Trends in the architectural design and computer modeling of optical metropolitan area networks

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Abstract: We review the latest progress in the architectural design and the performance modeling of transparent, optical metropolitan area networks. We identify key transmission impairments, which affect the performance of these networks.

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1. Introduction

Since the adoption of SONET/SDH standard, the architecture of optical metropolitan area networks (MANs) is constantly evolving. The predicted exponential increase in data traffic led to the introduction of wavelength division multiplexing (WDM) in optical MANs, as a means for cost-effective capacity upgrade. Early research efforts in this direction (e.g., RACE/ACTS [1] and DARPA-funded [2]-[4] consortia) proposed a number of transparent multiwavelength network elements (i.e., optical add/drop multiplexers (OADMs), optical crossconnects (OXCs)), which were designed to account for the technological constraints of that time period (e.g., small number of wavelengths, large channel spacing, limited selection of WDM components, etc.). Over the past few years, these constraints were partially alleviated due to the dramatic improvements in WDM component technology, and the original network element designs went through a succession of transformations [5], [6]. In parallel, there appeared the first commercial WMD metro network elements and their first tentative deployments in the existing network infrastructure.

It is apparent that the development of analytical/numerical models and commercial software products for computer-aided design of optical MANs followed a parallel evolution, see e.g., [7]-[10] and the references therein. The purpose of this paper is to review the latest research advances and forecast potential future developments in this exciting field.

2. Current optical MAN topologies and market review

In order to assess the current and future simulation needs, it is instructive to understand the latest migration scenarios from the already deployed SONET/SDH networks to fully transparent WDM optical MANs. Figs. 1, 2 summarize the initial vision of transparent WDM optical MANs and the current deployment status, respectively.

Fig. 1 shows a typical future optical MAN topology, derived from [6]. It is comprised of *feeder* [5] (referred to also as *interoffice* or *core*) and *distribution* [5] (referred to also as *collector* or *edge*) sections. The feeder sections aggregate traffic from distribution sections and deliver them to the backbone long-haul network. Typically, they are based on multiwavelength self-healing rings composed of reconfigurable optical add/drop multiplexers. Ring topologies are preferred due to their efficient fiber sharing and resiliency capabilities [11], [12]. The feeder sections can vary in size, of which the larger ones are referred to as metro *regional*. The distribution sections interface with customer premises, deliver and collect traffic. They can have a variety of topologies, e.g., tree, bus, single- and double-homed rings, can employ coarse WDM or no WDM and are totally passive, comprised of low-cost, low-maintenance components.

A likely deployment scenario was anticipated to be the introduction of WDM initially into the feeder sections, followed by further penetration into the distribution sections contingent upon the price decrease of WDM components. In addition, it was thought that static OADMs would be deployed in the beginning, with the option for automated (reconfigurable) operation in the future. Whether the interconnection of multiple feeder rings, feeder and distribution rings, or the feeder rings and the backbone sections of the network should be done in a transparent or an opaque way is still a matter of debate [5]. Other introduction scenarios have also been proposed in the literature [13].

Fig. 2 shows the current deployment status and a realistic evolution scenario of a typical network in a highly populated metro region which is serviced by an incumbent local exchange carrier (ILEC) [14]. The great majority of feeder and distribution sections are still based on SONET/SDH rings composed of electronic Add/Drop Multiplexers

(ADM) (green boxes) and Digital Cross-connect switches (DCS) (gray boxes). The last few years witnessed the gradual deployment of WDM as a fiber relief in short-haul, point-to-point between some nodes (called *super-hubs*) (black boxes) of the interoffice rings. It is anticipated that the next step, in the immediate future, is the transparent interconnection of multiple super-hubs, using reconfigurable OADM equipment in a ring (solid red line) or mesh topology (broken red line).

Fig. 2 indicates that the deployment of WDM in optical MANs is still at its initial stage. This is due to the low demand for wavelength-level services. Nevertheless, there currently exist several commercially available OADMs for metro feeder and distribution networks. These OADMs are typically static and are implemented using either a serial or a parallel architecture. The former design is more suitable for low add/drop channel counts whereas the latter performs better for high add/drop channel counts. In addition, both designs allow for hierarchical, multi-stage optical multiplexing and demultiplexing [15], i.e., a distinct set of wavelengths (i.e., waveband) is assigned to each OADM, enabling optical multiplexing/demultiplexing or node bypassing on a waveband basis. Commercially available OADMs use wavebands comprised of four wavelengths spaced 100-200 GHz. Wavebands are separated by a single channel, which is not in use (i.e., guard-band). The advantages of this hierarchical architecture are threefold: (i) pass-through channels experience significantly lower insertion loss than if they are fully demultiplexed and then multiplexed; (ii) the distortion induced by the concatenation of optical MUX/DMUXs is minimized; (iii) modular upgradability (i.e., pay-as-you-grow expansion). Alternatively, Broadcast-and-Select OADMs were proposed, which provide dynamic, cost-effective access of all wavelengths by incorporating MUX/DMUX, switching and channel power equalization in a single device (liquid-crystal-based wavelength blocker) [16]. Although the latter architectures were initially intended for long-haul applications, where a large amount of through traffic exists, their price recently decreased to the point where they are considered attractive candidates for metro use, as well [17], [18].

Commercially available OADMs can be used in feeder rings of typically 100-200 km circumference. Feeder rings typically carry 32 OC-48 or OC-192 channels in a combined C and L band at 200 GHz [19]-[20], or 33 channels at 100 GHz in a single band [21]. Finally, feeder rings typically include 5-10 OADM nodes, which support optical bypass.

3. Modeling issues

As explained in the previous section, current optical MAN topologies like the one shown in Fig. 2, are composed of short-haul point-to-point WDM systems. Future metro network topologies will be predominantly typified by a number of interconnected rings, as shown in Figs. 1, 2. They will use static/dynamic optical add/drop multiplexers and maybe transparent optical cross-connects. Optical signals will originate at various points in the network and routing will change over time. Other unique attributes of the metro environment are the short total distances (typically less than 100 km), small inter-node distances, fine granularity traffic of various modulation format types and bit rates, and increased cost sensitivity. The latter is the main driver for the installation of cheap components, which have imperfect transmission characteristics, in the optical network elements of MANs. Consequently, the design challenge is to optimize the network performance while minimizing the cost.

Recent theoretical [22] and experimental [23] results indicate that, in the current optical MAN architectures, the most significant transmission impairments are, in order of decreasing importance, the optical amplifier related effects (i.e., optical power ripple, optical signal-to-noise ratio divergence, amplified spontaneous emission (ASE) noise accumulation, and optical power transients), the signal distortion due to chromatic dispersion and its interplay with the transmitter chirp, the signal distortion due to optical MUX/DMUX concatenation, mainly in parallel architectures, the linear optical crosstalk, if transparent optical cross-connects are used, the polarization-dependent loss, the polarization-mode dispersion (PMD), in the case of long links of old legacy fibers, and the fiber nonlinearities, in the case of high bit rates and long distances.

Optical amplifier related effects can be studied numerically using wavelength-domain simulation [7]. A significant effect in closed-loop topologies (ring, mesh) is the performance degradation due to optical power transients occurring during network reconfigurations, fiber and/or equipment failures, protection switching, etc. Optical amplifiers need to be gain-controlled to prevent transient effects from propagating as reconfiguration of the network takes place. Electronic gain control is the predominant technology [24], [25].

Comprehensive models for the performance degradation due to ASE noise [26], optical MUX/DMUX concatenation [27], [28], and linear homodyne crosstalk [29] were recently proposed.

For chromatic dispersion mitigation, several optical chromatic dispersion compensation schemes have been proposed [30], [31]. However, most recently, electronic dispersion compensation technologies have been showing significant momentum due to their cost-effectiveness [30]. It is likely that in next generation metro networks, several system vendors will evaluate new technologies, in an effort to extend the reach provided at 10 Gb/s without incurring a high up-front cost. Such technologies may include the use of advanced modulation techniques and forward error correction.

In most cases, the combined impact of all aforementioned transmission impairments cannot be calculated accurately and the quest of efficient semi-analytical techniques for end-to-end performance evaluation is a current topic for research [8], [9], [32], [33]. Complete study cases of realistic optical MANs were also reported, e.g., [34].

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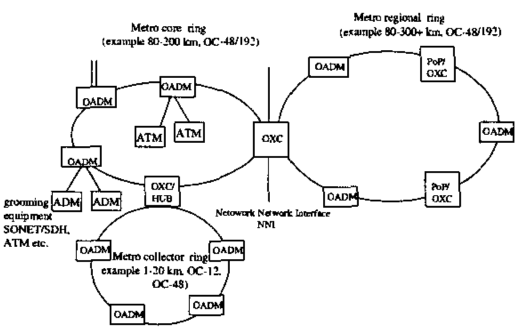

Fig. 1 Vision of all-optical metro network.

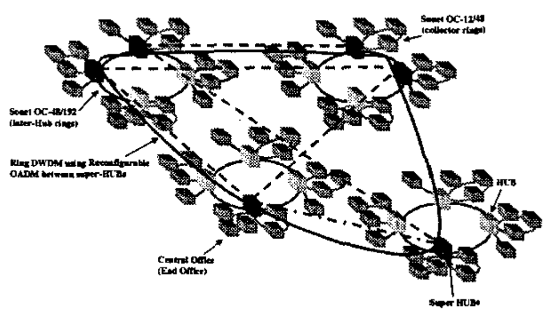

Fig. 2 Current deployed metropolitan network scenario.