Flexible Optical Infrastructure for Ethernet Transport: Solutions and Enabling Technologies in the ICT STRAUSS Project

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***Abstract*—Cloud applications and the global delivery of Ethernet services require a scalable, reliable, virtualizable and cost/energy efficient optical transport infrastructure able to support data rates beyond 100 Gb/s. The ICT STRAUSS project addresses the requirement of future optical infrastructures for Ethernet transport beyond 100 Gb/s, by combining two network switching technologies, namely Optical Packet Switching (OPS) and flexible Optical Circuit Switching (OCS). In this paper, cost/energy-efficient solutions and technology enablers are presented, specifically dealing with data plane aspects, such as the design and development of sliceable bandwidth variable transponders (S-BVT), fixed-length variable-capacity OPS, flexi-grid optical switching nodes and OPS/OCS integrated interface.**

Keywords—Ethernet; OPS; OCS; Flexi-grid; DMT; OFDM.

I. Introduction

The adoption of Ethernet technology on a global scale, including both intra- and inter- data center connectivity [1], and the data-intensive traffic of cloud applications are the main drivers for the development of an efficient network infrastructure able to deliver Ethernet services. Dense Wavelength Division Multiplexing (DWDM) networks supporting Optical Circuit Switching (OCS) provide a mature and robust infrastructure; however, optical bandwidth allocation based on a fixed grid does not allow an efficient usage of the spectral resources. On the other hand, the combination of OCS and electrical packet switching technologies seems to meet the requirements of the Ethernet transport. Nevertheless, major issues need to be addressed and solved for data rates beyond 100 Gb/s. Particularly, a new DWDM bandwidth allocation strategy based on the concept of flexi-grid, using 12.5 GHz spectrum slices, can be preferably adopted, as defined by the ITU-T recommendation G.694.1 [2]. In flexi-grid optical networks, a data plane connection is established and switched based on variable-sized frequency slots and configured depending on the requirements of transport tributaries, such as data rate, modulation format, spectral efficiency and quality of service [3]. To this extend, advanced multi-level and multi-dimensional modulation formats provide different degrees of robustness, adaptive spectral efficiency and spectrum occupation, based on varying the symbol rate and the number of bits per symbol by means of electronic digital signal processing (DSP) [4]. Optical multicarrier modulation techniques are suitable for software-defined transmission and are emerging as key enablers for flexi-grid optical networks thanks to their scalability to higher order modulation and distance adaptive capabilities [5]. In order to support flexible and efficient transmission technologies and enable advanced functionalities in the core network, evolved flexi-grid OCS nodes must be designed. Likewise, new switching and aggregation technologies at sub-wavelength granularity are required to reduce the cost and energy per bit and to increase scalability, maintaining a high throughput in terms of packets per second. These requirements can be met by adopting optical aggregation and switching technology based on Optical Packet Switching (OPS) [6].

In this context, the ICT STRAUSS (Scalable and efficienT oRchestrAtion of Ethernet services Using Software-defined and flexible optical networkS) project addresses the requirement of future optical infrastructures to support Ethernet transport beyond 100 Gb/s, by suitably combining the high-capacity flexi-grid OCS networks with flexible spectrum management and the high-throughput and statistically multiplexed OPS systems. In this paper, highly integrated and efficiently scalable software-defined optical data plane solutions are presented and discussed as envisioned by the STRAUSS project. This includes the key enabling technologies supporting sliceable bandwidth/rate variable connections, for the cost-effective transmission of Ethernet over OPS and flexi-grid OCS transport networks.

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II. STRAUSS ARCHITECTURE

The future software defined optical Ethernet transport network architecture proposed by the STRAUSS project is composed of four layers as shown in Fig. 1.

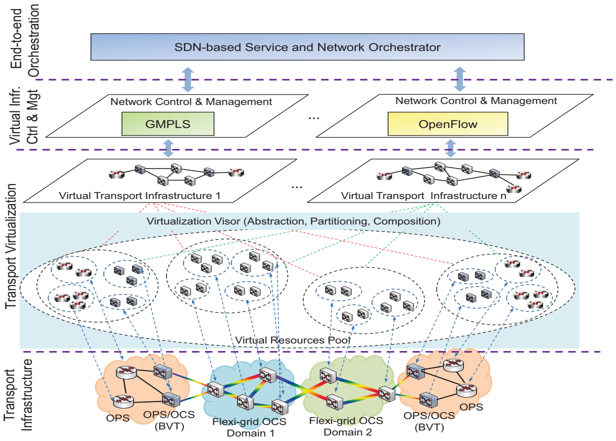


Fig. 1. The four layers of STRAUSS architecture.

The transport network infrastructure covers different/heterogeneous technologies based on:

- software-defined sliceable (multi-flow) bandwidth-variable transponders (BVT) supporting multiple data flows with different modulation formats and bit rates;
- OPS to provide scalable and cost/energy-efficient traffic grooming at sub-wavelength granularity;
- OCS to provide flexible spectrum managements, enabled by flexi-grid DWDM switching nodes;
- the integration of OPS and flexible OCS, enabling the combination of data plane technologies.

The transport network virtualization layer virtualizes the heterogeneous data plane resources. The physical infrastructure is partitioned and/or aggregated into virtual resources. Virtual resources of different domains are selected to compose end-to-end virtual transport infrastructures. Each virtual infrastructure can be individually controlled/managed.

The virtual infrastructure control and management layer employs GMPLS and/or customized network control based on OpenFlow sits over each virtual transport infrastructure, providing control and management functionalities.

The service and network orchestration layer is responsible for the interworking of different control plane paradigms to provide end-to-end Ethernet services. It uses software defined network (SDN)-based service and network orchestrator(s).

In the remainder of the paper, we will focus on the optical path-packet transport network infrastructure.

III. SLICEABLE BANDWIDTH VARIABLE TRANSCEIVER TECHNOLOGIES

Software-defined transmission technologies for Ethernet transport beyond 100 Gb/s are identified and implemented, to maximize the flexibility and scalability of the network and minimize its cost/energy consumption. The software-defined BVT can be adaptively reconfigured to multiple modulation formats or variable bandwidth occupancy by DSP. Optical orthogonal frequency-division multiplexing (OFDM) and discrete multi-tone (DMT), transmitting multiple orthogonal subcarriers/tones, are suitable technology options able to provide high spectral efficiency, unique flexibility, adaptive rate/bandwidth and sub-wavelength granularity, compared to single carrier modulations [7]. In fact, each subcarrier/tone can support a different modulation format, enabling bit/power loading to improve the performance of rate/distance adaptive systems and optimize the spectrum usage. To further enhance the flexi-grid network capabilities, the programmable BVT can be designed to be sliceable (S-BVT), thus able to deliver several flows to multiple destination nodes through different optical paths [8]. The S-BVT, as a set of virtual transponders, generates an aggregated flow, which can be sliced in time/frequency assigning to each slice a time slot/wavelength, by using single or multiple optoelectronic front-end(s).

A. DMT

The DMT technology is an OFDM based multicarrier modulation format, which is widely used in digital subscriber line (DSL) systems for its high spectral efficiency and simple configuration [9] [10]. DMT technology transmits data only by an intensity domain of the optical carrier signal and does not use a phase domain with a single-electrode modulator, and direct detection (DD) by a single photo detector (PD). Fig. 2 shows the concept of the DMT technology. The DMT signal comprises a group of subcarriers and the modulation format of each subcarrier is determined from the transmission characteristic of each subcarrier, which is obtained by transmitting the probe signal beforehand. The transmission characteristic of subcarriers has the frequency dependence due to the frequency response of the devices or chromatic dispersion of the transmission fiber. The spectral efficiency is improved by assigning the high multi-level modulation format to the subcarriers of good quality and the low multi-level modulation format to the subcarriers of bad quality, as in Fig. 2.

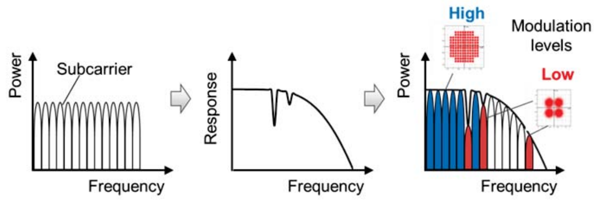


Fig. 2. Discrete multi-tone technology.

Fig. 3 depicts a block diagram of optical DMT transceiver. The input transmit data is modulated to a DMT source signal by a DSP and converted to an analog signal by a digital-to-analog converter (DAC). Then the signal is amplified by a linear driver amplifier and drives an optical modulator of a transmitter. A directly modulated laser (DML), an electro-absorption modulation laser (EML), or a lithium-niobate ($LiNbO_3$) Mach-Zehnder modulator (MZM) can be used. The optical signal is launched into a transmission fiber and the transmitted signal is detected by a single PD of a receiver. After being amplified by a linear transimpedance amplifier (TIA), the received signal is converted to digital signal by an analog-to-digital converter (ADC) and demodulated by DSP.

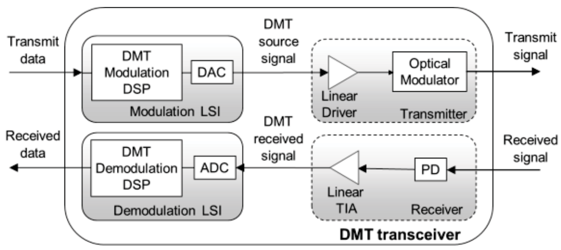


Fig. 3. Block diagram of DMT transceiver.

Fig. 4 shows an example of the spectrum and bit allocation of the DMT signal. The subcarrier number and cyclic prefix (CP) of the DMT signal were 1024 and 16, respectively and the total capacity of the signal was 105 Gb/s. The bit allocation shows that 6 bits corresponding to 64QAM were assigned to the subcarriers of low frequency and 2 bits corresponding to QPSK were assigned to those of high frequency. The total capacity of the signal can be variable by changing the bit allocation of the subcarriers by a digital signal processor.

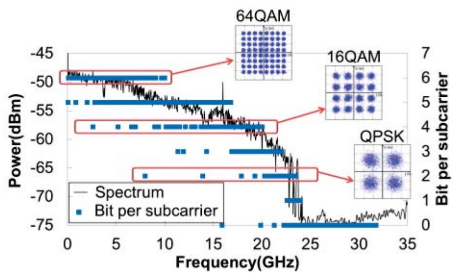


Fig. 4. Spectrum and bit allocation of DMT signal.

The total capacity of the BVT can be adaptively changed by request from the user or the transmission conditions, or etc. Fig. 5 shows the distance dependence up to 40 km of transmission characteristics as an example. When the transmission distance increases, the loss of the transmission fiber increases and the transmission characteristic would be degraded. By changing the transmission capacity of each distance adaptively, the constant BER of $1x10^{-3}$ was achieved for all distances. The capacity of the DMT signal was set to >120 Gb/s for distance shorter than 20 km and 100 Gb/s for 40 km.

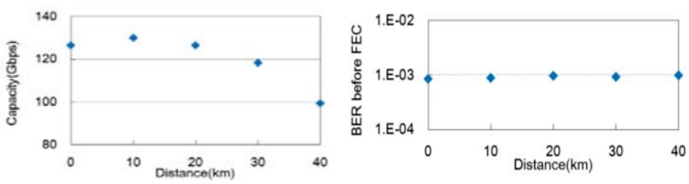


Fig. 5. Distance dependence of DMT transmission characteristics.

B. OFDM

According to the requirement of cost effectiveness for the transceiver solution, we propose an OFDM design using low complex DSP with simple optoelectronic front-end. The digital modulation can be based either on real-valued Fast Fourier Transform (FFT) or Fast Hartley Transform (FHT), which enables real-valued calculations and simplified channel estimation [11]. The cost-effective receiver is based on optically pre-amplified (DD). At the transmitter, either double sideband (DSB) or single-sideband (SSB) modulation can be implemented using an external MZM (followed by an optical filter for SSB). The mixing at an intermediate radio frequency, for software-defined tuning of the electrical signal band over the spectrum, is performed in the digital domain, without any additional electronic hardware. This transponder architecture only requires a single DAC at the transmitter and one ADC at the receiver. Alternatively, for improving the transponder performance, a more complex optoelectronic front-end can be employed. This approach uses two DACs to generate real valued driving signal for the MZM [12]. To enhance the BVT flexibility and capacity, sliceability can be implemented in time and frequency. A preliminary version of a cost-effective hybrid time/frequency S-BVT, based on DD-OFDM with DSB and low complex FHT processing, has been experimentally investigated in a realistic environment emulating a photonic mesh network [13]. It has been demonstrated that the proposed S-BVT is capable of concurrently serving multiple destination nodes at variable bit rate, while switching between different wavelengths / time slots. Compared to frequency-sliceable transmission, usually requiring a set of sub-transmitters and related optoelectronic front-end array, a single fast-tunable optoelectronic front-end is needed to implement a time-sliceable BVT, where different flows at different time slots share the same wavelength [14].

Another OFDM transmitter, which will be evaluated for Ethernet transport, is based on real-time FFT processing. Specifically, the transmitter is realized as an FPGA based real-time implementation. It uses 1024 OFDM subcarriers, can be clocked at up to 16 GHz and achieves a gross data rate of 64 Gb/s. Besides creating the OFDM signal, the transmitter inserts pilots, training sequences (TS) and CP. Real-time implementation enables the exploitation of the inherent flexibility of OFDM depending on the individual channel properties of multiple users and their instantaneous traffic load. Bit loading (BL) is implemented so that the rate can be dynamically adapted using an individually selectable modulation scheme (None, BPSK, QPSK, 16-QAM) and transmitter power for each sub-carrier. Using a highly parallel architecture, and a very efficient use of hardware resources, the OFDM transmitter fits onto a single Virtex-6 FPGA, including the interface to two digital-to-analog converters yielding the in-phase (I) and quadrature (Q) signals in real-time, as in Fig. 6.

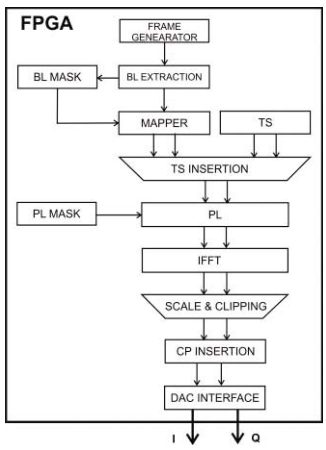


Fig. 6. Functional blocks of the FPGA based real-time OFDM transmitter.

IV. OPTICAL PACKET SWITCHING TECHNOLOGY

Electrical packet switching cannot operate in an energy-efficient way with rates of 100 Gb/s and beyond because it requires optical-to-electrical and electrical-to-optical conversions and parallel processing. OPS can potentially provide a solution to ultrafast, energy-efficient packet switching. OPS can provide time-sliced sub-wavelength logical path preferably in metro area network (MAN) and intra data center (DC) network. In OPS, there are two choices for the packet payload, either fixed-length or variable-length.

We will develop fixed-length variable-capacity (FL-VC) optical packet transport and switching infrastructure with Ethernet framing and simplified OPS nodes for transmission beyond 100 Gb/s. Motivations behind the FL-VC packet are that it naturally fits in a fiber delay line (FDL) buffer and ease of scheduling algorithm, compared to variable-length packets. Note that the buffer utilization of variable-length payload packet might become poor due to the void problem [15]. To meet both requirements for short reach (<40 km) and longer reach up to few hundreds of km, two approaches to multicarrier modulation formats will be considered, including DMT for the short reach and coherent OFDM for the longer reach. We have proposed and experimentally demonstrated a novel OFDM-based FL-VC optical packet switching [16]. It employs an adaptive modulation technique in OFDM with the optimum power loading to subcarrier-by-subcarrier bit under a given noise environment, based upon the water-filling algorithm [17]. In the OFDM payload of a packet, by adapting the number of loaded bits and/or allocated power per subcarrier based on the water-filling theorem, one can maximize the channel capacity or equivalently the energy efficiency of data transfer in colored noise environments. Here, the feature is exploited to pack incoming variable-length data sequences into a fixed-length optical packet in energy efficient manner as in Fig. 7.

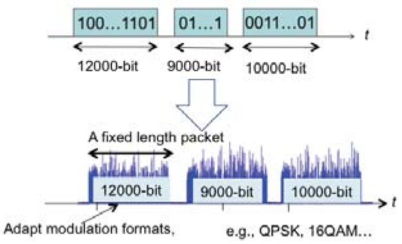


Fig. 7. Principle of FL-VC OFDM payload packet.

One of the advantages of FL-VC packet is distance-adaptability of the route between the source and destination nodes; according to the available route, the optimum modulation format can be adopted. Assume that two flows of packets with the same source and destination nodes, of which the transmission capacities are different, the larger capacity uses higher level of modulation format, and it requires higher signal-to-noise ratio (SNR), therefore, the shortest route has to be chosen. On the other hand, the smaller capacity uses lower level of modulation format, and it requires lower SNR, therefore, it can take the longer distance. At the OPS nodes, OpenFlow-enabled forwarding tables are provided from the control plane, which indicate the output port of the switch to forward the packet for the next hop. The optical packet transmitter/receiver are also aware of the packet information to be transmitted/received, so that modulation/demodulation of the packet can be adaptively performed. At the receiver, the DSP can compensate both carrier frequency offset (CFO) and signal impairments due to fiber dispersions as well.

V. FLEXIBLE OPTICAL CIRCUIT SWITCHING NODES

As it was mentioned in the introduction, (D)WDM offers a future-proof infrastructure, albeit with fixed-grid adaptability. Elastic optical DWDM technologies have been adopted in transmission to use the optical spectrum more efficiently and wisely. Thus, OCS nodes should have the capability to support several modulation formats with mixed bit rate signals (e.g., 10 Gb/s, 100 Gb/s, 400 Gb/s or even 1 Tbit/s) and provide a large range of circuit switch granularities, to fulfill the requirements of different applications. In addition, the OCS node should have the capability to handle sliceable bandwidth variable signals to provide more flexibility. Due to the variable and complex nature of the Internet, the data traffic demand may change in a large scale at times. To accommodate such changes, the OCS node should reconfigure the node architecture or reassign the node resources to satisfy the new demands. The reconfigurability/programmability of the OCS nodes provides a high level of flexibility and enables the OCS nodes to change the node type smoothly. Based on architecture-on-demand (AoD) [18] OCS nodes, the OCS node design can be easily reconfigured/reprogrammed. In addition, future AoD-based OCS designs will target functions rather than structures. The available network functions will be managed by the AoD-based OCS nodes. By aggregating the network requirements, the AoD node can maximize the node performance with optimized structure. To fulfill such flexibility in the OCS nodes, within the STRAUSS project, we develop a flexible and elastic AoD node based on an optical backplane. The AoD concept will be introduced to design the flexible, elastic and programmable optical node. The concept of the AoD node is shown in Fig. 8. An optical backplane, which consists of a large port-number 3D-MEMS, is depicted. The optical backplane manages the available subsystems and components and enables the interconnectivity of different network functional modules, such as super-channel add/drop, fast time switching, format conversion, etc., to deliver on-line diverse and reconfigurable architectures (e.g. broadcast-and-select, wavelength-modular, spectrum-routing, switch-and-select etc.). Fig. 9 shows two example scenarios of the on-demand function-composition of the AoD node. In scenario 1, all OPS data is converted to OCS domain and is sent to another OCS node.

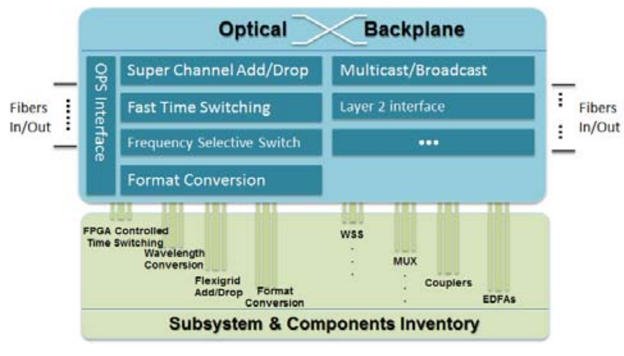
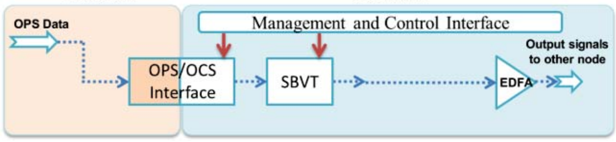
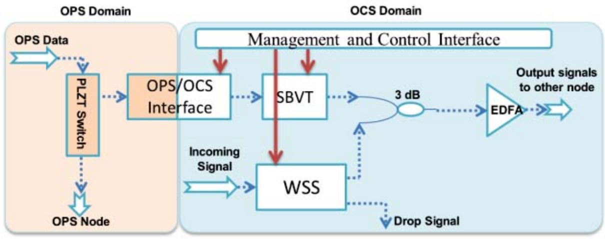


Fig. 8. Concept of AoD architecture node.



(a) **Scenario 1: Full OPS data converted to OCS domain with full load**



(b) **Scenario 2: Partial OPS data converted to OCS domain**

Fig. 9. Example for on-demand function-composition of AoD node.

In scenario 2, partial OPS data are converted to OCS domain and added to an existing OCS link. Due to different requirements, different interconnections are generated to efficiently use node resources. The dash line in Fig. 9 is the connection setup by the optical backplane. With the available subsystems and components, the AoD nodes can synthesize different network functions according to different application scenarios. The centralized managements of the subsystem and components enable performance optimization by rebalancing the same type of resources per degree/fiber link.

VI. OPS/OCS INTEGRATED INTERFACE

Fig. 10 shows the structure of integrated interface between OPS and OCS domain. Data streams leaving from OPS technologies in the access for the OCS core of the network are aggregated and groomed in the OPS/OCS gateway interface, which is implemented using high performance FPGA based optoelectronics (HTG Xilinx V6 PCIE board). The OPS/OCS grooming interface will receive and parse the access Ethernet traffic using multiple SFP+ interfaces and direct them to the right output interfaces, based on their destination MAC address and the virtual network slices they belong. The ingress traffic originating from the access area can be of variable size from 64 Bytes up to 1500 Bytes and flew-in on different bit rates up to 10 Gb/s per pair of differential SMA interface. The groomed and classified ingress traffic from multiple access links are then transferred to the S-BVT module on the OCS side, in which the aggregated streams are put on the allocated subcarriers and modulated accordingly to be transferred over the OCS network with the expected reach and bit rate. The streams from the OCS on the other hand are separated per subcarrier slice and after reception the Ethernet traffic should be extracted and sent off for the right 10 GE access interfaces. The interface, as the gateway interconnecting the two technological domains of OPS and OCS, is SDN-enabled and its control tables (Look-Up-Table memories) are populated by the network controller. To enable this communication with the control layer, a 10 GE link is designated on the FPGA to provide high speed exchange of information between the hardware and the software agent on top. The software agent then uses a RESTful API to communicate with controllers and applications from the higher layers.

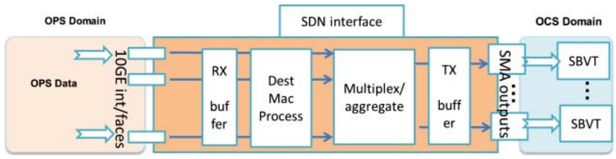


Fig. 10. Structure of Integrated interface between OPS and OCS.

VII. CONCLUSIONS

Efficiently scalable optical data plane solutions and promising enabling technology options have been presented, as envisioned by the STRAUSS project, for future optical network infrastructures able to support Ethernet transport beyond 100 Gb/s over OPS and flexi-grid OCS networks.

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