Energy Efficiency in Optical IP Networks with Multi-Layer Switching

Michael Z. Feng, Kerry Hinton, Robert Ayre, Rodney S. Tucker
Centre for Energy-Efficient Telecommunications, University of Melbourne, Victoria 3010, Australia
mzfeng@ee.unimelb.edu.au

Abstract: We show that significant savings in energy consumption can be achieved in optical IP networks with multi-layer switching by using a coordinated combination of IP aggregation, electronic bypass and optical bypass.

OCIS codes: (060.4250) Networks, (060.2330) Fiber optics communications

1. Introduction

With the continuous growth of traffic in Internet Protocol (IP) networks, the issue of energy consumption in these networks has been growing in importance. A number of papers in the literature have focused on developing estimates for energy consumption in IP networks and proposing strategies to reduce their energy consumption [1-3]. In previous work [4,5], we discussed the ideas of achieving savings in energy consumption through the appropriate use of key switching/routing technologies, including IP routing, Synchronous Digital Hierarchy/Synchronous Optical Networking (SDH/SONET) cross connection, and Wavelength Division Multiplexing (WDM). In [4], we analyzed the potential for a two-level electronic switching and grooming node architecture using IP/SDH/WDM to achieve savings in energy consumption for a network node. In [5], we extended the analysis to examine the opportunity for additional savings in energy consumption by including a Generalized Multi-Protocol Label Switching/Automatically Switched Optical Network (GMPLS/ASON) managed optical switching layer in an automated and intelligent optical network node.

In this paper, we further extend the analysis of single nodes in [4,5] to quantify the energy savings in a network of nodes with various multi-layer switching capabilities. We investigate and compare the energy consumption of a general mesh network when each of three node architectures is deployed in the network: IP/WDM, IP/SDH/WDM, and GMPLS/ASON-enabled nodes (abbreviated as GMPLS/ASON in this paper). The results show that GMPLS/ASON can attain significant reductions in energy consumption with appropriate multi-layer coordination between IP aggregation, electronic bypass and optical bypass in optical IP networks.

2. Node Architectures

The three different node architectures IP/WDM, IP/SDH/WDM, and GMPLS/ASON analyzed here are shown in Fig. 1(a), 1(b) and 1(c), respectively.

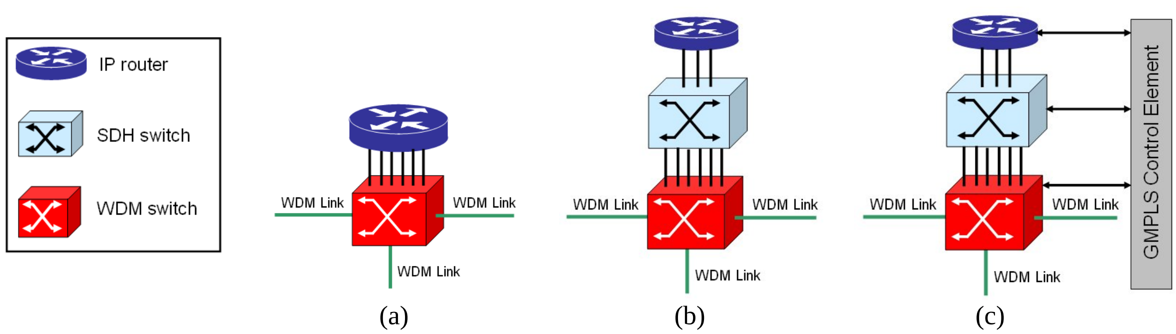

Fig. 1. Node architectures of (a) IP/WDM, (b) IP/SDH/WDM, and (c) GMPLS/ASON

The WDM or physical layer provides basic connectivity between the nodes. The switch in the WDM layer can take the form of an optical add-drop multiplexer or an optical cross-connect, which establishes connections under the network management system. In the IP/WDM model, all of the incoming wavelength channels are separated and presented to the IP router for IP packet processing. In the router, individual IP packets can be switched to a port (or a wavelength) on different outgoing routes, or groups of packets combined (using statistical multiplexing) to improve the utilization of the wavelengths on outgoing routes. This is a form of subwavelength grooming [6]. IP aggregation through subwavelength grooming enables a large number of traffic streams with low utilization to be combined into a smaller number of streams with higher utilization. This enables a reduction in the number of wavelengths and interface ports used in the network [4]. The SDH transport layer traditionally provides fixed-capacity connections (or virtual connections) across the network, and several such virtual connections can be multiplexed into a larger SDH payload. These fixed-capacity virtual connections are separated and rearranged within the SDH switch, which can take the form of a digital add-drop multiplexer or digital cross-connect. The SDH layer functions enable the fixed-capacity virtual connections to be aggregated and switched to a common path, again under the network management system, leading to an improvement in the network transport efficiency.

IP layer aggregation in routers can enable a higher utilization for wavelengths on the outgoing routes than that is possible by aggregation at the SDH layer. However, this is achieved at the expense of higher energy consumption because the IP routers need to process the data packet by packet. It has been shown in [1] that data processing in IP routers consumes significantly more energy than that in the underlying SDH and WDM layers. Thus, energy savings can be made if traffic streams that do not require IP router processing can be processed at the lower layers, allowing the use of a smaller router at the node. In Fig. 1(b), the traffic streams that do not need IP processing are switched at the SDH layer, electronically bypassing the IP router. The architecture shown in Fig. 1(c) extends this principle to include an actively managed optical switching layer, enabled by the GMPLS/ASON control plane, where some wavelengths are switched at the WDM layer, hence optically bypassing all the layers above. This will bring further energy savings because switching in the WDM layer consumes even less energy than that in the SDH layer [1].

The criterion for deciding whether traffic is to be processed in the IP layer or bypassed at the lower layers was discussed in [4,5] and is dependent on the utilization of the traffic streams. To illustrate this, consider the traffic streams arriving at the input ports of each node are in the form of IP traffic encapsulated within SDH frames. Each SDH frame, which may consist of a number of multiplexed sub-streams, is carried by a separate wavelength. Fig. 2 shows a convenient diagrammatic representation of a SDH frame (refer to [7] for the detailed representation).

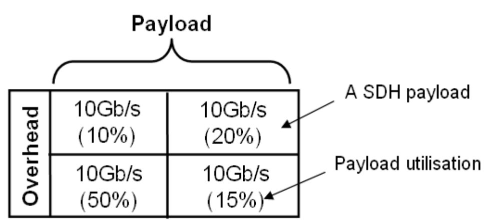

Fig. 2. Convenient representation of a SDH Frame

Table 1: Energy-per-bit values for different devices

	IP Router	SDH Switch	WDM Switch
Energy-per-bit	**10 nJ/bit**	**1 nJ/bit**	**0.5 nJ/bit**

In Fig. 2, the SDH frame is illustrated as including an overhead section and a payload section. The payload section includes four multiplexed SDH sub-streams of 10 Gb/s, giving a total capacity of 40 Gb/s. The percentage utilization of each of the sub-streams is the ratio of the number of IP traffic bytes carried by the sub-stream to its maximum traffic capacity. A higher value represents IP data bytes occupying more of the SDH payload. However, in order to avoid excessive packet loss, there needs to be upper limit to the IP aggregation of payload utilization. Using the numbers in Fig. 2 as an example, if this upper limit is set at 60%, then multiple sub-streams with low utilization (10%, 15% and 20%) could be aggregated in the IP router, while a sub-stream with high utilization (50%) would bypass the IP router. Implementation of such a cross-layer aggregation process does require traffic-level awareness by the network management system, but this is the basis of much GMPLS and ASON development.

3. Network Analysis

To compare the energy consumption between the different architectures shown in Fig. 1, we simulate deploying each of the three node architectures across a general mesh network which is simulated using an arbitrary network connection matrix. An arbitrary traffic matrix is generated to represent the traffic flows between multiple source-destination node pairs in the network. The connection and traffic matrices are used to construct a traffic routing table for the network. We consider 10 wavelengths arriving at the input of each of the source nodes, with each input wavelength carrying a SDH frame that takes the form shown in Fig. 2. Each sub-stream inside the SDH frame is given a payload utilization ranging from 5% to 60%, generated from a uniform probability distribution. We set the upper limit for IP aggregation at 60%, and bypass the IP router for sub-streams with payload utilization above 40% [5,8,9].

The energy consumption of the switches considered here is summarized in Table 1 [1,10,11]. In the calculation, we take into account of the increased energy-per-bit when ports and wavelengths are underutilized. We model the GMPLS control element (Fig. 1), using a Juniper MX240 Universal Edge Router engine, which consumes 90 W [5,12]. The power consumption P_T for a given node architecture is estimated by summing the power consumption of each IP router port, SDH port and wavelength used, with all of these adjusted to account for their payload utilization. Thus, $P_T = \sum^{IP\ ports}(E_{IP} \times LR_{IP})/U_{IP} + \sum^{SDH\ ports}(E_{SDH} \times LR_{SDH})/U_{SDH} + \sum^{Wavelengths}(E_{WDM} \times LR_{WDM})/U_{WDM} + P_{CE}$, where E_{IP} is the energy-per-bit for an IP router, LR_{IP} the line rate of an IP router port, and U_{IP} the payload utilization of sub-streams at the router ports. E_{SDH}, LR_{SDH}, U_{SDH} and E_{WDM}, LR_{WDM}, U_{WDM} are the corresponding parameters for a SDH switch and a WDM switch. P_{CE} = 90 W is the contribution of the GMPLS/ASON control element power consumption. For an IP/WDM node, power consumption of the SDH ports is zero and P_{CE} = 0. For an IP/SDH/WDM node, P_{CE} = 0. The power consumption of the network is the sum of the power consumption of all nodes in the network.

To compare the energy consumption of networks using the three node architectures in Fig. 1, 100 random mesh networks with 6 to 15 nodes was simulated, with the connection matrix, traffic matrix for the network and utilizations within the SDH payloads different for each of these 100 networks. The mean and variance of the total network power consumption was calculated for each of the three node architectures as a function of the number of nodes in the network ranging from 6 to 15. Fig. 3 shows the energy savings using IP/SDH/WDM and GMPLS/ASON nodes compared to networks using IP/WDM nodes. Each point in Fig. 3 shows the mean and variance for the 100 simulated networks. Fig. 3 shows that with appropriate IP aggregation and electronic bypass, energy savings in the vicinity of 36% are achieved compared to a network with IP/WDM nodes. Furthermore, Fig. 3 shows that deploying GMPLS/ASON-enabled nodes in which optical bypass is also available in addition to IP aggregation and electronic bypass, we attain energy savings in the vicinity of 43% relative to IP/WDM. Fig. 4 displays the energy savings of GMPLS/ASON relative to IP/SDH/WDM. Although the network structures and traffic flows vary widely over the various scenarios, the results are seen to be relatively independent of the network details. We have also examined the impact on energy savings when the number of wavelengths arriving at the input of each source node is varied (from 10 to 1000), and the results are relatively consistent across the range of increasing number of input wavelengths.

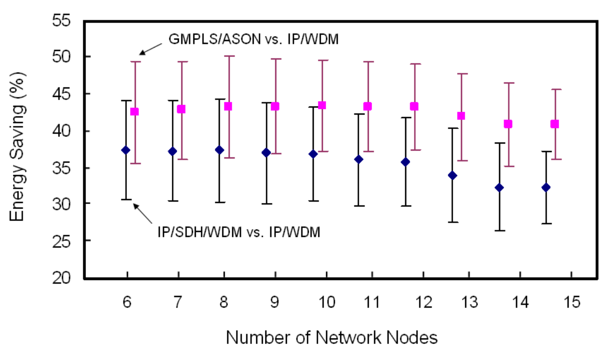

Fig. 3. Energy saving (GMPLS/ASON and IP/SDH/WDM vs. IP/WDM)

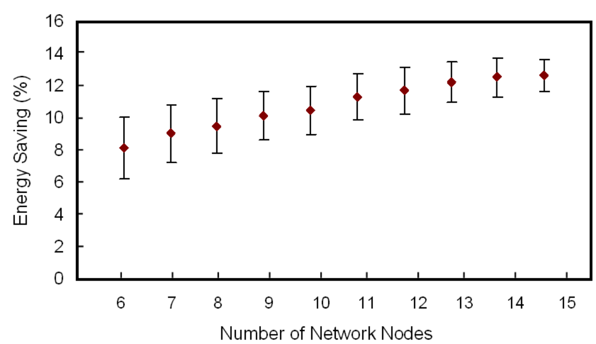

Fig. 4. Energy saving (GMPLS/ASON vs. IP/SDH/WDM)

4. Conclusions

We have compared the energy consumption of three node architectures, with different levels of multi-layer switching capability that can be deployed in optical IP networks. We show that GMPLS/ASON-enabled nodes that use a combination of IP aggregation, electronic bypass and optical bypass, can provide significant reductions in energy consumption in the network.

5. References

[1] J. Baliga, et al., "Energy Consumption in Optical IP Networks", *Journal of Lightwave Technology*, vol. 27, no. 13, pp. 2391-2403, Jul. 2009.

[2] R. S. Tucker, et al., "Evolution of WDM optical IP networks", *Journal of Lightwave Technology*, vol. 27, no. 3, pp. 243–252, Feb. 2009.

[3] M. Gupta and S. Singh, "Greening of the Internet," ACM SIGCOMM, Germany, Aug. 2003.

[4] M. Z. Feng, et al., "Reducing NGN Energy Consumption with IP/SDH/WDM", e-Energy 2010 Conference, Germany, Apr. 2010.

[5] M. Z. Feng, et al., "Energy Consumption in Intelligent Optical Networks", Green IT 2010 Conference, Singapore, Oct. 2010.

[6] R. Ramaswami and K. Sivarajan, "Optical Networks: A Practical Perspective", Morgan Kaufmann Publications, San Francisco, 1998.

[7] ITU-T G.707/Y.1322, "Network node interface for the synchronous digital hierarchy (SDH)", Jan. 2007.

[8] A. W. Moore, "Measurement-based management of network resources", PhD Dissertation, University of Cambridge, Apr. 2002.

[9] A. Odlyzko, "Data Networks are Lightly Utilized and will Stay that Way", *Review of Network Economics*, vol. 2, issue 3, Sep. 2003.

[10] O. Tamm, C. Hermsmeyer, and A. Rush, "Eco-Sustainable System and Network Architectures for Future Transport Networks", *Bell Labs Technical Journal*, vol. 14, issue 4, pp. 311-327, Feb. 2010.

[11] Infinera Data Sheets, Digital Optical System. [Online]. Available from http://www.infinera.com.

[12] Juniper Data Sheets, MX240 3D Universal Edge Router. [Online]. Available from http://www.juniper.net.