

Research Article

Energy Efficient Parallel Optical Burst Switching (POBS) Networks

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Abstract: Greening the Internet has recently become one of the main challenges for the research community due to economic and environmental reasons. In this context, optical technology can offer an energy efficient solution. As such it is interesting to examine Optical Burst Switching (OBS) network that provides an avenue for reducing energy consumption by significantly reducing the amount of header processing in the core switch. A variant of OBS, which is known as Parallel Optical Burst Switching (POBS), takes this concept further by transmitting bursts in two dimensions: the wavelength dimension and the time dimension. Consequently, this study investigates the power consumption in both the OBS and POBS technologies when used in the core network. The simulation results show that in the core network, the use of POBS can provide significant saving in energy as compared to the use of OBS. Furthermore, the use of POBS can lower the power consumption and the number of packets dropped in the network when appropriate parameter settings are used, particularly the burstification time and waveband granularity.

Keywords: Burstification Time (BT), energy, OBS networks, POBS networks, Two Dimensions Data Burst (2D-DB), waveband size (granularity)

INTRODUCTION

The rapid growth of the Internet has led to a tremendous increase in traffic load. However, this Internet growth may be restricted by power consumption rather than by bandwidth demand. Nowadays, the energy requirement of the Internet is a significant amount, estimated to be about 1-7% of total electricity consumption throughout the world (Tucker *et al.*, 2009). As the backbone of the Internet is mainly interconnected using fiber optic network, the use of Wavelength Division Multiplexing (WDM) has been proposed to increase the data rate of fiber optic communication. Consequently, many researchers are focusing on reducing power consumption in core WDM networks in their research works.

There are several proposals on the use of optical switching to exploit the advantages of WDM technology (Cai *et al.*, 2002; Ishio *et al.*, 1984). However, the development of such systems in optical networks is hindered by the limitations of the current optical technology, such as the lack of optical Random-Access Memory (RAM) and the lack of proven optical bit-level processing technologies (Amstutz, 1989; Lazzez, 2008). There are four switching paradigms for WDM networks: Optical Circuit Switching (OCS),

Optical Packet Switching (OPS), Optical Burst Switching (OBS), Parallel Optical Burst Switching (POBS). OBS and POBS technologies have been identified as an efficient and a viable solution compared to OCS and OPS (Abdelouahab *et al.*, 2011; Amstutz, 1989; Qiao and Yoo, 2000). OCS is inefficient in accommodating the bursty Internet traffic, while the implementation of OPS is hindered by the above mentioned limitations of the optical technology. On the other hand, OBS provides various size data burst to be transported optically over WDM systems in a cut-through manner and this allows for an efficient use of resources where there is no need for optical buffering as well as allowing for lower control overhead at intermediate nodes (Amstutz, 1989; Qiao and Yoo, 2000). Parallel Optical Burst Switching (POBS) is a variant of OBS model, takes this concept further by transmitting data bursts in two dimensions (Abdelouahab *et al.*, 2011).

For more efficient data transfer, it is inevitable that core network domain supports higher transmission rates and utilizes more energy. In this context, WDM Burst Switching (WDM-BS) strategy is found to possess energy efficient switching techniques that can reduce the switching processing, which occurs only once per

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burst with the burst being assembled from a number of packets (Kim *et al.*, 2010; Peng *et al.*, 2010; Zaiter *et al.*, 2012). The selection of architecture for the network depends on a number of factors such as power consumption, Capital Expenditure (CAPEX) cost and Operational Expenditure (OPEX) cost. In this study, we compare the WDM-BS (OBS and POBS) networks in terms of their power consumption in the core network.

METHODOLOGY

Energy saving techniques: In WDM networks, energy is mainly consumed by network switching and by the transmission equipment such as Optical Cross connects (OXCs), routers, transponders and amplifiers. Numerous research efforts emphasized on the reduction of power consumption in WDM networks because they support higher transmission rates. The energy efficiency of WDM networks can be further improved in three ways.

The first energy saving method is to turn off the underutilized core nodes. This can be achieved with the use of anycasting routing technique, whereby a probable destination is selected from a group of possible destinations for the purpose of minimizing power consumption in the network. This is done by the adoption of an OFF state for some of the nodes, to prevent traffic from being routed through them (Bathula and Elmirmhani, 2009a, b). In this approach, a longer path may be selected instead of the shortest path, if the longer path consumes less power. Unfortunately, this strategy may exponentially increase the blocking probability of the network as the load of network increases.

The second method, which is proposed in recent works (Kim *et al.*, 2010; Peng *et al.*, 2010; Zaiter *et al.*, 2012), recommends the increase in the size of Data Bursts (DB) in OBS networks. This is because with a larger burst size, the number of header required is fewer, which subsequently reduces the amount of header processing in the core switch. Another attractive feature of the OBS networks is the DB is forwarded in the optical domain without the need for Optical-to-

Electrical-to-Optical (OEO) converter (Jue and Vokkarane, 2005; Qiao and Yoo, 2000) and optical buffering (Xiong *et al.*, 2000).

The third method is by using Waveband Switching (WS) technique to merge multiple wavelengths (channel) into several waveband tunnels in order to reduce the number of required optical transmitting ports (Hou *et al.*, 2011; Shen and Tucker, 2009), hence reducing power consumption in the optical networks.

Only a small number of research works focused on energy savings. In terms of energy saving, the researchers in (Shen and Tucker, 2009) showed that energy can be saved as much as 45% in WDM networks. This is possible with the use of waveband grooming mechanism for transmission of lightpaths in the optical domain. For a medium-sized network, this is equivalent to savings of around 500 million US dollars each year. In Hou *et al.* (2011), the researchers proposed an integrated waveband grooming scheme to achieve port and energy savings by a combination of traffic grouping of both Internet-Protocol (IP) level and waveband-level. Meanwhile in Dharmaweera *et al.* (2012) the researchers explore and analyze the functionalities of power consumption of the most common waveband grouping policies. Consequently, this study formulates a power model for the calculation of power consumption of WDM Burst Switching (WDM-BS) networks, in order to study and compare energy efficiency of WDM-BS (OBS and POBS) networks.

Proposed power model: This section presents the proposed power model to measure power consumption in WDM-BS networks. In general, WDM Burst Switching (WDM-BS) network comprises of an optical edge and core nodes that are interconnected through WDM fiber links. Meanwhile, legacy systems are connected with the WDM-BS network through edge nodes as shown in Fig. 1.

Energy consumption of the components in WDM-BS network occurs in two different operations: switching and transmission. For switching, most of

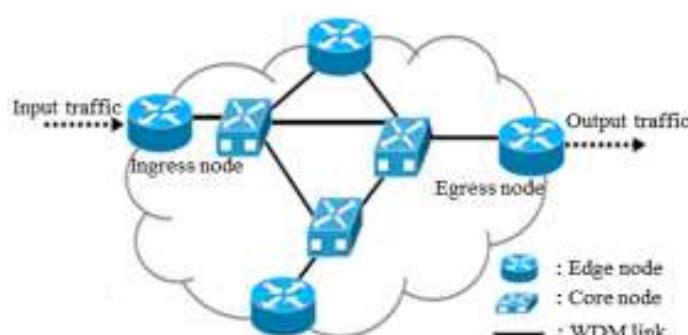


Fig. 1: The WDM-BS network main components

Table 1: Notations used in the power model

Notation	Meaning
$E_{I/O}$	Energy consumption of Input/Output (I/O) interface
E_{SW}	Energy consumption in switch fabric and switch control
E_{BU}	Energy consumption in buffers
E_{PB}	Energy consumption in power supply and blower
E_{FWD}	Energy consumption in forwarding engine
E_{RT}	Energy consumption in routing table and routing engine

the energy is consumed at the core and edge nodes. For transmission, if the system is implemented using WDM technology, energy is consumed at the transmitters, receivers, multiplexers, demultiplexers and amplifiers (in-line, pre- and post-amplifiers).

The physical topology of the network is denoted as $G = (E, C, L)$, where E is the set of network edge nodes, C is the set of network core nodes and L is the set of physical links connecting the edge and core nodes. It is assumed that each physical link is directed and composed of multiple Fibers (F); each fiber supporting W wavelength channels. The links connect nodes (edge or core) to each other by a bidirectional link. The

calculation of power consumption in a WDM-BS network is based on a power model that is designed to capture the energy consumption of commercially available subsystems. The topology is based on the core network of a simple model of the public Internet (Baliga *et al.*, 2007a). The energy parameters of the proposed power model are in J/bit and the notations for the power model are shown in Table 1.

The proposed power model is based on Cisco 12816 single-chassis router which has switching capacity of 1.28 Tb/sec with power consumption is 4.21 KW and Cisco CRS-1 multi-chassis router that has switching capacity of 92 Tb/sec and consumes approximately 1020 kW (Baliga *et al.*, 2007b). These two routers are used as edge and core nodes respectively. Table 2 shows the power consumption of these two routers.

Figure 2 illustrates the power model that estimates the power consumption in WDM-BS networks. The operation mode of this power model is the division of

Table 2: Power consumption of routers Cisco CRS-1 multi-chassis and 12816 single-chassis

Notation	Percentage of total power		Energy per bit	
	Single-chassis (%)	Multi-chassis (%)	12816 router (nJ/b)	CRS-1 router (nJ/b)
$E_{I/O}$	7	6.5	0.2	0.7
E_{SW}	10	14.5	0.4	1.6
E_{BU}	3.5	3.5	0.1	0.4
E_{PB}	35	33	1.0	3.6
E_{FWD}	33.5	32	1.0	3.5
E_{RT}	11	10.5	0.3	1.1
Total	100	100	3.0	10.9

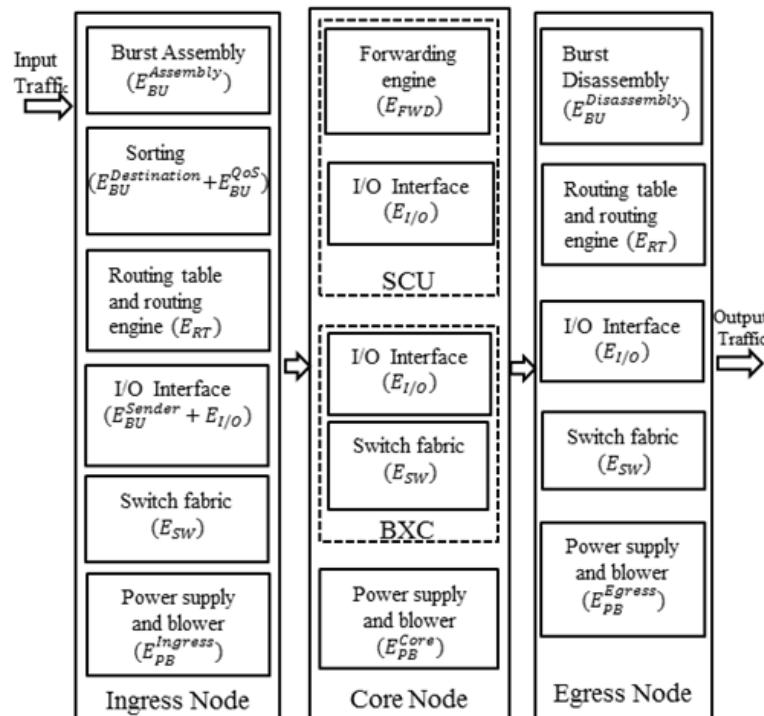


Fig. 2: Blocks of functions of nodes in WDM-BS network

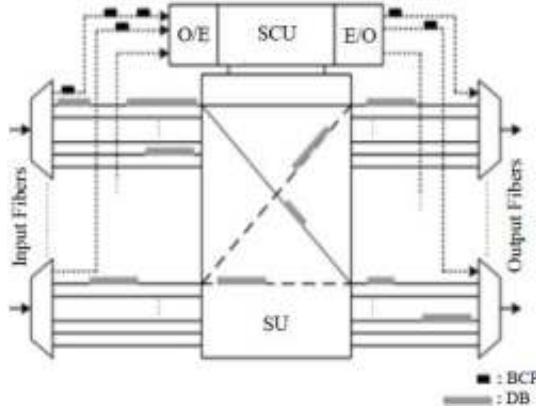


Fig. 3: Architecture of an OBS core node

the functions of the optical (edge and core) nodes in a network into sub-systems with the corresponding estimated energy consumption of each sub-system.

Four sets of buffers are required at the ingress nodes. Two of the sets are used for sorting packets according to destination and Quality of Service (QoS). The third buffer set is required for the assembly stage, where the sorted packets are assembled. The last buffer set is known as the output buffers, which are used to save the Data Bursts (DBs) in the case where no channel is available for transmission. In the edge nodes, the calculation of energy consumption in nJ/bit for ingress and egress nodes is as follows:

$$E_{bit}^{(Ingress)} = E_{I/O} + E_{BU}^{(Assembly)} + E_{BU}^{(Destination)} + E_{BU}^{(QoS)} + E_{BU}^{(Sender)} + E_{SW} + E_{RT} + E_{PB}^{(Ingress)} \quad (1)$$

$$E_{bit}^{(Egress)} = E_{I/O} + E_{BU}^{(Disassembly)} + E_{SW} + E_{RT} + E_{PB}^{(Egress)} \quad (2)$$

The energy consumed by the Cisco CRS-1 multi-chassis router is based on the transformed data unit of the packet size, while the energy consumption of WDM-BS core node depends on the transformed DB unit of the burst size. The bursts are assembled from a number of packets with header parsing and switching processing occurs only once per burst. Figure 3 illustrates the core node of OBS network, which consists of Switching Control Unit (SCU) and Switching Unit (SU). OBS provides all optical end-to-end paths by transmitting the DB in a solely optical domain, while the Burst Control Packet (BCP) is converted and processed in the electrical domain. The BCP is used for reserving the required transmission and switching resources for the corresponding DB along its path.

The consumption of energy in SCU and switching fabrics of SU can be reduced by increasing the number of packets in one burst, which is indicated in Eq. (4).

The number of packets in one burst (N_p) can be estimated by the division of the burst size in bytes (S_B) with the mean packet size in bytes (m_p). This is shown in Eq. (3):

$$N_p = \frac{S_B}{m_p} \quad (3)$$

Figure 2 shows that the total energy consumed at the core node of OBS networks depends on the energy consumption of its components, namely the I/O interface, the switching fabrics of SU and SCU, as well as the power supply and blowers. The relationship between the consumption of total energy at the core node and the energy consumption of its components, specified in nJ/bit, is indicated in the equation below:

$$E_{bit}^{(Core)} = E_{I/O}^{SU} + (E_{SW}^{SU} + (E_{I/O}^{SCU} + E_{FWD}^{SCU} + E_{BU}^{SCU})) / N_p + E_{PB}^{(Core)} \quad (4)$$

Where N_p is found in Eq. (3).

In an Optical Burst Switching (OBS) network, a data unit is known as a DB. DBs contain multiple packets which are switched in intermediate (core) nodes and the DBs pass through the nodes to the destination in a cut-through manner without storage requirement. Parallel Optical Burst Switching (POBS), which is a variant of OBS, is a new optical switching strategy for Ultra-Dense WDM (U-DWDM) (Abdelouahab *et al.*, 2011). However, each burst in POBS is built in a structure of Two Dimensions Data Burst (2D-DB), namely the time dimension and the wavelength dimension. Hence, the Data Sub Bursts (DSBs) are of a fixed size (m_{DSB}), this means the 2D-DBs are fixed in the time dimension, but vary in wavelength dimension. Consequently, the transmission of the burst in OBS network operates on one data channel (wavelength) as shown in Fig. 4a, while the transmission of the 2D-DB in POBS network operates on multiple wavelengths in one waveband as shown in Fig. 4b.

In the core node of POBS networks, the optical signal in the input fiber is demultiplexed into wavebands (B_1, B_2, \dots, B_M) using the Fiber-to-Band (FTB) demultiplexer, as shown in Fig. 5. Meanwhile, on the output side of BXC, the wavebands are multiplexed to the output fiber using the Band-to-Fiber (BTF) multiplexer. Hence, the wavelengths emanating from the ingress node with the same source-destination nodes are grouped together in a waveband for switching the multiple wavelengths by using a single port (Guo *et al.*, 2009; Huang *et al.*, 2007). Subsequently, the calculation of total energy consumption at the core node of POBS network, specified in nJ/bit, is shown in the equation below:

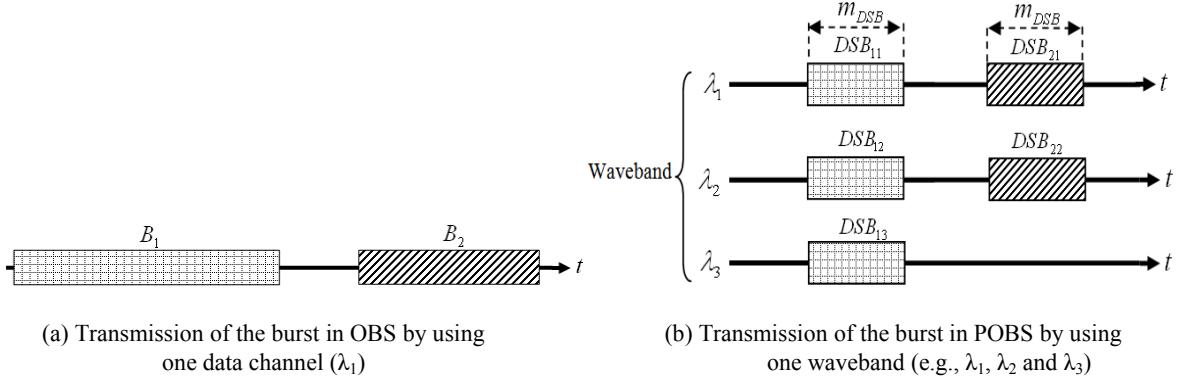


Fig. 4: Illustration for two different burst transmission mechanisms

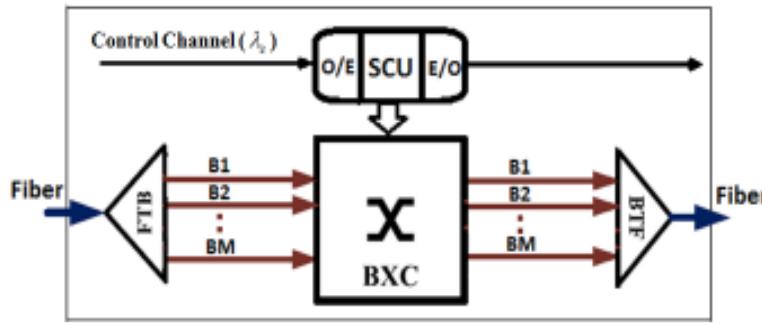


Fig. 5: Architecture of a POBS core node

$$E_{bit}^{(Core)} = E_{I/O}^{BXC} + (E_{SW}^{BXC} + (E_{I/O}^{SCU} + E_{FWD}^{SCU} + E_{BU}^{SCU})) / N_p + E_{PB}^{(Core)} \quad (5)$$

For this end-to-end grouping in Waveband Switching (WS) strategy, each port on the Band Cross-Connect (BXC) of the core node represents a waveband port and the switching is performed at the granularity of a WS to transient the 2D-DB simultaneously to the destination. In such a case, the number of required ports in the core node of POBS network can be reduced significantly; hence the energy consumption of the I/O interface is reduced by the ratio (x) as shown in Eq. (7). Equation (6) attempts to explain the relationship between the energy consumption of I/O interface in POBS and OBS networks that is reflected in the number of ports in both networks:

$$x = \frac{E_{I/O}^{BXC}}{E_{I/O}^{SU}} = \frac{F \times M}{F \times W} = \frac{M}{W} \quad (6)$$

where, F , M and W represent the number of fibers in one link, the number of wavebands in one fiber and the number of wavelengths in one fiber respectively. Consequently, the energy consumption of I/O interface of BXC ($E_{I/O}^{BXC}$) for core nodes in POBS network is reduced by the ratio x and subsequently the total energy consumption of the core node is reduced as well. The

value of $E_{I/O}^{BXC}$ in Eq. (6) can be substituted to Eq. (5) to generate Eq. (7):

$$E_{bit}^{(Core)} = x \times E_{I/O}^{SU} + (E_{SW}^{BXC} + (E_{I/O}^{SCU} + E_{FWD}^{SCU} + E_{BU}^{SCU})) / N_p + E_{PB}^{(Core)} \quad (7)$$

The total power consumption in the core nodes of WDM-BS network is as follows:

$$P^{(Core nodes)} = \sum_{j=1}^C E_{bit}^{(Core)} \times t_j \quad (8)$$

where, t_j represents the average bit rate in Mbps at the core node j . In the edge nodes, the total power consumption can be calculated as follows:

$$P^{(Edge nodes)} = \sum_{n=1}^E [E_{bit}^{(Ingress)} \times t_n^i + E_{bit}^{(Egress)} \times t_n^o] \quad (9)$$

where, t_n^i and t_n^o represent the input and output average bit rate in Mbps respectively at the edge node n . Finally, the total power consumption in WDM-BS network is calculated as follows:

$$P^{(Total)} = P^{(Edgenodes)} + P^{(Corenodes)} + A_r \times P^{(Amplifier)} \quad (10)$$

where, A_r represents the total number of amplifiers in the network while $P^{(\text{Amplifier})}$ represents the power consumption (in watts) of the amplifier respectively. The power consumption of the amplifier Erbium-Doped Fiber Amplifier (EDFA) is 12 W (Jirattigalachote *et al.*, 2011). The total number of amplifiers in the network is calculated as follows:

$$A_r = \sum_{i=1}^L [F_i \times (\frac{l_i}{d} - 1 + 2)] \quad (11)$$

where, F_i , l_i and d denote the number of fibers in the link i , the distance between two adjacent nodes on the link i and the span distance between two amplifiers respectively. The value 2 is used in Eq. (10) to cater for pre- and post-amplifiers (Zaiter *et al.*, 2012).

SIMULATION AND RESULTS

In this section, we compare the power consumption of different types of WDM-BS (OBS and POBS) networks. To test POBS networks, we have developed a POBS simulator by extending the open-source NCTUns-6.0 network simulator (Wang *et al.*, 2010). Hence, to simulate POBS, the NCTUns-6.0 modules that include Optical Burst Switching (OBSW) and Optical Burst Wavelength Assignment (OBWA) modules are replaced with Parallel Optical Burst Switching (POBSW) and Parallel Optical Burst Wavelength Assignment (POBWA) modules, respectively. The POBWA module is used to perform the functions of the edge (Ingress/Egress) nodes of the POBS networks. Meanwhile, the POBSW module is used to carry out the POBS core nodes functions.

Simulation setup: We use the National Science Foundation Network (NSFNET) topology (link distances in km) as shown in Fig. 6 for our simulations study. Table 3 shows the values of network parameters used to obtain the simulation results in WDM-BS networks.

Table 3: Various simulation parameters

Parameter	Value
Simulator	NCTUns-6.0
Burstification Time (BT)	4 usec, 2 usec
BCP processing time	2 ns
Reservation protocol	JET
Number of FDL	0
Bandwidth/channel	1 Gbps
Data Sub-Burst (DSB) length	15360 KB
Number of edge nodes	10
Number of core nodes	14
Total number of channels/fiber	64
Number of waveband/fiber	3, 6

The NSFNET topology as shown in Fig. 7 consists of 14 switches (core nodes), 10 routers (edge nodes), 10 personal computers and 21 bi-directional links between core nodes. In each link, there are 64 channels (60 channels for DBs and 4 channels for BCPs) and the data rate of each channel is 1 Gbps. In the simulation, every host generates User Datagram Protocol (UDP) traffic and the traffic is transmitted to a random host. There are ten UDP connections. The packets arrive at each ingress node according to an independent Poisson process with an arrival rate λ and the connection holding times are negatively exponentially distributed μ^{-1} ; consequently, the network load is λ/μ Erlang. The core nodes do not support any kind of buffering and wavelength conversion. In addition, the routing algorithm is based on a fixed shortest path to destination and all switching nodes use FIFO queuing strategy for BCPs. Table 2 tabulates the amount of energy consumed for each function of the edge and core nodes except for power supply and blowers. The calculation for power consumption of power supply and blowers is to multiply the percentage of total power for power supply and blowers obtained from Table 2 with the total energy consumption of the node. For example, the energy consumption of power supply and blowers of the egress node can be calculated as follows:

$$E_{PB} = (E_{I/O} + E_{BU} + E_{RT} + E_{SW} + E_{PB}) * 0.35$$

$$E_{PB} = ((0.2 + 0.1 + 0.3 + 0.4) * 0.35) / (1 - 0.35)$$

$$E_{PB} = 0.5nJ/bit$$

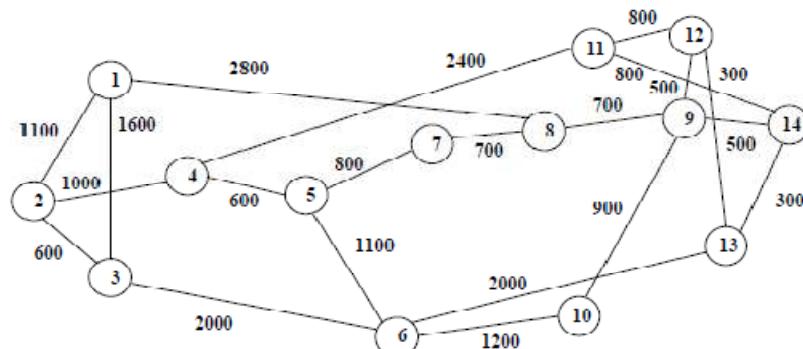


Fig. 6: The NSF network composed of 14 nodes and 21 bi-directional links

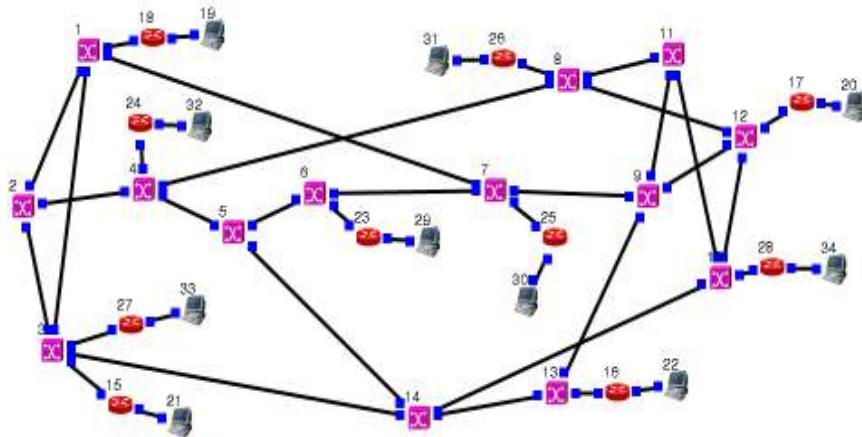


Fig. 7: NSFNET with 14 core nodes to simulate POBS network (NCTUns 0.6 screenshot)

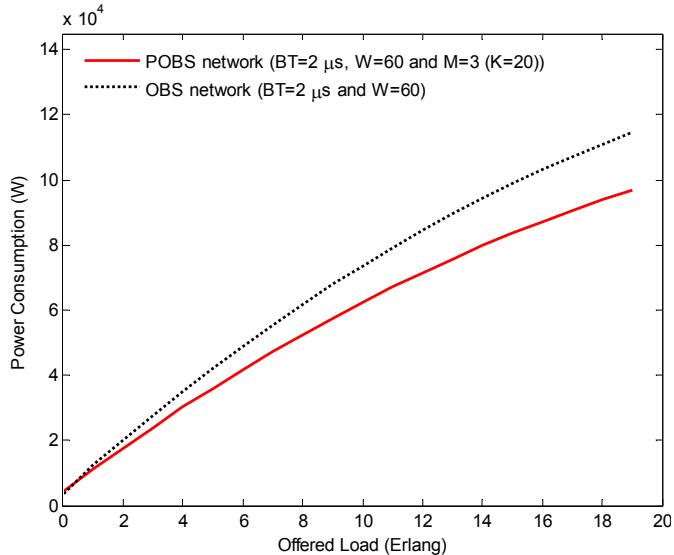


Fig. 8: Comparison of power consumption in the NSFNET for OBS and POBS networks under varying traffic loads

The values of energy consumption of power supply and blowers in nJ/bit of core and ingress nodes are 3.2 and 0.7, respectively.

Power consumption comparison: This sub-section validates the proposed power model by making comparisons between power consumption in the OBS network and POBS network. The power consumption is calculated for the OBS network with the parameters given in Table 3 with a fixed BT of DB of 2 μ sec and span distance between two amplifiers 80 km (Jirattigalachote *et al.*, 2011). The calculation is repeated for POBS network with the same parameters given in Table 3 and with the number of wavebands is set to 3 per fiber ($M = 3$). This means that the waveband granularity (K) is 20 wavelengths per waveband ($K = 60/3 = 20$).

Figure 8 shows the simulation results. It is found that at high-traffic load, power consumption of the OBS

network is almost 15% more than the power consumption of the POBS network.

The following is a discussion of the comparison of the simulation results of the power consumption for various WDM-BS networks. One of the findings is that the POBS network is more energy-efficient than the OBS network in the core (backbone) networks. This is evident as the switching strategy of POBS network has significantly reduced the number of port counts. This strategy uses only a single port of Waveband Switching (WS) (group of wavelengths) instead of using multiple ports where each wavelength is allocated one port. As a consequence, power consumption of the I/O interfaces in the core node is reduced. In addition, an increase in the BL of WDM-BS network decreases the power consumption of the WDM-BS network. This is because the burst switching strategy provides an effective energy-saving solution by reducing the amount of header processing in the core switch significantly.

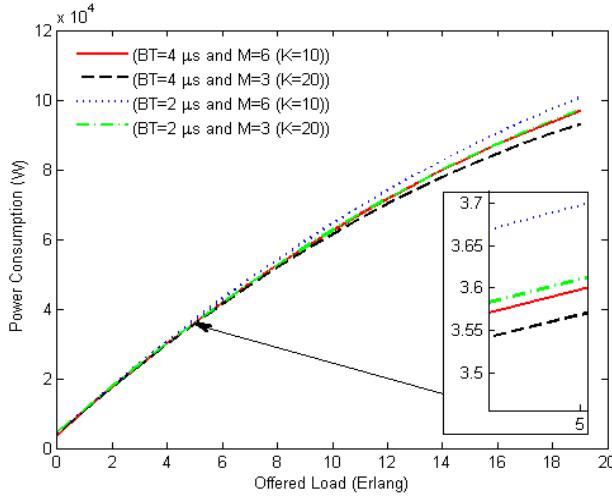


Fig. 9: Power consumption vs. network load for the POBS network in NSFNET

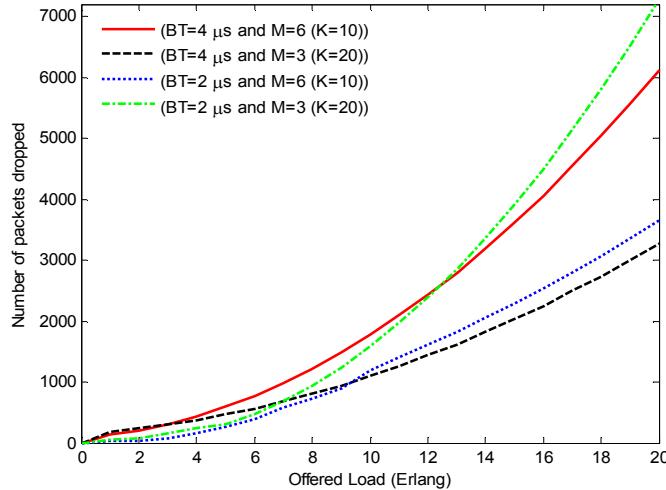


Fig. 10: Total number of packets dropped vs. network load for the POBS network in NSFNET

Effects of the POBS network parameters on power consumption and performance: The findings in the sub-section above have indicated that the POBS network is more energy-efficient than the OBS network. It is necessary to investigate the POBS network further for the purpose of enhancing the performance of the POBS network. Therefore, this sub-section investigates the effects of the parameter setting, particularly, the waveband size (waveband granularity) and the Burstification Time (BT) on the power consumption and the performance of the POBS network. The NCTUIns-6.0 simulator, NSFNET topology and traffic load scenario as illustrated in sub-section of simulation setup with the parameters listed in Table 3 are used for the calculation of power consumption and performance of the POBS network.

Effects of the POBS network parameters on power consumption: The simulation experiment is repeated

for the calculation of power consumption of POBS network in four cases. Each case combines one value of BT (2 or 4 μ sec) with a fixed value of waveband granularity (K) with 10 or 20 channels in one waveband. Figure 9 shows the impact of BT and waveband granularity on the power consumption of the POBS network with the increase in traffic load.

The results show that as BT is increased from 2 to 4 μ sec with a fixed waveband granularity of 10 or 20, there is a decrease in total power consumption in the POBS network. When the waveband granularity is increased from 10 to 20 channels in one waveband with a fixed BT of 2 or 4 μ sec, the total power consumption in POBS network continues to indicate a reduction in power consumption. From this result, it can be deduced that the total power consumption in POBS network can be minimized by using a BT of high value (4 μ sec) and high granularity in waveband (20 channels per waveband).

Performance evaluation of POBS network: This sub-section evaluates the performance of the POBS network. To determine the performance of this network, it is necessary to investigate the impact of waveband granularity and BT on the number of packets dropped in the network. The NSFNET topology is used for the calculation of the number of packets dropped with increasing traffic load. The values given for BT and waveband granularity are similar to the four cases as described in sub-section above. The results are illustrated in Fig. 10. It is evident that when BT is high (4 μ sec), the minimum number of packets dropped in the network is recorded when the granularity is high, at 20 channels per waveband. When BT is low (2 μ sec), the minimum number of packets dropped in the network is recorded when the granularity is low, at 10 channels per waveband. Consequently, it can be deduced that the number of packets dropped in POBS network can be minimized by designing a network with high BT (i.e., 4 μ sec) and high waveband granularity (i.e., 20 channels per waveband). Furthermore, this configuration does not only minimize the packets dropped, but it also minimizes the power consumption as well.

CONCLUSION

This study presents the power model to measure power consumption in WDM Burst Switching networks and the simulation results clearly indicate that POBS network is more energy-efficient than OBS networks. The POBS networks are based on the transmission of burst in two dimensions (wavelength dimension and time dimension), while switching is performed at the granularity of a Waveband Switching (WS) with end-to-end grouping strategy for the reduction in the number of lightpaths and switching ports. These features can reduce the amount of energy required by the I/O interface in the core nodes, hence allowing for a significant reduction in energy consumption of the network. Based on the simulation results, it can be concluded that both power consumption and the number of packets dropped in POBS network can be minimized when the values of Burstification Time (BT) and granularity of waveband are high.

REFERENCES

- Abdelouahab, A., F. Abbou and H. Ewe, 2011. Parallel Optical Burst Switching (POBS) for Ultra-Dense WDM (U-DWDM) systems. Proceeding of International Conference on the Information Technology and Multimedia (ICIM).
- Amstutz, S.R., 1989. Burst switching-an update. *IEEE Commun. Mag.*, 27(9): 50-57.
- Baliga, J., R. Ayre, K. Hinton and R. Tucker, 2007a. Photonic switching and the energy bottleneck. Proceeding of the Photonics in Switching, pp: 125-126.
- Baliga, J., K. Hinton and R.S. Tucker, 2007b. Energy consumption of the Internet. Proceeding of the Joint International Conference on Optical Internet, 2007 and the 2007 32nd Australian Conference on Optical Fibre Technology (COIN-ACOFT 2007), pp: 1-3.
- Bathula, B.G. and J.M. Elmirghani, 2009a. Energy efficient Optical Burst Switched (OBS)networks. Proceeding of the IEEE GLOBECOM Workshops, pp: 1-6.
- Bathula, B.G. and J.M. Elmirghani, 2009b. Green networks: Energy efficient design for optical networks. Proceeding of the IFIP International Conference on Wireless and Optical Communications Networks (WOCN'09).
- Cai, J.X., M. Nissov, C.R. Davidson, A.N. Pilipetskii, G. Mohs, H. Li and D.G. Foursa, 2002. Long-haul 40 Gb/s DWDM transmission with aggregate capacities exceeding 1 Tb/s. *J. Lightwave Technol.*, 20(12): 2247-2258.
- Dharmaweera, N., R. Parthiban and Y.A. Sekercioglu, 2012. Waveband grouping policies for reducing energy consumption in optical internet backbone networks. Proceeding of the IEEE Region 10 Conference (TENCON 2012-2012), pp: 1-6.
- Guo, L., X. Wang, W. Ji, W. Hou and T. Yang, 2009. A new waveband switching method for reducing the number of ports in wavelength-division-multiplexing optical networks. *Opt. Fiber Technol.*, 15(1): 5-9.
- Hou, W., L. Guo and X. Wei, 2011. Robust and integrated grooming for power-and port-cost-efficient design in IP over WDM networks. *J. Lightwave Technol.*, 29(20): 3035-3047.
- Huang, Y., J.P. Heritage and B. Mukherjee, 2007. A new node architecture employing waveband-selective switching for optical burst-switched networks. *IEEE Commun. Lett.*, 11(9): 756-758.
- Ishio, H., J. Minowa and K. Nosu, 1984. Review and status of wavelength-division-multiplexing technology and its application. *J. Lightwave Technol.*, 2: 448-463.
- Jirattigalachote, A., C. Cavdar, P. Monti, L. Wosinska and A. Tzanakaki, 2011. Dynamic provisioning strategies for energy efficient WDM networks with dedicated path protection. *Opt. Switch. Netw.*, 8(3): 201-213.
- Jue, J.P. and V.M. Vokkarane, 2005. Optical Burst Switched Networks. Springer, Optical Networks Series 2005.
- Kim, Y., C. Lee and J.K.K. Rhee, 2010. Analysis of energy consumption in packet burst switching networks. Proceeding of the 9th International Conference on Optical Internet (COIN), pp: 1-3.
- Lazzez, A., 2008. Optical burst-switched networks: Design, modeling and performances analysis. Ph.D. Thesis, University of Carthage, Tunisia.

- Peng, S., K.J. Hinton, J. Baliga, R.S. Tucker, Z. Li and A. Xu, 2010. Burst switching for energy efficiency in optical networks. Proceeding of the 2010 Conference on (OFC/NFOEC) Optical Fiber Communication (OFC), Collocated National Fiber Optic Engineers Conference, pp: 1-3.
- Qiao, C. and M. Yoo, 2000. Choices, features and issues in optical burst switching. *Opt. Netw. Mag.*, 1(2): 36-44.
- Shen, G. and R.S. Tucker, 2009. Energy-minimized design for IP over WDM networks. *IEEE/OSA J. Opt. Commun. Netw.*, 1(1): 176-186.
- Tucker, R.S., R. Parthiban, J. Baliga, K. Hinton, R.W. Ayre and W.V. Sorin, 2009. Evolution of WDM optical IP networks: A cost and energy perspective. *J. Lightwave Technol.*, 27(3): 243-252.
- Wang, S.Y., C.L. Chou, C.C. Lin and C.H. Huang, 2010. The protocol developer manual for the NCTUng 6.0 network simulator and emulator. National Chiao Tung University, Tajwan.
- Xiong, Y., M. Vandenhoute and H.C. Cankaya, 2000. Control architecture in optical burst-switched WDM networks. *IEEE J. Sel. Area. Comm.*, 18(10): 1838-1851.
- Zaiter, M. J., S. Yussof, A. Abdelouhab, C.L. Cheah and A. Saher, 2012. On the energy consumption in Optical Burst Switching (OBS) networks. Proceeding of the IEEE Symposium on Computer Applications and Industrial Electronics (ISCAIE, 2012), pp: 233-236.