounds on the power consumption of the bypass IP over WDM network can be obtained in a similar derivation to the non-bypass case. Router ports are only used at the source and destination nodes of each demand.

The power consumption of router ports:

$$\eta_n \left(\sum_{s \in N} p_r Q_s + \sum_{s \in N} \sum_{d \in N} \frac{p_r}{B} L^{s,d} \right) = 2\eta_n \left(\frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} \right) \quad (34)$$

which can be rewritten as:

$$2\eta_n \frac{p_r}{B} N(N-1)\bar{L} \quad (35)$$

Using the same derivation approach as the one used in the non-bypass case we have:

$$P \leq 2\eta_n \frac{p_r}{B} N(N-1)\bar{L} + \eta_n N p_s + Eb_{(\max)} \sum_{s \in N, d \in N} L^{s,d} h^{s,d} \quad (36)$$

$$P \geq 2\eta_n \frac{p_r}{B} N(N-1)\bar{L} + \eta_n N p_s + Eb_{(\min)} \sum_{s \in N, d \in N} L^{s,d} h^{s,d} \quad (37)$$

where

$$Eb_{(\max)} = \frac{1}{B} \left(\eta_n p_t + \frac{p_f A_{(\max)}}{W} + p_g G_{(\max)} \right) \quad (38)$$

$$Eb_{(\min)} = \frac{1}{B} \left(\eta_n p_t + \frac{p_f A_{(\min)}}{W} + p_g G_{(\min)} \right) \quad (39)$$

are the bypass upper and lower energy consumption coefficient, respectively. For equal traffic demands, the total power consumption is bounded by:

$$P \geq N(N-1)\bar{L} \left(2\eta_n \frac{p_r}{B} + Eb_{(\min)} h \right) + \eta_n N p_s \quad (40)$$

$$P \leq N(N-1)\bar{L} \left(2\eta_n \frac{p_r}{B} + Eb_{(\max)} h \right) + \eta_n N p_s \quad (41)$$

Similar to the non-bypass case, an upper bound and lower bound on the total power consumption of unequal traffic demands is attained when all traffic demands are routed through the minimum hop count $h_{(\min)}$ and the maximum hop count $h_{(\max)}$, respectively:

$$P \geq 2\eta_n \frac{p_r}{B} N(N-1)\bar{L} + Eb_{(\min)} h_{(\min)} \sum_{s \in N, d \in N} L^{s,d} + \eta_n N p_s \quad (42)$$

$$P \leq 2\eta_n \frac{p_r}{B} N(N-1)\bar{L} + Eb_{(\max)} h_{(\max)} \sum_{s \in N, d \in N} L^{s,d} + \eta_n N p_s \quad (43)$$

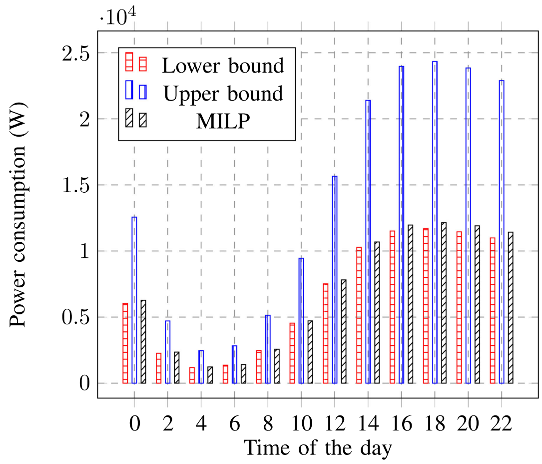


Fig. 3. Power Consumption and its bounds of the Original AT&T Topology, 2020 BAU+GT Components, 40 Gbps, bypass, Sleep and Energy Efficient Protection considering Equal Traffic Demands.

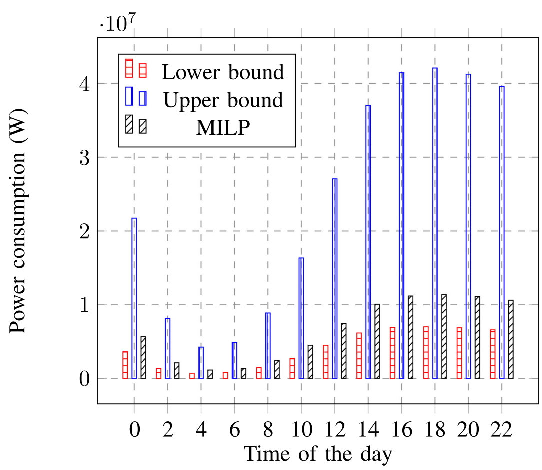


Fig. 4. Power Consumption and its bounds of the Original AT&T Topology, 2020 BAU+GT Components, 40 Gbps, bypass, Sleep and energy efficient Protection Considering Unequal Traffic Demands.

This can be simplified to:

$$P \geq N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(\min)}h_{(\min)}\right) + \eta_n N p_s \quad (44)$$

$$P \leq N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(\max)}h_{(\max)}\right) + \eta_n N p_s \quad (45)$$

Considering energy inefficient protection resources, the total power consumption becomes bounded by:

$$P \geq 2N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(\min)}h_{(\min)}\right) + \eta_n N p_s \quad (46)$$

$$P \leq 2N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(\max)}h_{(\max)}\right) + \eta_n N p_s \quad (47)$$

Figure 3 and Figure 4 show the upper and lower bound of the bypass IP over WDM network power consumption and compare them to the MILP model results using equal traffic and the general traffic case, respectively. As with the non-bypass case, the MILP results are closer to the lower bound than the upper bound.

IV. Bounds on Power Consumption Under Mixed Line Rates, Sleep and Energy Efficient Protection

Here we develop upper and lower bounds, as well as an approximating expression of the IP over WDM network power consumption under the optimum MLR solution considering the bypass and non-bypass approach, sleep, energy efficient protection and equal average traffic demands.

The total power consumption of a non-bypass IP over WDM network using mixed line rates can be approximated by:

$$\begin{aligned} P = {} & \eta_n \left(\frac{p_r}{B} \sum_{s\in N} \sum_{d\in N} L^{s,d} + \sum_{m\in N} \sum_{n\in N_m} f_p(\tilde{w}_{mn}) \right) \\ & + \eta_n \sum_{m\in N} \sum_{n\in N_m} f_t(\tilde{w}_{mn}) \\ & + \frac{p_f A}{B} \sum_{m\in N} \sum_{n\in N_m} \lambda_{m,n} + N p_s \eta_n \\ & + G \sum_{m\in N} \sum_{n\in N_m} f_g(\tilde{w}_{mn}) \end{aligned} \quad (48)$$

Where $f_p(\tilde{w}_{mn})$ is the function relating the power consumption at a given selected line rate $\tilde{w}_{mn}$ for router ports. Similarly, $f_t(\tilde{w}_{mn})$ and $f_g(\tilde{w}_{mn})$ are the corresponding functions for the transponder and the regenerator. This function is concave due to the increase in energy efficiency per bit as the selected line rate increases. Using Jensen's inequality, given a concave function $f(x)$:

$$f_t\left(\sum_{m\in N} \sum_{n\in N_m} \tilde{w}_{mn} \right) \geq \sum_{m\in N} \sum_{n\in N_m} f_t(\tilde{w}_{mn}) \quad (49)$$

Therefore, the power consumption is upper bounded by:

$$\begin{aligned} P \leq {} & \eta_n \left(\frac{p_r}{B} \sum_{s\in N} \sum_{d\in N} L^{s,d} \right) + \eta_n f_p \left(\sum_{m\in N} \sum_{n\in N_m} \tilde{w}_{mn} \right) \\ & + \eta_n f_t \left(\sum_{m\in N} \sum_{n\in N_m} \tilde{w}_{mn} \right) \\ & + \frac{p_f A}{B} \sum_{m\in N} \sum_{n\in N_m} \lambda_{m,n} + N p_s \eta_n \\ & + G f_g \left(\sum_{m\in N} \sum_{n\in N_m} \tilde{w}_{mn} \right) \end{aligned} \quad (50)$$

which can be shown to be equal to:

$$P \leq \eta_n \left(\frac{p_r}{B} \sum_{s \in N} \sum_{d \in N} L^{s,d} \right) + \frac{\eta_n}{B} f_p \left(\sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} \right) + \frac{\eta_n}{B} f_t \left(\sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} \right) + \frac{p_f A}{WB} \sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} + N p_s \eta_n + \frac{G}{B} f_g \left(\sum_{s \in N} \sum_{d \in N} L^{s,d} h^{s,d} \right) \quad (51)$$

Assuming equal traffic demands:

$$P \leq \eta_n \frac{p_r}{B} N(N-1)\bar{L} + \frac{\eta_n}{B} f_p \left(N(N-1)\bar{L}h \right) + \frac{\eta_n}{B} f_t \left(N(N-1)\bar{L}h \right) + \frac{p_f A}{WB} N(N-1)\bar{L}h + N p_s \eta_n + \frac{G}{B} f_g \left(N(N-1)\bar{L}h \right) \quad (52)$$

After rearranging the terms:

$$P \leq N(N-1)\bar{L} \left(\eta_n \frac{p_r}{B} + \frac{p_f A}{WB} h \right) + \frac{\eta_n}{B} f_p \left(N(N-1)\bar{L}h \right) + \frac{\eta_n}{B} f_t \left(N(N-1)\bar{L}h \right) + N p_s \eta_n + \frac{G}{B} f_g \left(N(N-1)\bar{L}h \right) \quad (53)$$

Let :

$$u = N(N-1)\bar{L}h \quad (54)$$

then

$$P \leq \left(\eta_n \frac{p_r}{Bh} + \frac{p_f A}{WB} \right) u + \frac{\eta_n}{B} f_p(u) + \frac{\eta_n}{B} f_t(u) + N p_s \eta_n + \frac{G}{B} f_g(u) \quad (55)$$

Figure 5 shows the power consumption obtained from the MILP model and the analytical upper bound for the 2020 network using non-bypass and MLR assuming equal traffic demands.

Equation (56) presents a bound that tries to approach the optimum power consumption value. To get upper and lower bounds, the concave function representing the power consumption vs the data rate is approximated as a linear function with a slope corresponding to the lowest port power consumption and the highest port power consumption, respectively. This means that the MLR has the best power savings if all ports can use the most efficient ports (i.e., proportionally using the highest port), and the worst power savings when using the least efficient port. Note that $f_p(u)$, $f_t(u)$ and $f_g(u)$ are obtained from Table I where a linear interpolation is assumed in between the given data rates (40 Gb/s, 100 Gb/s, 400 Gb/s and 1 Tb/s).

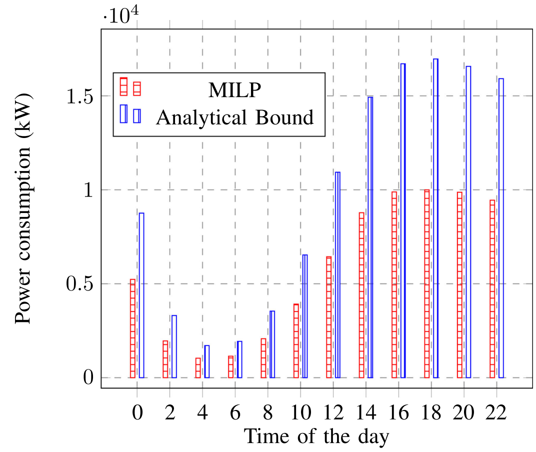


Fig. 5. Power Consumption and its bounds of the Original AT&T Topology, 2020 BAU+GT Components, with MLR, sleep and Energy Efficient Protection using Equal Traffic.

TABLE I
POWER CONSUMPTION VALUES FOR THE DIFFERENT CORE NETWORK COMPONENTS AS ESTIMATED IN 2020 [3]

Device	2020 Power consumption
Router Port 40 Gb/s	21.3 W
Router Port 100 Gb/s	39.2 W
Router Port 400 Gb/s	46.7 W
Router Port 1 Tb/s	53.9 W
Transponder 40 Gb/s	27.6 W
Transponder 100 Gb/s	86 W
Transponder 400 Gb/s	332.6 W
Transponder 1 Tb/s	801.3 W
Regenerator 40 Gb/s	55.2 W
Regenerator 100 Gb/s	172 W
Regenerator 400 Gb/s	665.2 W
Regenerator 1 Tb/s	1602.6 W
EDFA	15.3
Optical Switch	8.5

The value $p_r^{\Downarrow}$ and $p_r^{\Uparrow}$ are the power consumption of the lowest considered port (i.e., 40 Gbps) and the highest considered port (i.e., 1 Tbps). The same applies to the transponders ($p_t^{\Downarrow}$ and $p_t^{\Uparrow}$) and the regenerators ($p_g^{\Downarrow}$ and $p_g^{\Uparrow}$). Therefore the power consumption at a given line rate is bounded for the three equipment as follows:

$$p_r^{\Downarrow} \tilde{w}_{mn} \geq f_p(\tilde{w}_{mn}) \geq p_r^{\Uparrow} \tilde{w}_{mn} \quad (56)$$

$$p_t^{\Downarrow} \tilde{w}_{mn} \geq f_t(\tilde{w}_{mn}) \geq p_t^{\Uparrow} \tilde{w}_{mn} \quad (57)$$

$$p_g^{\Downarrow} \tilde{w}_{mn} \geq f_g(\tilde{w}_{mn}) \geq p_g^{\Uparrow} \tilde{w}_{mn} \quad (58)$$

For the router ports, transponders and regenerators respectively. Therefore, starting from equation (49), the lower bound is given as:

$$P \geq \eta_n \left(\frac{p_r}{B} \sum_{s\in N}\sum_{d\in N} L_{s,d} + \sum_{m\in N}\sum_{n\in N_m} p_r^{\Downarrow}\tilde{w}_{mn}\right) + \eta_n \sum_{m\in N}\sum_{n\in N_m} p_t^{\Downarrow}\tilde{w}_{mn} + \frac{p_f A}{B}\sum_{m\in N}\sum_{n\in N_m}\lambda_{m,n} + N p_s \eta_n + G\sum_{m\in N}\sum_{n\in N_m} p_g^{\Downarrow}\tilde{w}_{mn} \quad (59)$$

Which gives:

$$P \geq \eta_n \left(\frac{p_r}{B}\sum_{s\in N}\sum_{d\in N} L_{s,d}\right) + \frac{\eta_n}{B} p_r^{\Downarrow}\left(\sum_{s\in N}\sum_{d\in N} L_{s,d} h^{s,d}\right) + p_t^{\Downarrow}\frac{\eta_n}{B}\left(\sum_{s\in N}\sum_{d\in N} L_{s,d} h^{s,d}\right) + \frac{p_f A}{WB}\left(\sum_{s\in N}\sum_{d\in N} L_{s,d} h^{s,d}\right) + N p_s \eta_n + \frac{G}{B} p_g^{\Downarrow}\left(\sum_{s\in N}\sum_{d\in N} L_{s,d} h^{s,d}\right) \quad (60)$$

Assuming equal traffic demands:

$$P \geq \eta_n \frac{p_r}{B} N(N-1)\bar{L} + \frac{\eta_n}{B} p_r^{\Downarrow}\left(N(N-1)\bar{L}h\right) + \frac{\eta_n}{B} p_t^{\Downarrow}\left(N(N-1)\bar{L}h\right) + \frac{p_f A}{WB} N(N-1)\bar{L}h + N p_s \eta_n + \frac{G}{B} p_g^{\Downarrow}\left(N(N-1)\bar{L}h\right) \quad (61)$$

Which gives:

$$P \geq \left(\eta_n \frac{p_r}{Bh} + \frac{p_f A}{WB} + \frac{\eta_n}{B} p_r^{\Downarrow} + \frac{\eta_n}{B} p_t^{\Downarrow} + + \frac{G}{B} p_g^{\Downarrow}\right) u + N p_s \eta_n \quad (62)$$

And similarly, the upper bound is given as:

$$P \leq \left(\eta_n \frac{p_r}{Bh} + \frac{p_f A}{WB} + \frac{\eta_n}{B} p_r^{\Uparrow} + \frac{\eta_n}{B} p_t^{\Uparrow} + \frac{G}{B} p_g^{\Uparrow}\right) u + N p_s \eta_n \quad (63)$$

Similarly, The power consumption of the MLR approach under the bypass approach can be shown to have the following bounds:

The lower bound:

$$P \geq 2N(N-1)\bar{L}\frac{\eta_n}{B} p_r^{\Downarrow} + \frac{\eta_n}{B} p_t^{\Downarrow}(N-1)\bar{L}h + \frac{p_f A}{WB} N(N-1)\bar{L}h + N p_s \eta_n + \frac{G}{B} p_g^{\Downarrow} N(N-1)\bar{L}h \quad (64)$$

which is simplified to:

$$P \geq \left(2\eta_n \frac{p_r^{\Downarrow}}{Bh} + \frac{p_f A}{WB} + \frac{\eta_n}{B} p_t^{\Downarrow} + \frac{G}{B} p_g^{\Downarrow}\right) u + N p_s \eta_n \quad (65)$$

And similarly, the upper bound is given as:

$$P \leq \left(2\eta_n \frac{p_r^{\Uparrow}}{Bh} + \frac{p_f A}{WB} + \frac{\eta_n}{B} p_t^{\Uparrow} + \frac{G}{B} p_g^{\Uparrow}\right) u + N p_s \eta_n \quad (66)$$

V. Bounds and Closed Forms of Power Consumption Under Topology Optimization, Bypass, Sleep and Energy Efficient Protection

Here we develop upper and lower bounds on the power consumption of the optimum energy efficient topology for IP over WDM network under the bypass approach considering sleep, energy efficient protection and equal traffic demands. We also develop closed form expressions for the power consumption of various regular topologies and present a unified polynomial formula with the corresponding coefficients for each topology. A topology optimized to minimize the network power consumption is decided based on the traffic demands $L^{s,d,t}$ and distance between nodes. The traffic demands determine the number of router ports and transponders at each hop while the distance determines the number of EDFAs and regenerators. Starting from equation (21), the power consumption of the optimal topology can be given as:

$$P = \min(\eta_n \frac{p_r}{B} N(N-1)\bar{L} + \sum_{s\in N}\sum_{d\in N} E_c L^{s,d} h^{s,d}) = \eta_n \frac{p_r}{B} N(N-1)\bar{L} + \sum_{s\in N}\sum_{d\in N} E_c L^{s,d}\min(h^{s,d}) \quad (67)$$

where

$$E_c = \left(\eta_n p_r + \eta_n p_t + \frac{p_f A}{W} + p_g G\right) \quad (68)$$

Assuming equal demands, the total power is given as:

$$P = \eta_n \frac{p_r}{B} N(N-1)\bar{L} + \bar{L}\sum_{s\in N}\sum_{d\in N}\min(E_c h^{s,d}) \quad (69)$$

The optimal topology power consumption lies between the following bounds, where we assumed all links to deploy the maximum and minimum number of regenerators and EDFAs:

$$P \geq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(\min)} h_{op}\right) \quad (70)$$

$$P \leq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(\max)} h_{op}\right) \quad (71)$$

where h_{op} is the average hop count of the optimal topology.

The power consumption of the optimal topology is lower bounded by the power consumption of a full mesh, i.e., h = 1 where all links are of the minimum distance between nodes given as:

$$P \geq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(\min)}\right) \quad (72)$$

The optimal topology connects node pairs with a direct link unless the power consumption of regenerators and EDFAs in the direct link is greater than the power consumption of an additional

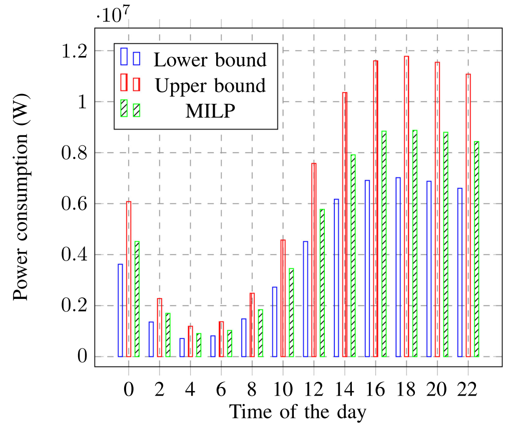


Fig. 6. Power Consumption of the optimal topology and its bounds, 2020 BAU+GT Components, 40 Gbps, bypass, sleep and energy efficient Protection, considering equal traffic demands.

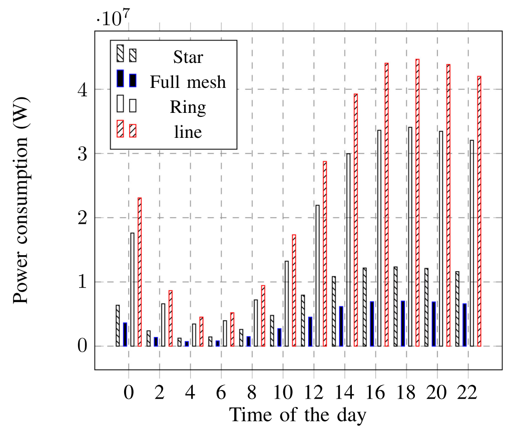
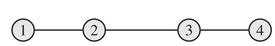


Fig. 7. Power Consumption of the regular topologies with 2020 BAU+GT Components, 40 Gbps and Sleep, considering equal traffic demands.

	1	2	3	4
1	0	1	2	3
2	1	1	1	2
3	2	1	0	1
4	3	2	1	0

(a)



(b)

Fig. 8. The hop counts of a 4-node line topology.

hop. Therefore a full mesh with links of the maximum distance will have a higher power consumption that the optimal topology:

$$P \leq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(\max)}\right) \tag{73}$$

Figure 6 shows that the power consumption of the optimal topology given by the MILP model is bounded by the lower bound for the optimal topology given by equation (72) and upper bounded by the equation (73).

For different regular topologies (line, ring, and star topologies) a closed form expression of the power consumption can be obtained using the closed form expressions of the hop count given below and substituting them in equation (69). The power consumption of the considered regular topologies at different times of the day considering equal traffic demands is shown in Figure 7 where the regular topologies used the same set of equipment, same power consumption values, same number of nodes, and same traffic as the other topologies. For link distances, the average link distance was used.

A. Star Topology

$$\sum_{s\in N}\sum_{d\in N\, s\neq d} h^{s,d} = 2(N-1) + 2(N-1)(N-1) = 2(N-1)^2 \tag{74}$$

where the first term $2(N-1)$ is the total hops from each node to the center of the star considering bidirectional demands, and the second term $2(N-1)(N-2)$ is for the demands from nodes to each other excluding the center of the star.

$$h = \frac{2(N-1)^2}{N(N-1)} = \frac{2(N-1)}{N} \tag{75}$$

$$\begin{aligned} P &= N(N-1)\bar{L}\left(\eta_p \frac{p_r}{B} + p_c \frac{2(N-1)}{N}\right) \\ &= 2p_c \bar{L}N^2 + \left(\eta_p \frac{p_r}{B} - 2p_c\right)\bar{L}N + \left(2p_c - \eta_p \frac{p_r}{B}\right)\bar{L} \end{aligned} \tag{76}$$

This means that the power consumption of the star topology is a polynomial in the network size, N, of the order 2.

B. Ring Topology (N odd)

$$\begin{aligned} \sum_{s\in N}\sum_{\substack{d\in N\\ s\neq d}} h^{s,d} &= 2N\left(1 + 2 + 3 + \cdots + \frac{N-1}{2}\right) \\ &= 2N\left(\frac{1}{2}\left(\frac{N-1}{2}\right)\left(\frac{N-1}{2} + 1\right)\right) \\ &= \frac{N(N^2-1)}{4} \end{aligned} \tag{77}$$

where each node takes an incremental number of hops to reach nodes on one side, and similarly for the other side, and this is repeated for all nodes. Note here the total number of nodes on each side to reach be a node is $\frac{N-1}{2}$.

$$h = \frac{N(N^2-1)}{4N(N-1)} = \frac{N+1}{4} \tag{78}$$

$$\begin{aligned} P &= N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + E_c \frac{N+1}{4}\right) \\ &= \frac{\eta_n}{4}\bar{L}N^3 + \frac{p_r}{B}\bar{L}N^2 - \left(\eta_n \frac{p_r}{B} + \frac{E_c}{4}\right)N\bar{L} \end{aligned} \tag{79}$$

C. Ring Topology (N Even)

$$\begin{aligned} \sum_{s\in N}\sum_{\substack{d\in N\\ s\neq d}} h^{s,d} &= N\left[2\left(1 + 2 + 3 + \cdots + \frac{N}{2} - 1\right) + \frac{N}{2}\right] \\ &= N\left[\left(\frac{N}{2} - 1\right)\frac{N}{2} + \frac{N}{2}\right] = \frac{N^3}{4} \end{aligned} \tag{80}$$

Because of the even number of nodes, the number of nodes on one side is higher than the number of nodes on the other side by

TABLE II
REGULAR TOPOLOGIES POLYNOMIAL COEFFICIENTS

Topology	a	b	c	d
Star	0	$2E_cL$	$(\eta_n \frac{p_r}{B} - 2E_c)L$	$(2E_c - \eta_n \frac{p_r}{B})L$
Ring (odd)	$\frac{E_c}{4}\bar{L}$	$\eta_n \frac{p_r}{B}\bar{L}$	$-(\eta_n \frac{p_r}{B} + \frac{E_c}{4})\bar{L}$	0
Ring (even)	$\frac{E_c}{4}\bar{L}$	$\eta_n \frac{p_r}{B}\bar{L}$	$-(\eta_n \frac{p_r}{B})\bar{L}$	0
Line	$\frac{E_c}{3}\bar{L}$	$\eta_n \frac{p_r}{B}\bar{L}$	$-(\eta_n \frac{p_r}{B} + \frac{E_c}{4})\bar{L}$	0
full mesh	0	$\bar{L}(\eta_n \frac{p_r}{B} + E_c)$	$-\bar{L}(\eta_n \frac{p_r}{B} + E_c)$	0

TABLE III
SUMMARY OF THE BOUNDS FOR THE DIFFERENT SCENARIOS

Scenario	Lower bound	upper bound
Non-bypass		
Equal traffic and Efficient protection	$P \geq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(min)}h\right) + \eta_n N p_s$	$P \leq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(max)}h\right) + \eta_n N p_s$
Unequal traffic and Efficient protection	$P \geq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(min)}h_{(min)}\right) + \eta_n N p_s$	$P \leq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(max)}h_{(max)}\right) + \eta_n N p_s$
Unequal traffic and Inefficient protection	$P \geq 2N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(min)}h_{(min)}\right) + \eta_n N p_s$	$P \leq 2N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(max)}h_{(max)}\right) + \eta_n N p_s$
Equal traffic, efficient protection, and MLR	$P \geq \left(\eta_n \frac{p_r}{Bh} + \frac{p_f A}{WB} + \frac{\eta_n}{B} p_r^{\Downarrow} + \frac{\eta_n}{B} p_t^{\Downarrow} + + \frac{G}{B} p_g^{\Downarrow}\right) u + N p_s \eta_n$	$P \leq \left(\eta_n \frac{p_r}{Bh} + \frac{p_f A}{WB} + \frac{\eta_n}{B} p_r^{\Uparrow} + \frac{\eta_n}{B} p_t^{\Uparrow} + \frac{G}{B} p_g^{\Uparrow}\right) u + N p_s \eta_n$
Bypass		
Equal traffic and Efficient protection	$P \geq N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(min)}h\right) + \eta_n N p_s$	$P \leq N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(max)}h\right) + \eta_n N p_s$
Unequal traffic and Efficient protection	$P \geq N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(min)}h_{(min)}\right) + \eta_n N p_s$	$P \leq N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(max)}h_{(max)}\right) + \eta_n N p_s$
Unequal traffic and Inefficient protection	$P \geq 2N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(min)}h_{(min)}\right) + \eta_n N p_s$	$P \leq 2N(N-1)\bar{L}\left(2\eta_n \frac{p_r}{B} + Eb_{(max)}h_{(max)}\right) + \eta_n N p_s$
Equal traffic, efficient protection and MLR	$P \geq \left(2\eta_n \frac{p_r^{\Downarrow}}{Bh} + \frac{p_f A}{WB} + \frac{\eta_n}{B} p_t^{\Downarrow} + \frac{G}{B} p_g^{\Downarrow}\right) u + N p_s \eta_n$	$P \leq \left(2\eta_n \frac{p_r^{\Uparrow}}{Bh} + \frac{p_f A}{WB} + \frac{\eta_n}{B} p_t^{\Uparrow} + \frac{G}{B} p_g^{\Uparrow}\right) u + N p_s \eta_n$
Equal traffic and Optimal topology	$P \geq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(min)}\right)$	$P \leq N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + Ec_{(max)}\right)$

a single node. The number of nodes on each side after removing a node to make it symmetric is $\frac{N}{2} - 1$. And the hop count to the removed node is counted for by the term $\frac{N}{2}$.

$$h = \frac{N^3}{4N(N-1)} = \frac{N^2}{4(N-1)} \tag{81}$$

$$P = N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + E_c \frac{N^2}{4(N-1)}\right)$$
$$= \frac{E_c}{4}\bar{L}N^3 + \eta_n \frac{p_r}{B}\bar{L}N^2 - \eta_n \frac{p_r}{B} N\bar{L} \tag{82}$$

D. Line Topology

The total number of hops used by all demands is given by equation (83), which can be explained with the aid of Figure 8. To the right is a 4-node line topology and the array to the left

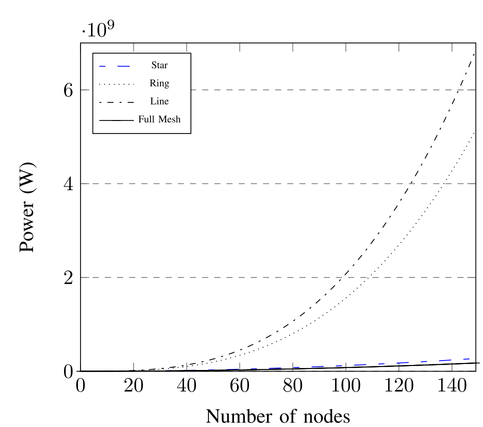


Fig. 9. Power Consumption of the different topologies at different node sizes, 2020 BAU+GT Components, 40Gbps, bypass, Sleep and energy efficient Protection, considering equal traffic demands.

shows the hop count of a routed traffic between each source and destination node pair. The following equation calculates the total hop count by realizing the asymmetry in this matrix, and realizing that the total hop count follows this pattern: hop count 1 exists 6 times, hop count 2 exists 4 times and hop count 3 exists twice. The following equation generalizes it to a N number of nodes.

$$\sum_{s\in N}\sum_{\substack{d\in N\\ s\neq d}} h^{s,d} = 2\sum_{i=1}^{N-1} i(N-i) = 2N\sum_{i=1}^{N-1} i - 2\sum_{i=1}^{N-1} i^2$$

$$= \frac{N(N-1)(N+1)}{3} \tag{83}$$

$$h = \frac{N(N-1)(N+1)}{3N(N-1)} = \frac{N+1}{3} \tag{84}$$

where we used the fact that:

$$\sum_{1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6} \tag{85}$$

therefore

$$\begin{aligned} P &= N(N-1)\bar{L}\left(\eta_n \frac{p_r}{B} + E_c \frac{N+1}{4}\right) \\ &= \frac{E_c}{4}\bar{L}N^3 + \eta_n \frac{p_r}{B}\bar{L}N^2 - \left(\eta_n \frac{p_r}{B} + \frac{E_c}{4}\right) N\bar{L} \end{aligned} \tag{86}$$

The total power for the aforementioned topologies can be given as a 3rd order polynomial:

$$P = aN^3 + bN^2 + cN + d \tag{87}$$

In Table II we summarize the values for the coefficients a, b, c, and d for the different regular topologies. The table, alongside Figure 9 show that the star and the full mesh topologies have lower power consumption than other topologies as the most significant polynomial coefficient is zero (a = 0). It shows also that the full mesh topology has a close but lower power consumption to the star topology, which gets better as the number of nodes increases because the b and c coefficients are higher in the star topology. It shows that the line topology consumes more power than the two variants of the ring topology, and the highest power consumption over other topologies due to the higher significant polynomial coefficients.

In Table III we summarize the lower and upper bounds for the different approaches considered in this paper. This table will be useful for quick and easy reference to the bounds and the reader can refer to previous sections for more details about the derivation steps and assumption. The table is divided into two parts where the first part considers the non-bypass case and the second is the bypass case. In each part, incremental scenarios that build on the basic approach are shown in sequence.

VI. Conclusions

In this paper we developed bounds on the power consumption of core networks for the non-bypass, bypass, MLR and topology optimization scenarios to verify the individual elements of the optimization models produced in our previous GreenTouch core network energy efficiency models. The bounds and formulas give insights into the behavior of the systems and facilitate predictions at situations where the MILP model is too complex. They also give approximations to the optimum results found by the MILP models. The power consumption of the optimum scenario generally lies close to the lower bound while the upper bound is far from the optimum case because it takes into consideration extreme cases that are not usually found in practice. We have also shown that the full-mesh topology is a very good estimate of the optimal network topology and in general, regular topologies can be represented as a polynomial of the third order, with different coefficients for different topologies. We also provide closed form expressions for the network paths average hop counts for regular topologies.

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