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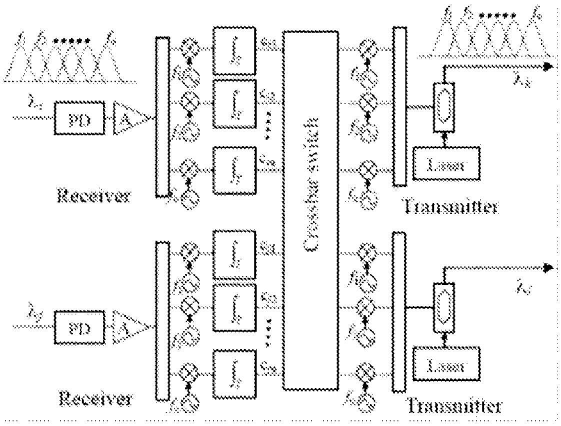

Fig. 5

(57) Abstract: The present technology provides reduced power dissipation at the optical transport network layer by utilizing Digital Subcarrier Optical Networks (DSON) executed on a digital subcarrier cross-connect architecture. DSON has advantages for wireless communications due to its spectral efficiency and robustness against signal corruption and consumes less energy than traditional electric switches.

A DIGITAL SUBCARRIER OPTICAL NETWORK UTILIZING DIGITAL SUBCARRIER CROSS-CONNECTS WITH INCREASED ENERGY EFFICIENCY

RELATED APPLICATIONS

The present U.S. non-provisional patent application is related to and claims priority benefit to an earlier-filed provisional patent application titled POWER EFFICIENT OPTICAL NETWORK CROSS-CONNECT BASED ON FREQUENCY-DIVISION MULTIPLEXING AND RF SWITCHING, Serial No. 61/424,581, filed December 17, 2010. The identified earlier-filed application is hereby incorporated by reference into the present application as though fully set forth herein.

SPECIFICATION

The present disclosed technology relates generally to communication networks and more specifically, Optical Transport Networks (OTN) as designated by the International Telecommunication Union.

Optical networks are connected through optical fibers with elements capable of providing optical channel transport, multiplexing, routing, management of the network, supervision and redundancy for survivability. Many telecom and data carriers around the world are increasing the use OTN for their long-haul and metro-area networks. The growth of OTN overtaking Synchronous Optical Networking and Synchronous Digital Hierarchy (SONET/SDH) use to the potential of boosting bandwidth and increase networking functionality.

Optical networks utilize optical fibers and lasers or highly coherent light from light-emitting diodes to transfer multiple digital bits streams of data over the network. SONET/SDH was originally designed to replace Plesiochronous Digital Hierarchy (PDH) system which was used to transport large amounts of telephone calls and data traffic over the same fiber without synchronization problems. This earlier system, PDH, used circuit-switch and was efficient if the sources of the transmissions through the circuits were synchronized. However, as theses optical networks continued to grow, so did the traffic on them. SONET and SDH, a superset of SONET, were developed to support real-time, uncompressed, circuit-switched voice encoded data. SONET/SDH allows for simultaneous transporting of many different circuits of differing origin in which a single framing protocol and SONET/SDH is also ideal for transporting Asynchronous Transfer Mode (ATM) frames, internet protocol (IP) packets or Ethernet frames. Generally, a frame is a group of data bits in a specific format (ATM, Ethernet, IP and others) with a flag at the beginning and the end of the data bits to define the individual frame.

The message protocol transported by SONET and SDH are similar with a few exceptions. SONET is typically used in North America whereas SDH is widely used throughout the world. The protocol of SONET/SDH is a multiplexed structure wherein a header is interleaved between the data to permit the encapsulated data to have its own unique frame rate and be present within the SONET/SDH frame structure and rate. The protocols buffer data during transit for at least one frame before sending. This buffering allows for multiplexed data to move within the overall framing (transmission) to compensate for different frame rates. The protocol becomes more complex due to the decision of when and where in the data stream padding is needed and at what level of the multiplexing structure.

In optical networks, the SONET/SDH –layer and Equipment: regenerator, add-drop multiplexer, digital cross connect system. These routers and multiplexers have high power consumption and with the increased demand of these networks for communication, by industry, public works, schools and residential use, all increase energy needs. The networking community's energy saving object is becoming more important now that Internet traffic is expected to continue in its steep growth driven by video applications and cloud computing advances.

Energy consumption is a consideration in designing communication networks including hardware, routers and multiplexers, and the architecture. For example, Internet Protocol (IP) routers can lower their packet processing rate when traffic volume is low to reduce energy consumption in both optical and electrical networks. Current, all-optical Wavelength Division Multiplexing (WDM) networks can be more energy efficient by bypassing the optical-electrical-optical conversion at the intermediate optical cross-connection nodes. One layer of the communication networks where increase energy efficiency is desirable in current and future networks is in the third network layer, the Optical Transport Network (OTN). The OTN layer is often used between the IP and the WDM layer to provide sub-wavelength capacity to the links of routers. Present day OTN solutions perform similarly as SONET/SDH and perform digital time division multiplexing of multiple sub-wavelength channels to fill out the entire wavelength of a channel. For example, if a 2.5 Gigabits/second (Gb/s) channel is used to transport data, by performing digital time division multiplexing, data can be transport across the entire wavelength of the channel, such as 40 Gb/s). Each sub-wavelength channel is individually routed using digital subcarrier cross-connects (DSXC) and each DSXC requires approximately 10 Watts per 10 Gigabits/second of carried data to perform transportation functionalities.

As energy consumption of telecom networks is forecasted to double within one decade due to rapid increase of traffic volume in broadband networks, combined with expectation of higher energy price and increasing concerns of government policies and legislative acts regarding global warming, finding energy-efficient solutions becomes an important issue for telecom networks.

At the IP layer, energy-aware packet forwarding techniques suggest that IP packets with smaller size increase energy consumptions of routers, so optimizing size of IP packet can make routers more energy efficient. However, reducing switching delay and lowering energy consumption need to be carefully balanced. New network architecture comprising two parallel networks have been proposed. The current Internet and a "super-highways" network which uses pipeline forwarding for IP packets is used in conjunction with the current Internet which carries traditional traffic and signaling between routers that set up synchronous pipes in "super-highways" networks. The "super-highways" would carries traffic that has deterministic patterns and require high bandwidth.

In WDM networks, high energy consumption originates from the optical network equipment which is used for traffic grooming. Hence, energy-efficient traffic grooming, which reduces the number of required lightpaths, considerably increases energy savings. Other approaches to reduce energy consumption include routing and wavelength assignment heuristics that minimize the number of lightpath interfaces and using digital signal processing to for wavelength translation of the frequencies of each specific wavelength on the optical fiber. However, this process may be cost prohibitive due to the expense in optical equipment to create the wavelength translation. Other possible solutions include concentration of reducing energy consumption of each network operation for dynamic traffic grooming.

Current telecom networks are based on an architectural model of three classes of network domains: core, metro, and access. In core networks, efforts to reduce energy consumption can be divided into two categories: energy-efficient network design, and energy-efficient network operations. The energy consumption of IP routers, EDFAs, and transponders is jointly minimized for an IP-over-WDM network by utilizing Mixed Line Rates (MLR). Likewise, shutting down idle network elements is a major energy-efficient network operation. To identify the maximum number of idle nodes and links while still supporting the ongoing traffic, an MILP model can be used to reduce the powered nodes (or equipment) on off-peak hours and during traffic fluctuates at different hours of the day. Similarly, idle line cards can be shut down when traffic load is low, while keeping the physical topology invariant can be used to reduce power needs. "Green Routing" is proposed, which uses energy consumption of network equipment as the optimization objective. Also, more and more attention is paid on renewable energy, an idea to reduce carbon footprint is to establish core servers, switches, and data centers at locations where renewable energy can be found, and then to route the traffic to the "Green areas".

The present technology provides reduced power dissipation at the OTN layer by utilizing Orthogonal Frequency Division Multiplexing (OFDM) technology executed on an OFDM cross-connect architecture. OFDM has advantages for wireless communications due to its spectral efficiency and robustness against signal corruption. With advances in digital CMOS electronics and the increased use of optical networks, the disclosed OFDM technology can be applied can be used to perform the same transport functions of existing DSXCs while reducing energy consumption of the OTN layer by an order of magnitude. Energy consumption is also reduced by efficiently designing the network routing and resource assignment algorithms using provided OFDM cross-connect functionalities including routing frequency assignment (RFA) algorithms.

The OFDM cross-connect architecture may also be used to lower the power consumption of existing communication networks with the introduction of the technology in various network segments. For example, packet transport networks make use of MPLS-TP routers to create virtual circuits and these networks consume power at the approximate level of DSXC. The reduction in power consumption of in the OTN layer may assist in the expansion of communication, Internet, and education services to economically depressed area. Likewise, these low power consuming OFDM cross-connect nodes or "routers" may be power by renewable energy such as solar cells or wind generators.

The drawings constitute a part of this specification and include exemplary embodiments of the disclosed subject matter illustrating various objects and features thereof, wherein like references are generally numbered alike in the several views.

FIG. 1 is a diagram of three layers of a network using Internet Protocol, Optical Transport Layer and Wavelength Division Multiplexing;

FIG. 2 is a block diagram representing a digital cross-connect switch;

FIG. 3a is a block diagram illustrating power usage of an electronic router;

FIG. 3b is a block diagram illustrating power usage of an optical circuit switch;

FIG. 4 is an illustration of a digital subcarrier optical network structure.

FIG. 5 is a block diagram of a digital subcarrier cross-connect architecture;

FIG. 6 is an illustration of a digital subcarrier cross-connect architecture and coherent transceivers;

FIG. 7 is a graphical representation of the optical spectra of orthogonal frequency division multiplexer signals with 1, 5 and 10 subcarrier channels each carrying a 2 Gb/s QPSK signal;

FIG. 8 is a graphic representation of a system BER versus optical-to-noise-ratio;

FIG. 9 is an illustration of a process of subcarrier channel selection; and

FIG. 10 is an illustration of a crossbar switch.

As required, detailed aspects of the disclosed subject matter are disclosed herein; however, it is to be understood that the disclosed aspects are merely exemplary of the invention, which may be embodied in various forms. Therefore, specific structural and functional details disclosed herein are not to be interpreted as limiting, but merely as a basis for the claims and as a representative basis for teaching one skilled in the art how to variously employ the present invention in virtually any appropriately detailed structure.

Certain terminology will be used in the following description for convenience in reference only and will not be limiting. For example, up, down, front, back, right and left refer to the invention as orientated in the view being referred to. The words, "inwardly" and "outwardly" refer to directions toward and away from, respectively, the geometric center of the aspect being described and designated parts thereof. Forwardly and rearwardly are generally in reference to the direction of travel, if appropriate. This terminology will include the words specifically mentioned, derivatives thereof and words of similar meaning.

Current telecommunications networks rely on multiple technologies to send and route optical or electrical signals to a desired location. Internet Protocol (IP) routers offer packet switching control, achieving efficient statistical multiplexing of the available network resources across the user population. The optical layer cross-connects (OXC) offer wavelength (or lambda) switching, i.e., lightpaths 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., 10Gb/s, 40Gb/s, 100Gb/s. Traffic grooming, a circuit that receives data bits and routes the data to the designed destination, is provided by a third intermediate (transport network) layer placed between the IP and the optical layer to offer fine bandwidth granularity to the links of the router. The three layers coexisting in the network, each layer offering unique functionalities, is illustrated in Fig. 1. Multilayer network 2 as shown in Fig. 1 has an IP layer 4 which utilizes a packet switched connection, OTN layer 6 utilizing digital subcarrier cross-connect switch and WDM layer 8 having an optical fiber link.

Current Optical Transport Networks (OTN) (such as SONET/SDH) using digital subcarrier cross-connects (DSXC) as shown in Fig. 2, utilize time division multiplexing (TDM) circuit switching. TDM circuit switching is used to create end-to-end circuits with sub-wavelength bandwidth granularities and can be provisioned to interconnect routers or other add-drop multiplexing devices. The capacity of the OTN circuits is fixed and set to standard rates, e.g., 0.625, 2.5, or 10Gb/s. As shown in Fig. 2, DSXC switch 10 receives data frames along 3 input paths such as a single optical fiber with each having a unique wavelength. The DSXC switch monitors each data frame, reads the header of the frame and directs the frame to the correct output fiber. Fig. 2 illustrates the complexity of the digital subcarrier cross-connect switch and the need for time padding or buffering to receive, read and re-order the frames and send to the correct out output wavelength.

From a power consumption stand point, electronic processing of transported data, required in both OTN DSXC and IP MPLS-TP routers, consumes significantly higher electrical energy compared to optical circuit switching performed by OXC. Table 1 reports typical examples of power consumption of electrical and optical routers.

Component	Capacity	Power	W/Gb
Core IP Router	92Tb/s	1020 kW	11W
SONET ADM	95Gb/s	1.2 kW	12.6W
WDM transponder	40Gb/s	73W	1.8W
DSP Agile Engine [2]	46Gb/s	10W	0.2W

Table 1

Figure 3a is a graphical representation of energy consumption (Watts per Gb of data) for a typical electronic router. The packet forwarding engine and buffer together constitute 37% of the total energy consumption. The packet switch and control plane consume 10% and 11% respectively. An estimated 35% of the overall energy consumption is due to cooling, such as blowers and fans, and circuit inefficiency.

Fig. 1.2 (a) shows the breakdown energy consumption (Watts per Gb of data) for a typical electronic router [3]. The packet forwarding engine and buffer together constitute 37% of the total energy consumption. The packet switch and control plane consume 10% and 11% respectively. An estimated 35% of the overall energy consumption is due to cooling, e.g., blowers/fans, and general circuit inefficiency.

Another available transport option is MPLS Transport Profile (MPLS-TP). MPLS-TP is a profile of MPLS, which is designed for use as a network layer technology in transport networks. It is a connection-oriented packet-switched (CO-PS) solution and offers a dedicated MPLS implementation by adding mechanisms that provide support of critical transport functionality. MPLS-TP is to be based on the same architectural principles of layered networking that are used in longstanding transport network technologies like SDH, SONET and OTN.

It will be appreciated that the components of digital subcarrier optical network can be used for various other applications. Moreover, the digital subcarrier cross-connect architecture can be fabricated in various sizes and from a wide range of suitable materials, using various manufacturing and fabrication techniques.

It is to be understood that while certain aspects of the disclosed subject matter have been shown and described, the disclosed subject matter is not limited thereto and encompasses various other embodiments and aspects.

DETAILED DESCRIPTION

1 Introduction: the OFDM Network Architecture Rationale

Telecommunications 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., lightpaths or circuits of light can be switched end-to-end across the optical network layer. The capacity of the optical circuit is fixed

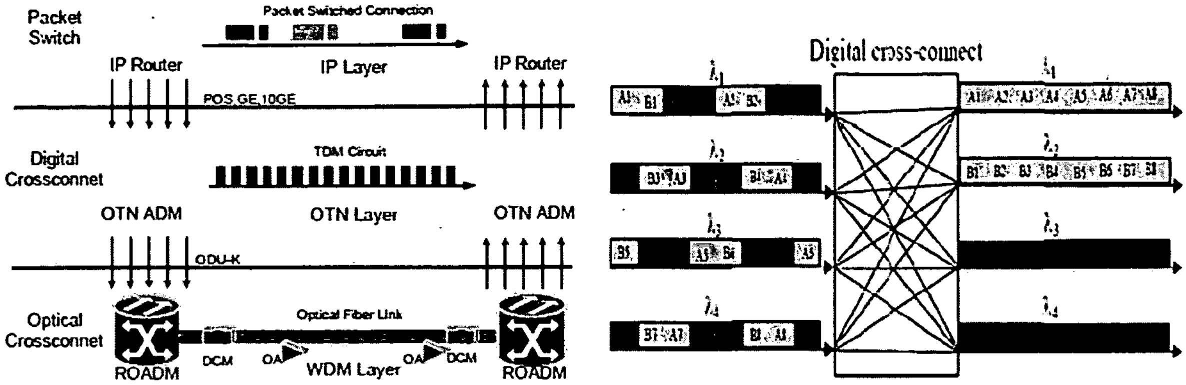

Fig. 1.1: (left) Today's network structure 1: IP + OTN + WDM. (right) DXC architecture.

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) shown in Fig. 1.1 (right) 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. The capacity of the OTN circuits is fixed and set to standard rates, e.g., 0.625, 2.5, or 10Gbps. Fig. 1.1 (left) depicts the three layers coexisting in the network, with each layer offering unique functionalities.

Another available transport option is MPLS Transport Profile (MPLS-TP). MPLS-TP is a profile of MPLS, which is designed for use as a network layer technology in transport networks. It is a connection-oriented packet-switched (CO-PS) solution. It offers a dedicated MPLS implementation by adding mechanisms that provide support of critical transport functionality. MPLS-TP is to be based on the same architectural principles of layered networking that are used in longstanding transport network technologies like SDH, SONET and OTN.

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 with fast protection schemes (5-9s reliability). However, they can only offer end-to-end optical circuits 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 (5-9s) and cost per switched byte of data that is favorable compared to IP routers.

From a power consumption stand point, electronic processing of transported data – which is required in both OTN DXC and IP MPLS-TP router – consumes significantly higher electrical energy compared to optical circuit switching performed by OXC. Table 1.1 reports some typical examples of power consumption [1]. Fig. 1.2 (a) shows the breakdown energy consumption (Watts per Gb of data) for a typical electronic router [3]. The packet forwarding engine and buffer together constitute 37% of the total energy consumption. The packet switch and control plane consume 10% and 11% respectively. An estimated 35% of the overall energy consumption is due to cooling, e.g., blowers/fans,, and circuit inefficiency.

Table 1.1: Equipment power consumption [1].

	Capacity	Power	W/Gb
Core IP Router	92Tb/s	1020 kW	11W
SONET ADM	95Gb/s	1.2 kW	12.6W
WDM transponder	40Gb/s	73W	1.8W
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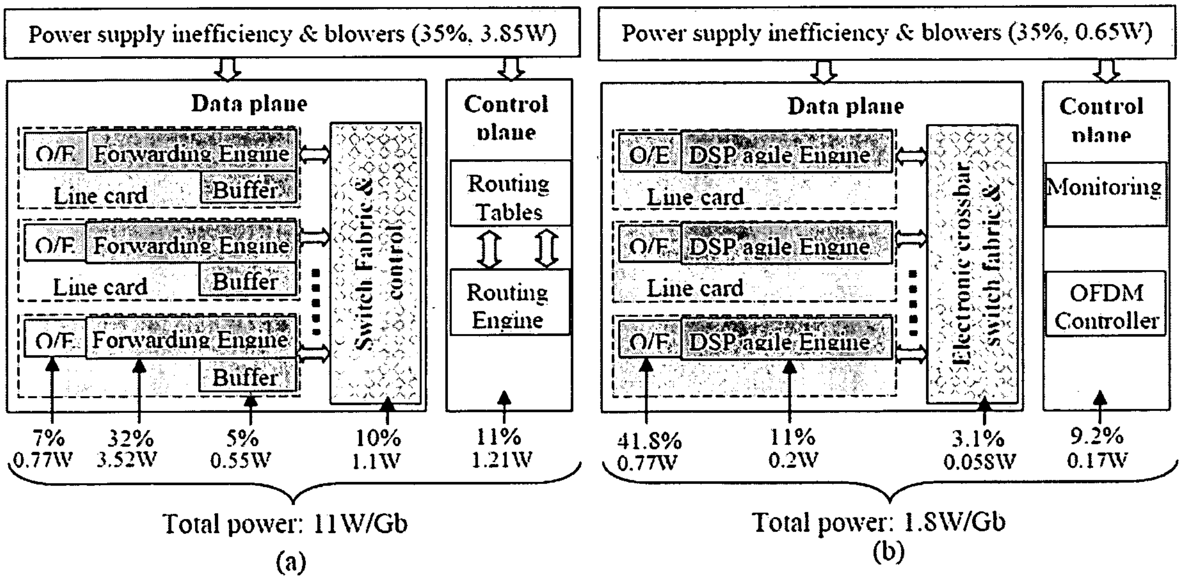

Fig. 1.2: Power consumption comparison between (a) typical electronic router and (b) proposed

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 times when the offered load is relatively low in the network [53]. 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 [54, 55]. 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.

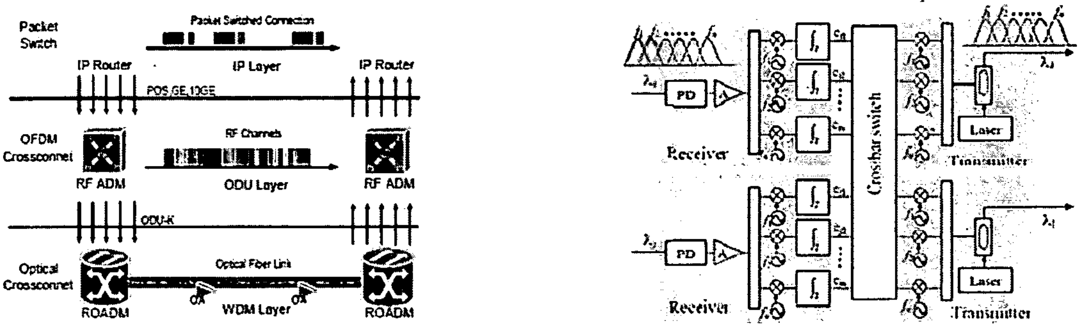

Fig. 1.3: (left) proposed OFDM network structure. (right) proposed FOXC architecture, subcarrier (sub-wavelength) channels (*c*11, *c*12, 6 *c*1*n*) are independently cross-connected via a crossbar switch in baseband with frequency down and up-conversion.

With this proposal, the PIs plan to investigate the adoption of OFDM in the transport network as an alternative to OTN/SONET/SDH, with the objective of designing an innovative cross-connect architecture (based on sub-wavelength frequencies that are orthogonal, hence the given name FOXC) that will significantly decrease the power consumption at this layer (Fig. 1.3) while maintaining good spectral efficiency, channel granularity, data rate flexibility, as well as circuit switching speed. Switching and routing of sub-wavelength channels is performed in the frequency domain (rather than time domain) using orthogonal subcarrier channels. More specifically, OFDM technology has the potential to

(1) significantly reduce the power consumption at the cross-connect by using a circuit switch architecture which eliminates both the forwarding engine and packet buffering of the current transport solutions, and reduces power consumption taking place at the cross-bar switch (see Fig. 1.2 (b)), and

(2) offer an adjustable transmission (line) rate at the sub-wavelength level (instead of entire wavelength) using fast electronic-domain switch (as opposed to all-optical switch in WDM) to more efficiently support the offered amount of traffic with the minimal required energy consumption of the transceivers.

In fact, the main reasons for the high electrical power consumption in routers are the forwarding engine, digital buffer and packet switch fabric (Fig. 1.2), while for DXCs they are I/O buffer and line cards (Table 1.1). On the other hand, FOXC 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 FOXC 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 FOXC circuit switch architecture. The key enabling technology here is the recent progress in digital signal processing (DSP), which can now perform OFDM (successfully used in radio networks) at high data rates. Fig 1.2 (b) shows the projected power consumption distribution across the FOXC modules, which can be directly compared to the consumption of the electronic router modules shown in Fig. 1.2 (a). The reported consumption of each module in FOXC is based on available data sheets (see Section 3.2), 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 FOXC 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 SONET equipment shown in Table 1.1.

Besides reducing energy consumption, the proposed OFDM transport architecture offers the following additional advantages (which will be further discussed in Section 3):

- 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 FOXC and without being adversely affected by the signal transient instability that may originate in the optical layer [56],
- flexible data rate of each subcarrier to support a variety of concurrent bandwidth/capacity requirements, almost as flexible as MPLS-TP.

2 State of the Art

As energy consumption of telecom networks is forecasted to double within one decade due to rapid increase of traffic volume in broadband networks [1], combined with expectation of higher energy price and increasing concerns of government policies and legislative acts regarding global warming, finding energy-efficient solutions becomes an important issue for telecom networks.

At the IP layer, energy-aware packet forwarding techniques have been proposed by several researches [4, 5]. Reference [4] shows that IP packets with smaller size increase energy consumptions of routers, so optimizing size of IP packet can make routers more energy efficient. However, reducing switching delay and lowering energy consumption need to be carefully balanced. [5] proposes a new network architecture comprising two parallel networks: current Internet and a "super-highways" network which uses pipeline forwarding for IP packets, where current Internet carries traditional traffic and signaling between routers that set up synchronous pipes in "super-highways" networks, which carries traffic which have deterministic patterns and require high bandwidth.

In WDM networks, energy consumption originates from optical network equipment [4], which is heavily used for traffic grooming, hence energy-efficient traffic grooming, which reduces the number of required lightpaths, also increases energy savings considerably [6]. Several approaches, which reduce energy consumption in WDM networks have been proposed, including routing and wavelength assignment heuristics that minimize the number of lightpath interfaces [7,8], investigation of energy consumption of each network operation for traffic grooming [9,10], effect of multilayer traffic engineering schemes on energy efficiency [11] and dynamic traffic grooming based on traffic profile [12,13].

Nowadays, the telecom network is based on an architectural model of three classes of network domains: core, metro, and access. Many techniques are studied for minimizing energy consumption in optical core, metro and access networks. In core networks, the approaches to reduce energy consumption can be divided into two categories: (i) energy-efficient network design, and (ii) energy-efficient network operations. In [14], energy consumption of IP routers, EDFAs, and transponders is jointly minimized for an IP-over-WDM network by a novel design approach. Mixed Line Rates (MLR) is introduced in [15], the authors present a mathematical model to determine the energy efficiency of an MLR optical network. Shutting down idle network elements is a major energy-efficient network operation. To identify the maximum number of idle nodes and links while still supporting the ongoing traffic, an MILP model was proposed in [16] and heuristics were proposed in [17]. Traffic fluctuates at different hours of the day, so that it is possible to reduce the powered nodes (or equipments) on off-peak hours. In [18], a scheme to shut down idle line cards when the traffic load is low is proposed, while keeping the physical topology invariant. "Green Routing" is proposed, which uses energy consumption of network equipments as the optimization objective [4]. Also, more and more attention is paid on renewable energy, an idea to reduce carbon footprint is to establish core servers, switches, and data centers at locations where renewable energy can be found, and then to route the traffic to the "Green areas" [19]. Energy-efficient traffic grooming is also considered in core networks, the energy consumed by operations in traffic grooming is identified in [4] and [8].

Wireless-Optical Broadband Access Network (WOBAN) is a novel access architecture, and can provide high-bandwidth services. Energy savings in the optical part of WOBAN by sleeping mechanism is studied in [23]. In [24], energy-efficient design of a unidirectional WDM ring network is investigated.

Energy-efficiency is a major problem for data centers, which are vital to support today's data applications. Optical networks play an important role in both data center inter- and intra-connections. An approach to reducing the energy consumption of high-speed intra-connection (inside data centers) links is proposed in [25]. Load distribution across data centers in different locations is also related with power-conservation. How to optimally distribute requests is studied in [26].

Solutions based on frequency division multiplexing (FDM) were widely used in the pre-SONET/SDH era, to multiplex transport channels together using spectral diversity [30,31]. These transport solutions were then abandoned, RF/microwave in fiber optics is still in use to carry radio signals between antennas and base station [32], due in part to their low spectral efficiency and with the advent of TDM and synchronous transmission techniques, such as SONET and SDH [33]. Another problem of traditional FDM (or 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.

OFDM has made multiple significant impacts in wireless communications and related networking products due to its good spectral efficiency and robustness against noise and crosstalk [29]. Its application in high speed optical transmission only started a few years ago thanks to the availability of high speed digital electronics to perform DSP functionalities [34,35]. In addition to high spectral efficiency, OFDM in optical systems is also insensitive to various transmission impairments such as chromatic dispersion and polarization mode dispersion (PMD).

Although industry leaders are adopting OFDM in high-speed optical transmission, a systemic study is still required to fully understand the impacts of this technology on the network layer. For example, the Spectrum-Sliced Elastic Optical Path Network (SLICE) project [20] 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 used here to obtain the desirable transmission rate for a given optical circuit (as opposed to our proposed FOXC which makes use of OFDM to perform the cross-connect operation). The most critical enabling technologies for SLICE are bandwidth-variable transponders and bandwidth-variable wavelength selective switches (WSS) [5]. WSS with adjustable wavelength and bandwidth enables transparent optical switch with improved granularity, while bandwidth-variable transponder using orthogonal frequency division multiplexing (OFDM) eliminated the requirement of spectral guard-band between adjacent wavelength channels, which maximizes the fiber bandwidth efficiency. From the energy consumption point of view, SLICE is expected to operate in the 0.7 to 1.1 W/Gb range, which is even less than our proposed FOXC solution. However, for a fair and complete comparison between the two solutions, one must take into account other factors, such as the supported number of channels and the switching time of the cross-connect. In SLICE, 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. In FOXC, as many as 4000 channels per fiber and switching time in the sub-millisecond range are expected to be within reach.

3 FOXC Architecture and Research Plan

As stated at the end of the previous section, FOXC has the potential to offer thousands of channels per fiber, sub-millisecond switching time, and less than 2W/Gb power consumption. This section provides further technical details and preliminary results about the proposed OFDM transport network. Some of the open challenges are discussed in Sections 3.1 and 3.2. The proposed research activities along with defined deliverables are presented in Section 3.3. A collaboration and group management plan is described in separate attachement.

3.1 OFDM Cross-Connect Capabilities and Preliminary Assessment

In comparison to packet switched cross-connect, circuit switch requires much less electric power. In a similar manner to OXC, FOXC only needs to set up static paths across a crossbar switch, thus power consumption is minimal.

WDM, SCM vs. OFDM: In conventional WDM and SCM systems, adjacent channels must be separated by a guard band to avoid inter-channel crosstalk [36], 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 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. 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 FOXC operation principle is illustrated in Fig. 3.1, where each wavelength signal carries u orthogonal subcarrier channels.

An OFDM receiver detects the incoming optical signal at λi and decomposes it into u baseband RF outputs ci1, ci2, ... ciu. 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 FOXC, a 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.

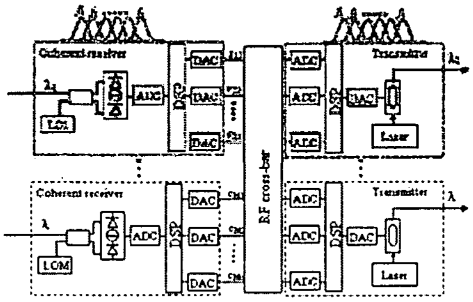

Fig. 3.1: FOXC architecture and coherent transceivers.

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 80W power [41]. With proper modification, ADC, DAC and DSP in this type of digital optical transceivers can be readily reconfigured to perform OFDM operation [40, 42]. The block diagram shown in Fig. 3.1 is FOXC 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 [6]. 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 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).

To proof the concept, we have reconfigured a CIENA 10Gbps eDCO transceiver, originally designed for electronic domain dispersion compensation, into an OFDM transmitter [38,39,40]. This transmitter has an on-board 22Gs/s DAC with digital interface, and an IQ modulator was also added on board to enable both intensity and phase modulation. At the receiver, any subcarrier channel can be selected by tuning the wavelength of the local oscillator (LO). A 90° optical hybrid was also used before the photodetector to separate I and Q components. 75km standard single-mode fiber was used between the transmitter and the receiver. Fig. 3.2 (a) shows an example of the measured optical spectra of DSCM signals with 1, 5 and 10 subcarriers each carrying 2Gbps QPSK data. The total optical bandwidth on this wavelength is 10GHz, and the total data rate is 20Gbps. Fig. 3.2 (b) shows the measured BER vs. optical carrier-to-noise ratio (OCNR) with different number of channels. There is negligible increase of OCNR penalty when the number of subcarrier channels increases from 1 to 5 where all the 5 subcarrier channels are located on the lower sideband with respect to the center optical carrier. When the other 5 subcarrier channels on the upper sideband of the spectrum are added to make the total channel count to be 10, an approximately 1 dB OCNR penalty was introduced. This can be partly attributed to the imperfect sideband suppression in the single-sideband modulation process. While there is negligible OCNR degradation introduced by 75km transmission fiber, the 1.5dB OCNR degradation of the measured BER compared to numerically simulation can be attributed to pass-band ripples in the RF amplifiers, multi-pass reflections in the optical system, as well as time jitter in the receiver.

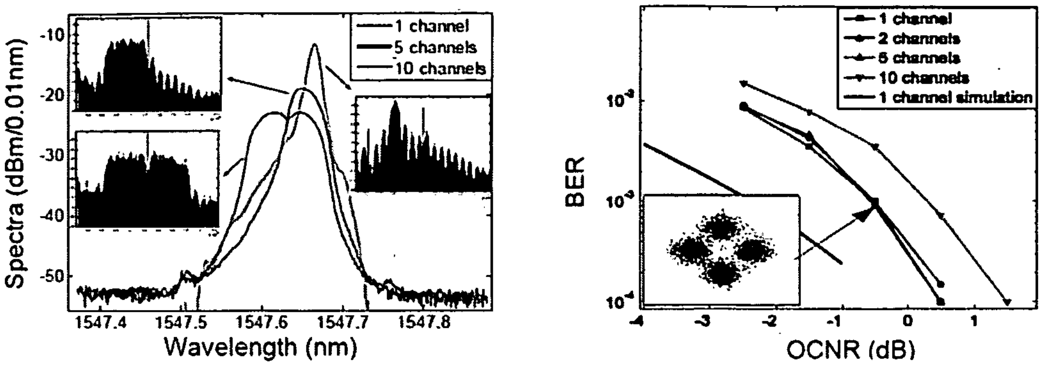

Fig. 3.1: (a) optical spectra of OFDM signals with 1, 5 and 10 subcarrier channels each carrying 2Gbps QPSK signal and (b) system BER versus optical carrier-to-noise-ratio.

This DSCM system is highly flexible because the receiver can select any one or multiple subcarriers without changing the transceiver hardware. Channel selection is achieved by tuning the optical LO to the desired subcarrier frequency in the received optical spectrum, and coherent IQ detection translates the optical spectrum to the electrical domain. All subcarrier channels within the receiver electrical bandwidth can be detected individually and crosstalk between them can be removed through digital processing. Fig. 3.3 (a) shows the simultaneous detection of channels C6 through C10 when the LO was set at the central frequency of channel C9. The BER was measured when OCNR was 1.5 dB. No significant performance variation was found among these channels. We also set the local oscillator wavelength to the center of the signal optical carrier as showed in Fig. 3.3 (b) in an attempt to detect all the ten subcarrier channels. The results show reasonably uniform BER performance except for the two outmost channels C1 and C10. The increased BER in these two channels is due to the bandwidth limit of our receiver which is only 6GHz, and the spectra of channel C1 and C10 are already partially outside the receiver bandwidth. The impact of bit time synchronization between adjacent subcarrier channels is shown in Fig. 3.3(c). Bit time misalignment has to be kept below ±20% of the bit length T to avoid significant BER degradation.

In the FOXC cross-connect architecture shown in Fig. 3.1, different number of subcarrier channels can be bundled together and switch to the same destination. This capability of mixed data rate provides additional flexibility in an optical network. Furthermore, since subcarrier channels are generated digitally, high order modulation formats such as M-PSK and M-ary with M > 4 can be used to further improve spectral efficiency if required.

In addition to DSCM transceivers, another critical building block in FOXC architecture is the electronic crossbar circuit switch. There are a number of options, including analog RF switch, and regenerative digital switch. The choice depends on the required number of subcarrier channels, data rate, switching speed, and maturity of the device technologies.

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 [43] 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 [44] with k columns and pk rows can be constructed using 6x6 switch building-blocks (p = 6). To support M = pk+1 channels, the required total number of 6x6 switches is N = k pk. Suppose each subcarrier channel has 1Gbps capacity, a 100Tb/s FOXC will need 105 ports. This requires approximately 9x104 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 FOXC 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.

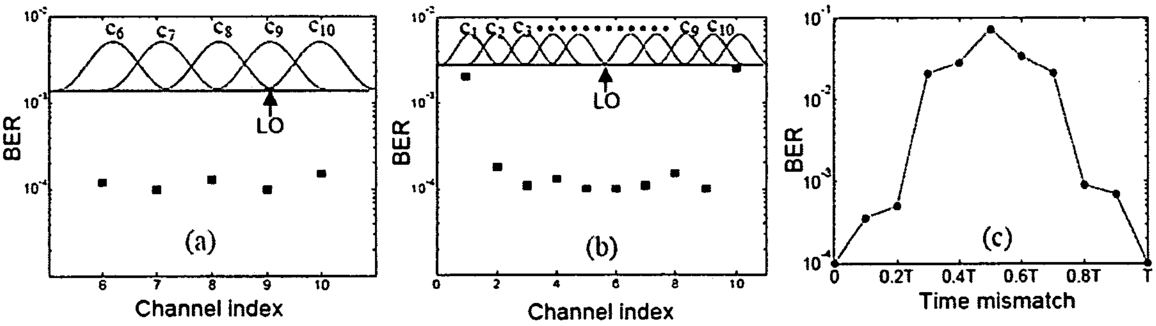

Fig. 3.3: subcarrier channel selection.

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-3140 chip [45] 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 4.2 Gbps with an electrical power consumption of approximately 16W. Using the switch at full bandwidth, the total chip switching capacity is about 600Gbps and the power efficiency is 26.5mW/Gb. To scale up switching capability, multiple VSC-3140 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 10 Tb/s with a power efficiency of 100mW/Gb – still two orders of magnitude more efficient compared to TDM DXC.

In the CMOS-based regenerative crossbar switch, the major power consumption is caused by changing the state of flip-flop representing each data bit, and thus it is linearly proportional to the actual traffic volume [46]. Note that this solution does not require memory/buffers and digital shift registers for data re-grouping as for a typical TDM DXC.

The main focus of our research is on the DSCM optical systems and their impact on optical networks. We will use commercially available crossbar circuit switching devices to demonstrate the concept. The impact on CMOS circuit design will also be investigated in terms of minimum power consumption, and the results will motivate the development of new crossbar switch devices.

3.2 FOXC Architectural Options and Network Design Challenges

Fig 1.2 (b) reports the estimated power consumption of the crossbar switch fabric to be 58mW/Gb. This result was obtained from the datasheet of the 144×144 Vitesse VSC3144 chip, which consumes 21W for a total bandwidth of 144 • 10Gbps. A larger 2880×2880 switch can be build using three stages of 20:40:20 VSC3144 chips, thus offering a total capacity of 28.8Tbps for a 1680W total consumption (hence the 58mW/Gb). While this is already a quite sizable switch, we expect FOXC architectures to be designed to address even larger cross-connect solutions as illustrated in the following example. Let F be the number of fibers reaching the network node, W the wavelengths per fiber, and O the number of orthogonal frequencies (subcarrier channels) per wavelength. For reasonable values of these three parameters, e.g., F = 9, W = 40 and O = 100, the total number of subcarrier channels available at the node ( ) greatly exceeds the 3 stage 2,880 available crossbar size. A number of crossbar modules must then be combined to cross-connect the whole set of frequencies. One of the project's scopes will be to identify the most appropriate (from both cost and power dissipation point of view) architectures for interconnecting multiple crossbar modules. In this section we present a simple two-stage FOXC architectural solution to discuss some preliminary findings. Assume that M crossbar modules are interconnected to form the FOXC as shown in Fig. 3.4, with Md decentralized modules, each connected to Cd incoming and Cd outgoing subcarrier channels, and Mc = M – Md, centralized modules being used to interconnect the Md decentralized modules. Each centralized module has Cc input ports and Cc output ports. On average, Cc/Md of these ports are assigned to interconnect the centralized module with one decentralized module. Note that there are two options to cross-connect an incoming subcarrier channel as shown in Fig. 3.4: (i) both the input port and the output port of the channel belong to the same decentralized module, and (ii) the input port and the output port of the channel belong to distinct decentralized modules, in which case one centralized module is required to cross-connect the channel from one decentralized module to the other. Option (i) is preferred over (ii) whenever possible, as it reduces the total number of crossbar modules required (and energy dissipated) in the FOXC. Assuming that the fraction of channels that requires option (ii) is x, the total number of required crossbar modules is approximately:

$$M_c = F \cdot W \cdot O \cdot x / C_c$$
$$M_d = F \cdot W \cdot O \cdot (1 + x) / C_d$$

Some numerical examples based on these two equations are reported in Table 3.1.

Table 3.1: Numerical examples obtained using F=9, W=40, O=100, C_c=2880, C_d=144, subcarrier channel rate of 10Gbps, and power dissipation of 21W per VSC-3144 chip.

x	M_c	M_d	M	FOXC W/Gb
0	0	250	250	0.015
15	19	625	644	0.313
30	38	1000	1038	0.589
50	63	1500	1563	0.954

Table 3.2: The rightmost column shows the fraction of traffic that requires wavelength conversion (case k=1) in arbitrary mesh WDM networks with average nodal degree F=8, obtained by running the heuristic in [41] on a PC Intel P4, 3.4 GHz machine with 1 GB memory.

$\lvert N\rvert$	$\lvert L\rvert$	#of circuits	#of converters	Run-time (s)	x
100	446	7383	386	60	5.2
200	890	12869	1254	122	9.7
400	1789	23075	3590	348	15.6
500	2231	24857	4321	508	17.4

As already mentioned, two options are available when cross-connecting a channel: (i) only one decentralized module is required, (ii) three modules, one centralized and two decentralized are required. The computation of routing and

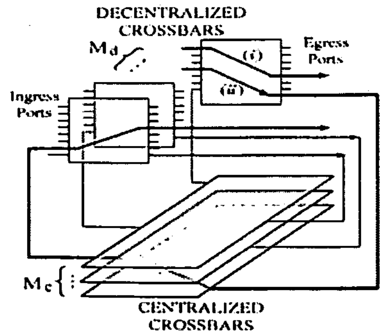

Fig. 3.4: Crossbar switch: M_d decentralized crossbars are interconnected by ML centralized crossbars.

frequency assignment (RFA) for the end-to-end circuit requests is a critical step in ensuring that the value of x (and amount of energy dissipated) is minimized. It can be demonstrated that solving the frequency assignment problem is an effort related to finding the solution to the improper coloring of a conflict graph [57,58], as shown next. Assume that the network is modeled as a graph G(N,L), N being the set of |N| nodes and L being the set of |L| links. Without loss of generality, assume that the every node is equipped with the same FOXC architecture shown in Fig. 3.4. Let D(n,d) indicate the d-th decentralized crossbar module at node n=1,2,...|N|. Assume that the decentralized modules are connected via the network links in L to form Md subnets as follows: modules D(n,i) n=1,2,...,|N| are interconnected and belong to Subnet i. If the circuit request is routed using only the crossbar modules of one subnet, its assigned subcarrier channel is cross-connected using option (i) only. If a circuit request is routed using two or more subnets, each time its subcarrier channel changes subnet, option (ii) is required at one FOXC node. Assume that the routing of each circuit request is given, i.e., a path consisting of an ordered subset of nodes in N. A conflict graph is then created in which each vertex represents one of the circuits, and a pair of vertices is connected by an edge if the two corresponding circuits share at least one common link in L. The conflict graph can be improperly colored using existing algorithms [59,60] to assign each vertex a color such that at most k neighboring vertices are colored with the same color, while attempting to minimize the number of required colors overall (the chromatic number of the conflict graph). By choosing k to be the maximum number of subcarrier channels that can be supported by one decentralized crossbar module, all vertices (circuits) colored with color i will be assigned to Subnet i, and the chromatic number will indicate how many subnets (Md) are required to avoid the use of centralized crossbars. A variant of the problem is when Md cannot be as large as the chromatic number of the graph. In which case, the vertices (circuits) colored with any color up to Md will be routed using option (i), the other circuits will need to be routed using option (ii), i.e., will make use of two or more subnets and require some centralized crossbars. As a special case (k=1), the problem of minimizing Mc is equivalent to the problem of minimizing the number of wavelength converters when solving the routing and wavelength assignment (RWA) problem for a set of lightpath requests in a WDM network [61,62,63,64]. Table 3.2 reports some RWA results recently published by the PIs stressing their heuristics' capability to handle large size networks.

The extension of these heuristics to solving the RFA problem (k > 1) is one of the critical missions of this proposal.

3.3 Research Tasks and Deliverables

In this collaborative research, cross-layer investigation and design must be performed, investigating transmission, switching, and networking issues. Part of the research effort at the University of Kansas (KU) will be devoted to building sub-system demonstrators to proof feasibility with off-the-shelf components and understand design limitations. Part of the effort at the University of Texas at Dallas (UTD) will focus on network wide design and control, taking into account the findings/constraints from the sub-system demonstrators.

3.3.1 Task KU-1: develop and optimize multi-carrier DSCM optical systems for FOXC

A traditional OFDM system developed for wireless communications [29, 37] typically requires IFFT in the transmitter and FFT in the receiver and the entire OFDM frame has to be detected in the receiver before recovering into the original data streams. Another type of OFDM system, known as electro-optic OFDM, makes use of an optical comb generator to create a group of mutually frequency-locked optical carriers [47,48]. Similar to WDM, electro-optic OFDM is an optical-domain solution as used in SLICE, in which each data channel is encoded into an optical carrier through a dedicated modulator. For a FOXC requiring a large number of subcarrier channels with relatively low data rate (such as 1Gbps per channel) for acceptable bandwidth granularity, such an optical-domain technique is not the best solution.

DSCM is another form of OFDM in which digital electronics is used in the transmitter to generate coherent subcarriers and each subcarrier carries an independent data stream. In comparison to optically generated subcarriers, it is much easier to ensure precise frequency spacing between subcarriers when they are generated digitally. Our preliminary works include computer simulation using a VPI simulation package [49] as well as the setup of an experimental test-bed.

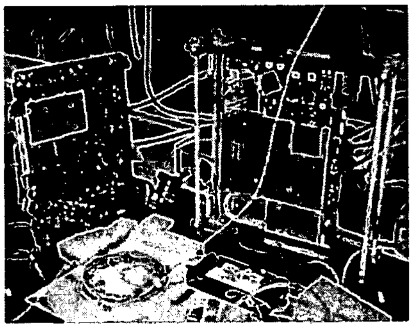

Fig. 3.2: Digital transceiver cards donated by CIENA Corp.

In a FOXC cross-connect illustrated in Fig. 3.1, data bits carried by different wavelengths may not be synchronized. If the RF switch fabric does not provide retiming function, after the switch and regrouping, bit-time misalignment between adjacent subcarrier channels may cause BER degradation as indicated in Fig. 3.3(c). In addition, the electrical bandwidth of an OFDM receiver has to be wide enough to include the spectral sidebands of each subcarrier channel; otherwise crosstalk cancelation would be incomplete. We will also explore the use of narrowband Nyquist filters to spectrally separate subcarrier channels [21] and eliminate the crosstalk. This type of digital filter may not be feasible in optical domain, but it is straightforward to realize in digital electronics. This also eliminates the need for bit-time synchronization.

The major focus of this task is to setup a DSCM system test-bed with enough flexibility of adopting various different modulation formats as well as detection algorithms. Performance analysis and comparison between different system architectures will be conducted for the application in FOXC. Implementation complexity is an important consideration including the complexity of DSP algorithms and the electronic circuit realization. Coherent detection will be used in the optical domain in the test-bed based on the available equipment in our laboratory (including a number of CIENA digital transceiver cards shown in Fig. 3.5). While we have already demonstrated 20Gbps per wavelength capacity using QPSK, 40Gbps is readily achievable using 16-QAM.

Our previous works on OFDM systems used post processing, in which a digital signal analyzer performed data acquisition and ADC, while data recovery was performed numerically in a computer. To demonstrate cross-connect switching of subcarrier channels, real-time signal processing has to be used [51]. For demonstration purpose, we will use a National Semiconductor ADC08D1500DEV, which has dual ADC of 1.5Gbps, connected to a Xilinx Virtex4 FPGA [52]. This will allow us to configure a real-time OFDM system. Note that in this demonstration, there is no attempt to break record in transmission capacity; instead, our purpose is to proof the DSCM cross-connect switching concept. In addition, since a commercial simulation package has many restrictions, not flexible enough for new OFDM/DSCM systems and modulation formats such as ours, we will also develop a software program based on Matlab for system modeling.

3.3.2 Task KU-2: demonstration of FOXC, i.e., cross-connection of subcarrier channels

Based on the OFDM systems developed in task KU-1, we will demonstrate cross-connect switching capabilities based on subcarrier channels. Both RF-based analog switch and CMOS-based regenerative switch will be investigated.

RF-based analog switch will utilize Honeywell HRF-SW1031 as described in sec. 3.1. In fact, we have used this device in the undergraduate senior design lab, and our students developed an evaluation board for this device as shown in Fig. 3.6, which was part of a smart sensor. We will build a 12x12 circuit switch fabric based on the 1x6 RF switch unit to test the feasibility in the test-bed. It is important to note that in RF-based analog crossbar switch architecture, crosstalk and propagation loss may accumulate when the number of channels and switch units increase, thus limiting the scalability. Therefore RF-based analog switch may be most suitable for cross-connectors of relatively small sizes.

On the other hand, CMOS-based regenerative switches such as Vitesse VSC-3140 integrated circuits or the equivalent [45, 50] have the potential to build large scale cross-connectors. We will implement a 144x144 switch using Vitesse VSC-3140 in our test-bed and demonstrate the any-to-any crossbar switch. Clock recovery, digital regeneration and synchronization will be implemented in the switch based on the real-time DSCM receivers described in task KU-1. Issues such as performance limitations and switch size scalability will also be investigated. We will collaborate with researchers at Texas Instruments (TI) and investigate the design rules of CMOS electronic circuits for digital crossbar switch with special focus on power consumptions.

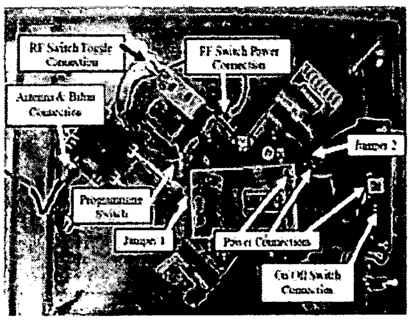

Fig. 3.3: RF switch board developed by KU undergraduate students.

3.3.3 Task KU-3: understand the system impact of cross-bar sub-wavelength switch

In the proposed research of FOXC, subcarrier channels will be switched and regrouped with other subcarrier channels which were originally carried by other wavelengths. In an optical network, different subcarriers may travel over different distances, and pass through different numbers of network nodes (cross-connect switches) as chosen by the network routing algorithms. The impact of relative delay and difference in data quality will need to be investigated. In order to equalize their transmission performance, it would be advantageous to apply unequal power provisioning as well as different levels of modulation (such as M-ary) for different subcarriers at cross-connect switch nodes. The impact of unequal subcarrier channel power and data rate on the crosstalk has to be evaluated and the overall impact on the optical network performance will be investigated.

3.3.4 Task KU-4: explore the feasibility of mixed data rate of subcarrier channels

From a network standpoint, a cross-connect has to provide fine enough granularity to satisfy users with varying bandwidth demands. With the trend of rapidly increasing capacity demand, SONET cross-connect switches are moving to higher base rates, from OC-3 to OC-12 and even to OC-48, which simplifies the transceiver MUX and DEMUX complexity. Similarly, for the proposed FOXC, a higher subcarrier data rate reduces the number of subcarriers for a certain overall capacity. This will help decrease both the required port-count of the switch fabric and FOXC power dissipation. Although a single data rate for all subcarrier channels would imply simple system architecture, mixed data rates will allow the tradeoffs between traffic demand, power dissipation and system complexity, and thus provide more options when optimizing the overall network performance.

In principle, hybrid data rate is possible with OFDM if the data rates are integer multiples of the lowest rate. In this case, bandwidth efficiency will be reduced and the integration at the receiver has to be performed over the longest bit period. On the other hand, if Nyquist filters are used to spectrally separate subcarrier channels as in [21], this integration is not required, but the digital bandpass filters with sharp edges would require longer delay taps and thus making CMOS realization more difficult. Detailed theoretical analysis, tradeoffs and computer simulations will be performed to evaluate the impact on transmission performance, as well as possible complications in system realization. In the proposed research, since all subcarriers will be generated by digital electronics, the full benefit and flexibility of DSP will be explored in terms of modulation, detection, data recovery and crosstalk cancellation.

3.3.5 Task UTD-1: investigate possible FOXC and network architectures

Accounting for the findings and measurements originating from tasks KU-1 through KU-4, we plan to design a number of FOXC architectures with varying sizes, blocking and non-blocking switching capabilities, and power consumption levels. Beside the straightforward

FOXC architecture described in Section 3.2, other options will be investigated, besides the C=144 used for decentralized modules and size C=2880 used for centralized modules. With the reasonable assumption that networks will continue to grow in capacity, number of nodes and links, special attention will be given to scalable solutions while maintaining the power consumptions levels below 20% of currently available transport network equipment.

The designed FOXC architectures will be tested in a number of network scenarios spanning across multiple metro and core domains. Their impact on end-to-end circuit performance and availability will be evaluated through simulation studies (see tool developed under task UTD-4). In performing this network wide study, traffic distributions will be created to represent also cloud computing applications being available from a number of data centers. Reliability of the OFDM circuits and availability of the applications between the data center and the client will be both evaluated, accounting also for the application mobility. UTDallas Ph.D. candidate Ning So (contributor to the IETF CSO group [65,66]) will participate in the project and will both provide industrial guidelines to the construction of the simulation framework as well as facilitate the dissemination of the project findings within the IEFT community. Suitable control planes for the proposed network architecture will be designed or identified (e.g., GMPLS), along with specific functionalities of the FOXC architecture to perform subcarrier channel monitoring, fault detection, and restoration mechanisms. The MPLS signaling test-bed available at UTDallas [67] will be leveraged to carry out this investigation.

3.3.6 Task UTD-2: design and evaluate RFA algorithms

Accounting for the designed FOXC architectures and identified network control plane(s) in task UTD-1, routing and orthogonal frequency assignment (RFA) algorithms will be needed to choose which subset of network resources (subcarrier channels) must be reserved for the incoming end-to-end circuit requests. The optimal RFA solution can be shown to be a hard problem (RWA can be seen as a special case of RFA, and it is known to be NP-hard [68]). The PIs will leverage their past experience in designing near optimal RWA algorithms to tackle the RFA problem. Some recently published RWA heuristics [22,41,61,69] are particularly promising as they show good scalability properties (applicable in up to 2500 node networks) along with good versatility in accommodating various types of circuit: e.g., unidirectional vs. bidirectional [41], unicast vs. multicast [22], unprotected vs. dedicated protection [61] and shared protection switching [69]. As documented by these papers, the PIs have designed and implemented a number of algorithms whose aim is to minimize the number of wavelength converters in WDM networks (problem described in Section 3.2 with k=1). The main objective of this task will be to extend the problem definition to also include k>1, and look for innovative solutions by leveraging for example improper conflict graph coloring results [57,58]. As discussed in Section 3.2, the solution of the problem with k>1 can be then translated into a solution that minimizes the number of centralized crossbar modules required in the FOXC. Minimizing the number of centralized crossbar modules in the FOXC has the double advantage of reducing the FOXC cost and power dissipation levels as shown in Table 3.2.

3.3.7 Task UTD-3: build a planning tool for joint design of OFDM and WDM layers

The RFA algorithms in task UTD-2 will be integrated as software modules in an existing multilayer planning tool, thus enabling it to perform joint optimization of OFDM and WDM layers. These modules will be made available online for the community to extend or modify the designed RFA algorithms.

This task will be carried out by leveraging an already existing planning tool, called PlaNet [26], [27]. The PlaNet tool under development at UTDallas since 2007, consists of 200k lines of code and comprises a variety of network planning algorithms that are integrated to form an optimization platform for OTN, WDM and packet transport networks (MPLS-TP). The modular design of the tool makes it flexible to integrate new modules and extend or replace existing ones. PlaNet - being a multilayer planning tool - enables the network designer to select the modules and features individually or as a combination. The RFA algorithms developed as part of this project will be incorporated into PlaNet. The resulting tool will be extensively tested by the students involved in the project and will then be made available to the community through a dedicated server hosting a code source repository with version control and software documentation, and log of the configuration and parameters used on every session.

Some of the features that will be incorporated include: FOXC functionalities as they are assessed with the demonstrators developed in task KU-2, power dissipation attributes for the featured equipment, power consumption to be used as the design objective function during the optimization procedure, and a set of basic data visualization features to analyze traffic and network changes effect over time.

3.3.8 Task UTD-4: build a network simulator for joint evaluation of OFDM and WDM layers

The UTDallas team will develop a network wide simulator that accounts for the measured performance of the critical parameters (e.g., channel crosstalk) of the OFDM subsystems developed in task KU-2. It will incorporate the functionalities and constraints that are part of the FOXC architectures and network control plane(s) designed and identified in task UTD-1. The outcome produced by the planning tool developed in Task UTD-3 will be automatically used as network and equipment descriptors (input) to the simulator, thus allowing a researcher to first design the network with a given optimization objective and/or possible power consumption constraints, and then run simulation experiments to estimate the network performance. Performance parameters measured by the simulator will include circuit blocking probability, setup time, latency, bit error rate, reliability, restoration time, etc. Traffic generators will be implemented to represent data exchange that takes place between clients and servers. Simulation of application mobility across multiple data centers in the network will be available to analyze the network performance under stressing and highly demanding scenarios.

We plan to accomplish this task by customizing an already existing event driven network protocol simulation tool under development at UTDallas since 2004 consisting of 20k lines of code. The simulator code will be made available online, and will also be maintained as part of the software repository and version control system. Unit and regression testing will be executed as well as result validation and verification, before any code release. The simulator will then be made available online to other researchers with a simple UI to facilitate its use.

4 Integration of Research, Education and Outreach

A major outcome of the proposed project will be the training of undergraduate and graduate students at the two participating institutions. A total of 3-4 undergraduate students and 3-4 graduate students are expected to be directly involved in the project over three years. These students will gain an appreciation for research that is broadly interdisciplinary, which involves both physical layer fiber-optical transmission systems and optical modulation, and network layer scheduling and optimization. The PIs have a history of involving undergraduate researchers in their laboratories. The project will strengthen the already existing interdisciplinary research collaboration between KU and UTD.

Involvement of undergraduate students: The education program for undergraduates will involve their participation in the proposed research (PIs plan to request the support for 2 additional undergraduate students through the NSF REU supplement program). In the past we have had good experiences in working with undergraduates in our research projects. The PIs have worked with a number of REU students in the past. For example, one of the graduates who will be involved in this proposed project at KU, Adam Crifasi, has been working with the PI since his college junior year, and became a graduate student this year. Currently our laboratories, both at KU and in UTD, involve undergraduate research assistants working in various areas. The PIs have all been active nationally and internationally in research and education, as well as engagement with local community. Dr. Tacca (a senior person involved in the proposed project) is currently the coordinator for the UTDesign effort. UTDesign is a form of senior design project where undergraduate (UG) students must complete a team project. UG students form teams of 3 to 5 people and then choose a project from a pool of candidate projects. The project is defined by a sponsor, in most cases an industry sponsor. The education plan includes UG students to perform their UTDesign on tasks related to the proposed research, e.g., run experiments using both the network planning tool (task UTD-3) and network simulation tool (task UTD-4) to evaluate the network power dissipation versus performance.

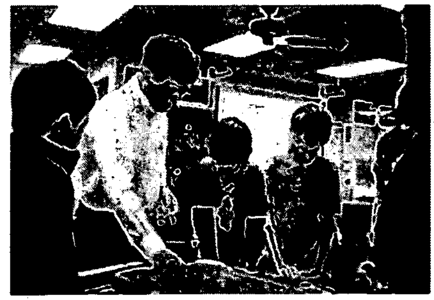

Fig. 4.1: "It's so cool! The PI is demonstrating fiber-optics to local school students in their classes.

Involvement of underrepresented minority: In order to engage underrepresented students, the University of Kansas has a long-term connection with Haskell Indian Nations University in Lawrence, Kansas. For example, Mr. Vernon Dempsey, a Haskell student, is an undergraduate research assistant in our laboratory at KU and worked on the measurements of temperature sensitivity of optical waveguides. The NSF support would greatly enhance our strength in attracting students by further developing this cross-layer research in optical communication systems and networks. Through these types of research activities, students will be exposed to the cutting-edge technologies as well as the excitements of discovery. We intend to target the Hispanic underrepresented group for recruitment to our graduate programs. This will be accomplish by leveraging the existing agreements between UTDallas and CONACYT (National Council for Science and Technology of Mexico), which involves more than 13 universities, research centers and other educational institutions in Mexico. During the past decade, UTDallas has developed a bilateral relation with these Mexican institutions. Students and teachers have been part of this agreement trough exchange programs, which include short stays, summer programs and full graduate studies. Master and Doctoral students participating in this program will be encouraged to join our project, as well as Hispanic undergraduate students showing interest in learning the skills needed to be actively involved. This critical mission will be lead by PI Dr. Miguel Razo, who is a faculty of Computer Science at UTDallas. Dr. Razo completed his Ph.D. at UTDallas in Fall 2009 while being sponsored by CONACYT, and he will leverage his past experience to facilitate the active participation of Hispanic students in the project activities. Student population at OpNeAR Lab is diverse, and we plan to enrich this diversity by encouraging women on engineering fields related to our project to join our team. This can initially be achieved by inviting the SWE branch at UTDallas to our monthly presentations, and project meetings.

Involvement of graduate students: Energy saving and green photonics is an emerging research area. Cross-layer design in optical networks has the potential to bring breakthroughs in improving energy efficiency. The proposed research tasks require faculties with complementary expertise. The nature of the resulting interdisciplinary research will ultimately have a profound effect on how we learn, work, communicate, and cooperate. 3 to 4 graduate students will be involved in this research over the 3 years. In addition to work with their faculty advisors, they will work together and learn from each other. Clearly, as the research continues to develop, new knowledge gained from this effort will be incorporated into graduate courses. For example, Dr. Hui at KU is teaching an undergraduate course in Fiber-optic communications" (EECS628) and two graduate course in "advanced fiber optic communications" (EECS828) and "Fiber-optic measurement and sensors" (EECS728). He has been constantly adding new materials reflecting new developments in fiber-optic communications and networks from his own research and from the interaction with industry and the research community. In addition, both graduate and undergraduate students involved in this project will benefit from the close collaboration between the two research groups.

Other outreach activities: Our photonics laboratory within ITTC (Information and Telecommunication Technology Center) at KU frequently invites local K-12 students to participate in our open-house visit demonstrating various engineering-related researches. Dr. Hui is also a frequent speaker in local schools presenting his research in electrical engineering and fiber-optics. We plan to continue our participation in various science workshops/program on campus and in the region. The intended impact of the undergraduate research opportunity is to recruit undergraduate students who are enthusiastic about pursuing advanced education and/or careers in energy-efficient technology. The recruitment will emphasize women, underrepresented populations and students from non-research institutions. The project will also offer the participating students hands-on research experience at state-of the-art research facilities with staff committed to career training and support.

5 Previous NSF Results

NSF CNS-0435381, Period Covered: 10/2004 – 9/2008, (PIs: A. Fumagalli, & R Hui)

Project title: "NeTS-NR: Collaborative Research: High-Speed Self-Configuring Networks Based on Cost-Effective Plug-and-Play Optical (PPO) Node" We proposed a self-configuring optical network topology and have developed fast transmission simulation tools which allow impairment-aware optical routing and network optimization. We have also developed novel techniques to extract physical parameters of optical systems such as chromatic dispersion polarization mode dispersion and polarization-dependent loss, which allows the in-situ monitoring of traffic-carrying optical networks. Especially, we have developed an in-service PMD monitoring technique and helped telecom service providers such as Sprint to evaluate fiber parameters in their terrestrial optical networks as well as the transatlantic fiber system (TAT14) without interrupting the commercial traffic. Tech transfer has been negotiated with a number of companies. A network planning tool was designed and developed at UTDallas, able to perform cross layer optimization, including packet transport network (PTN), optical transport network (OTN) and wavelength division multiplexing network (WDN) called PlaNet [27], [28]. Features of the PlaNet include: multiple protection schemes for P2P and P2MP traffic, including FRR (detour and bypass) and multilayer (OTN and WDM), routing constraints for services at each layer (PTN, WDM and OTN) such as include/exclude node/link/SRLG, service bundle in WDM and OTN, equipment constraints per node and link, network equipment cost minimization, load balancing of traffic, and user-controlled run time of the optimization process. PlaNet is able to provide, among others, optimization of service routes, link capacity placement, node and link equipment configuration, at the PTN, OTN and WDM layers.

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POINTS

1. OFDM or equivalent digital signal processing is used to enable spectrally efficient multiplexing capability of orthogonal channels (circuits) in optical communications and networking. Solutions include fiber based networks as well as free space optics (e.g., infrared communications). We may need one or more figures here.

2. Individual or group of channels can be individually routed across a network of nodes via specially designed crossconnect nodes. We may need one or more figures here.

2b. Special Gateway or Add Drop Multiplexing nodes are designed to provide the necessary interface for other network technologies to establish and use the channels in the network created using our solution. See Point 16. for examples of network technologies that can be supported.

3. The transmission rate can be individually assigned to each channel, thus offering a comb of transmission rates to be offered end-to-end across the network. Rates may be as low as sub-Gbps and as high as hundreds of Gbps. For comparison, current technologies like OTN, SONET and SDH can only offer ODU-0 (1 Gbps), ODU-1 (2.5 Gbps), ODU-2 (10 Gbps), ODU-3 (40 Gbps), ODU-4 (160 Gbps) and ODU-Flex, the latter offering products that are ODU-2 or greater.

4. The frequency used for a channel (or the frequencies used for a group of channels) can be changed along the end-to-end path by using the specially designed crossconnect architecture, thus giving more flexibility to routing.

5. The solution can be used in conjunction with WDM, and the wavelength used to carry the frequency of the channel (frequencies of a group of channels) can be changed along the end-to-end path by using the specially designed crossconnect architecture, thus giving more flexibility to routing.

6. Points 4. and 5. can be jointly apply to the same channel (or group of channels).

7. With the proposed solution, network wide time synchronization is not required as multiplexing is performed in the frequency domain. For comparison, similar existing solutions are based on time multiplexing, and network wide synchronization is needed, e.g., OTN, SONET, SDH.

8. In our solution, channels may be provisioned statically.

9. In our solution, channels may be set up and torn down dynamically at all possible time scales, down to milliseconds or less if technology allows it.

10. In our crossconnect, transmitted data need not be buffered for synchronization and crossconnection purposes, like it is the case in other solutions, e.g., OTN, SONET, SDH.

11. Our solution offers end-to-end circuits that can be built across access networks, including PONs.

12. Our solution offers end-to-end circuits that can be built across Local Area Networks (LANs), including enterprise network.

13. Our solution offers end-to-end circuits that can be built across Metro Area Networks (MANs), including ring networks.

14. Our solution offers end-to-end circuits that can be built across Wide Area Networks (WANs), including WDM networks based on ROADMs.

15. Points 11. through 14. can be combine in all possible permutations.

16. End-to-end channels or circuits can be used to interconnect IP routers, OTN, SONET, SDH nodes, end user equipment, data center (Cloud) network interfaces, enterprise and residential user equipment.

17. Unicast, anycast, and multicast traffic are all supported options in our solutions, individually or combined.

18. All types of network management, network control, and network monitoring software may be used in conjunction with our solutions, for the overall network to function properly.

19. All types of signaling and interfaces may be used in conjunction with out solution in order to setting up. tearing down, restore, reroute, etc. channels or circuits across the network.

20. All known protection and restoration mechanisms may be applied to the circuits created with our solution, including dedicated protection, shared protection, fast reroute, etc.

21. Power consumption per unit of traffic carried is expected to be lower compared to other electronically based transport network technologies (OTN, SONET, SDH, MPLS-TP).

22. When not in use, part of the electronics in the specially designed crossconnect can be switched off, to reduce power consumption to run the network.

23. The crossconnect architecture can be single stage, or multi-stage to offer scalable solutions.

24. Hierarchical multiplexing may be applied to our solution, to offer multiple levels of traffic multiplexing. The advantage of hierarchical multiplexing is to offer modular options to span across a large spectrum of transmission rates, ranging from sub-Gbps to 100s Gbps rates.

WHAT IS CLAIMED

1. A method of transporting data along an optical transport network from an input port to an output port using a digital subcarrier cross-connect switch, the method comprising:

(a) monitoring input data traffic of an input port having data units on a first optical fiber having a first wavelength channel;

(b) separating the first wavelength channel into sub-wavelength channels to create multiple input subcarrier channels;

(c) directing an input data unit on the optical fiber to a input subcarrier channel having a frequency;

(d) establishing a static traffic output subcarrier channel having the same frequency as the input subcarrier channel; and

(e) transferring the input data over the input subcarrier channel to the output subcarrier channel to the output port.

2. The method of claim 1 wherein the step of separating the first wavelength channel into sub-wavelength channels further includes performing orthogonal frequency division multiplexing on the first wavelength channel to create subcarrier channels wherein each subcarrier channel has a unique frequency.

3. The method of claim 1 wherein the frequency of the input subcarrier channel is equal to a transfer data rate on the first wavelength channel.

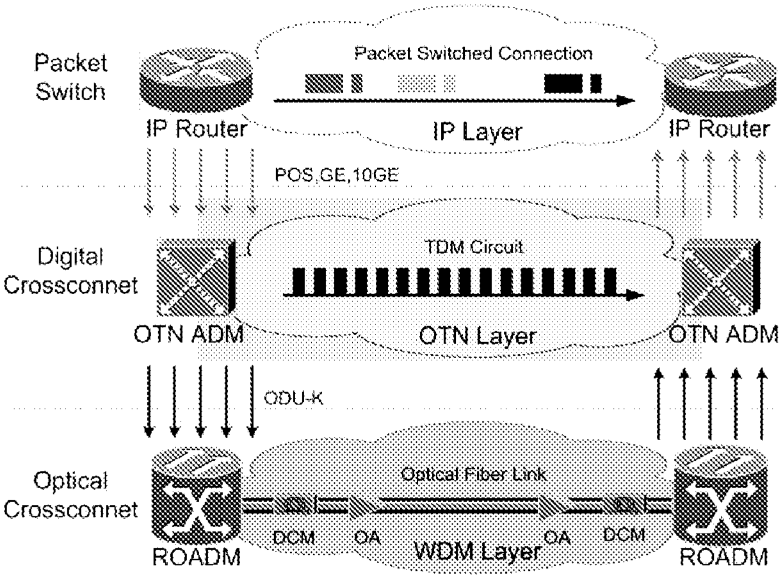

Packet Switch
IP Router
Packet Switched Connection
IP Layer
IP Router
POS,GE,10GE
Digital Crossconnet
OTN ADM
TDM Circuit
OTN Layer
OTN ADM
ODU-K
Optical Crossconnet
ROADM
Optical Fiber Link
DCM
OA
WDM Layer
OA
DCM
ROADM

Fig. 1

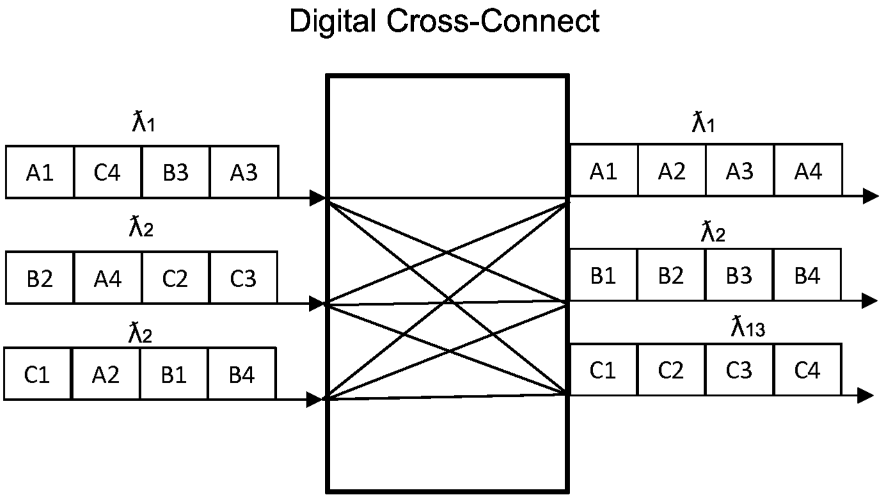

Digital Cross-Connect
λ1
A1 C4 B3 A3
λ2
B2 A4 C2 C3
λ2
C1 A2 B1 B4
λ1
A1 A2 A3 A4
λ2
B1 B2 B3 B4
λ13
C1 C2 C3 C4

Fig. 2

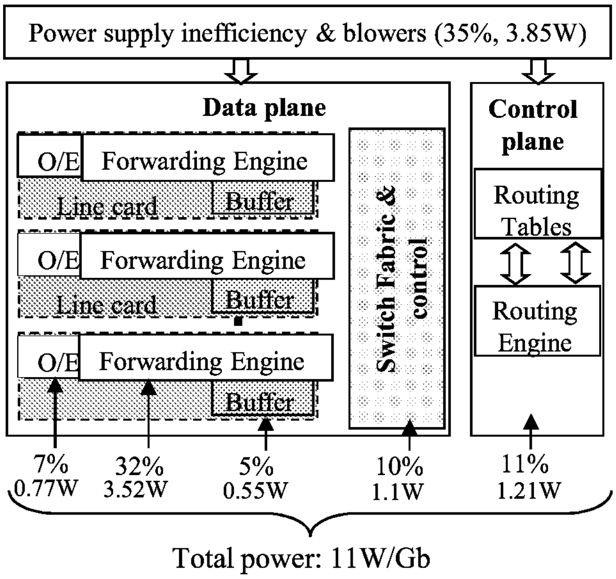


Fig. 3a

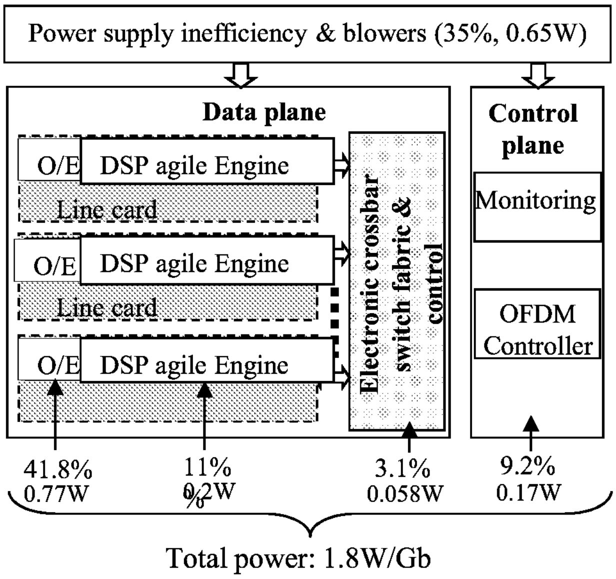


Fig. 3b

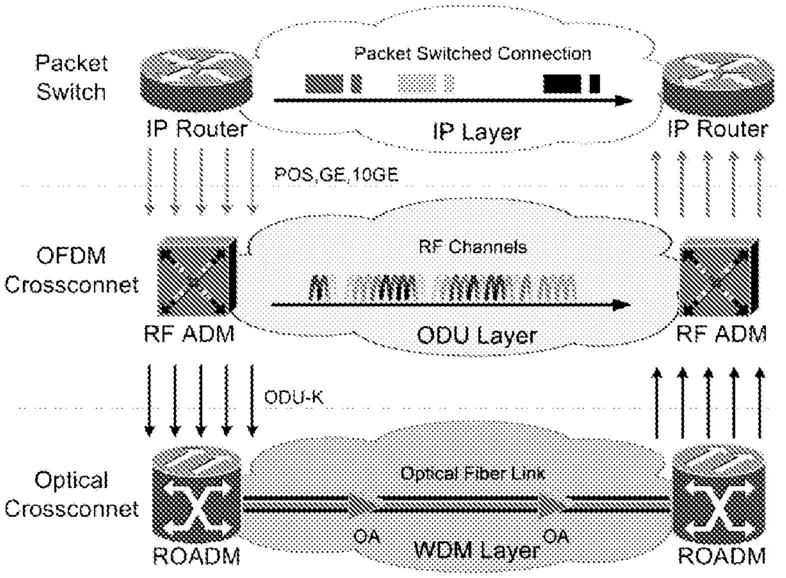


Fig. 4

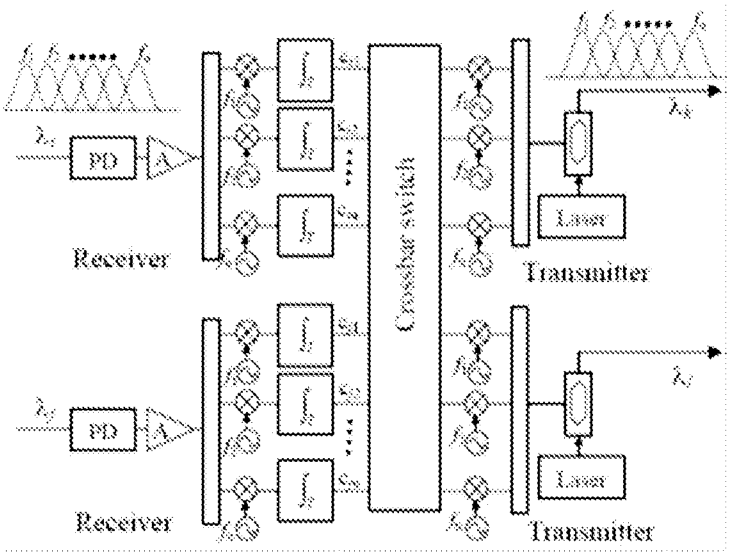

f1 f2 ••••• fn
λ1
PD
A
Receiver
s11
s12
s1n
Crossbar switch
Laser
Transmitter
λN
λ1
PD
A
Receiver
s21
s22
s2n
Laser
Transmitter
λ1

Fig. 5

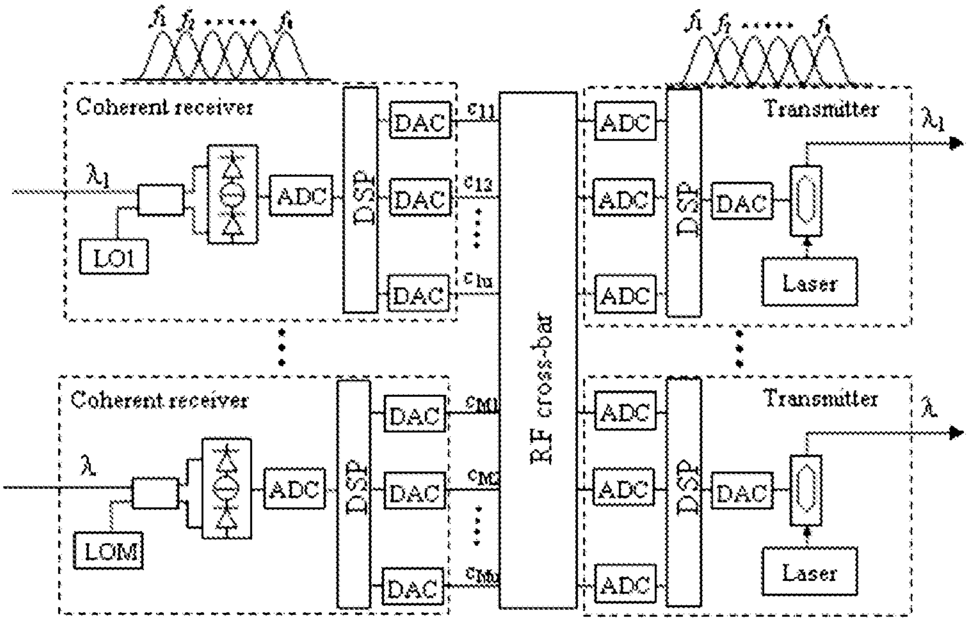

f1 f2 •••••• fn
Coherent receiver
λ1
LO1
ADC
DSP
DAC
DAC
DAC
c11
c12
c1n
RF cross-bar
ADC
ADC
ADC
DSP
DAC
Transmitter
λ1
Laser
Coherent receiver
λ
LOM
ADC
DSP
DAC
DAC
DAC
cM1
cM2
cMn
ADC
ADC
ADC
DSP
DAC
Transmitter
λ
Laser

Fig. 6

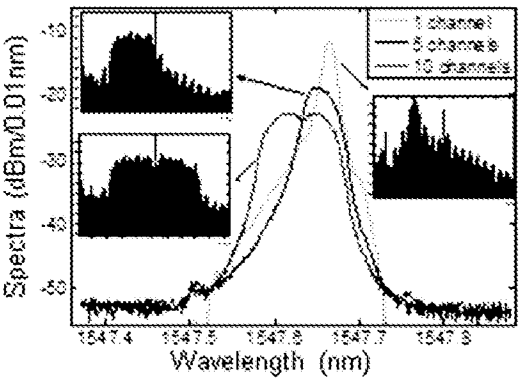


Fig. 7

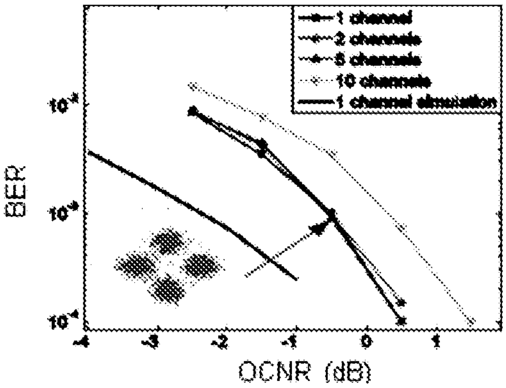
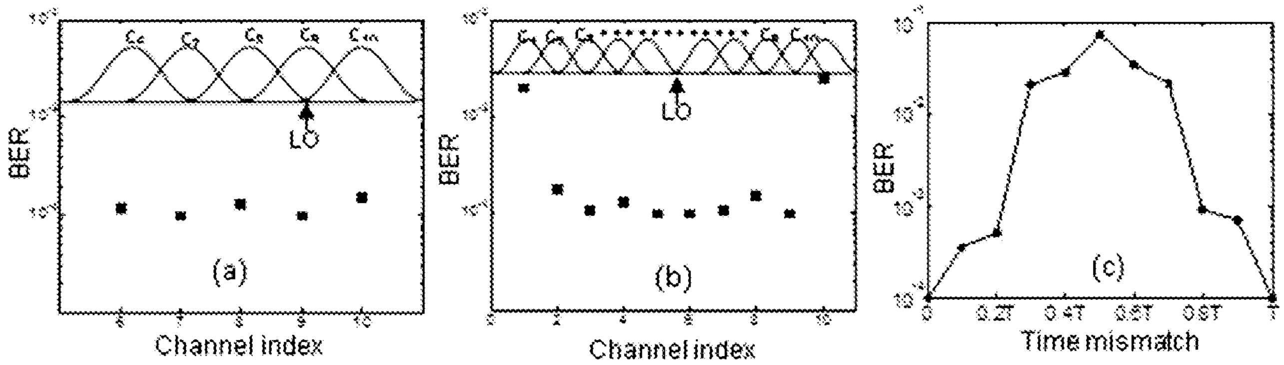


Fig. 8



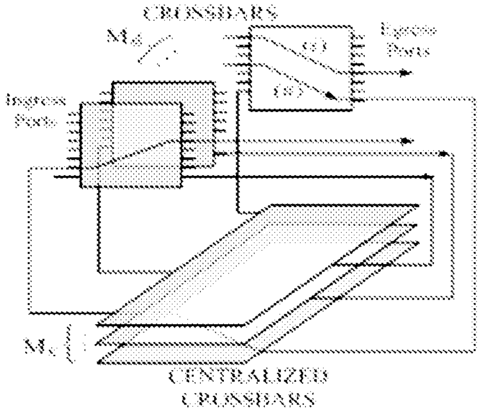


Fig. 10

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2011/065947

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G02F 1/00 (2012.01)
USPC - 398/1
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8) - G02F 1/00, G02F 2/00, and H01S 3/00 (2012.01)
USPC - 398/1, 398/2, 398/79

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
MicroPatent, Google Patents, and ACM

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,956,165 A (FEE et al) 21 September 1999 (21.09.1999) entire document	1-3
Y	US 2010/0008242 A1 (SCHEIN) 14 January 2010 (14.01.2010) entire document	1-3
A	US 2010/0080571 A1 (AKIYAMA et al) 01 April 2010 (01.04.2010) entire document	1-3
A	US 7,796,898 B2 (ARMSTRONG) 14 September 2010 (14.09.2010) entire document	1-3

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search 22 February 2012	Date of mailing of the international search report 09 MAR 2012
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-3201	Authorized officer: Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774