Digital Subcarrier Optical Networks (DSONs)[1]

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ABSTRACT

Energy efficient networks are increasingly becoming a desirable feature in today's market. Both the number of users and the average amount of data traffic generated by each user continue to grow, requiring more powerful network routers and switches, which in turn dissipate large amount of electric power to operate. This problem is in part circumvented by deploying all-optical wavelength division multiplexing (WDM) solutions in the network, which eliminate any electronic processing of the in-transit data at the intermediate network nodes by dedicating a path of light (a wavelength) across the network to directly interconnect two edge nodes. However, the all-optical approach is only suitable when the average quantity of traffic to be exchanged by two edge nodes is sufficient large to warrant one entire (or many) dedicated wavelength(s). Considering that optical transmission rates are moving up from today's 10 Gbps to 40, 100 and even 160 Gbps per wavelength, the fraction of edge nodes that exchange such amount of traffic is not (surprisingly) limited, as many of the edge node pairs would require only sub-wavelength connectivity.

Sub-wavelength connectivity is today offered by either Optical Transport Network (OTN) or Multi Protocol Label Switching with Transport Profile (MPLS-TP). These solutions run on top of the WDM layer. Unfortunately, the amount of required electronic processing in these solutions is such that an order of magnitude higher power consumption results compared to all-optical networks. Part of this extra power consumption is due to the electronic buffering of the in-transit data at the intermediate nodes.

This paper points to an alternative solution to achieving sub-wavelength bandwidth assignment to edge node pairs, which eliminates the need for data buffering at the intermediate nodes. Sub-wavelength channels or circuits are creating by using spectrally efficient orthogonal frequencies in each wavelength, with each frequency carrying a fraction of the wavelength bandwidth. By assigning one or more such frequencies to one edge node pair, an end-to-end sub-wavelength circuit is created. At the intermediate nodes, incoming frequencies are switched to outgoing frequencies via specially designed frequency selective switches or cross-connects. The power consumption required to switch frequencies in and out is estimated to be only a fraction of the power dissipated by current transport solutions, thus mitigating the energy consumption struggle when assigning sub-wavelength capacities to edge nodes.

Keyword: energy efficiency, orthogonal frequency division multiplexing, transport network, circuit switched network, optical flow.

1. INTRODUCTION

Telecommunication networks rely on multiple technologies. 1) The Internet Protocol (IP) routers offer packet switching control, achieving efficient statistical multiplexing of the available network resources across the user population. 2) The optical layer cross-connects (OXC) offer wavelength (or lambda) switching, i.e., light-paths or circuits of light can be switched end-to-end across the optical network layer. The capacity of the optical circuit is fixed and set to the transmission rate available at the physical (fiber optics) layer, e.g., 10Gbps, 40Gbps, 100Gbps. 3) Traffic grooming is provided by a third intermediate (transport network) layer placed between the IP and the optical layer to offer fine bandwidth granularity to routers links. For example, Optical Transport Network (OTN) (such as SONET/SDH) digital cross-connects (DXC) offer time division multiplexing (TDM) circuit switching, i.e., end-to-end circuits with sub-wavelength bandwidth granularities can be provisioned to interconnect routers or other add-drop multiplexing devices.

From a power consumption stand point, electronic processing of transported data which is required in both OTN DXC and IP/MPLS router consumes significantly higher power compared to optical circuit switching performed by OXC. So in current telecommunication networks, higher energy efficient switching technology has

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to sacrifice the channel granularity and data rate flexibility. In recent years, network researchers proposed solutions that reduce power consumption in a number of network architectures. A comprehensive summary of these efforts can be found in [1]. The most effective of these solutions targets IP/MPLS routers, recommending a reduction of packet rate processed in the router or even the complete switch-off of some IO cards at day time when the offered load is relatively low in the network [2]. In the optical domain, energy consumption is already relatively low compared to the electronic layer, and can be further reduced by switching off an entire wavelength channel, or even the full set of wavelength channels of a single fiber, which allows the in-line fiber amplifiers to be switched off during low traffic periods [3], [4]. However, these recent solutions do not address the power consumption that takes place in the transport network. In fact they do not even reduce the power consumption that is required to maintain the wavelength transmission link between fully functional nodes, besides offering the transmission card switch on/off option already mentioned.

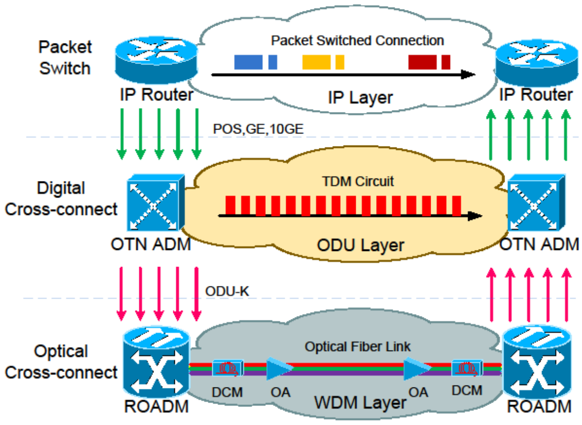

Fig. 1. Today's network structure: IP + OTN + WDM

In this paper, a new transport layer solution – Digital Subcarrier Optical Network (DSON) is introduced for the first time. DSON can offer sub-wavelength granularity transmission and switching, which facilitates to create end-to-end connections with flexible data rates between edge node pairs. Meanwhile, due to discarding the electronic buffering and digital cross-connect in the intermediate nodes, the energy consumption required by DSON is only a fraction of extant solutions, e.g., OTN/SONET/SDH. Orthogonal Frequency Division Multiplexing (OFDM) is one option to be used in DSON to perform subcarrier multiplexing and switching operation. It is the first time that OFDM is used to achieve high speed sub-wavelength switching in the transport network, although industry leaders are adopting OFDM in high-speed optical transmission. For example, the Spectrum-Sliced Elastic Optical Path Network (SLICE) project [9] uses optical cross-connects to perform switching operations, while enabling flexible data rate to be used on each wavelength with improved data rate granularity in comparison to the current WDM-based wavelength-routed optical path network. OFDM is only used in SLICE to obtain the desirable transmission rate for a given optical circuit. One critical enabling technology for SLICE is bandwidth-variable wavelength selective switches (WSS). Both the number of channels supported in one fiber and the switching time are quite limited by the MEMS or liquid crystal technologies required to build the WSS. Unlike SLICE, in DSON, Radio Frequency (RF) crossbar circuit-switch and advanced Digital Signal Processing (DSP) algorithms are used to perform the desired cross-connection. Therefore, as many as 4000 channels per fiber and switching time in the sub-millisecond range are expected to be within reach.

DSON is a promising transport layer solution, which can support current transport layer applications, e.g., GE, ODU1, etc., and HyperFlow applications [10]. OFDM-based Passive Optical Network (PON) is also candidate architecture for the future high speed optical access networks [11]. By means of DSON and PON, high speed end-to-end circuits can be created even between residential user and Data Centre (DC) in future Internet. Furthermore, advanced DSP algorithms also allow the compensation of various transmission impairments such as chromatic dispersion and Polarization Mode Dispersion (PMD).

2. THE ORTHOGONAL FREQUENCY TRANSPORT NETWORK (DSON)

According to different switching technologies applied with, today's telecommunication network can be divided into three layers (Fig. 1): packet switching layer, TDM based digital cross-connect switching layer, and optical cross-connect switching layer. Not like TDM techniques, such as SONET and SDH, OFDM based Frequency Division Multiplexing (FDM) is one option which can be used in DSON to perform data transmission and cross-connection. Solutions based on FDM were widely used in the pre-SONET/SDH era, to multiplex transport channels together using spectral diversity. These transport solutions were then abandoned due in part to their low spectral efficiency and with the advent of TDM and synchronous transmission techniques. Another problem of traditional FDM or Subcarrier

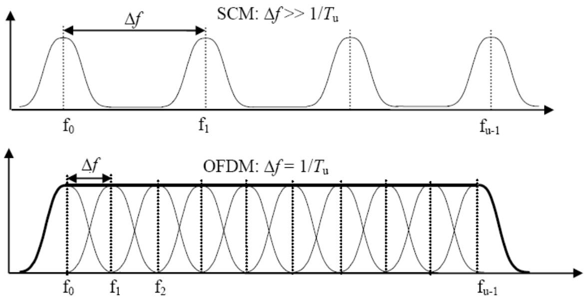

Fig. 2. Similarity and difference between an SCM (top) and an OFDM system (bottom)

Multiplexing (SCM), being analog systems, is their susceptibility to accumulated waveform distortion and crosstalk. For these reasons FDM is not a competitive solution for large-scale optical networks. As an extension of SCM, OFDM introduces orthogonality between adjacent subcarrier channels, so that no guard band is required between adjacent channels, which maximize optical bandwidth efficiency. In a conventional SCM system spectral overlap is not allowed and adjacent subcarrier channels must be separated by a guard band. With binary modulated optical channels, the SCM bandwidth efficiency is typically below 50%. In recent years, the rapidly advancing CMOS electronics has enabled ADC, DAC, and DSP to be performed on high frequency signals. Most of the once-analog-domain functions of SCM systems can now be performed in the digital domain, such as subcarrier generation, multiplexing, mixing, and de-multiplexing. High precision frequency and phase control of digitally generated subcarriers is now enabling OFDM to be applied at optical transmission rates. As illustrated in Fig. 2, in an OFDM system, frequency spacing between subcarriers is equal to the data rate carried by each channel, and spectral overlap is allowed. By adoption of OFDM, one wavelength bandwidth in WDM network can be divided into multiple sub-wavelengths in DSON, so that it provides high spectral efficiency and flexible granularities, and one (or more) sub-wavelengths bandwidth can be assigned to edge node pairs for different upper layer applications.

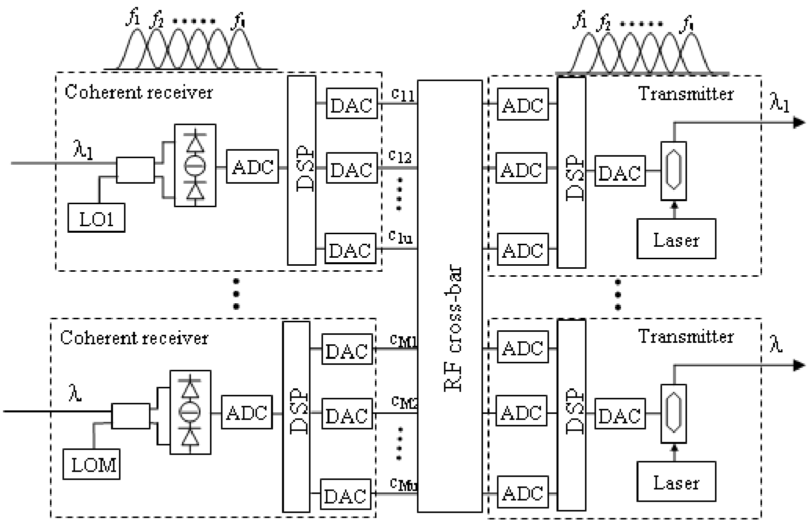

Fig. 3. Node architecture in DSON

By virtue of the distinct digital subcarrier channels (each with sub-wavelength bandwidth granularity) carried by the optical signal, Digital Subcarrier Cross-connect (DSXC) operations of such channels are facilitated as follows. The DSON operation principle is illustrated in Fig. 3, where each wavelength signal carries *u* orthogonal subcarrier channels [8]. An OFDM receiver detects the incoming optical signal at λ_i and decomposes it into *u* baseband RF outputs c_{i1}, c_{i2}, … c_{iu}. Data packets on each subcarrier are arranged such that they all have the same destination node, and therefore, each subcarrier channel does not have to be decomposed into individual packets (which would require buffering and re-grouping operations as in a TDM cross-connect). After the crossbar switch, each subcarrier is assigned a new frequency (like wavelength conversion) and regrouped according to the destination, and modulated on to an outgoing wavelength signal. So that DSON can be used as an alternative to the OTN/SONET/SDH network to support the application which requires sub-wavelength bandwidth from upper layer (Fig. 4).

In a similar manner to OXC, DSON only needs to set up static paths across a crossbar switch, thus power consumption is minimal. Table 1 reports some typical examples of power consumption for some major equipment in different layer of transport network. In comparison to TDM cross-connect and packet switching cross-connect, DSON require much less electric power. That's because DSON does not buffer in transit information, which instead is the case for both OTN and MPLS-TP.

Optical cross-connect switch in WDM layer (ROADM) is the most energy efficient equipment in today's network. However due to the super high bandwidth granularity (more than 10Gpbs) and wavelength continuity constraint, optical cross-connect switch cannot provide flexible data rates and wavelength conversion capability. In these cases, electronic processing is needed on top of WDM network to provide more flexibility to requirements which need sub-wavelength transmission and switching in the application layer. The comparison between DSON and WDM network requires some additional discussion, provided in the next section.

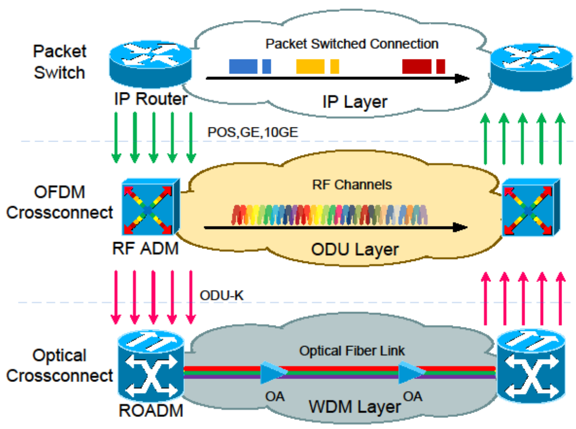

Fig. 4. Proposed DSON structure

3. CONSUMPTION COMPARISON WITH WDM NETWORK

Table 1. Equipment power consumption

	Capacity	Power	W/Gb
Core IP Router [1]	92Tb/s	1020 kW	11
SONET ADM [1]	95Gb/s	1.2 kW	12.6
WDM transponder [1]	40Gb/s	73W	1.8
DSP Agile Engine [2]	46Gb/s	10W	0.2
OTN OXC [7]	95Gb/s	1.017kW	10.7
DSON single stage [8]	28.8Tb/s	51.8kW	1.8
WDM ROADM [7]	800Gb/s	720W	0.9

In today's Internet, IP routers are deployed to carry different applications on the edge of transport networks, which require sub-wavelength types of capacity. Optical cross-connect can achieve best energy efficiency in current optical transport network as mentioned in Section 2, while the bandwidth granularity flexibility is not good. The all-optical approach is only suitable when the average quantity of traffic to be exchanged by two edge nodes is sufficient large to warrant one entire (or many) dedicated wavelength(s). In current WDM network, wavelength channel rates are moving up from 10 Gbps to 40, 100 and even 160 Gbps per wavelength. Unless two edge routers have a massive amount of traffic to exchange, it is likely that sub-wavelength capacities are going to be the majority of the solutions to support upper layer applications. In this section, integer linear programming (ILP) formulation for point-to-point requests is developed to compare the properties of WDM network (without wavelength converters) and DSON. The aim of this comparison is to check the difference between WDM network and DSON with the respect of granularity flexibility and power consumption. WDM network can provide one single wavelength or more to the request from source to destination. On the contrary, DSON can provide sub-wavelength granularity to the request depending on the bandwidth needed by the application. Let *F* be the number of fibers reaching the network node, *W* the wavelengths per fiber, and *O* the number of orthogonal frequencies (sub-wavelength channels) per wavelength. In WDM network, only *W* channels can be created in one fiber and assigned to the requests. In DSON, $W \cdot O$ sub-wavelength channels can be created, however each channel can only support one-*Oth* bandwidth of a wavelength. Such that the total bandwidths provided by WDM network and DSON in one fiber are the same, but DSON can provide smaller granularity than WDM network. One-hop connection between source and destination is created for each request in WDM network or DSON, as long as there are enough bandwidth resources in the network. In this case, the transmission would stay in transport layer. However, sometimes the one-hop connection cannot meet the constraints in the physical layer (e.g. wavelength continuity constraint), then an upper layer device (e.g. IP router) need to be used. This is also the strategy used in current IP-Over-WDM network. The utilization of upper layer equipments may definitely increase the flexibility of the WDM network, but meanwhile it also increases the total power consumption for the demand traffic. The objective is to accommodate as many requests as possible in the network. In this simulation, to the purpose of a fair comparison, only the power consumption for the traffic load (W/Gb) in the network is counted, that means the idle components (boards, interfaces, etc.) can be switched off in the network. Because of the scalability issue for ILP solver, NSF 14 nodes topology is used for this simulation. It is assumed that every pair of adjacent nodes in the topology are connected by a pair of fibers, and in each fiber $W = 2$ and $O = 4$. For this small sized network, in DSON, one single RF chip is powerful enough to handle all frequencies (sub-wavelengths) in the fiber. Based on the power consumption for different kinds of transport equipments in Table 1, it is assumed that for WDM network the power consumption is 1W/Gb, for DSON the power consumption is 2W/Gb, and for core IP router, the power consumption is 10W/Gb. The simulation results are shown in Table 2. The load in the demand matrix is increasing from 10 LSPs to 60 LSPs (one LSP indicates one point-to-point unit bandwidth requirement). Source and destination nodes of LSPs are randomly chosen in the NSF 14 nodes topology. For each scenario (same quantity of traffic load), ten different cases are simulated, and results are averaged. In Table 2, E[one-hop LSPs] indicates the averaged accepted one-hop requests, $\#LSP_O/\#LSP_W$ indicates the ratio between accepted one-hop requests in DSON and WDM network. P_{Trans} indicates the power consumption only from the transport layer (DSON or WDM network). P_{Total} indicates the power consumption by the transport layer and IP layer. In this case the one-hop constraint is relaxed, so that more requests can be accepted in the network.

In a light loaded network (e.g. the number of LSPs is equal to 10), WDM network shows its advantage (lower power consumption than DSON with same traffic load). But in a heavy

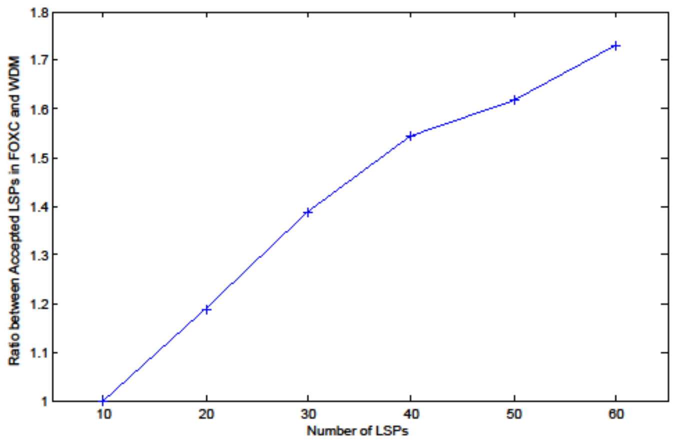

Fig. 5. Comparison of Flexibility between WDM and DSON

loaded network (e.g. number of LSPs is equal to 40 or more), the power consumption in DSON is less than half of that in IPoWDM network. That's because in order to support more traffic load, WDM network has to transmit the traffic to the IP routers. In this case, IP routers are used to break the on-hop constraint. In Fig. 5, without the help of IP routers, with the increasing of the number of LSPs (demanding traffic load), more and more LSPs are blocked in WDM network, while DSON still keeps a good flexibility to accommodate new requests. That's because WDM network cannot offer sub-wavelength granularity for requests, while DSON can handle sub-wavelength requests. So that DSON provides more flexible granularities than WDM network and accommodates more requests with fairly low power consumption.

4. CONCLUSION AND OPEN CHALLENGES

To design an energy efficient telecommunication network is a hot research topic. In this paper, Digital Subcarrier Optical Network is proposed for the first time, which provides sub-wavelength bandwidth granularity and eliminates the need for data buffering at the intermediate nodes in the network. DSON has the potential to offer thousands of channels per fiber, sub-millisecond switching time, and less than 2W/Gb power consumption. Compared with extant technologies in transport network, this DSON will significantly decrease the power consumption, meanwhile maintaining good spectral efficiency, channel granularity, data rate flexibility, as well as circuit switching speed.

While the proposed DSON network shows many advantages, especially the energy efficiency, it also presents new challenges. To implement DSON to real world transport network, DSON should be designed to be scalable, e.g., F = 9, W = 40 and O = 100, the total number of subcarrier channels available at the node ($F \cdot W \cdot O = 36{,}000$). Accounting for the designed DSON, routing and orthogonal frequency assignment (RFA) algorithms are needed to choose which subset of network resources (subcarrier channels) must be reserved for the incoming unicast or multicast requests. Although there are still many open challenges for DSON, It has shown promising potential to be an alternative transport network to OTN/SONET/SDH, and support different kinds of applications in Internet, e.g., GE, circuit-on-demand, and HyperFlow applications.

Table 2. Consumption comparison between WDM Network and DSON (W = 2 and O = 4)

#LSPs	Type	E[one-hop LSPs]	$\#LSP_O/\#LSP_W$	P_{Trans}	P_{IP}	P_{Total}	P_O/P_W
10	WDM	10.0	1.00	10.0	0.0	10.0	2.00
10	DSON	10.0	-	20.0	0.0	20.0	-
20	WDM	16.8	1.19	16.8	32.0	48.8	0.82
20	DSON	20.0	-	40.0	0.0	40.0	-
30	WDM	21.6	1.39	21.6	94.0	115.6	0.52
30	DSON	30.0	-	60.0	0.0	60.0	-
40	WDM	25.9	1.54	25.9	141.0	166.9	0.48
40	DSON	40.0	-	80.0	0.0	80.0	-
50	WDM	30.9	1.62	30.9	191.0	221.9	0.45
50	DSON	50.0	-	100.0	0.0	100.0	-
60	WDM	34.6	1.73	34.6	253.0	287.6	0.42
60	DSON	59.9	-	119.8	0.0	119.0	-

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