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Analysis of Energy Efficiency in Dynamic Optical Networks Employing Solar Energy Sources

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***Abstract*—The paper presents energy efficient routing in dynamic optical networks, where solar energy sources are employed for the network nodes. Different parameters are evaluated, including the number of nodes that have access to solar energy sources, the different maximum solar output power, traffic type and the locations of solar powered nodes. Results show a maximum 39% savings in energy consumption with different increases in connection blocking probability.**

I. Introduction

As the growing energy consumption and emissions of CO_2 in networks are becoming major issues for network development today, various researches have been working to build an eco-sustainable network environment. While the majority of the work done in the optical domain is focused on the device/hardware level, this paper puts focus on the network operation level, utilizing Generalized Multiprotocol Label Switching (GMPLS [1]) control plane in optical core networks. In compliance with the development of Smart Grid networks, the telecommunication networks in the future will have the possibility to choose among different energy sources, some of which (i.e. green energy sources) can replace the traditional energy sources (i.e. coal, oil energy sources), so as to reduce the non-renewable energy consumption. The availability of green energy sources can be greatly influenced by natural phenomena, such as sunlight and wind, or by geographic location. Thus, in order to operate the network in a greener manner, it is necessary to have the energy source information spread and updated in the whole network area, which can influence the routing decision towards a greener aspect.

In this paper, the authors assume a solar energy availability/unavailability to each network node, as an alternative to the traditional non-renewable energy sources. The focus is on reducing the non-renewable energy consumption of the network by using the available solar energy. The solar energy availability information is updated in the whole network by utilizing Traffic Engineering (TE) extensions proposed for Open Shortest Path First - Traffic Engineering (OSPF-TE [2]) protocol. Connection requests are routed through nodes with access to solar energy sources as much as possible. The impact of solar energy sources on reducing the non-renewable energy consumption of the network is studied; the maximum output power of solar energy panel, the number of network nodes that have access to solar energy sources, the type of traffic and the locations of solar powered nodes are taken into consideration. Section II introduces related work, the energy model used for calculating the energy consumption is given in Section III, the simulation environment and parameters are given in Section IV, results from dynamic network simulations are given in Section V, and a short conclusion is given in Section VI.

II. Related Work

The researches of energy efficiency in optical networks are quite active for the moment, and different researchers have proposed various approaches to deal with the energy efficiency problems in the core networks. In [3], the authors discuss energy efficiency using mathematical approach, their proposed heuristic methods effectively solve the energy saving problems in a static environment. Many researches have been focusing on switching on/off unused nodes/links during non-busy hours, as proposed in [4] and [5]. However, the ideas are often accompanied by network reliability issues. In order to reduce the risk caused by sleeping nodes/links, the authors in [6] have raised the idea of letting only part of the bundled links sleep. In this paper, the authors propose dynamic routing method using solar energy sources. A similar concept for utilizing solar energy sources is explored in previous work [7], where the application scenario is a static network environment. Our work is among the earliest attempts to address the issue in a dynamic network setup.

III. Energy Model

In order to evaluate the impact of employing solar energy sources in the network nodes, a simple energy model is employed to provide an estimate of the non-renewable energy consumption of the network. The energy consumption in a node is assumed to comprise of two components: a fixed one, due to the consumption needed for keeping devices powered on, which is independent of the traffic through the node, and a dynamic one, dependent on the amount of traffic through the node. The Optical Amplifiers' (OA) energy consumption are assumed to be traffic independent, since the OA (like erbium-doped fiber amplifier) amplifies the entire C-band. 3R (re-amplifying, re-shaping, and re-timing) regenerators' energy consumption are traffic dependent, and is only activated when the particular wavelength passing through the node needs to be regenerated. The node which has access to solar energy sources prioritizes to use solar energy first in setting up new connections, and non-renewable energy is used again when solar energy drains out. The node that has no access to solar energy sources uses non-renewable energy to set up new connections. Thus, the non-renewable energy consumption of a light path p is given by (excluding the fixed part of the consumption in a node):

$$C_p = \left\lfloor \sum_{n \in p} e_n \cdot b_p \cdot t_n + \sum_{n \in p} \left(\frac{l_l}{\kappa_{3R}} \right) \cdot (r_n \cdot b_p \cdot t_n) + \sum_{l \in p} \frac{e_l \cdot l_l}{\omega_l \cdot \theta_{OA}} \right\rfloor \cdot d_p \quad (1)$$

with

$$t_n = \begin{cases} 0 & \text{solar energy used for connection} \\ 1 & \text{non-renewable energy used for connection} \end{cases} \quad (2)$$

where e_n is the energy consumption per Gbps for the specific traffic type passing through node n, b_p is the bandwidth of the path in Gbps, t_n is a constant, indicating if this part of energy consumption should be included (i.e., the non-renewable energy case) or not included (i.e., the solar energy case), l_l is the length of the link, κ_{3R} is the maximum allowed link length without need of 3R re-generations. The last node on the path before the signal reaches κ_{3R} needs to perform 3R operations. r_n is the energy consumption per Gbps to perform 3R re-generation. e_l is the energy consumption of an OA on link l, w_l is the wavelengths used on link l, θ_{OA} is the maximum allowed link length without need of amplifying, d_p is the duration of the connection. Note that the fixed part of the node's energy consumption always exists, but is excluded from the formula and the graphs for simplification.

IV. Software Implementation

The proposed network environment is implemented in the event driven simulator - OPNET [8]. The model utilizes Open Shortest Path First - Traffic Engineering (OSPF-TE [9]) as the routing protocol, and Resource Reservation Protocol - Traffic Engineering (RSVP-TE [10]) as the signaling protocol. In order to evaluate the impact of employing solar energy sources in the network, the NSFNET network topology is used as an example of a real network scenario. The optical network is assumed to be composed of network nodes (optical cross-connects, OXCs) and links, with OAs every 80km. 3R re-generation activities are performed in network nodes, and is only needed before the signal has been carried to maximum 1000km. Each link is assigned 16 wavelengths. In the simulation model, the first fit algorithm is applied for the wavelength assignment. Label Switched Path (LSP) connection requests are generated as a Poisson process, with exponentially distributed connection duration (with a mean value of 6 hours). A variation of traffic demand, referenced from a realistic model [7], is obtained by adjusting the mean inter-arrival rate, taking different time zones into account. The total traffic load per node is given by the connection duration and the inter-arrival rate, and the theoretical value is varied between 2 to 12 Erlangs. A caption of real average traffic is shown in Fig. 1 (may vary with different simulation seed value).

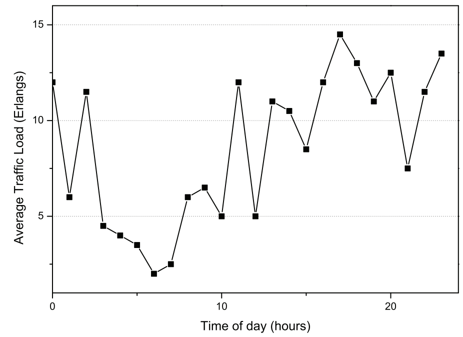

Fig. 1. Actual traffic in the simulation environment.

TABLE I
SOLAR ENERGY MODEL ASSIGNMENT.

Time Zone	Node Name
PST	Seattle, Palo Alto, San Diego
MST	Salt Lake City, Boulder
CST	Lincoln, Houston, Urbana Champaign
EST	Ann Arbor, Pittsburgh, Ithaca, College Park, Princeton, Atlanta

The output power of the solar energy sources is geographically related, varying during the day (sunrise/sunset). The NSFNET topology is divided into four time zones, namely Pacific Standard Time (PST), Mountain Standard Time (MST), Central Standard Time (CST) and Eastern Standard Time (EST), as shown in Fig. 2. Taking sunrise/sunset into consideration, a solar energy output power model can be derived [7], with nodes allocation as shown in Tab. 1. The referenced model is assuming a maximum solar energy output of 20kW, which requires a total solar cell area of about $100m^2$ [7]. In the same way, a maximum solar energy output model of 10kW, 30kW and 40kW can also be derived. In the next section, the effects of using different energy output levels are discussed. In the implemented model, solar energy is assumed to be an alternative energy source than the traditional energy source, and the possibility to have access to this alternative energy source or not, can be user defined. That is to say, for nodes that are configured to have no access to solar energy sources, only traditional energy sources can be used. Meanwhile, for nodes that have access to solar energy sources, the solar energy output level follows the output power model described in [7], and traditional energy sources are once again used when the solar energy is drain. In this way, the effects of availability of solar energy and the amounts of solar powered nodes can be investigated.

At fixed time intervals (referred to as *EnergyUpdateInterval* in this paper), a new update of the available solar energy information is originated and flooded between neighbors using OSPF-TE extension. The extension can be carried by opaque link state advertisement (LSA [11]). After the solar energy

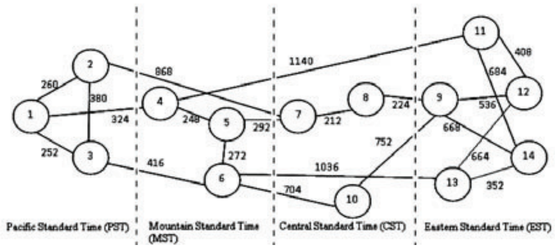

Fig. 2. NSFNET network with zone division [7].

information is flooded over the network, a new weight for the Dijkstra algorithm can be calculated and used for routing decision. The weighted edge value can be expressed as:

$$\zeta - \frac{1}{2} \cdot (c_s + c_d) \tag{3}$$

where ζ (kW) is the maximum solar energy output power in the solar energy model, c_s (kW) and c_d (kW) are the current solar energy output power of the nodes at the ends of the edge. When there is no solar energy available in any of the network nodes, which equals all c_s and c_d are zero, the algorithm becomes a pure shortest path algorithm, taking only routing hops length into consideration. Upon flooding the TE-LSA over the whole network, the new routing information is updated in each LSA database. According to Equation (3), the higher value the solar energy is at both of the end nodes, the lower the edge value is for the routing calculation. Routing decision is thus selecting the path with the lowest cost, where the most solar energy is available.

V. Results and Discussions

Two performance metrics have been evaluated: average non-renewable energy consumption per day (Fig. 3), and average connection blocking probability (Fig. 3). Two different update intervals (*EnergyUpdateInterval*) are evaluated (3 and 12 hours), during 30 days of simulation runtime. For any node in the proposed network, traffic can be divided into non-bypass traffic and bypass traffic, which consumes different amount of energy when passing through the node. The impact of traffic type is also evaluated. Results are shown with increasing number of nodes that have access to solar energy (abscissa-axis), under different maximum solar output power (10, 20, 30, 40kW), update intervals and traffic type. In order to investigate the impact of the locations of the solar powered nodes on the total non-renewable energy consumption, a selection of five central nodes (Salt Lake City, Boulder, Houston, Lincoln, Ann Arbor) and five periphery nodes (Seattle, Palo Alto, Atlanta, Ithaca, College Park) are compared in terms of total non-renewable energy consumption (Fig. 5). Results are generated with 95% confidence intervals from 20 prime number seeds.

Fig. 3 shows the non-renewable energy consumption results with the proposed energy model, which excludes the fixed energy consumption of the nodes, as explained previously. The non-renewable energy consumption decreases almost linearly with the increasing number of solar energy powered nodes,

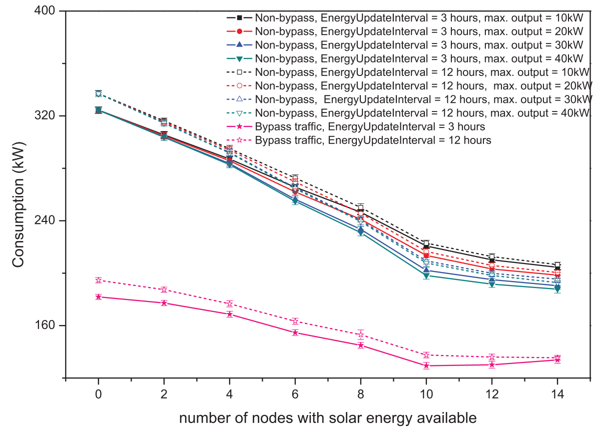

Fig. 3. Average energy consumption under different number of solar energy powered nodes.

with maximum savings of around 39% for non-bypass traffic, and around 30% for bypass traffic. Higher solar energy output power can achieve more savings, but the trend is not apparent after reaching 30kW maximum output power, as there might be no more traffic going through the solar energy powered nodes. For bypass traffic, the savings are the same from maximum output power of 10kW and above period, this is due to the much smaller amounts of energy required [12] for processing bypass traffic compared to non-bypass traffic. The energy savings also become flatter after reaching 10 nodes powered by solar energy, which is where the majority of nodes (10 out of 14) have access to solar energy. Under the same maximum output power level, a lower *EnergyUpdateInterval* can achieve higher savings. This is due to the fact that a more frequent flooding of solar energy information helps to maintain a more acurate routing table. Meanwhile, new connection requests can be routed to the nodes with more solar energy available, avoiding being routed through the same few nodes which might not be the most ”green” nodes anymore. A much lower energy consumption is recorded for bypass traffic, due to a much lower processing power used in the node, i.e. no electronic to optical (EO) or optical to electronic (OE) conversions in the forwarding part.

At the same time, the *EnergyUpdateInterval* is of major influence to the connection blocking probability, as Fig. 4 shows. Longer *EnergyUpdateInterval* gives a higher inaccuracy of energy source availability information in the routing tables, causing more connections to be routed through the same routes, which results in a higher blocking probability. Under the same *EnergyUpdateInterval*, the blocking probability is almost the same despite the different traffic type and solar energy output power, since the traffic is routed in the same way with the same information in the routing tables. Generally, the blocking probability increases compared to using pure shortest path algorithm (as shown when the number of solar powered nodes is 0). When the number of solar powered nodes reaches 10, the energy consumption savings become flatter, while

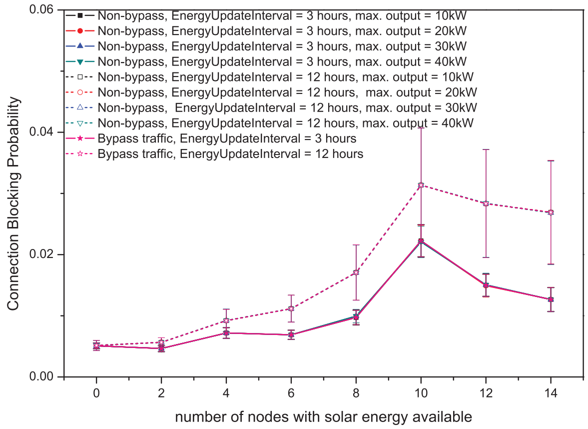

Fig. 4. Average connection blocking probability under different number of solar energy powered nodes.

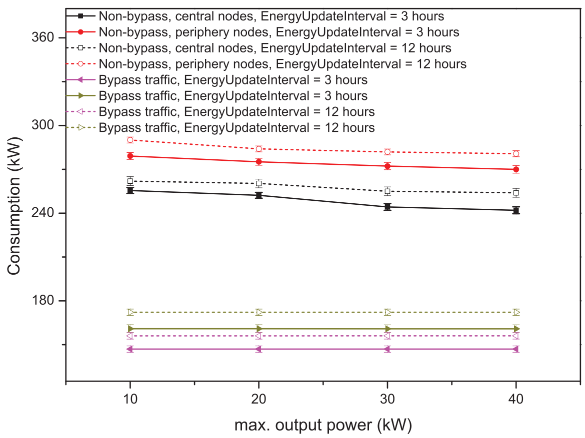

Fig. 5. Consumption of central nodes vs. periphery nodes.

the blocking probability starts to decrease. This shows that adding more nodes with available solar energy after reaching a certain threshold might not lead to more savings, but may help in connection blocking rate as a result of improved routing choices. However, an extra processing cost and more overhead in the network must be considered when enabling a more frequent flooding of energy information in the network, which is not counted in the total energy cost in this work.

The locations of solar powered nodes also have impact to the non-renewable energy consumption. According to the previous work [7], central network nodes would have higher impact on the reduction of the non-renewable energy consumption than the periphery nodes. The authors in [7] have also given an optimal selection of nodes regarding locations using Linear Programming (LP) approach. With the proposed selection, the authors' statement also holds true in the dynamic case in this study, as shown in Fig. 5, with approximately maximum 18% difference.

VI. Conclusion

In this paper, the impact of solar energy on the reduction of non-renewable energy consumption is studied, and results are collected from a dynamic simulation environment. Results show almost linear dependence between the reduction of non-renewable energy consumption and the number of solar powered nodes. The reduction becomes flatter after the number of solar powered nodes reaches a certain threshold, after which further increase does not bring any improvement to the energy reduction, but brings improvement to the blocking probability. A more frequent flooding of solar energy information gives better results in energy savings, as well as blocking probability. However, in any dynamic network, a more frequent flooding of routing information would cause extra network overhead, thus increased operational cost. A much lower energy consumption can be obtained for bypass traffic, which indicates the potential of energy savings done in optical switching layer. The locations of the solar powered nodes have different impact to the reduction of non-renewable energy consumption. If the nodes are situated in the center of the network, higher savings are achieved compared to a case where the nodes are situated on the edge of the network. This is through strictly topology dependent and might change with network connectivity and traffic demand distribution.

Acknowledgment

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