Digital Subcarrier Cross-connects (DSXCs)[1]

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ABSTRACT

Traditional (analog) Frequency Division Multiplexing (FDM) was widely used in the pre-SONET/SDH era, to multiplex transport channels together using spectral diversity. These transport solutions were then gradually abandoned due in part to their low spectral efficiency and with the advent of Time Division Multiplexing (TDM), which lead to synchronous transmission techniques, such as SONET and SDH. Another problem of traditional FDM or Subcarrier Multiplexing (SCM) ─ being analog ─ is its susceptibility to accumulated waveform distortion and crosstalk. For these reasons FDM is not competitive in today's transport networks.
Digital signal processing continues to reach new record high rates, thus enabling Digital Subcarrier Cross-connects (DSXCs) to operate even at the high transmission rates of optical signals. In DSXC, the incoming subcarriers are switched to the outgoing subcarriers by a controlled Radio Frequency (RF) crossbar switch. The power consumption required to switch subcarriers in and out is estimated to be only a fraction of the power dissipated by current TDM and packet switching based transport network solutions. Multiple DSXCs can be combined to design Digital Subcarrier Optical Networks (DSONs) [1], which are a promising energy efficient alternative to current electronic-based transport network techniques, e.g., OTN/SONET/SDH/MPLS-TP. The DSXC's basic functionalities and modules are introduced and discussed in this paper.

Keyword: energy efficiency, transport network, circuit switched network, digital subcarrier, digital subcarrier optical network, digital subcarrier cross-connect.

1. INTRODUCTION

According to their employed switching technology, today's telecommunication networks can be divided into three layers: packet switching layer, TDM-based digital cross-connect switching layer, and optical cross-connect switching layer. In packet switching layer, Internet Protocol (IP) routers offer packet switching control, achieving efficient statistical multiplexing of the available network resources across the user population. In optical layer, optical cross-connects (OXCs) offer wavelength (or lambda) switching, i.e., lightpaths or circuits of light can be established 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. TDM-based digital cross-connect layer (transport network) provides traffic grooming between the IP and the optical layer to offer fine bandwidth granularity to routers links.

In general and with some exceptions, the IP routers are the most flexible and most expensive solution that is used in the access and at the edge of the core network where packets are classified at the ingress IP router and sent over pre-provisioned circuits to reach the egress IP router. The OXCs offer a cost effective solution in Wavelength Division Multiplexing (WDM) network. However, they can only offer end-to-end optical connections with the (large) granularity of an entire wavelength channel (e.g., 10, 40, 100Gbps). Both OTN DXCs and MPLS-TP routers offer end-to-end circuits across the core network with fixed (the former) or variable (the latter) capacity, that achieve sub-wavelength bandwidth granularity, along with fast protection schemes (five 9s) and cost per switched byte of data that is favorable compared to IP routers. But 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 to sacrifice the channel granularity and data rate flexibility.

Digital Sub-carrier Optical Network (DSON) [1] offer a potential solution to the problem mentioned above. DSON can offer sub-wavelength granularity transmission and switching, which facilitates the creation of end-to-end connections with flexible data rates between edge node pairs. Meanwhile, due to the elimination of electronic buffering and digital cross-connect in the intermediate nodes, the power consumption in DSON is only a fraction of the consumption in extant solutions, e.g., OTN/SONET/SDH/MPLS-TP. Digital Subcarrier Cross-

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connect (DSXC) performs sub-wavelength bandwidth cross-connection in DSON and it is described in the next section.

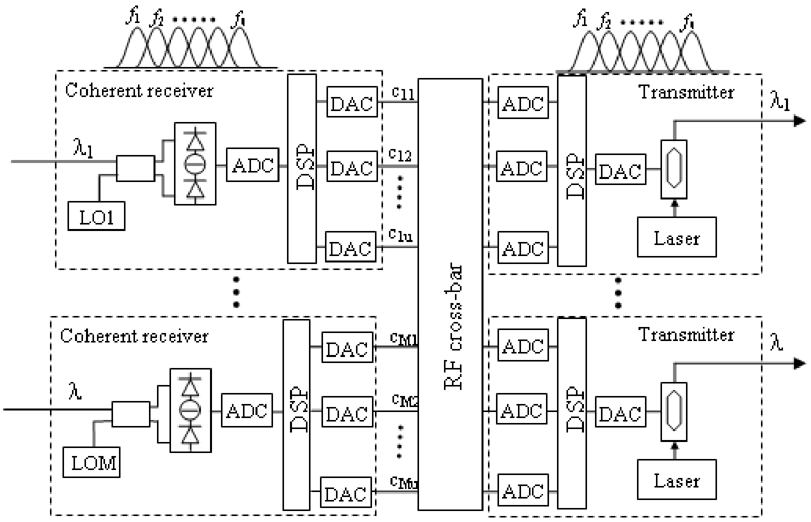

Fig. 1. DSXC architecture and coherent transceivers

2. DIGITAL SUBCARRIER CROSS-CONNECTS (DSXCs)

In comparison to packet switched cross-connect, DSXC is circuit switched technique. Switching and routing of sub-wavelength channels is performed in the frequency domain (rather than time domain) using orthogonal subcarrier channels. OFDM is used here to perform cross-connect operation, and the capabilities of OFDM cross-connect are illustrated in this section.

WDM, SCM vs. OFDM: In conventional WDM and subcarrier multiplexing (SCM) systems, adjacent channels must be separated by a guard band to avoid inter-channel crosstalk [7], and therefore the optical bandwidth is not fully utilized. In recent years, the rapidly advancing CMOS electronics has enabled very high speed ADC, DAC, and DSP. Most of the once-analog-domain functions of SCM systems can now be performed in the digital domain, such as subcarrier High precision frequency and phase control of digitally generated subcarriers is now enabling OFDM to be applied at optical transmission rates. In an OFDM system, frequency spacing between subcarriers is equal to the data rate carried by each channel, and spectral overlap is allowed. Digital integration over a bit period removes inter-channel crosstalk. Advanced DSP algorithms also allow the compensation of various transmission impairments such as chromatic dispersion and PMD.

OFDM-based cross-connect architecture. By virtue of the distinct OFDM subcarrier channels (each with sub-wavelength bandwidth granularity) carried by the optical signal, cross-connection operations of such channels are facilitated as follows. The DSXC operation principle is illustrated in Fig. 1, where each wavelength signal carries u orthogonal subcarrier channels. 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). If there are W wavelength channels coming into and departing from the DXSC, a $(W \cdot u)\times(W \cdot u)$ RF crossbar circuit-switch can perform the desired cross-connection. After the crossbar switch, each subcarrier is assigned a new frequency and regrouped according to the destination, and modulated on to an outgoing wavelength signal.

OFDM transceivers: In the last few years, the use of electronic processing to replace optical domain dispersion and PMD compensation has become an industry standard. CMOS electrical signal processing capabilities built in commercial optical transceivers can be utilized to perform OFDM operation. In addition, coherent detection has also become practical and adopted by telecom industry. As an example, an off-shelf coherent 46Gbps QPSK transceiver equipped with DSP Agile engine consumes approximately 10W power [4]. With proper modification, ADC, DAC and DSP in this type of digital optical transceivers can be readily reconfigured to perform OFDM operation [8, 9]. The block diagram shown in Fig. 1 is DSXC using digital transceivers based on coherent detection. A distinct advantage of using digital transceivers is that the accumulation of noise, crosstalk, and distortion can be avoided, which is critical in multi-hop optical networks with multiple cross-connection nodes. Cross-connect switch in the electronic domain and on the subcarrier level ensures the speed, the flexibility and granularity.

In a traditional OFDM system, the data stream is first mapped into a 2-D array row-by-row, and an IFFT is performed such that each column becomes a subcarrier channel. In this way an OFDM symbol is usually partitioned into different subcarriers [5]. In the corresponding OFDM receiver, an FFT process is used to convert the 2-D data array back into frequency domain and the original digital signal is reconstructed through parallel to serial conversion. In this process, it is not convenient to select a subset of subcarriers without detecting the entire OFDM frame. The OFDM transceiver in the proposed cross-connect architecture has to allow the selection of individual subcarrier channels. In this case, each input data stream is directly mapped onto a subcarrier, and no FFT is required in the receiver. As long as the symbols on subcarriers are mutually time-synchronized, the

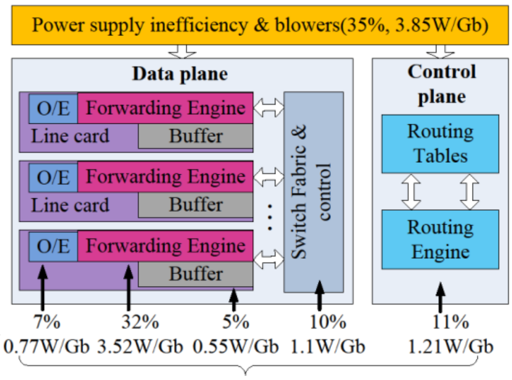

Fig. 2. Power consumption in core IP router

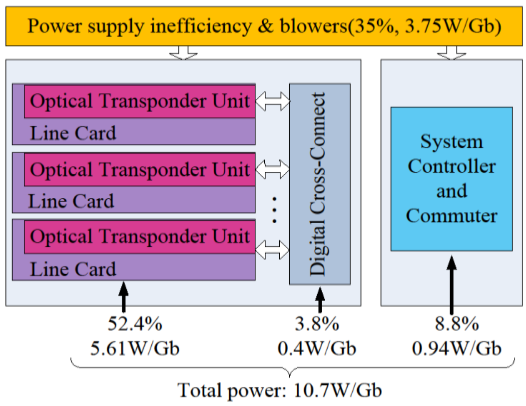

Fig. 3. Power consumption in OTN switch

crosstalk between then can be eliminated through integration over a bit period. Because this OFDM transceiver is not based on FFT, it can be simply regarded to as digital subcarrier multiplexing (DSCM).

Analog RF crossbar switch: A straightforward way to realize a crossbar switch is to use analog RF circuits. For example, a Honeywell HRF-SW1031 1x6 RF switch device consumes approximately 0.1mW power with 2GHz bandwidth per port. 6 units of such 1x6 RF switches can combine to make a 6x6 cross-connect, consuming 0.6mW overall. A large scale Shuffle-net [10] with k columns and p^k rows can be constructed using 6x6 switch building-blocks (p = 6). To support $M = p^{k+1}$ channels, the required total number of 6x6 switches is $N = k\,p^k$. Suppose each subcarrier channel has 1Gbps capacity, a 100Tb/s DSXC will need 10^5 ports. This requires approximately 9×10^4 units of 6x6 RF switches, consuming 54W quiescent power, which is only 0.54mW/Gb. Dynamic power consumption, on the other hand, depends on how frequently the DXSC has to be reconfigured, which is usually negligible for RF-based analog switches. Although analog RF crossbar switch uses minimum electrical power, and the power consumption is independent of the data rate of each port, realization of RF crossbar switch with large port count may be challenging, primarily due to crosstalk and power splitting loss. Innovative RF switch devices have to be developed for this purpose once there is a clear demand.

Digital regenerative crossbar switch: With the recent advances in CMOS electronics, large scale crossbar switches based on CMOS circuits have become commercially available. This type of switch provides retiming and reshaping of the signal waveforms, thus compensating for inter-channel crosstalk and power splitting loss. For example, Vitesse VSC-3144 chip is a non-blocking any-to-any switch with 144 input and 144 output ports. The bandwidth of each port can be as high as 10.709 Gbps with an electrical power consumption of approximately 21W. Using the switch at full bandwidth, the total chip switching capacity is about 1.5Tbps and the power efficiency is 14.6mW/Gb. To scale up switching capability, multiple VSC-3144 chips can be combined to form a multi-layered switch fabric. For example, a 2880x2880 non-blocking switch network can be constructed using 80 VSC-3140 chips arranged into 3 layers (20; 40; 20). In this case, the total switching capacity can reach 28.8 Tb/s with a power efficiency of 58mW/Gb. Further analysis about power consumption is given in the next section.

3. POWER CONSUMPTION ANALYSIS OF TODAY'S TRANSPORT EQUIPMENTS

In this section, the power consumption by the primer equipment in optical transport network is analyzed. Table 1 reports some typical examples of power consumption in each layer.

Table 1. Equipment power consumption

	Capacity	Power	W/Gb
Core IP Router [2]	92Tb/s	1020 kW	11
SONET ADM [2]	95Gb/s	1.2 kW	12.6
WDM transponder [2]	40Gb/s	73W	1.8
DSP Agile Engine [3]	46Gb/s	10W	0.2
OTN OXC [6]	95Gb/s	1.017kW	10.7
DSON single stage	28.8Tb/s	51.8kW	1.8
WDM ROADM [6]	800Gb/s	720W	0.9

Fig. 2 shows the breakdown power consumption (Watts per Gb of data) for a typical electronic router [5]. The packet forwarding engine and buffer together constitute 37% of the total power consumption. The packet switch and control plane consume 10% and 11% respectively. An estimated 35% of the overall power consumption is due to cooling, e.g., blowers/ fans, and circuit inefficiency. Fig. 3 and Fig. 4 show the breakdown power consumption for a digital cross-connect based OTN switch and a typical reconfigurable optical add/drop multiplexing (ROADM) switch [6]. From the figures shown above, the main reasons for the high electrical power consumption in routers are the forwarding engine, digital buffer and packet switch fabric, while for digital cross-connect based switch they are line cards. Optical cross-connect switch is the most energy efficient equipment in today's network. However due to the super high bandwidth granularity, optical cross-connect switch cannot

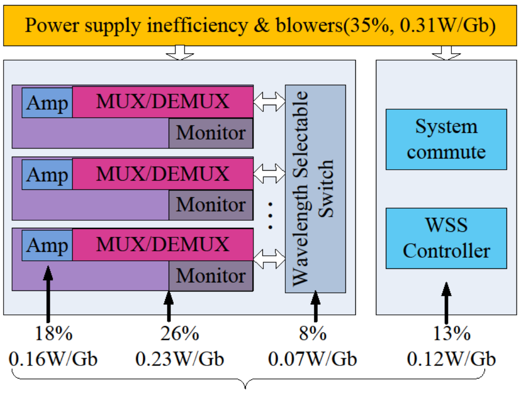

Fig. 4. Power consumption in ROADM OXC

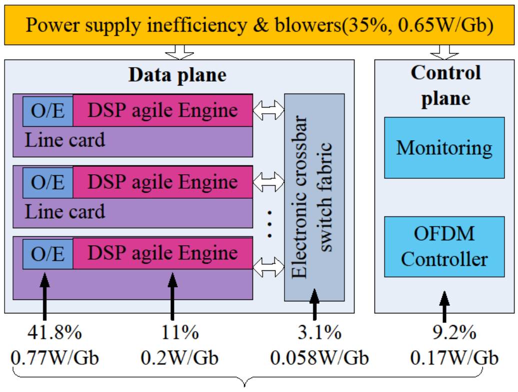

Fig. 5. Power consumption in DSXC

provide flexible data rate for upper layer applications. In order to design an energy efficient optical transport network, the cross-connect should provide fine granularity (sub-wavelength) to interconnect different kinds of add/drop multiplexing devices, meanwhile keep low power consumption. The estimated breakdown power consumption for the proposed OFDM-based DSXC is illustrated in Fig. 5. The reported consumption of each module in DXSC is based on available data sheets (see Section 3), anticipated power consumption for the control plane based on today's OTN control plane products, blowers and power inefficiency levels that are similar to those of already existing networking equipment. The overall power consumption of DXSC is projected to be around 1.8W/Gb, which offers a reduction factor of 5 compared to the 10W/Gb of both core IP routers and SDH equipment shown in Table 1.

4. ADDITIONAL ADVANTAGES WHEN USING DSXC

Not like the TDM, DSXC makes use of subcarrier multiplexing (SCM), a technology which multiplexes a large number of low data rate subcarrier channels into a high capacity wavelength channel. Each subcarrier channel carries data intended for its own destination. In a manner similar to an OXC, the DXSC crossbar switch simply needs to set up static traffic paths from input to output ports, and a low consumption crossbar switch suffices to perform cross-connection operation. More importantly, both forwarding engine and digital buffer are eliminated in the DXSC circuit switch architecture. Besides reducing power consumption, the proposed DXSC transport architecture offers the following additional advantages:

- high spectral efficiency when compared to traditional SCM solutions, due to the orthogonality between subcarrier channels, which can offer thousands of channels in a single fiber,
- fast switching speed using electronic cross-bar switch when compared to all-optical switch,
- signal robustness against optical transmission impairment, which entirely circumvent the use of dispersion and PMD compensators in the optical layer,
- direct access to individual subcarrier channels for traffic monitoring and add/drop functionalities, with the line rates that span from 1Gbps to 100Gbps,
- common functionality of transport network layer, e.g., fast protection switching and rerouting of subcarrier channels upon network element failure detection,
- fast provisioning and switching of subcarrier circuits (~100ns) in the DXSC and without being adversely affected by the signal transient instability that may originate in the optical layer [11],
- flexible data rate of each subcarrier to support a variety of concurrent bandwidth/capacity requirements, almost as flexible as MPLS-TP.

5. CONCLUSION AND FUTURE WORK

The design of energy efficient transport networks is becoming increasingly important and constitutes an open challenge. In this paper, the authors analyzed the power consumption in typical cross-connect and core router devices that are currently used in transport networks, and determined that the most energy consuming modules are the electronic forwarding engine, data buffering and line cards. A cross-connect architecture based on digital subcarrier (DSXC) was then introduced that has the ability to switch individual or groups of subcarrier signals, while limiting power consumption in the cross-connect and leveraging spectral efficiency in the optical fiber. DSXC requires neither the time synchronization nor data buffering of time division based solutions. It has the potential to support thousands of subcarrier channels per fiber, sub-millisecond switching times, and an estimated less than 2W power consumption per Gb of switched data. Compared with extant electronic switching technologies, this digital subcarrier-based cross-connect architecture has the potential to significantly decrease the transport network power consumption, meanwhile maintaining good spectral efficiency, fine channel granularity, good data rate flexibility, and fast circuit switching speed. Further investigation is needed to demonstrate the functionalities of various modules required in the DSXC, along with the design of scalable DSXC multi-stage architectures.

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