Engineering an 11 Tb/s US mesh metro network: design and transport performance

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ABSTRACT
A top-down methodology is used for the first time to enable a transparent metro network solution of a typical US carrier. It consists of traffic modeling based on projected traffic demands, network dimensioning, transport layer performance modeling and network engineering. A 29-node, 11-Tb/s US mesh metro network is engineered in a transparent way based on realistic network traffic requirements.

1 Introduction

The expansion of the Internet, in the past few years, has brought tremendous growth in broadband communication services. Even with the current market downturn, it is recognized that the need for more bandwidth exists and it is expected to grow in the next years. This will drive the further development and deployment of optical networks and their various technologies such as wavelength division multiplexing (WDM) which offers increased capacity and potentially lower cost. Up to now, WDM has not yet been extensively used in metro-area networks, compared to the extensive use in long-haul networks. One of the main reasons has been the existing legacy interfaces (e.g., SONET/SDH, ATM) and legacy fiber plants. Until recently all Incumbent Local Exchange Carriers (ILECs) have designed their network functionalities (i.e. signal add/drops, performance monitoring and fiber/wavelength cross-connecting) in the traditional electronic manner. This meant extensive optical-to-electrical and electrical-to-optical conversions at each node, an approach that is now beginning to be replaced by WDM's transparent philosophy. Another reason for the difference in approach between the metro environment and long-haul has been the fact that the nature of these networks is fundamentally different. A long haul network is optimized to transport high bit rates over long (or ultra-long) distances with few add/drops, whereas in a metro-network distances between adjacent nodes can be as small as 5 km and the signals may traverse many nodes. Furthermore, the variety of customers with different needs in the metro environment makes the design of the network more complex. Central office (CO) equipment is shared among less customers, than in the long haul case. As a result, WDM metro networks would have to offer increased functionality and performance at a lower cost per connection compared to their long-haul counterparts. Advances in new WDM component and equipment as well as vendor competition are beginning to offer this increased functionality and performance at a lower cost per connection. Nevertheless, there are more cost factors in the process of designing and engineering an optical network. It is important that the design and engineering tasks are completed in a time efficient way. The equipment and component cost can be addressed by looking at the network requirements and characteristics. For example in a metro network, there are distances between nodes that are less

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than 40 km, so in-line optical amplifiers may not be necessary. Of course, care should be taken to warranty that optical signal power is adequate at the receiver, so that electrical noise does not become a performance issue. Adequate optical signal power can be accomplished by proper choice of pre- and/or post-amplifiers at the node locations. Smaller distances between adjacent nodes also raise the issue of the deployment or not of dispersion compensation. Distances of 5 km may not need dispersion compensation. Nevertheless, having several of such uncompensated distances may cause some connection paths to be under-compensated to a degree that the signal performance is unacceptable. Network performance issues are directly linked with the network engineering, which depends in part on the network topology. The network topology is driven by the network traffic demands. Thus, a time efficient way is -required to study and engineer the metro network from the top (traffic demands) to bottom (network performance).

Wavelength division multiplexed (WDM) metro network optical layer engineering studies have been recently presented in [1-3], however most of them have been limited to either small [1,2] or rather symmetrical networks [3]. Furthermore, the above sample networks were not designed based on actual or projected traffic demands in the metro environment, but rather physical layer designs that were intended to demonstrate specific technical virtues. In this paper, we present for the first time an effective top-down simulation approach that enables the design of a 29-node, 11-Tb/s US mesh metro network in a transparent way based on realistic network traffic requirements [4]. Projected traffic demands based on current known values and existing COs are used to derive network architectures for a number of different US carriers for year 2005. A physical layer topology, based on network dimensioning, is then superimposed on the network architectures. The network is then engineered for 100% of the required optical connections using a three-step efficient simulation methodology which was presented in [5] and which is optimized for the metropolitan environment. This involves engineering paths with the longest length as well as the ones with the maximum number of optical hops using a combination of time- and wavelength-domain simulation steps followed by impairment budgeting using simple and accurate analytical models. Issues related with the proper choice of dispersion compensation as well as appropriate pre- and/or post-amplification are addressed in the engineering part of the work. It is shown in the derived mesh network topology that transparent paths with maximum lengths of 465 km and paths with maximum number of hops equal to twelve were possible, thus enabling all other paths in a 29-node mesh WDM metro optical network. We believe that the above approach is a typical one that metro network players like ILECs or CLECs will use to effectively and quickly engineer transparent networks as WDM evolves in the metro environment. It must be noted that although the whole study is based on methodologies and traffic/engineering models that have been previously published for the most part, the study is unique in the sense that it applies all the above for the first time to our knowledge in a top-down approach on an actual metro network topology.

2 Traffic Projection-Network Dimensioning

The optical network architecture under study is derived from traffic modeling of a major US metropolitan area and different market penetrations (low, moderate and high demand scenarios) of existing carriers referred to as Incumbent Local-Exchange Carriers (ILEC) and new carriers referred to as Competitive Local Exchange Carriers (CLEC) presented in [6]. The traffic projections are based on projected voice, transaction data and Internet traffic demands taking into account knowledge of current demands, the change of the population, the change of the non-production employees, and the Internet hosts [7]. The model has been described in [8,9] and uses publicly available data sources [10-12]. Note that the assumptions of the traffic projection and network dimensioning were general enough and cover a variety of solutions/approaches as well as low, moderate and high traffic demands for the three types of carrier groups. Moreover, large networks (such as that of an ILEC), relative large network (such as that of a major CLEC) and small networks (such as that of a small CLEC or a collaboration of small CLECs) were examined and thus the conclusions drawn can be generalized. In particular, three different carriers were considered: one ILEC with seventeen COs, one CLEC (CLEC1) with ten COs, and nine other new carriers (CLEC2) with only one or two COs each. There are also 12 peripheral nodes that represent the points where traffic from the greater metropolitan area is aggregated. The projected traffic demands and CO locations are used to derive individual traffic matrices for the different carriers.

The traffic demand of the core network (which excludes the peripheral nodes) is the driver of the assumed connectivity (selection of links connecting metro nodes – Fig. 1) [6]. After having selected a specific connectivity for the core, the projected traffic from the peripheral nodes is also considered and the connectivity is expanded further to include all possible connections between any two nodes in the network. Fig. 1 shows the resulting mesh for just the ILEC network topology. The nodes of all other carriers are left unconnected because they have less demanding network performance requirements as will be explained further below. A commercial network dimensioning and routing tool is then used to generate required network parameters, such as connection lengths, add/drop percentages, and number of fibers at each node, and to assign wavelengths for each connection [13]. For the network case study of Fig. 1, 40 wavelengths per fiber and 1 + 1 protection were considered.

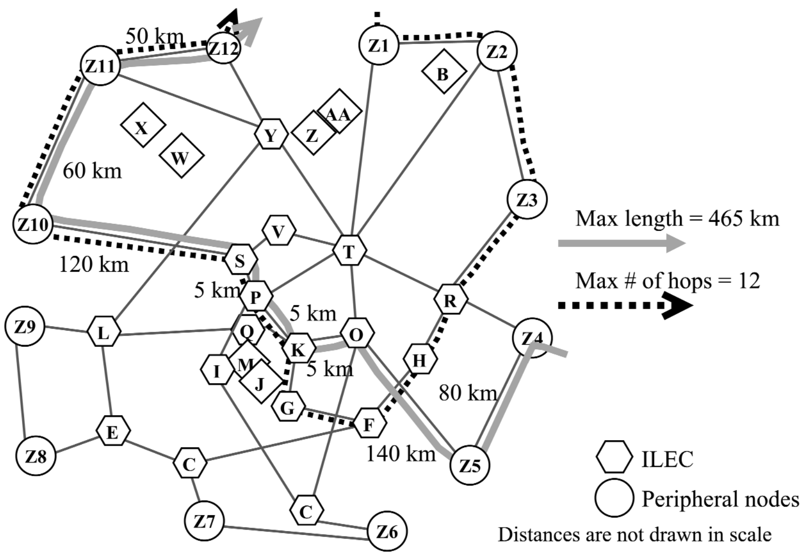

Figure 1: Metro network case study with identified longest-length path (solid) and maximum number of hops path (dotted). Examined network is that of an ILEC. Unconnected nodes are part of the CLEC carrier networks.

The peripheral nodes in Fig. 1 (e.g., Z4) that have connecting fibers coming from two directions (connectivity 2) are Optical Add/Drop Multiplexers (OADMs). All nodes with connectivity larger than two (e.g., O, K, etc) have Optical Cross-connect (OXC) equipment. Note that each fiber link of Fig. 1 may consist of more than one fiber and as a result the size of the OXC module as well as the number of ports of the switching fabric will vary. The design details of the OADMs and OXCs are beyond the scope of this article and thus in trying to maintain the generality of our methodology we used a "black box" approach for these network elements. Typical insertion losses, filter, crosstalk and noise characteristics from commercial components are used for the transport layer analysis below.

After studying the different market share scenarios presented in [6] for 2.5 Gbps and 10 Gbps, we concentrated our transport layer performance modeling study on 10 Gbps, since this will be typical of metro-area networks in the near-term, however results will be presented for the 2.5 Gbps case as well. It was shown that 92% of the required ILEC connections have connection lengths of less than 250 km, while they traverse no more than seven hops (Fig. 2). *Hops* are number of nodes that the signal has to traverse in an end-to-end connection (excluding the originating node). The statistics of the three different carrier networks are shown in Table 1, where the min, max, average and standard deviation of the connection length and number of hops of the different carrier groups (2 CLECs and the ILEC) is shown. Table 1 shows that the CLEC networks have less demanding performance requirements since they have smaller connection distances and less number of hops on the average than the ILEC network. It must also be noted that both working and protection paths were studied. As a case study, we chose to study the longest length- and maximum number of hops-paths because they represent the worst-case engineering scenarios. The former will suffer from more fiber nonlinearities and chromatic dispersion whereas the latter will accumulate the worst crosstalk, filtering and ASE noise effects. We model Z4-Z5-O-K-P-S-Z10-Z11-Z12 (longest length, 465 km) and Z1-Z2-Z3-R-H-F-G-K-P-S-Z10-Z11-Z12 (maximum number of hops, 12 hops) paths in Fig. 1. Engineering for the above worst case scenario paths assures acceptable performance for the rest of the connection paths of the ILEC network as well as the smaller size CLEC networks.

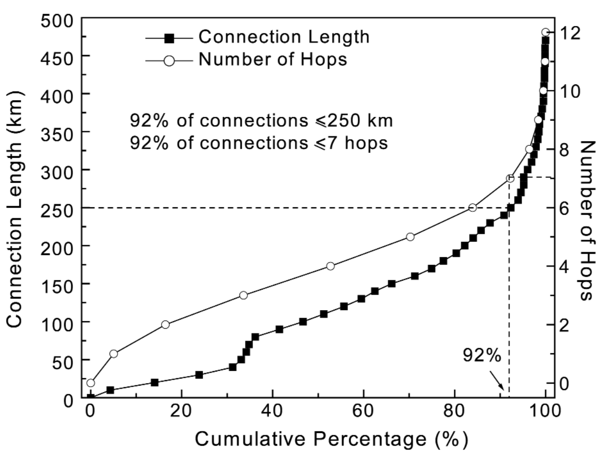

Figure 2: Distribution of the lengths and number of hops required for all connections in the metro network under study.

	Connection Length (km)			Number of Hops		
	ILEC	CLEC1	CLEC2	ILEC	CLEC1	CLEC2
Average	117.4	106.3	168.4	4.5	2.7	3.6
St. Dev.	88.9	74.7	64.0	2.0	1.0	2.2
Max	**465.0**	240.0	286.0	**12.0**	5.0	7.0
Min	3.0	5.0	80.0	1.0	1.0	1.0

Table 1: Statistics for the three different carriers.

3 Network Engineering

The remaining part of our simulation methodology presents the network engineering part of the work based on the superimposed physical layer topology presented above. In trying to engineer the identified worst-case paths of Fig. 1, different transport layer impairments that will degrade system performance need to be examined. These include amplified spontaneous emission (ASE) noise, power ripple of components, chromatic dispersion, optical crosstalk, waveform distortion due to filter concatenation, fiber nonlinearities and polarization effects such as polarization mode dispersion (PMD), and polarization dependent loss (PDL). Complete time/frequency-domain simulation of such a large network is a very time consuming process. As a result, a three-step computationally efficient simulation methodology is derived. The first step involves performing wavelength-domain simulation on the entire network [14], followed by conventional time/frequency-domain simulations on the identified worst-case paths. Finally, a budgeting approach based on accurate impairment models and information obtained from the previous two simulation steps is used to estimate the Q-performance on these worst-case paths in the network [3].

Metro-optimized erbium-doped fiber amplifiers (EDFAs) are used as pre- and post-amplifiers at each OADM and as in-line EDFAs in long links (e.g., >80 km). EDFAs are engineered to gains of 10 to 21 dB, with noise figures 8.7 to 5.4 dB, respectively. These numbers are typical numbers for metro-optimized EDFAs. Standard single-mode fiber and per-link chromatic dispersion compensation is used if needed as will be described below. Typical through insertion loss used is 26 dB for the OXC and 12dB for the OADMs. Fig. 3 shows the longest path modeled (path: Z4-Z5-O-K-P-S-Z10-Z11-Z12). A transmitter power of 0 dBm is used. After amplification the signal is launched through the initial add/drop-node into the network. For short node-distances (e.g., 5km) no in-line amplification is implemented. For longer distances in-line amplification is required, as well as mid-stage dispersion compensation (at the amplifier sites). We try to fully compensate the dispersion of all of the long links, while all the short

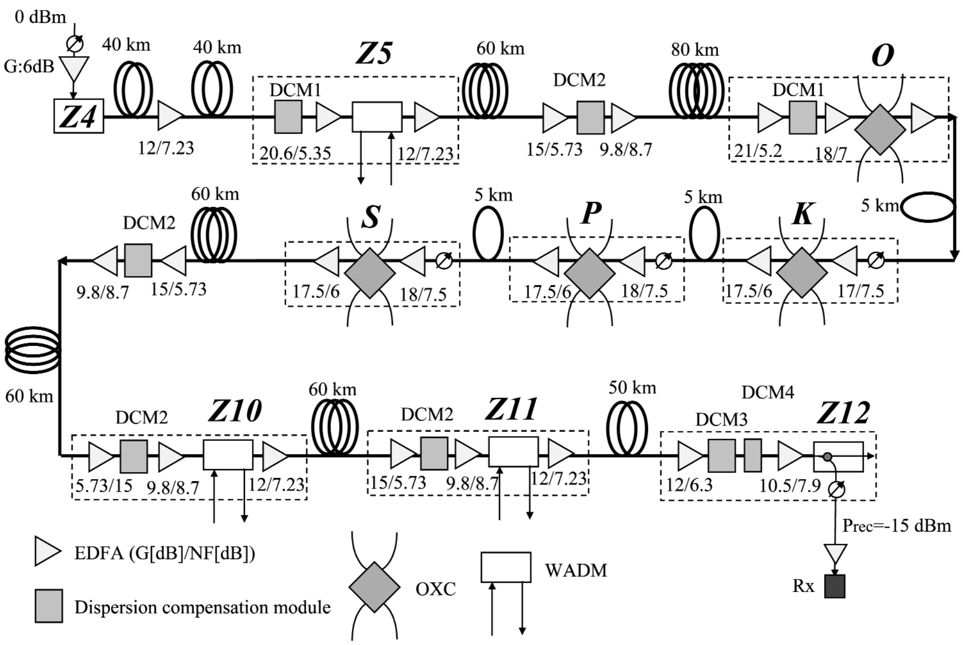

Figure 3: Optical engineering rules/methodology of the longest path. The lengths of the fiber links, the gain and noise figure of the EDFAs are shown. Dispersion Compensation Modules for 80 km (DCM1), 60 km (DCM2) and 40 km (DCM3) as well as 10km (DCM4) are used.

links are left uncompensated. The signal is then routed through the different nodes and is finally dropped at node Z12.

During the *first simulation step* (wavelength-domain) an efficient simulation technique is used to calculate a first-cut performance of the network and to identify the worst-case paths [14]. This approach essentially consists in under-sampling the various spectra while doing the simulation (for reducing the computational complexity) and ignoring the phase of the signals, which means ignoring their modulation and representing their spectra by simple impulses in the frequency-domain. The main assumptions in doing so are that the frequency characteristics of typical optical components (i.e. MUX/DMUX, optical amplifiers) generally vary slowly within the individual signal bandwidths and can be effectively described in this domain in terms of the values of their transmittance transfer functions (gain, loss) and that ignoring the modulation of the carriers does not affect the behavior of the amplifiers. A result of the under-sampling performed in wavelength-domain simulation is that switching between time- and frequency-domains is not possible. However, this is not needed since this approach is used to calculate the average signal powers and Optical Signal-to-Noise Ratio (OSNR) and not to evaluate the waveform evolution of channels through the optical components of the network. In addition, all types of linear crosstalk terms generated at each of the network components can be collected when wavelength-domain computer simulation of a network is performed. Since no modulation, phase or polarization information for signals is propagated in the wavelength-domain, the collected crosstalk terms are simply represented in terms of average powers and are stored separately as distinct narrowband optical signals. The crosstalk-induced penalty in the network can then be evaluated at the receiver after making certain assumptions (described below). Moreover, non-linear effects in the fiber and other optical components, as well as polarization effects are not captured in the wavelength-domain simulations and are studied only on individual paths of the examined networks as part of the time-domain simulation step. So during this part, OSNR calculations are performed and the optical crosstalk terms generated in all of the paths of the network of Fig. 1 are calculated and identification of worst case paths, for crosstalk and/or OSNR, are obtained. For the purposes of this work only common-channel crosstalk is considered (leakage terms at the same nominal wavelength) since this is always the most detrimental form of crosstalk [15]. Furthermore, as a worst-case scenario, it is assumed that the signal and the crosstalk terms have identical polarizations but uncorrelated phase noises (incoherent homodyne crosstalk case). Typical sources of such crosstalk are MUX/DMUXs, switch fabrics, and optical filters. Only terms with crosstalk level above −110 dB are considered in the

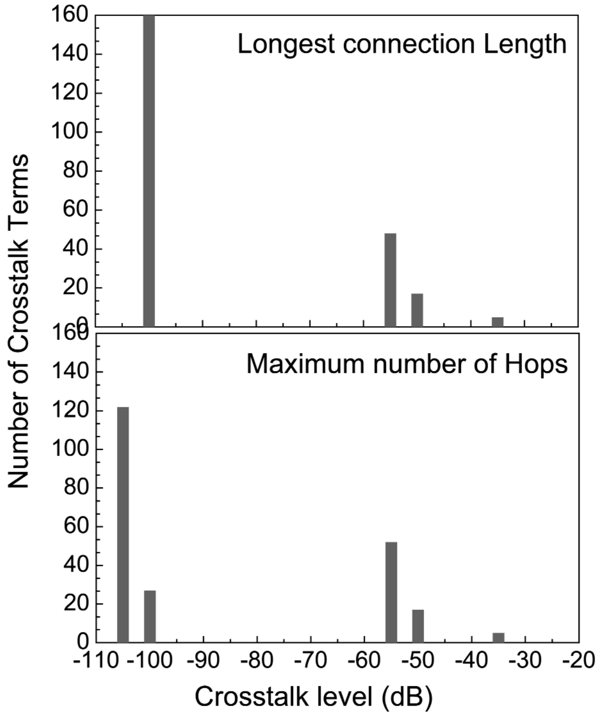

Figure 4: Histogram of the crosstalk terms generated by the wavelength-domain simulation step for the paths having the longest connection length and the maximum number of hops of Fig. 1.

simulations. Fig. 4 shows the histogram of the crosstalk terms generated for the path with the longest length and the maximum number of hops, respectively. For the case of the maximum number of hops about 210 terms are collected from which the dominant ones (two at −35 dB) are generated at the OADMs (−35dB is used as a typical OADM crosstalk value). Fourteen crosstalk terms are at −50 dB (−25dB per MUX/DMUX) and forty-nine terms at −55 dB below the signal originating from the OXCs. Similar numbers of crosstalk terms were observed for the longest connection length case too. Once the crosstalk contributions are calculated we then calculate the crosstalk-induced Q-penalty which is defined as the difference in Q (dB, defined as 10 log(Q_{lin})) at the optical receiver that is observed at a given error probability (P_e) for the case of crosstalk-free system and the one that contains the effects of crosstalk. For the evaluation of the P_e of an optically amplified direct-detection receiver in the presence of N interferers at the same nominal wavelength as the signal, we calculate the characteristic function of the photocurrent at the receiver and then calculate its probability density function (pdf) by taking the inverse Fourier transform [16]. A total crosstalk-induced Q penalty of 1dB at an Optical Signal-to-Noise Ratio (OSNR) of 24.5dB is obtained for both examined paths. The above crosstalk model allows the calculation of the itemized contributions of the different contributors (crosstalk, ASE noise, thermal and shot noise, ASE-ASE and crosstalk-ASE beatings). Note that

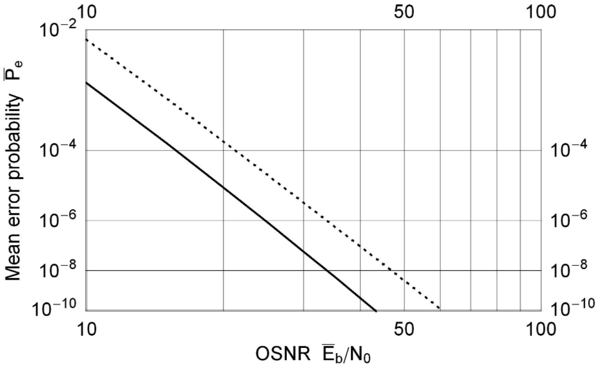

Figure 5: Mean error probability vs. OSNR for the maximum hops path of Fig. 1. Back-to-back (solid) is compared to system with optical filters (dotted).

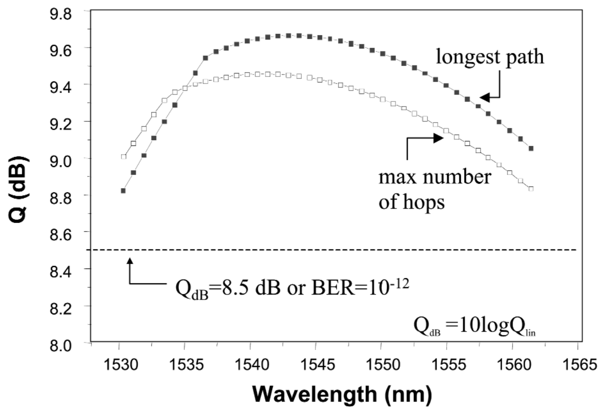

Figure 6: Q-performance results obtained using the Q-budgeting simulation approach for both the longest path as well as the maximum-hops path of Fig. 1.

the main Q-penalty contribution is due to the crosstalk terms of −60 dB and above and in particular 0.75 dBQ coming from the two crosstalk terms at −35dB.

Once the first simulation step has been employed to identify the worst-case paths of the network as outlined in [5] the *second simulation step* consists of time-domain simulations on the identified two worst-case paths. Accurate error probability calculations are performed for each path taking into account filter concatenation, and ASE noise accumulation. This is done using a semi-analytical technique [17,18] that takes into account the correct pulse shape, MUX/DMUX and electronic low-pass filter transfer functions and non-Gaussian photocurrent statistics at the output of the direct detection receiver. Fig. 5 shows the error probability as a function of the received OSNR for the case of the optical path that includes the filters (dotted) versus the back-to-back case. A 0.75 dB Q-penalty due to filter concatenation was calculated at a Bit-Error-Rate of 10^{-12}. Nonlinearities and polarization effects are further budgeted with 0.5 dB Q-penalty. This number is obtained from experience and previous similar calculations that showed that fiber non-linearities can be controlled by designing the metro network appropriately [19].

Q-budgeting is used as a *third and final simulation step* in trying to engineer the above network design. This is a budgeting approach where Q-penalties for the various effects obtained from the previous steps of the simulation methodology are used. The Q-performance of all possible wavelengths to be considered for this channel, applied on the worst-case paths, can then be calculated by keeping track of the signal and ASE noise powers through the network. Channel power divergence, dispersion/chirp, ASE noise, receiver noise terms and budgeting for all other impairments in the form of dBQ is considered. Note that this is different from a simplistic Q-budget since the margin allocated for each impairment is not fixed, but it is calculated from a corresponding impairment model. The main limitation of the above overall approach is the trade-off of accuracy with speed. During the implementation of the final step (i.e., budgeting analysis on the worst-case path), in trying to do the network engineering, certain parameters may change. All three steps of the methodology would need to be repeated each time a parameter change occurs increasing the simulation time. In fact, in actually engineering the performance of the network of Fig. 1, as presented above, we run the above three-step procedure with several iterations until the right configuration and parameters as presented in Fig. 3 are derived. Amplifier positioning, gain values, resulting black box noise figure values and dispersion compensator placements were some of the parameters that we varied during this multi-iteration engineering procedure. The parameters presented are the most optimum conditions to the above engineering problem. Fig. 6 presents the final results of the three-step transport layer simulation methodology. The Q-performance of all possible wavelengths for both of the paths examined in Fig. 1 are above the required 8.5 dB (Bit Error Rate $<10^{-12}$). The shape of the curves is due to the dispersion map of the system. It is important to note that Fig. 6 demonstrates that engineering for the above worst-case paths assures that 100% of the paths of the mesh metro network for the typical ILEC can be transparently engineered.

4 Summary

A new top-down simulation methodology for successfully enabling transparent optical networks in the metro environment is presented. A 11 Tb/s ILEC network was engineered based on projected traffic demands for a typical medium size US metropolitan area. The approach combines traffic modeling, network dimensioning, and transport layer performance modeling. The latter is further composed of three main simulation steps: wavelength-domain simulations for network crosstalk analysis, time-domain simulation for determining Q-penalties for pulse propagation effects and finally a Q-budgeting approach that combines the above results for flexible network design and engineering. As a result metro players like

ILECs or CLECs can effectively and quickly engineer transparent networks in the metro environment using simulation methodologies like the above.

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In 1998, he joined Corning Inc. as a senior research scientist at the Photonic Research & Test Center in Somerset, NJ where he worked on design/engineering of customer solutions based on company products. He later became a supervisor leading a team doing next generation product value analysis work and research on advanced fiber optic systems and networks to support development of telecommunication fiber and optical network elements. In summer

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Ioannis Roudas received his B.S. in Physics and an M.S. in Electronics and Radio-engineering from the University of Athens, Greece in 1988 and 1990 respectively, and an M.S. and a Ph.D. degree in coherent optical communication systems from Ecole Nationale Supérieure des Télécommunications, Paris, France in 1991 and 1995, respectively.

During 1995-1998 he was with the Optical Networking Research Department at Bell Communications Research (Bellcore), Red Bank, NJ. During 1999-2002 he was with the Photonic Modeling and Process Engineering Department at Corning Inc., Somerset, NJ. In addition, he taught, as an adjunct professor, the graduate course entitled "Lightwave Systems" at the Electrical Engineering Department of Columbia University during the fall semesters 1997 and 1998.

He participated as a theoretical research scientist in the DARPA-funded MONET (Multiwavelength Optical Networking) project (1995-1998), the NIST-funded PCAD (Photonics Computer-Aided Design) project (1998), the development of the Corning MetroCor™ fiber (1999-2000), and the design of a higher-order polarization-mode dispersion monitor for Corning. He has research experience in the modeling of optical components (direct detection and coherent detection receivers for different modulation formats, multi-stage erbium-doped fiber amplifiers, DFB semiconductor lasers and electro-absorption modulators, servo-controlled attenuators, polarization mode dispersion monitors), transmission effects (distortion due to laser/filter frequency misalignments, coherent optical crosstalk, DFB laser chirp and phase noise, optical power transients), network elements (optical add/drop multiplexers, optical crossconects), metropolitan area network topologies (chain, ring, mesh) and optical network functionalities (protection switching).

He recently joined the Department of Electrical and Computer Engineering at the University of Patras, Greece, as an Associate Professor of Optical Communications. His current research interests concern the modeling and optimal design of the optical transport layer of metropolitan and wide area networks.

He is the author or co-author of more than 40 papers in scientific journals and international conferences and holds two patents. He serves as a reviewer for the IEEE/OSA Journal of Lightwave Technology, the IEEE Photonics Technology Letters and Optics Communications.

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Mark Vaughn is a 1998 graduate of Georgia Institute of Technology, in Atlanta, where he earned a doctorate in Electrical Engineering. His Ph.D. was concentrated on the area of optical subcarrier multiplexed signal processing using semiconductor optical amplifiers.

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Richard E. Wagner received the B.S. and M.S. degrees in mechanical engineering from the Ohio State University in 1969, and the Ph.D. degree in optics from the Optical Sciences Center at the University of Arizona in 1976.

From 1998-2002, Richard E. Wagner was Manager of Optical Network Architecture and Equipment Research at Corning Incorporated, having joined that effort in early 1998. The activity focused on the application of WDM and optical switch technologies for building an optical layer network infrastructure.

Prior to that, he was a Director at Bellcore, where he was the Bellcore project manager of the Multiwavelength Optical Networking (MONET) program since its start in December 1994. The MONET program involved research into national-scale configurable WDM networks. From 1986 until 1994, he was responsible for managing research in heterodyne lightwave systems technology at Bellcore. Before 1986 he was with Bell Laboratories, where he supervised an undersea transmission group that investigated 1300 nm and 1550 nm singlemode lightwave systems. From 1976 to 1980, he was involved with exploratory development of multimode lightwave connectors, switches, and multiplexers.

Dr. Wagner has been the chair of the Photonics Division of the Optical Society of America, and chair of the Optical Networks Technical Group of LEOS. He was associated with organizing the OFC conference for more than 15 years, and has helped to organize more than 20 other international conferences in fiber optics. He has authored or coauthored more than one-hundred-fifty papers and holds four patents in the field of fiber optics.