Invited Paper

Optical Technology Innovation in Metropolitan Networks

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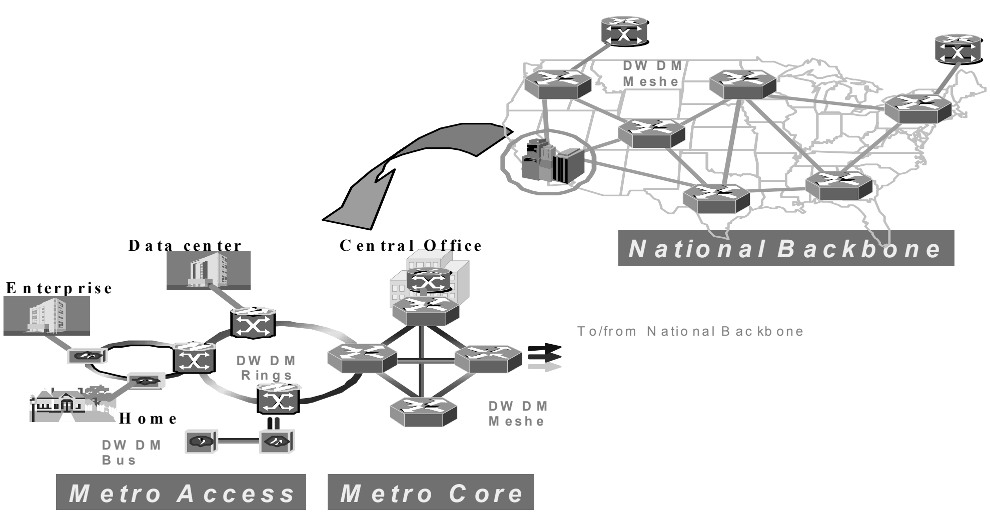
ABSTRACT

This paper evaluates the network architectures, the innovation in optical (WDM) system design, and the related transport technologies that have enabled metropolitan networks to scale to hundreds Gb/s of capacity, and to hundreds km of reach, meeting the diverse service needs of enterprise and residential applications, while maintaining cost lower than traditional long-haul optical transport. The analysis have lead to the development of a multi-service WDM system scalable to more than 300 Gb/s, and 500 km, exceeding the previous related demonstrations in reach and network (OADM) complexity. The most important performance achievements are summarized. The paper finally discusses future important technologies that hold promise to further enhance the cost-effectiveness of metropolitan optical systems.

Keywords: Metropolitan network architectures, optical transport, WDM design, optical transmitter dispersion robustness, pluggable modules, electro-absorption modulated lasers, tunable lasers, forward-error-correction, electronic post-detection equalization.

1. INTRODUCTION

Metropolitan area networks (MANs) are currently the main focus in the efforts of network operators and system providers towards developing efficient and scalable networks [1, 2]. These efforts are motivated by the significant metropolitan, as well as the local area (LANs), networking needs of the enterprise, storage, and broadband access applications, which are the main impetus for the (still significant) growth in network traffic and capacity demand [3]. Moreover, the successful introduction (over the last 10 years) of optical technology, and especially wavelength-division-multiplexing (WDM), in long-haul (LH) transport has enabled national and international backbone networks with many Tb/s of capacity, placing increased emphasis on the scalability of the MANs that eventually originate (and terminate) the network services and the corresponding traffic (Fig. 1).



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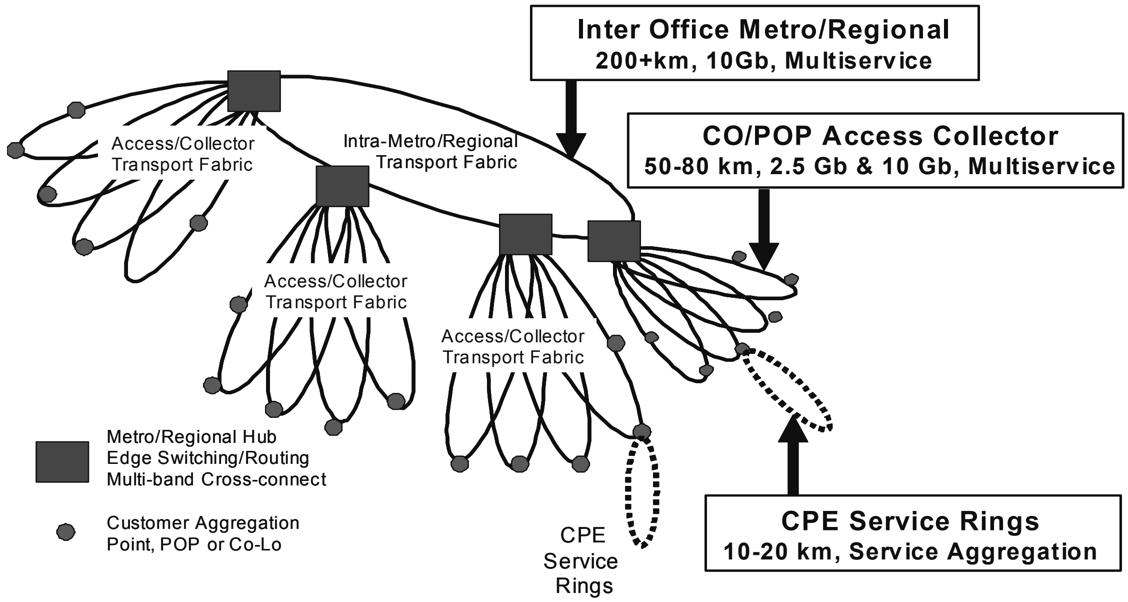


MAN architectures have correspondingly evolved to address the service (applications), and scalability needs; internetworking multiple access traffic collector fiber rings in a larger regional MAN, as summarized in figure 2 [2]. Each metro access collector ring, typically less than 100 km, aggregates the different types of traffic, including time-division-multiplexing (TDM) services (like DS-1 or E-1) and "native" data services (Ethernet or Fiber Channel), to a metro regional hub. Then, all (typically 5-10) metro regional hub nodes are interconnected, typically in a "logical" mesh, through a metro regional MAN, that often extends to distances of hundreds of km. Finally, few selected points of presence (PoP) of the regional MAN also connect through the national backbone LH transport network to complete internetworking (Fig. 1).

A successful generation of systems addressed the initial need for efficient bandwidth provisioning in such mutli-service MAN architectures, mostly leveraging the prevalent TDM (SONET/SDH) transport, and the advancements in electronics and high speed - 2.5 Gb/s and 10 Gb/s (corresponding to STM-16 and STM-64 respectively) - optical interfaces [4, 5]. More recently, WDM has additionally been utilized in regional MAN, and to some extend even in access and enterprise (LAN) networks, initially to address any fiber deployment limitation, and eventually to enable the interconnection of the multiple service nodes through optical add-drop multiplexing (OADM) architectures, with bandwidth that cost-effectively and transparently scales to hundreds of Gb/s [6]. Unlike, however, LH WDM transport, where the main design objective has been to maximize the capacity and reach of networks with typically well-defined (often simple point-to-point) topologies, MAN call for cost-sensitive, "open" architectures that allow for service flexibility. This summary evaluates in detail the innovation in WDM system design, and the current and future optical transport technologies that enable high performance multi-service MAN [7].

2. METRO NETWORK OPTIMIZED WDM TRANSPORT

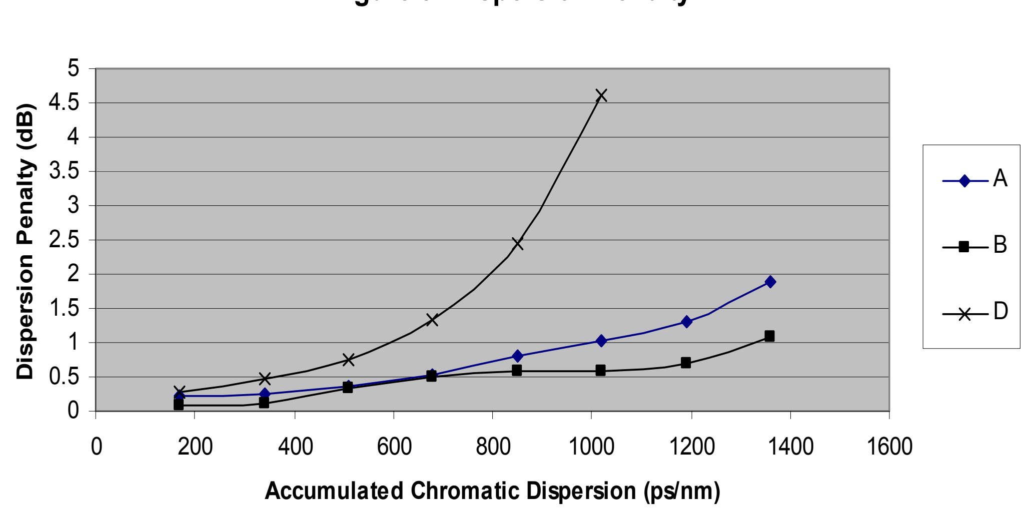
The MAN services requirements essentially call for optical add/drop multiplexing (OADM) WDM architectures that enable both "logical" star and meshed connectivity in a physical ring. Moreover, the regional MAN bandwidth scalability needs practically call for optically amplified (OA) WDM transport of all 100 GHz (scalable to 50GHz) spaced channels of the C-band, in order to leverage the advancements (motivated by LH WDM) in erbium-doped-fiber amplifiers, and chromatic dispersion compensation technologies. In this sense, optical amplification (spontaneous emission or ASE) noise, and chromatic dispersion, especially for 10 Gb/s (STM-64) transport, are the primary physical impairments that limit the system performance. More complex regional MAN designs also get limited by optical power degradation due to amplifier gain ripple or transients, filter concatenation and loss variation, span loss variation due to ageing and repairing, and in the case of mesh networks ASE noise lasing. Unlike, however, traditional LH transport systems where optical-signal-to-noise (OSNR) is optimized for each individual channel, the evolving nature of metro networks, from a simple access application to much longer regional reach, with higher number of nodes, while maintaining low cost, span flexibility, and installation/upgradeability simplicity, places a significant challenge on the MAN WDM design. Most notably, the LH practice of having tight control of the channel power along the link using per channel gain equalizer would lead to significant cost penalty. In this sense, innovative MAN-optimized solutions are needed to address the trade-off between service (OADM placement) flexibility and OSNR guaranteeing bit-error-rate performance (BER < 10^{-12}) requirements, even when protection takes the long way around a multiple-node ring, while minimizing intricate (or inflexible) channel banding, and cost [6].

By leveraging the fact that most of the physical impairments of interest in a MAN have an impact on the total optical power, we have developed internally an innovative WDM design that achieves metro regional performance by monitoring and regulating the multiplex power (rather than for each individual channel) at selected critical point along the fiber ring. Simple optical tap couplers and photodiodes are used to monitor the optical power, and then control a variable optical attenuator (VOA) to regulate power within each node. Moreover, an automatic power control (software) layer has been developed to establish the appropriate to in-line VOA and optical amplifier gain settings, based on all photodiode measurements. Such advanced metro-optimized WDM design and control, along with OA with variable gain, and variable-loss mid-stage access, have enable WDM transport to cost-effectively scale to hundreds of km. More specifically, in 32x10Gb/s (non-return-to-zero NRZ with forward-error-correction) WDM network with equally spaced OADM nodes guaranteed (BER) performance for 8x13dB reach has been achieved, and in the case of fully de-multiplexed nodes the reach extends to 15x15dB (i.e. 900 km), well exceeding previous demonstrations [8]. Furthermore, the control layer is able to self adjust each node, permitting an automatic node setup during the installation phase, as well as automatic adjustment that would account for ageing effects and/or traffic changes.

At the same time, the development of optical transceiver modules has enabled WDM optical interfaces to be integrated into the MAN multi-service systems, eliminating the cost of any unnecessary regeneration, and increasing design versatility. This first generation of transceiver modules has achieved metro regional performance leveraging technologies initially developed for LH transport, such as continuous-wave (CW) lasers with external Mach-Zender interferometer (MZI), typically $LiNbO_3$, modulators for the 10 Gb/s transmitters. Unlike, however, typical LH discrete custom designs which maximized performance, transceiver modules leverage industry-standard volume manufacturing, and packaging to reduce cost [9].

The use of MZI based modulation in 10 Gb/s transmitters also minimizes the dispersion compensation requirements, allowing the lowest cost, most versatile (broad-band) solution based on dispersion compensating fiber (DCF) to address

Figure 3: Dispersion Penalty



the needs of even the most demanding regional MAN WDM designs. This is different, once again from LH transport, where channel-based designs have often been employed to account for residual dispersion compensation. In MAN WDM, however, residual dispersion would not exceed a couple of hundreds of ps/nm, even for the channel at the edge of the C-band after a few hundreds of km of propagation in fiber with high dispersion slope (e.g. LEAF). For the majority of MAN transport over the standard single mode fiber (SSMF, typically SMF-28) and for conventional DCF, such a calculation yields: $50.\Delta\tilde{\lambda}.L$ in fs/nm^{2}km, with $\Delta\lambda = |\lambda - 1545|$ in nm, and L the link distance in km [6]. Figure 3 evaluates the chromatic dispersion induced power penalty (in SSMF) in a 10 Gb/s NRZ channel for 3 different modulators, employing the α-chirp factor model [10]. The typical performance of (case A) a balanced MZI (unchirped $LiNbO_3$) modulator is compared against a chirped $LiNbO_3$ with α= - 0.7 (case B), and an 800 ps/nm electro-absorption modulated laser (EAM) transmitter (case C). The analysis establishes low power penalty, acceptable for MAN. Furthermore, the symmetric nature (for positive negative dispersion) of the balanced MZI minimizes any WDM design complexities, which is desirable for most OADM architectures. The choice of the appropriate transmitter technology, especially at 10 Gb/s, is very important as it typically dominates the overall transport cost [11]. A few emerging technologies have been aiming to reduce further the overall multi-service transport cost, and improve network flexibility.

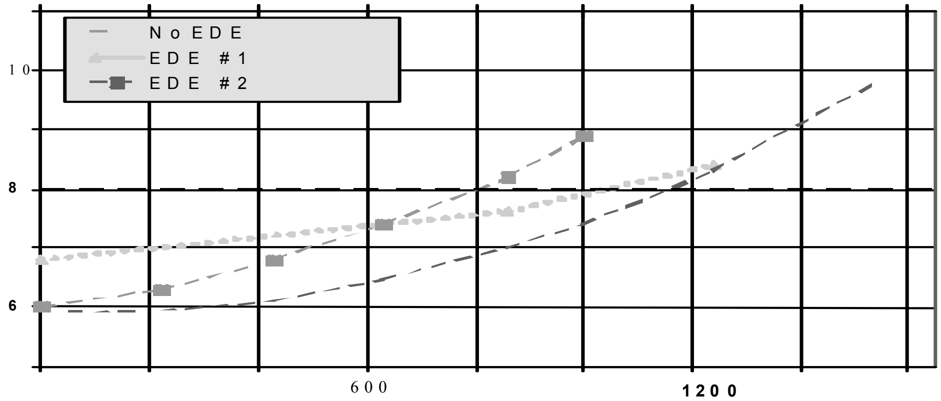
3. EMERGING METRO TRANSPORT TECHNOLOGIES

Optical transceiver technology has typically benefited by the transition from large, complex, and expensive modules to simple serial ones with minimal features. In such serial transceivers, most electronic functions are handled by silicon circuits outside the module. This transition usually occurs when silicon technology advances enough to handle the communication channel data rate. Another key advance in multi-service transport has been the creation of "pluggable" optical transceivers that can be inserted and removed from a system (line-card) without impacting traffic carried on adjacent ports. Such pluggable optics allow bandwidth to be installed (and maintained) in smaller increments, helping to lower capital and operational cost. Pluggable transceiver technology, has been increasingly maturing, currently allowing Coarse-WDM (CWDM) products at 2.5 Gb/s, and promising dense (100GHz) WDM designs even at 10 Gb/s data rates. At such high data rates, however, optical performance, predominantly dispersion tolerant (chirp minimized) modulation, becomes increasingly important. External ($LiNbO_3$) modulators, that have traditionally addressed such performance needs, are not appropriate, due to their size, high voltage, and packaging cost, while the currently available directly modulated laser (DML) technology does not meet the metro requirements of most 10 Gb/s systems. Electro-absorption modulated lasers (EAM) are considered a promising alternative, although challenges still exist for 10 Gb/s long reach WDM applications as the requirements for both high output power and controlled (reduced) chirp operation significantly compromise the EAM manufacturing yields [11].

Advanced modulation, encoding, and signal processing techniques also promise to enhance the cost-effectiveness of optical fiber transport, mitigating some the physical impairments of the digital communication channel. Forward error correction (FEC) is the most celebrated such example, for allowing standard electronic (silicon-based hence low-cost) implementations to mitigate non-deterministic (ASE) noise impairments, so extending the optical channel SNR operational regime, and hence its reach. The current standard (G.709) FEC implementation (another LH motivated technology) offers more than 6 dB of OSNR gains, and has been successfully leveraged in regional MAN [6]. Future FEC designs promise to offer further performance enhancements [12], potentially allowing systems to be within 1 dB of the theoretical ("Shannon") limit (using FEC based on soft decision algorithms), although significant implementation details (mostly related to silicon integrated circuit density and standardization) have to be tackled before any commercial development.

More recently, advances in electronics have also permitted the implementation in a 10Gb/s receiver of signal processing techniques that mitigate inter-symbol interference (ISI) impairments related to fiber dispersion (chromatic, polarization, or modal). While a few different equalization techniques have been considered in optical communication systems [13], each offering distinct advantages, electronic post-detection equalization (EDE) technology is rightfully drawing significant practical interest for its low "silicon" cost. EDE related efforts initially addressed mostly polarization mode dispersion (PMD) impairments [13]. More recently, however, EDE-based chromatic dispersion mitigation has also been discussed. We have evaluated the performance enhancements (in 10Gb/s NRZ optical signals) for the available EDE implementations [14]. Figure 4 indicates typical results of (FEC-enabled) OSNR at different chromatic dispersion level, for two different initial EDE samples, utilizing the same nominally balanced (0 chirp) $LiNbO_3$ external modulator (Fig.

Fig. 4: OSNR (dB) vs Dispersion (ps/nm)



3A). We conclude that currently available EDE technology could allow for a 30-40 % improvement compared to the typical 800 ps/nm of dispersion-limited reach for a 2dB OSNR penalty for no EDE (lower dashed line). Although, significant implementation details have still to be determined, such improvements in the dispersion limited reach would offer some moderate enhancements in WDM design flexibility. Moreover, we believe that EDE could be leveraged to enable lower cost optical transceiver modules, which will constitute an even more attractive alternative use of this technology in multi-service networks [15].

Progress in optical technologies have also provided significant enchantments, and will improve further the MAN WDM performance. Array waveguide gratings (AWG), for example, have become the most cost-effective wavelength selective filter technology for nodes with many (> 16) optical (de)multiplexed channels. AWG technology further offers a very promising platform for reconfigurable OADM solutions that would address the MAN planning needs [16]. Along the same lines, tunable laser technologies have also achieved significant progress, and are being increasingly employed in WDM transport, although substantial proliferation of their use in MAN will require further cost reductions because inventory is the main application of interest [17].

4. CONCLUSIONS

Rapid growth in the demand for data services is pushing WDM technologies from the LH to the MAN and LAN. This paper evaluates the challenges in the emerging multi-service MAN WDM architectures and associated trade-offs, and summarizes the innovation in WDM design and transport technologies that could enable optical systems to offer the required service flexibility, and scalability, cost-effectively. Leveraging this analysis a multi-service WDM system was developed with performance that scales to more than 300 Gb/s, and 500 km, exceeding previous demonstrations in reach and network (OADM) complexity. Future technologies such as pluggable or tunable transceivers, reconfigurable OADM, EAM, FEC, and EDE promise to further enhance system flexibility and cost-effectiveness, enabling further use of WDM in multi-service networks.

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