Optical metro networks 2.0

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Invited Paper

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ABSTRACT

Fueled by the steady traffic increase in access and enterprise networks, optical metro networks represent a major growth opportunity for system vendors and component manufacturers. This paper reviews new developments from a technical and economic point of view. Topics such as network and node architectures, high-speed transmission, integrated optical/electronic switching as well as management and control will be discussed.

Keywords: WDM, metro networks, next-generation access

1. INTRODUCTION

Optical metro networks underwent rapid changes in the last decade. Having started with purpose-built systems for capacity/reach extension of time-division multiplex (TDM), data and storage services, they are evolving to use modular optical transport platforms with integrated optical and electronic switching capabilities. This paper provides an overview on novel technologies in optical metro networks and discusses their value proposition:

- With the steady traffic increase in access and enterprise networks, coarse wavelength-division multiplex (CWDM) technologies are now being pushed down into access networks. Dense wavelength division multiplexing (DWDM) technologies with a channel spacing down to 50 GHz are started to getting used in metro networks.
- The optical transport hierarchy (OTH) provides a multiplexing and payload-independent digital wrapper technology. It standardizes layer 1 (L1) switching at wavelength granularity (1, 2.5, 10, 40, 100 Gb/s) and facilitates interoperability in multi-carrier/multi-vendor scenarios.
- Ethernet extends from a local area network (LAN) technology into the metro area network/wide area network (MAN/WAN) segments. Enhanced with carrier-class features, it offers network-wide virtual line and LAN services using multi-protocol label switching (MPLS) based pseudo wires (PW) and/or virtual LAN (VLAN) based provider/provider backbone bridges.
- Multi-degree reconfigurable optical add/ drop multiplexers (MD-ROADMs) increasingly replace fixed OADMs (FOADMs) and form the foundation of an agile optical bypass layer. They eliminate unnecessary electronic signal regeneration and facilitate an automated establishment of end-to-end wavelength circuits.
- At 10 Gb/s data rate, pluggable small form factor DWDM transceivers allow to double equipment density at the same performance of previous conventional designs. At 40 Gb/s and 100 Gb/s line rates, advanced modulation formats deliver 10 Gb/s-like performance at 4x/10x the spectral efficiency.
- Modular platform architectures help to flexibly optimize a network element for a particular application. With various capacity, switching, and reach options, they yield low first-installed costs whilst preserving headroom for future capacity build-outs.
- A generalized multi-protocol label switching (GMPLS) control plane provides network discovery, path computation and signaling functions. Taking equipment and physical constraints into account, it facilitates an automated circuit provisioning across multiple layers as well as meshed restoration functions.

In what follows, the different topics described here are discussed in more detail.

2. NETWORK ARCHITECTURES

Optical transport networks are hierarchically structured and comprise several network tiers. Typically, there is a meshed core/backbone network which connects to multiple metro network domains.

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The metro networks frequently split into a metro core and a metro access/backhaul part. They often contain Aggregation Switches (AGS) for layer 2/3 services and/or synchronous optical network/synchronous digital hierarchy (SONET/SDH) equipment for layer 1 services. Metro nodes are connected with WDM links, with ring topologies more prevalent towards the core and trees towards the access. The core/backbone network can be segmented into a long-haul (LH) and regional part. Typical distances for the long-haul, regional and metro core networks are 1,500, 600, and 200 km, respectively, albeit these numbers vary in practice. Historically, different distances were addressed by purpose-built WDM systems. Today, optical transport platforms are available which cover all applications and reach classes. Whilst metro networks are shorter in distance, they often possess a larger number of optical nodes. As a transparent node pass through incurs a similar performance degradation than the transmission over a fiber span with the same loss, performance requirements for metro and core networks start to converge. Along with savings in optical/electronic/optical (O/E/O) conversion, this fact has lead network operators to consider a flat regional network architecture with collapsed metro/core tiers as an alternative to hierarchical multi-tier approach[1].

The trend towards consolidation of transport networks is reflected in Fig. 1. The metro core and the LH backbone can be based on the same DWDM technology, supporting 10/40/100 Gb/s capacity per channel on a 50 GHz channel grid and employing ROADMs for reconfigurability in the photonic domain. In the backbone MD-ROADMs are used, whereas in the metro core degree-2 ROADMs (D2-ROADMs) are more frequent. The metro access/backhaul domain employs WDM-PON technologies which are preferably integrated into the metro WDM platform. Solutions with long reach (up to 100 km), high bit rates (1..10 Gb/s per channel), and a high splitting ratio (up to 1000) are required.

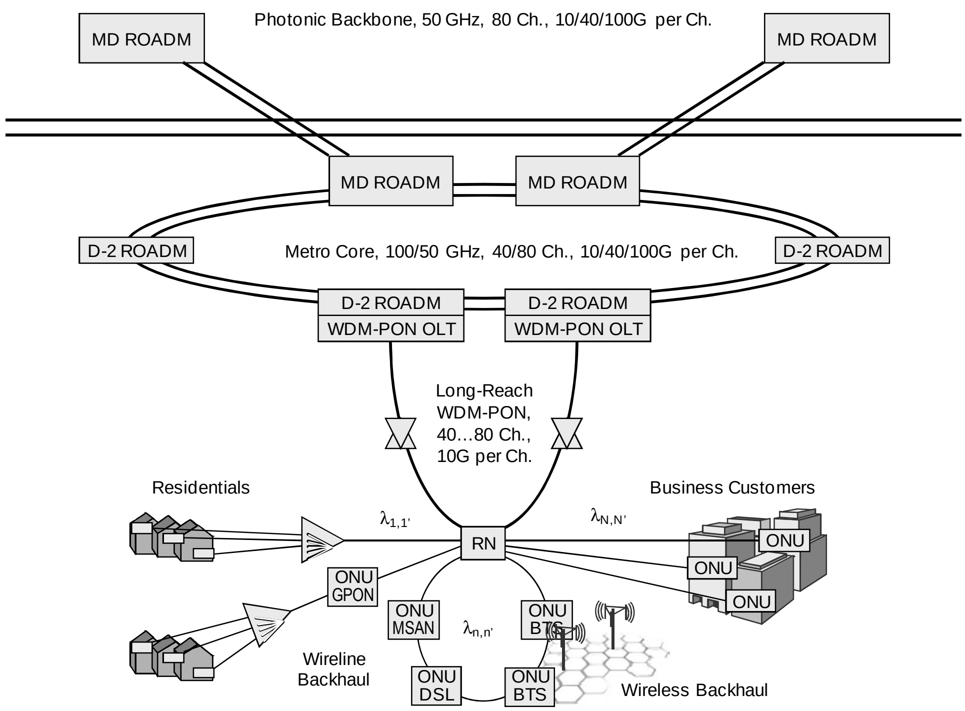

Fig. 1. Converged transport network. In the metro area, access and backhaul are based on high-capacity, long-reach WDM-PON. The Optical line terminals (OLTs) connect redundantly to high-capacity metro core rings which again are redundantly connected to a meshed photonic backbone (RN: Remote node, ONU: Optical network unit, GPON: Gigabit passive optical network, MSAN: Multi-service access node; BTS: Base transceiver station).

The long-reach requirement stems from the necessity of network operators to consolidate their networks in order to save cost (in particular, OpEx)[2]. The consolidation includes the introduction of universal transport systems and a massive reduction of the number of active sites[3]. This site reduction is possibly complemented by the elimination of one aggregation stage. The respective functionality, however, is still needed for transport efficiency and has then to be integrated into the access and/or the metro transport part. Reducing active sites leads to longer distances between the remaining sites, which is what is demonstrated in Fig. 2. The upper part of the figure shows the current network architecture. The lower part of the figure depicts the target architecture with less active sides and distances in both the access and metro domain.

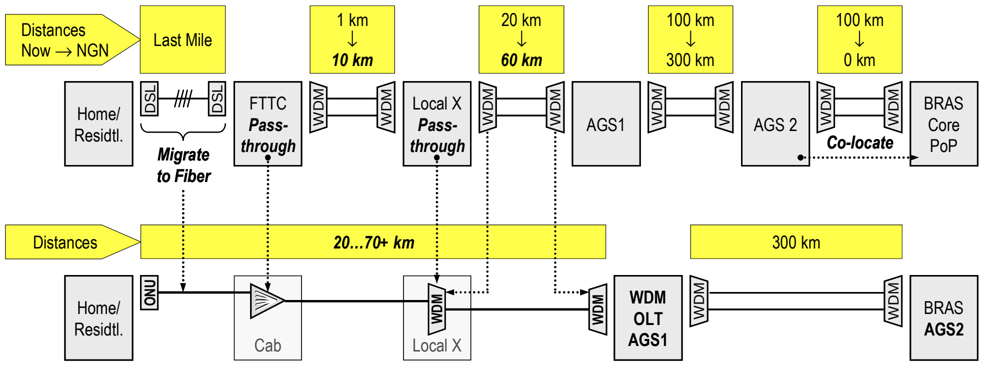

Fig. 2. Metro and access network consolidation. The numbers shown are typical for large European network operators. Top: network with two dedicated aggregation layers (AGS1, AGS2). Bottom: consolidated network with less active sites and increased distances (NGN: Next-Generation Network, FTTC: Fiber to the curb, Local X: Local exchange, BRAS: Broadband remote access server, PoP: Point of presence, Cab: Cabinet).

3. PROTOCOLS

Historically, metro networks used WDM technologies for delivering wavelength services. SONET/SDH as well as proprietary schemes were used to efficiently fill these wavelengths. OTH was deployed in metro core applications, mostly for point-to-point wavelength services, where forward error correction and enhanced OAM capabilities were required. With Ethernet becoming the dominant user interface and SDH/SONET technologies starting to reach their end of life, it is expected that OTH will increase its presence in next generation metro networks and evolve from a point-to-point to a switched network layer. OTH add/drop multiplexers (ADMs) and cross-connects (XCs) will be used to efficient filling of WDM channels with the required redundancy and flexibility.

OTH was defined by the ITU–T G.709 standard in 2001 and originally focused on 2.5, 10 and 40 Gb/s (ODU1/2/3) services (i.e. high-speed SONET/SDH links). It provides a digital wrapper technology for client-independent transport, multiplexing, and switching on layer 1. Client signals to the OTN can either be packet or continuous bit rate (CBR) signals. The low latency of OTH facilitates its use also for storage, video and high-performance computing applications. Where required, signals can be timing and bit transparently mapped into optical channel data units and transported through multi-operator/multi-vendor domains. By providing extensive OAM and protection functions, OTH delivers managed wavelength services over standardized digital interfaces. Tandem connection monitoring (TCM) facilitates a client-independent channel monitoring across multiple network domains.

In 2008-09, G.709 has been extended[4] to better address Ethernet and other packet services, making it a true multi-service technology. Most notably, a new payload type (PT = 21) with 1.25 Gb/s granularity was added to complement the existing 2.5 Gb/s tributary slot scheme (PT = 20). With the definition of an ODU0, a digital container for the timing-transparent transport of GbE services was introduced. The ODU2e was included in the G.709 standard as an overclocked variant of the existing ODU2. It allows a bit and timing transparent transport of 10 GbE. An ODU4 was defined as wrapper for emerging 100G services such as 100GbE. To address clients between 2.5 and 100 Gb/s rates in a simpler and finer granular manner than previously possible, a new ODUflex structure was introduced. ODUflex uses the standard ODU1 frame structure and extends over an integer multiple of 1.25 Gb/s tributary slots. A new generic mapping procedure (GMP) was also added to the standard which allows a more flexible client mapping and ODU multiplexing. It compensates for frequency offsets between client and server signals using a widely adaptable byte/bit-stuffing mechanism. Fig. 3 shows the new OTH multiplexing hierarchy.

OTH provides an efficient transport for $\geq$ 1 Gb/s leased line services. It lacks, however, an efficient multiplexing/ switching scheme for lower granular services down to e.g. 100 Mb/s. Whilst GMP mapping of such a signal into an

ODU0 is possible and standardized, the bandwidth efficiency of such a scheme is only 10%. Being a layer 1 technology, OTN does also not support multipoint services or statistical multiplexing. For these reasons, most operators look at Ethernet/MPLS technologies as standardized solutions to complement the OTH functions.

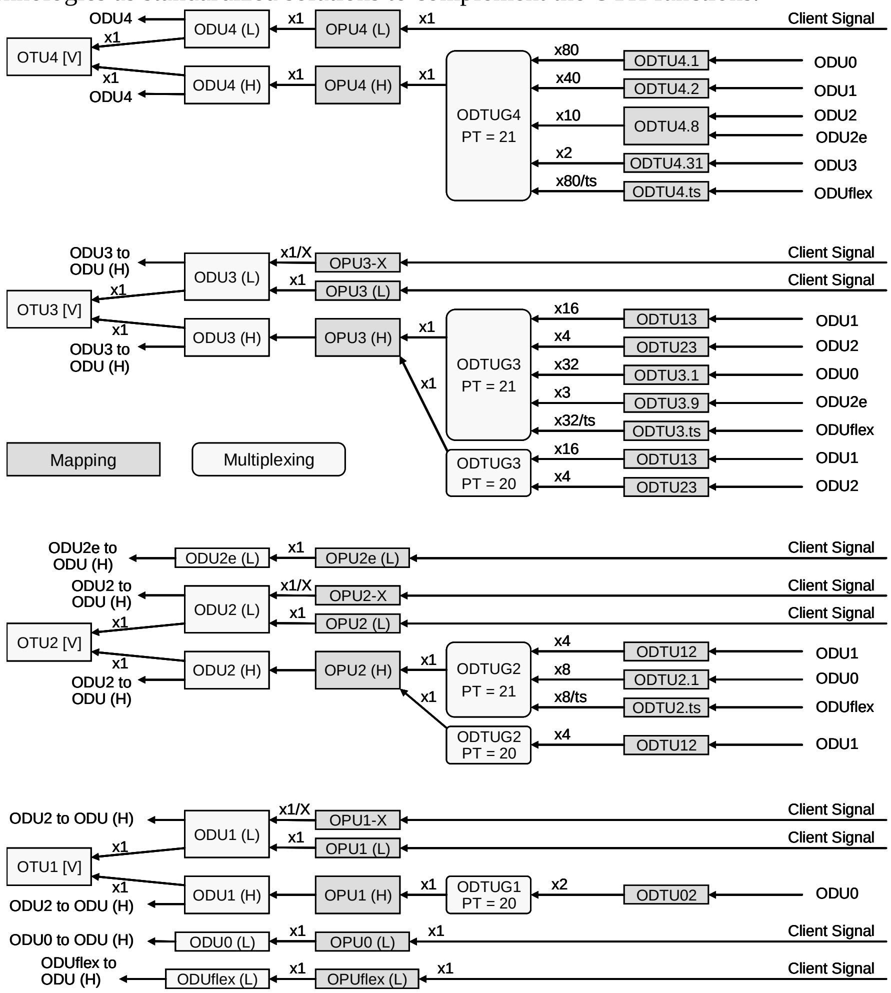

Fig. 3. OTH mapping and multiplexing (OTU: Optical Transport Unit, ODU: Optical Channel Data Unit, OPU: Optical Payload Unit, ODTUG: Optical Channel Data Tributary Unit Group, ODTU: Optical Channel Data Tributary Unit, H: Higher order, L: Lower order)

Many operators already use an IP/MPLS network running on top of their photonic backbone. Extending the MPLS functionality down into the metro network would hence be a logical step. The IP/MPLS network today is typically used for business VPN and residential services provided on layer 2. There is a current debate whether high bandwidth, premium Ethernet virtual circuit (EVC) services[5] (see Fig. 4) should run over the same IP router infrastructure or use dedicated switching functions integrated with the optical transport equipment. Many carriers prefer the latter approach and ask for packet-optical transport platforms (POTPs).

Service Type	Port-Based (All-to-One Bundling)	VLAN-Based (Service Multiplexed)
E-Line **(Point-to-Point EVC)**	Ethernet Private Line **(EPL)**	Ethernet Virtual Private Line **(EVPL)**
E-LAN **(multipoint-to-multipoint EVC)**	Ethernet Private LAN **(EP-LAN)**	Ethernet Virtual Private LAN **(EVP-LAN)**
E-Tree **(rooted multipoint EVC)**	Ethernet Private Tree **(EP-Tree)**	Ethernet Virtual Private Tree **(EVP-Tree)**

Fig. 4. Ethernet service definitions according to the Metro Ethernet Forum (MEF)

In the access network, a plain Ethernet solution with virtual bridging based on VLAN tags according to IEEE 802.1q[6] and provider bridging technology according to 802.1ad (sometimes referred to as Q-inQ) is commonly used. The Metro Ethernet Forum (MEF) (business and backhauling services) and Broadband Forum TR-101[7] (residential services) architectures offer alternate ways to manage customer traffic flows. They both provide methods for mapping and stacking customer (C–VLAN) and service provider VLAN (S–VLAN) tags to service type and instance, access equipment, and user ports.

To obtain a similar operation, administration and maintenance (OAM) and protection functions in Ethernet as for SDH/OTH leased lines, carrier class extensions to Ethernet are required. Ethernet performance monitoring and OAM functions have been recently standardized by the IEEE with the 802.1ag (connectivity fault management) and 802.3ah (Ethernet in the First Mile) standards, respectively, and by the ITU–T with the Y.1731 recommendation (Ethernet OAM). For resilience, mechanisms such as Rapid Spanning Tree Protocol (RSTP, 802.1d), Multiple Spanning Tree Protocol (MSTP, included in 802.1q), and Link Aggregation Control Protocol (LACP, 802.3ad) were already available and enable fault recovery in <1 s. These mechanisms have recently been augmented by Ethernet linear 1+1 and ring protection (ITU-T G.8031 and G.8032 recommendations) with 50 ms recovery time.

To obtain a scalable solution for Ethernet end-to-end services, an interconnection between the provider bridges can be established by pseudo-wires as defined by the IETF[8]. Running over MPLS Label-Switched Paths (LSPs), pseudo-wires can create a full logical mesh between the MPLS provider nodes over which the Ethernet traffic is tunneled. Ethernet and MPLS multicast functionalities can readily be integrated into such a network solution. Provider backbone bridging according to IEEE 802.1ah (PBB, sometimes referred to as Mac-in-Mac) and hierarchical VPLS (H–VPLS, as defined by the IETF) can further improve the scalability of L2 provider[9]. MPLS-based traffic engineering, in conjunction with differentiated services, can be used for providing class-based quality of service (QoS).

The IETF, with support from the ITU-T, is currently defining MPLS-TP (MPLS transport profile) as a transport-oriented MPLS variant in RFC-5654. MPLS-TP aims at delivering packet transport network services by combining MPLS packet experience with the operational experience and practices of optical transport networks. Main characteristics of MPLS-TP are: Connection-orientation, fast protection capabilities (similar to ITU-T 8031 for 1+1 protection) and enhanced OAM capabilities (similar to ITU-T Y.1731). MPLS-TP does not need a control plane for provisioning, and can also be configured manually or through network management. The fact that MPLS-TP is constructed similar to wavelength and TDM services, however, allows a single GMPLS control plane instance to run wavelength, OTH and EVC/MPLS-TP services under a common umbrella.

Combining the different technologies discussed in this section results in a protocol stack as shown in Fig. 5. WDM forms the basis of any metro transport to provide an efficient utilization of fiber capacity. On shorter access links, native carrier Ethernet can directly be used on top of WDM. For longer links, enhanced L1 functions, and non-IP/Ethernet services, OTH is used as an intermediate layer. MPLS can both run over Ethernet where its layer 2 functionality is required or directly over OTH using a GFP mapping into appropriate ODU(flex) containers.

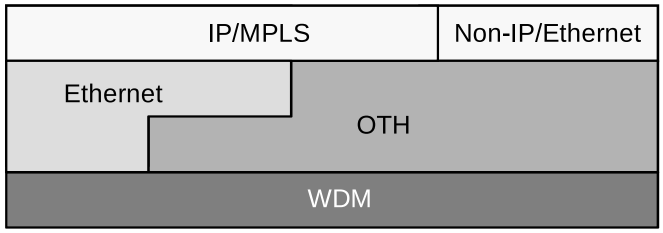

Fig. 5. Unified protocol stack.

4. NODE ARCHITECTURES

In scalable metro networks, switching and multiplexing functionality should be provided on the lowest-possible layer. The remaining higher-layer functionality should be concentrated in fewest possible sites for highest operational efficiency. Overall, a modular metro node architecture is desirable which allows a flexible combination of optical bypass, electronic multiplexing/aggregation and layer1/2 switching functions in a single network element. Fig. 6 depicts a block diagram of such generalized node architecture.

On the optical layer, MD- or D2-ROADMs are used. In certain sites with low optical add/drop traffic, these can be substituted by optical filter based FOADMs to save capital expenditures (CapEx). ROADMs do not only provide bit rate transparency, they also support an automated reconfiguration. This feature simplifies the provisioning of new optical circuits and supports an optical re-routing in case of link failures or scheduled maintenance actions. The CapEx for ROADMs can be partially offset by the built-in optical channel power equalization and monitoring functions which otherwise would require additional equipment.

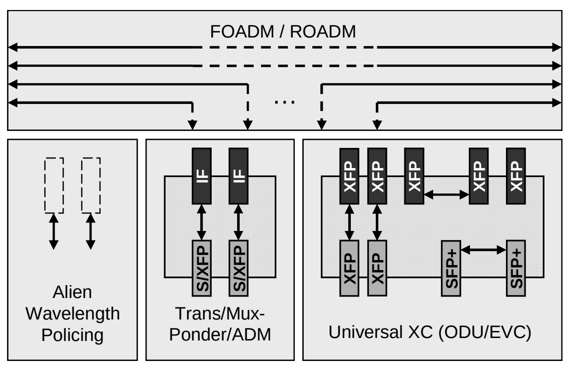

Fig. 6. Generalized node architecture. In the photonic layer, connectivity is provided by reconfigurable (ROADM) or fixed (FOADM) optical add/drop. In the electrical layer, colored clients ("alien wavelengths") can be directly connected. Gray or colored clients alternatively can be connected through transponders, groomed by muxponders and add/drop multiplexers (ADM), or flexibly cross-connected (XC: Cross connect) on ODU and/or EVC layer (XFP: 10 Gigabit Small Form Factor Pluggable, SFP(+): Small Form Factor Pluggable (Plus), IF: Interface)

For cost, modularity and resilience reasons, ROADM (in particular MD-ROADM) functionality is typically provided by wavelength-selective switches (WSS) rather than large all-optical space switch matrices. On the through path, wavelength can be arbitrarily switched between the different trunk paths. On the add/drop path, clients are often connected through fixed optical multiplexers/demultiplexers attached to a particular trunk port. This architecture makes a particular wavelength channel on this trunk port accessible to a pre-wired client port. To enable more flexible reconfiguration capabilities, it is desirable that the add/drop ports can randomly access any wavelength from any trunk port. This functionality is sometimes also referred to as a color-less and direction-less add/drop. A block diagram of a colorless, direction-less MD-ROADM is shown in Fig. 7.

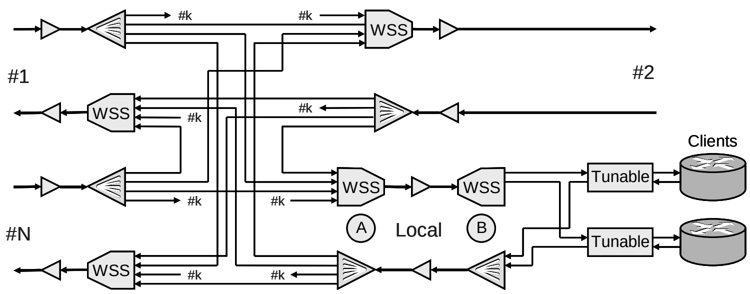

Fig. 7. Colorless, direction-less MD-ROADM. The WSS/splitter pair (A) is used to provide direction-less connectivity, WSS/splitter pair (B) in conjunction with tunable interfaces allows color-less client access.

Based on 9x1 WSS's, the MD-ROADM can terminate up to 8 trunk ports. In ingress direction, all wavelengths received on a trunk port are broadcast by power splitters. In egress direction, the WDM channels are selected from the ingress trunk ports on a per wavelength basis by the WSSs. One WSS is required per trunk port, yielding a linear scalability with the nodal degree. One additional trunk port (A) is used to provide the direction-less add/drop connectivity. Color-less add/drop connectivity is obtained by connecting the WSS/splitter pair (A) to one further WSS/power splitter combination (B). This architecture allows direction-less and colorless functionality based on standard components. Large scale WSS components allow ~20 add/drop channels to be terminated in a single block. More channels can be addressed by putting multiple combinations (B) in series. The directionless block (A) only allows terminating a particular wavelength once. For this reason as well as to avoid single points of failures in the add/drop architecture, typically two or more directionless blocks (A) are used.

As shown in Fig. 6, various options exist to connect clients to the photonic layer. Colored clients from external equipment can directly be connected as "alien wavelengths", if they comply with the optical interface specification of the metro node. Wavelength policing (power monitoring and control) takes place as integral function of the photonic layer. For a demarcation/digital monitoring/domain conversion of a client signal (e.g. between grey/CWDM and DWDM channels) transponders are used. Additional grooming/multiplexing/aggregation functions are provided by muxponders or add/drop multiplexers (ADM). Further flexibility and bandwidth efficiency is obtained by an electrical cross-connect function on OTH (layer 1, ODU) and/or Ethernet (layer 2, EVC) level. Whilst cross-connect functions with up to 100Gb/s capacity are often integrated into multi-port transponder cards, larger scale cross-connects require a dedicated redundant central switch matrix. Whilst former equipment often possessed two matrices, one for packet and the other one for TDM traffic, a hybrid approach with a universal switch matrix for both OTH and EVC traffic avoids stranded bandwidth in one of the layers and is most scalable and future proof[10]. In conjunction with software-programmable line cards, a universal switch allows to customize features and to augment the equipment functionality over the product lifetime. A standard compliant switching of TDM traffic over a universal matrix is ensured by an appropriate prioritization of the TDM traffic as well as tightly controlling jitter and timing.

5. HIGH-SPEED TRANSMISSION

10 Gb/s on-off-keying (OOK) is the dominant DWDM interface technology in metro core networks today. The channel grid evolves from 200 GHz over 100 GHz to 50 GHz, leaving both higher per-channel bit rates (40 Gb/s, 100 Gb/s) and a narrower channel grid as evolution options for a future capacity increase. 10 Gb/s DWDM transceiver technology has developed from fixed discrete designs over tunable 300-pin MSA transceivers to XFPs. XFPs started with fixed wavelengths and reduced performance and are shortly being available as tunable XFPs with 300pin-MSA LH performance. The trend from discrete designs to tunable XFPs was driven by lower cost, better compactness, lower power consumption, and higher flexibility. The power consumption is reduced from >10 W for 300-pin MSAs down to ≤3.5 W for tunable XFPs. The flexibility is increased by the pluggability and the possibility to place XFPs directly in client equipment. It is likely that XFPs will remain the dominant interface technology in metro DWDM networks for the next years to come, with the prospects of reducing the form factor even further to SFP+ and integrating more electronics functionalities on the host platform.

40 Gb/s DWDM interfaces also developed during the last few years. Starting with 100 GHz carrier suppressed return-to-zero (CSRZ) OOK and 50 GHz compatible non-return to zero (NRZ) duobinary systems, they evolved to 50 GHz capable NRZ differential phase-shift keying (DPSK) systems with better sensitivity and improved impairment tolerance.

Next generation 40 Gb/s technologies include coherent NRZ Dual-Polarization quadrature phase shift keying (NRZ-DP-QPSK) and self-coherent RZ differential quadrature phase shift keying (DQPSK) systems. NRZ-DP-QPSK is based on coherent intradyning[11]. It uses a digital signal processor (DSP) for frequency and phase locking of the local laser, demultiplexing of the polarization and in-phase and quadrature (I/Q) components, and also chromatic dispersion (CD) and polarization mode (PMD) compensation. Together with the massively reduced baud rate (~11 GBd for a 43 Gb/s system) this scheme offers very high CD and PMD tolerance >> 1000 ps/nm and 10 ps, respectively. RZ-DQPSK requires twice the baud rate (~21.5 GBd). It yields lower CD and PMD tolerance, higher robustness against nonlinear fiber effects, and does not use a DSP but a tunable optical dispersion compensator and an optical preamplifier instead. The success of any 40G solution in metro networks is more a question of cost than of technology: A cost parity of the 40G DWDM interface with 4 XFPs will need to be demonstrated to allow a massive 40G deployment.

Many solutions for 100 Gb/s DWDM transport have been investigated during the last years. These include higher-order modulation (m-ary PSK or QAM) and combinations with dual-polarization and dual-carrier approaches, as well as more disruptive approaches such as Orthogonal Frequency-Domain Multiplexing (OFDM) and Multicarrier Modulation (MCM). For high-performance applications, coherent (NRZ-) DP-QPSK has emerged as the de-facto standard with transmitter/receiver building blocks, the optical module and electrical interfaces defined by the Optical Internetworking Forum[12] (OIF). Operating on a 50 GHz channel grid, 100 Gb/s DP-QPSK offers a 2 bit/s/Hz spectral efficiency. In conjunction with DSP technologies, it allows the complete elimination of linear transmission impairments such as CD and PMD and facilitates a system reach in excess of 1500 km. For overlay ("brown field") installations, it has to be noted, though, that existing CD compensation (e.g., optimized for standard 10 Gb/s transport) somewhat limits the maximum system capabilities – the ultimate bit-rate×distance limit is achieved without optical inline-dispersion compensation due to better suppression of nonlinear inter-channel effects. A schematic diagram of coherent DP-QPSK is shown in the upper part of Fig. 8.

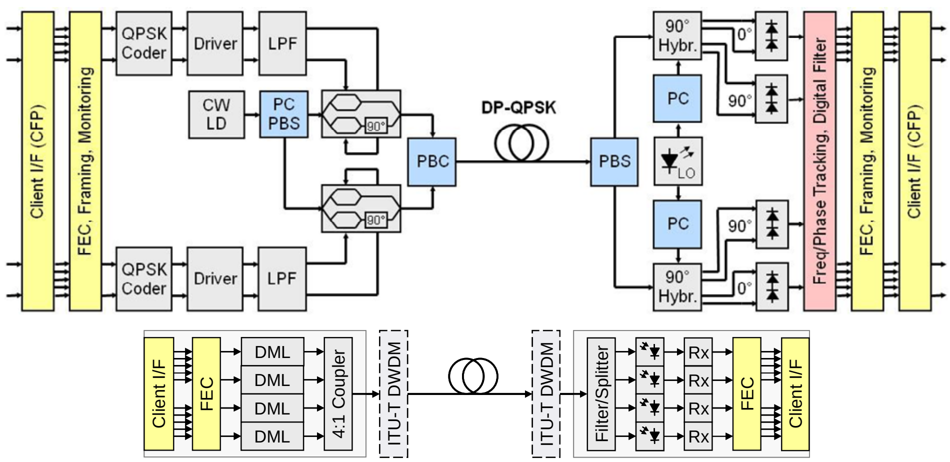

Fig. 8. Two solutions for 100 Gb/s WDM transport. Top: quasi-standardized metro/core coherent NRZ-DP-QPSK for high reach and spectral efficiency. Bottom: low-cost metro/access solution based on Multicarrier Modulation (LPF: Low-pass filter, CW LD: Continuous wave laser diode, PC: Polarization control, PBS: Polarization beam splitter, Rx: Receiver, FEC: Forward error correction, CFP: 100 Gb/s small form factor pluggable).

Whilst core networks require high spectral efficiency and performance, this requirement is often not so stringent for metro access and enterprise networks. Cost, power consumption, and footprint, however, are critical factors in such configurations. Most 100 Gb/s solutions so far did not address these requirements appropriately. One possible solution is Multicarrier Modulation (MCM) as shown in the lower part of Fig. 8. MCM uses a simultaneous transmission of 4 x 28 Gb/s DWDM channels. Directly modulated lasers (DML) and receiver arrays can be used in a similar way than in standard 100GbE CFP transceivers.. With proper pulse shaping, a subcarrier spacing of 25 GHz can be achieved allowing a spectral efficiency of 1 bit/s/Hz over < 200 km. If subcarrier spacing of 50 GHz is chosen, the maximum reach can be extended to 500…600 km. Spectral efficiency and maximum reach can thus be balanced by choosing the MCM channel spacing. MCM has the potential for a significant cost advantage over DP-QPSK. It also reduces complexity and technology risks, so that first commercial products could become available earlier than DP-QPSK solutions. Tab. 1 summarizes relevant parameters of the 100 Gb/s transport solutions discussed so far.

Tab. 1. Parameters of 100-Gb/s MCM and DP-QPSK

	MCM	DP-QPSK
Carriers	4x28G, spaced 50 / 25 GHz	Single (28 GBd)
Modulation	Filtered DML	DP-QPSK
Detection	Direct	Coherent intradyne + DSP
C-Band Capacity	2 / 4 Tb/s	8 Tb/s
Spectral Efficiency	0.5 / 1.0	2.0
OSNR Requirement	21 / 24 dB	15 dB
CD Tolerance	> 200 ps/nm	>>1000 ps/nm
PMD Tolerance	5 ps	>10 ps
Maximum Reach	600/200 km	2000 km
Energy Consumption	75%	100%
Form Factor	66%	100%
Cost	50%	100%

For large network roll-outs, the use of different 100 Gb/s technologies can help minimizing the total network cost. Assuming that the less-complex solution has somewhat lower downtime, the impact of a second 100 Gb/s variant on operational cost can be positive rather than negative. Additionally, the low-complexity MCM solution saves on CapEx and energy consumption in those cases where neither the longest reach nor the highest spectral efficiency is required.

6. NEXT-GENERATION ACCESS

Broadband access networks mainly use copper (ADSL2+, VDSL2, HFC), fiber-based point-to-point, or passive optical networking (PON) technologies in the first mile. PONs can be further subdivided into broadband PON (BPON), Ethernet PON (EPON) and GPON networks with aggregated downstream (DS) and upstream (US) rates ranging from 622 Mb/s to 2.5 Gb/s. They make use of time-division multiple access (TDMA) to support up to 32 subscribers through a single feeder fiber. The next generation of these systems (10G-EPON, XG-PON1/2) will run DS rates of 10 Gb/s and US rates of 1.25/2.5 Gb/s and, later, also 10 Gb/s. They will also support increased splitting ratios of up to 128. For all these technologies, WDM-based metro access/backhauling will be required to cope with the aggregated uplink bandwidths.

Solutions beyond 10G-EPON and XG-PON aim at long-reach, high splitting ratio and high per-subscriber. In the Full Service Access Networks (FSAN) Group [13], these are referred to as NG-PON2. Realization options include TDMA at even higher bit rates (40 Gb/s), ultra-dense WDM-PON (UDWDM-PON) and WDM-PON with multi-user wavelength sharing. The latter solutions are sometimes referred to as Hybrid PONs and could use a layer 2 port aggregation, TDMA or SCMA (Subcarrier Multiple Access) for wavelength sharing. Fig. 9 shows two configuration examples of hybrid WDM/TDMA-PONs for very high splitting ratios.

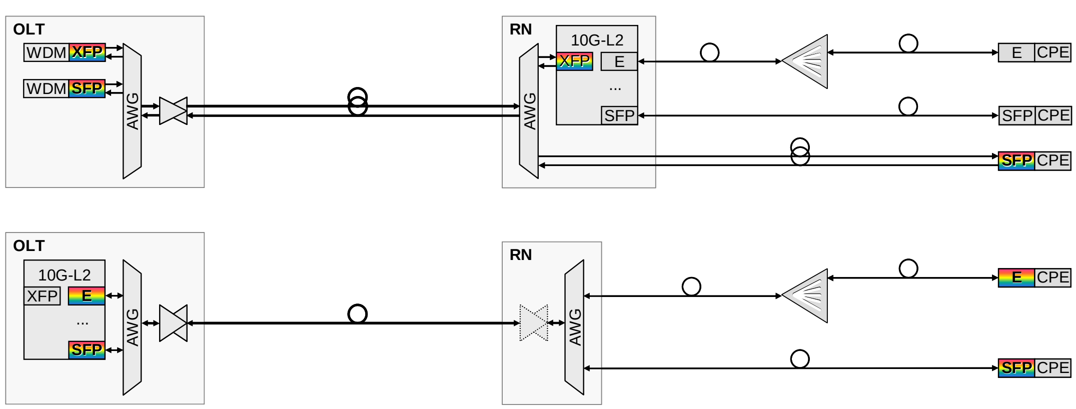

Fig. 9. Two solutions for next-generation access (NGA) with very high splitting ratio. Top: 10G DWDM-PON with active per-wavelength EPON splitting. Bottom: Hybrid PON running colored EPON (or GPON).

In cases where sufficient trunk fibers are available or moderate subscriber numbers of 40…80 are sufficient, simple DWDM-PONs can also from appropriate solutions. For operational simplicity, it is desirable that the ONU transceivers are colorless, i.e., a single type of ONU must support all wavelength channels. Fig. 10 shows two DWDM-PON designs in support of this scenario[14].

The upper configuration depicted in Fig. 10 is based on a Photonic Integrated Circuit (PIC) for the WDM-PON OLT and accommodates high-density transmitter (Tx)/receiver (Rx) arrays. Such integration is necessary in order to allow low per-channel cost, small form factor, and low energy consumption. Various options for these PICs exist with respect to channel count and the partitioning of the transmitter and receiver blocks. The ONU transceivers are based on low-cost tunable lasers. A cost reduction over standard tunable transmitters can be achieved by using different material systems, simplified and more automated manufacturing/test procedures, and removal of sub-components such as wave lockers and external modulators. The transceivers must support auto-tuning enabled by a suitable closed-loop control.

The WDM-PON system shown in the bottom half of Fig. 10 is based on reflective transceivers in both the OLT and the ONUs. In the OLT, a Multi-Frequency Laser (MFL) seeds a Reflective EAM (REAM) array through a first circulator. The REAMs modulates the seed wavelength and reflects it back in DS. This design is capable of supporting 10 Gb/s per wavelength. A second MFL is added to the DS via a WDM band combiner and a second circulator. The arrayed waveguide grating (AWG) multiplexer in the Remote Node (RN) lets a specific wavelength pass to a particular ONU. In the ONU the seed signal is amplified and modulated and sent back US in a reflective device (a reflective semiconductor optical amplifier, an REAM, or an injection-locked Fabry-Perot laser). A combination of these two approaches may form an interesting compromise: The reflective designs could offer lower cost at the OLT, whereas a low cost tunable at the ONU avoids the complexity and performance issues normally associated with of remote seeding.

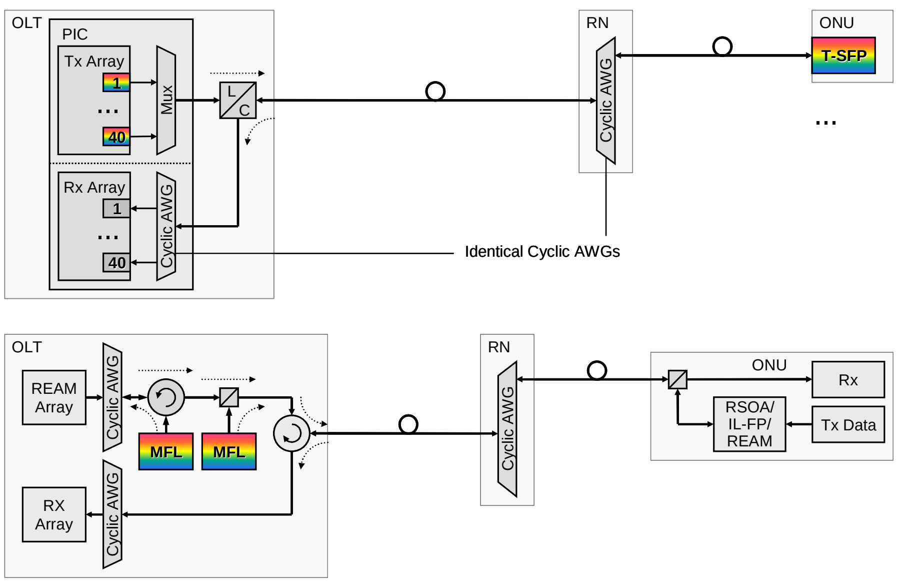

Fig. 10. Two solutions for colorless DWDM-PON. Top: PON using OLT PIC for high-density Tx/Rx arrays, and tunable SFPs in ONUs. Bottom: PON using MFL-seeded REAM array in OLT, and seeded reflective ONUs based on RSOAs, IL-FP lasers, or REAMs. Both solutions use cyclic AWGs for single-fiber working.

7. MANAGEMENT AND CONTROL

With a flexible transport platform, the set-up and monitoring of end-to-end circuits can be a non-trivial task. This is particularly true if equipment, wavelength and physical layer constraints need to be taken into account. With a graphical user interface, wizards and templates, a service manager can help to administer the network inventory not only to display but also to create, modify and terminate network services. In large networks, a service manager can be complemented by a GMPLS control plane and provide visualization support to it.

A GMPLS control plane can greatly simplify network operation and offers increased flexibility in service delivery, protection and restoration capabilities. A standards based control plane implementation consists of three components: It provides automated network/network element discovery, end-to-end path computation, and signaling/provisioning functions. OSPF-based routing modules as employed for the data communication network (DCN) are, along with traffic engineering (OSPF-TE) and GMPLS extensions (GMPLS-TE), used to discover the topology and capabilities of the data plane. A path computation element (PCE) as defined by the IETF RFC 4655 relies on constrained based shortest path first (CSPF) algorithms to calculate end-to-end paths fulfilling service, network and redundancy. A signaling component using the resource reservation protocol (RSVP) along with traffic engineering (RSVP-TE) and GMPLS extensions (GMPLS-RSVP), can be used to allocate and provision resources across an end-to-end path. It can also automate the configuration of ROADM devices and facilitate end-to-end equalization of optical power levels along the service path. By adopting e.g. a GMPLS peer model, interworking between a GMPLS-controlled transport network and IP/MPLS routers as clients is easily possible.

Fig. 11 shows a possible software architecture of a GMPLS control plane. A single control plane instance can be used for wavelength, ODU and Ethernet virtual circuits.

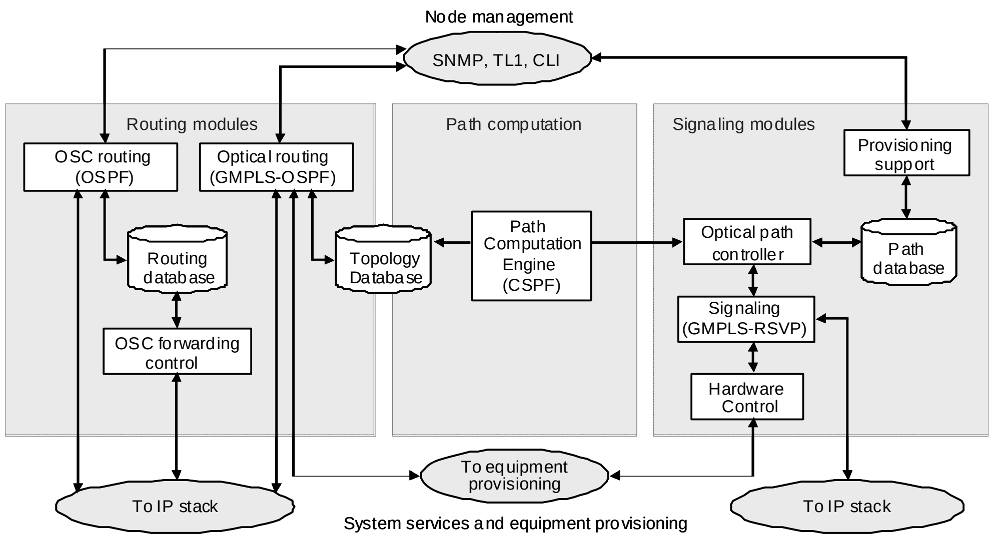

Fig. 11. An optical GMPLS control plane architecture.

In conjunction with a reconfigurable optical layer, an attractive capability of a GMPLS control plane is to provide optical restoration. Direction-less, colorless ROADMs enable more flexible restoration as compared ROADMs with fixed add/drop function. An example is shown in Fig. 12. The left part of the figure shows a simple network. End nodes (E) are connected via trunk interfaces A and run on a certain wavelength (“red”). The same wavelength may also be used on trunks B and C. In case of a failure of trunk A, restoration is performed in the photonic layer. Without direction-less switching (middle part of Fig. 12), a restoration detour via trunk D has to be configured, assuming no other path is available. To accommodate this demand, wavelength conversion (regeneration) would be required in regenerator nodes R1 and R2. With colorless and direction-less capability (Fig. 12, right), however, the end nodes can perform both, change of wavelength and trunk interfaces. The result is a shorter and less complex detour.

Optical restoration is not only interesting as stand-alone mechanism but also in combination with protection. Complementing a fast 1+1 protection with a somewhat slower optical restoration provides enhanced resilience against multiple failures and allows increased maintenance/repair times.

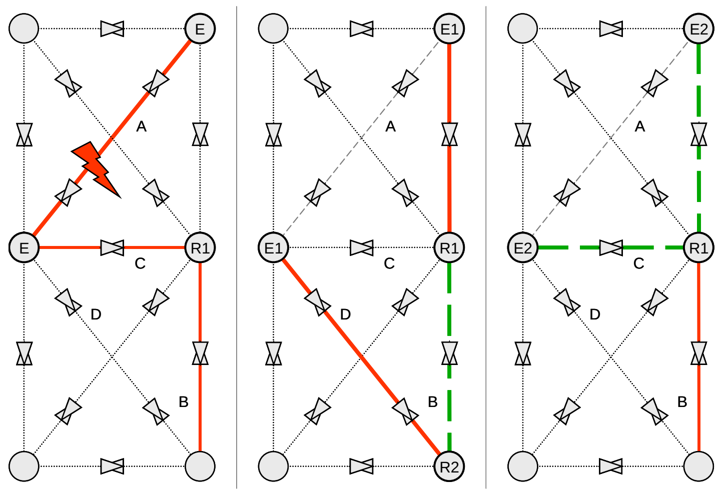

Fig. 12. Restoration enabled by ROADMs. Left: link A between end nodes (E) is failing. Middle: direction-less end nodes (E1) perform switch-over, additional wavelength conversion in regenerator nodes (R1), (R2) is necessary if original wavelength is also used on links C and B. Right: direction-less and colorless end nodes (E2) perform switch-over and wavelength conversion directly, enabling shorter detour.

8. SUMMARY

New optical and Ethernet technologies turn static metro networks from the past into agile networks of the future. With a large range of interface and switching options, it is difficult to design specialized node equipment for every individual application. A modular transport platform with flexible configuration options is essential to address the full application range and make best use of optical and electronic functions.

REFERENCES

1. Fricke, M.: "Examining the flexibility benefits of Next Generation optical networks", IRR WDM & Next Generation Optical Networking Conference, Conf. Proc., Nice, Jun. 2009
2. Davey, R. P. et.al.: "Long-Reach Passive Optical Networks", IEEE J. Lightwave Tech., vol. 27, no. 3, Feb. 2009, pp. 273-291
3. Heckwolf, A.: "Employing passive WDM to cost optimise transport network operations", IIR WDM & Next Generation Optical Networking, Cannes, June 2008
4. ITU-T G and Y series of recommendations. Online available at www.itu.int/rec/T-REC/en
5. MEF technical specifications. Online available at www.metroethernetforum.org/
6. IEEE 802.x standards. Online available at standards.ieee.org/getieee802/
7. Broadband Forum technical reports. Online available at www.broadband-forum.org/technical/trlist.php
8. IETF requests for comments. Online available at www.rfc-editor.org/rfcsearch.html
9. Grobe, K., Elbers, J.-P., Magee, A.: "Optical+Ethernet: Foundation for Next-Generation Networks", Telekomm. Aktuell, vol. 62, 2008
10. Gringeri, S., Bitar, N., Egorov, R., et al.: "Optimizing Transport Systems to Integrate TDM and Packet Services", OFC/NFOEC 2007, paper NTuA4, Anaheim, 2007
11. Derr, F., "Coherent Optical QPSK Intradyne System: Concept and Digital Receiver Realization," IEEE J. Lightwave Tech., Vol. 10, No. 9, September 1992, pp. 1290-1296
12. OIF technical specifications. Online available at www.oiforum.com/
13. Kani, J. and Davey, R.: "Requirements for Next Generation PON", ITU-T/IEEE Workshop on NGOA Systems, Jun. 2008, Geneva
14. Grobe, K. and Elbers, J.-P.: "PON in adolescence – From TDMA to WDM-PON", IEEE Comm. Mag., Jan. 2008, pp. 26-34