High-Speed Self-Configuring Networks Based on Cost-Effective Plug-and-Play Optical (PPO) Nodes

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This proposal visualizes a future ad-hoc multi-gigabit network infrastructure connecting a very large number of inexpensive optical nodes. Such nodes will look like today's Fast Ethernet switches, providing however, 2-3 orders of magnitude higher bandwidth, and larger geographical network coverage. Users will connect nodes using already installed fibers by a simple plug-and-play operation.

Once connected, the Plug-and-Play Optical (PPO) nodes will continuously communicate with other nodes for a self-configuration of both network and nodes. An on-board optical micro-lab, advanced transmission models and an intensive signal processing are the key components to build a system that is able to intelligently adjust optical data flows and wavelength selection. The PPO node configuration will account for varying traffic patterns and changing conditions of the optical physical layer, e.g., introduction and removal of PPO nodes, aging of optical components, temperature changes, soft failure of network elements.

The objective of this proposal is to identify the required technologies, to study protocols and algorithms, to develop suitable transmission models, to design and fabricate critical parts of an integrated optical micro-lab that will make the envisioned scenario a reality, and to amalgamate all the achieved results for proving the PPO node concept feasibility. The research efforts will focus on three research areas.

The first area will focus on network control and signaling, which will enable PPO nodes to auto-discover network resources, and provision optical circuits to the end-user rapidly. Efficient protocols and algorithms required for these tasks will be identified. They will utilize the real-time knowledge of optical signal quality, signaling and processing capabilities at the PPO node, dynamic addition and removal of PPO nodes. Algorithms will also detect possible malfunctioning user's interfaces, whose generated optical signal may deteriorate other (correctly functioning) signals, and determine a prompt disconnection of a faulty interface from the network.

The second research area will focus on transmission models that will be used at the PPO nodes for real-time characterization of the optical layer transmission properties and the signal quality. On-board optical sensors will be used to determine various link parameters, e.g., power loss, optical signal-to-noise ratio, fiber dispersion, cross-phase modulation, etc. Based on these parameters, system modeling will generate real-time feedback for the network protocols and algorithms to make prompt decisions as to what optical circuits and rates ought to be used. The complexity and the accuracy of the models will have to be commensurate with the quality of the measured transmission parameters.

The third research area will focus on the realization of integrated optical devices for compact, batch manufactured, low-cost PPO nodes, with built-in sensors. The research will focus on the use of micro-fabrication technologies for the co-integration of refractive gratings, CMOS photo-diode arrays, micro-mirrors, and readout electronics. The study will lead to the fabrication of a micro-OSA that, using a Fabry-Perot Interferometer will enable high-resolution spectra (sub-GHz resolution) analysis. A low-voltage, low-power DSP will ensure the required signal processing after the analog-digital interface and data conversion.

Three demonstrators, one for each area of research, will prove the key functionalities required by the PPO node. Such demonstrators will exploit already existing test-beds and the micro-fabrication facilities available at UTD and The University of Kansas. The combined expertise of a multi-disciplinary team composed of 3 PIs in the USA, and a well-established international collaboration with CPqD, Campinas, Brazil — the largest telecommunication research center in South America — will be leveraged to tackle these challenging tasks. Additional funding is being sought by the PIs to realize a more comprehensive field trial demonstrator of the PPO node concept.

The scientific results of this proposal will support a future scenario in which latest advances in optical technologies will enable end-to-end user's communications in the gigabit per second range. Today's delayed deployment caused by an excessive cost of the optical network infrastructure, complex design, installation and maintenance procedures will be resolved by the PPO node concept. Hopefully, the proposed research will generate new business activities and efficient services.

Section C — Project Description

High-Speed Self-Configuring Networks Based on Cost-Effective Plug-and-Play Optical (PPO) Nodes

1 Motivation and Envisioned Scenario

The latest advances in optics widely demonstrate that today's technologies have the potential to enable end-to-end user's communications in the gigabit transmission range [59, 57]. Some of the advantages of optical networking include the possibility to reduce the electronic processing within the network and to benefit from the degree of transparency, provided by setting up optical circuits, or lightpaths, in wavelength routed networks. However, the deployment of optical networks is mainly delayed by two factors: the excessive cost of the optical node and the highly complex procedures for design, installation, and maintenance of the overall network.

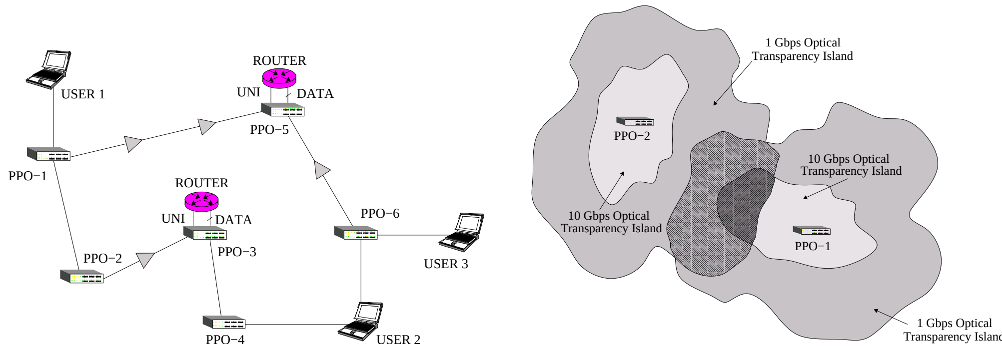
The high cost of an optical node is due to fabrication, packaging and assembly of the numerous discrete components that are required, e.g., wavelength de/multiplexer, switch fabric, and various sensors for optical signal quality monitoring. The network design complexity originates from the fact that a large number of measurements must be performed in the laboratory to make sure that the network planning phase has been correctly performed by trained engineers. These measurements mainly relate to the quality of the optical signals, e.g., optical signal-to-noise ratio (SNR), propagating across the fibers and the optical nodes. (Notice that in conventional (*first generation*) optical networks, the signal propagation is limited within two physically adjacent nodes, which greatly limits the number of measurements that need to be performed.) The network installation is complex, because upon equipment installation, several on-field measurements are required to confirm the proper installation of the equipment. This task involves sending a team of engineers on the field to make sure that the various network elements are running as planned. Network management is complex too, since continuous monitoring of the optical signal quality must be performed to detect malfunctions, and, where possible, to anticipate element failures. In addition to the above burdens, whenever an upgrade is needed in the network, the entire process must be repeated, as newly added nodes affect existing nodes and the way optical circuits are established.

To circumvent the cost and complexity burden of extant optical networks, the PIs of this proposal plan to investigate a novel approach to deploying *ad-hoc* optical networks, that may become viable in a 5 to 10 years time-frame. The enabling component of the proposed approach is a cost-effective, self-configurable, integrated *Plug-and-Play Optical*, or PPO, node.

A PPO node consists of an optical mux/demux and switch fabric for optical circuit switching, an optical sensing micro-lab for signal quality monitoring, a suitable amount of processing capabilities, and low speed service channel interfaces for network management and control. Its cost is contained by: 1) avoiding electronic processing of user's data packets at the PPO node, thanks to the so called *optical transparency* [24, 8], 2) using low speed service channels between PPO nodes and user's interfaces, and 3) including an integrated micro-OSA (Optical Spectrum Analyzer) for optical signal monitoring. Simple real-time transmission models process the measurements produced by the micro-OSA and provide estimation of the transmission rates allowed between clients — e.g., end-users, routers, and other electronic nodes.

Similar to today's Fast Ethernet switches capabilities, ad-hoc optical topology could be easily deployed by connecting a large numbers of PPO nodes, via already existing fibers. Once connected, a PPO node will cooperate with the other already existing nodes, and will efficiently make use of available optical resources, such as fibers and wavelengths, to provide high speed optical circuits to the connected clients.

An example of the envisioned ad-hoc network is shown in Fig. 1(a). In the figure, only a subset of PPO nodes and I/O ports are connected to electronic client nodes. A user can request the creation of a lightpath for transmitting data directly to another user (*single-hop transmission*). Alternatively, a user can request a lightpath to reach a preferred router. With this option, the router will perform electronic forwarding of the received packets toward the intended final destinations (*multi-hop transmission*) and, additionally, can statistically multiplex multiple user's connection requests in a single lightpath. Routers can also request lightpaths to be created to reach other routers or desired end-users. With any of these lightpath creation alternatives, a technique similar to the one used by modem technology is envisioned, in which a lightpath (the equivalent of the phone circuit) is requested, and the transmission rate is selected based on channel quality. Contrary to the user determining the phone number to call, in the envisioned PPO scenario a distributed



(a) PPO node and network concept

(b) Optical transparency island

Figure 1: Proposed network architecture

and automatic procedure determines: 1) which client must connect to which client and 2) which route, wavelength, and transmission rate ought to be used to achieve good performance, e.g., minimize network congestion and blocking probability of user's connection requests. Due to the large number of possible circuits provided by the PPO nodes and the numerous parameters affecting the quality of the optical circuits (e.g., four-wave mixing and polarization mode dispersion to mention a few), the resulting optimization problem is much more complex than the one in the case of modem technology.

But – when the above problem is solved – the design, installation and management of the proposed ad-hoc optical network will be extremely simple due to the fact that PPO nodes have built-in features of auto-discovery, self-configuration, and self-monitoring capabilities. No need for complex network planning, nor engineering team sent to the field to check correct installation of equipment and to monitor network functions is required. Tasks will be automatically performed, using the measured network parameters and the on-board signal processing features, in a cooperative manner by the PPO nodes. As a result, minimal training will be required to install, operate, and maintain such nodes, thus considerably reducing the overall network cost. A large number of PPO nodes will thus be deployed to create ad-hoc access, local area, metropolitan area, and possibly wide area networks.

1.1 PPO Node and Network Functionalities

This section provides a more detailed description of the proposed PPO node and network concept. The envisioned PPO network architecture is based on the assumption that in a 5-10 years time-frame, gigabit Ethernet cards will be inexpensive, following the same cost pattern of today Fast Ethernet. Thus, end-users will have direct access to wavelength channels. These gigabit cards are expected to have tunable capabilities (in transmission and reception), variable bit rate (multi-rate) interfaces, adjustable transmission power, and a dedicated low rate service channel, used for signaling between the network ingress point (the PPO node which is physically connected to the user's card) and the user's card. Similar features are expected to be available at the interfaces of the routers that are connected to PPO nodes. End-users, routers, and other electronic nodes are generally referred to as *clients* in this proposal, as PPO nodes and the optical layer act as a server for them.

Upon request, PPO nodes must provide clients with lightpaths that may span across multiple PPO nodes. Due to various transmission impairments and network status, it might not be always possible to connect two clients using a lightpath at the desired transmission rate. For this reason, the PPO node must first be able to use accurate models of the transmission impairments in order to predict the quality of any given lightpath. In addition, models must take into account the effects that lightpaths sharing the same fiber, on spectrally adjacent wavelengths, may have on optical signal quality.

An exhaustive trial-and-error approach is not practical due to the number of possible lightpaths that grows exponentially with the number of PPO nodes, client nodes and wavelengths. Predicted transmission rates must be verified once the lightpath is created using the micro-OSA available at the PPO nodes. The result of this transmission analysis indicates which clients can be connected, and which transmission rates can be used without significant signal degradation of the lightpath under consideration and of the spectrally adjacent lightpaths.

It is possible to define the *optical transparency island* of a given PPO node as the subset of PPO nodes that can be reached all-optically. Notice that an optical transparency island is individually defined for each PPO node with partial overlaps with other PPO nodes' islands. Its extension is strongly dependent on its transmission rate, as illustrated in Fig. 1(b), and might vary over time due to changes of physical parameters (e.g., temperature) and distribution of existing lightpaths. The PPO node can detect and react to such changes by using and processing the measurements produced by the micro-OSA.

Whenever two clients cannot be connected using a single lightpath due to either transmission impairments, or traffic engineering optimization, end-user's connection requests are fulfilled using a concatenation of routers and lightpaths using multi-hop transmission. To accomplish these various tasks, three modules are required:

- the PPO network (server layer) management and control module,
- the client network management and control module, and
- the micro-OSA module.

1.1.1 PPO Network Management and Control Module

This module is responsible for:

1. setting up, tearing down, and reconfiguring lightpaths to satisfy user requests;
2. advertising and auto-discovering of available resources within the optical transparency island;
3. predicting the effect of transmission impairments using analytical models, e.g., determining if a lightpath is feasible, at what transmission rate, and the impact of a newly created lightpath on already existing lightpaths;
4. monitoring the status of the network, e.g., detecting optical signal degradation of existing lightpaths, possibly malfunctioning user's interfaces, changes of transmission parameters.

PPO nodes can use a service channel on a dedicated control wavelength (e.g., at 1.3 μm outside the amplifier window) to exchange control information with physically adjacent PPO nodes. For cost-effectiveness, the transmission rate of the service channel may be limited, e.g., 100 Mbps. The management and control protocol limits the exchange of control messages (e.g. in the form of IP packets) generated by a PPO node within its optical transparency island. By exchanging control messages, each PPO node maintains two distinct databases. The first database is used to keep track of available resources within the optical transparency island of the PPO node and to self-discover newly added/removed resources. The second database keeps track of the measurements made by the micro-OSA, both locally and at remote PPO nodes and of the information required and generated by the transmission models. Both databases can be updated using extensions of the OSPF protocol. In certain instances, it may be necessary to create temporary dummy lightpaths between PPO nodes to test transmission impairments, e.g., generate the dispersion map, and provide accurate estimates of the optical signal quality.

A client communicates with its adjacent PPO node(s) via a User to Network Interface (UNI) using the service channel. A client requests the creation of a lightpath using the UNI. Upon receiving a request for lightpath, the PPO node solves the routing and wavelength assignment (RWA) problem [58, 63, 38] by using both databases. In addition to solving the conventional RWA problem, the PPO node must determine a set of physical parameters that characterize the profile of the requested lightpath, e.g., range of acceptable transmitted power, transmission rate, maximum acceptable wavelength drift, etc. Transmission models are used by the PPO node to ensure that the profile of the newly created lightpaths conforms to the client's request, without negatively impact already created lightpaths in the network. During the lifetime of the lightpath, the PPO node continuously monitors the signal received from the client to make sure it meets the assigned profile. In the case of violation, the PPO node could, for example, send a disconnect message and release the network resources to other lightpath requests.

1.1.2 Client Network Management and Control Module

This module is responsible for handling end-to-end traffic flows at the electronic layer. Transmission impairments limit the reach of a PPO node, i.e., the size of its optical transparency island. In order to provide clients with connectivity that goes beyond the optical transparency island, multi-hop transmission must be used. In this case, the end-user data traffic is electronically processed by a sequence of routers.

Routers handles client's packets electronically, and can operate at a much finer multiplexing granularity than the wavelength granularity of a lightpath. For example, MPLS [6, 5] can be used to provide traffic engineering at this layer. Routers have a set of input ports which are equipped with Optical Line Terminals (OLT) that convert the incoming optical signal into the electronic domain. Output ports are equipped with tunable lasers that convert electronic signals back into the optical domain.

At the electronic layer, control messages are exchanged using inband signaling, i.e., routers exchange control messages using the available logical links[1]. Being clients, routers communicate with the underlying PPO node through the UNI. Using both the service channel and inband signaling, each router maintains two routing tables. The first one (T1) keeps track of the reserved resources, using extensions of standard IGP protocols [72], such as OSPF. The second routing table (T2) keeps track of the potential logical links (lightpaths) that could be created by the PPO nodes (Fig. 2). If needed, the router requests the underlying PPO node to set up a new lightpath using the UNI. T2 may be updated using two different techniques. The first technique makes use of the UNI toward the PPO node, which provides to the router the list of routers that can be reached within the optical transparency island. The information collected this way is then advertised to other routers using inband signaling over existing lightpaths. The second technique makes use of the dummy lightpaths that are created periodically by the PPO nodes to measure the transmission parameters of the optical layer. While dummy lightpaths are created, the router can exchange control messages with the routers at the other end of the dummy lightpaths.

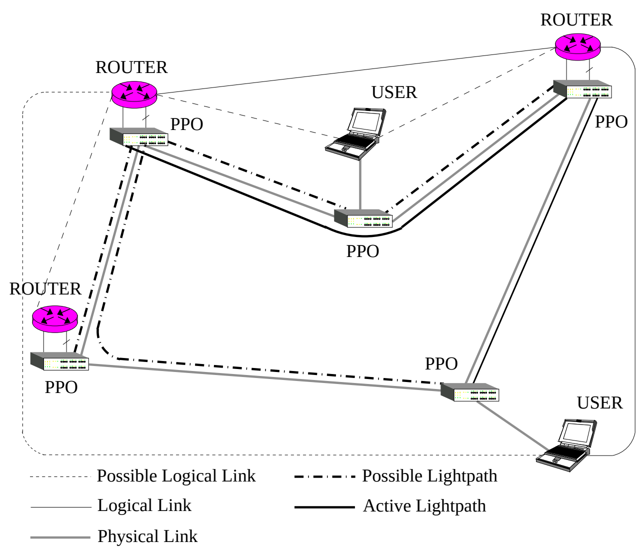


Figure 2: Logical links and potential logical links

A client node, say router R1, has different options to choose from when it attempts to establish a data flow with another client: try to use already existing lightpaths, i.e., use routing table T1 to reach the destination, or create new lightpath(s) using routing table T2. In the latter case, R1 asks the underlying PPO node to create a lightpath to reach the intended destination client. If the PPO node determines that the required connection is possible within its optical transparency island, the new lightpath is created. If such lightpath is not possible, or the allowed transmission rate on such lightpath is not sufficient, R1 must select an intermediate router, say R2, that is within reach of the PPO optical transparency island. R2 repeats the same procedure as R1. The multi-hopping procedure is repeated until the client destination node is reached.

[1]Lightpaths in the optical layer correspond to logical links at the electronic layer.

With the above routing strategies, routers are provided with novel techniques to handle congestion, in addition to the conventional congestion avoidance procedure, e.g., Random Early Discard (RED) strategy. For example, the router can operate locally with the underlying PPO node using the UNI, and request additional bandwidth on the outgoing logical links[2]. Another alternative is to reduce the traffic coming from upstream neighboring routers, using the inband signaling mechanism, and requesting them to create new lightpaths that bypass the congested router.

1.1.3 Micro-OSA Module

This module is responsible for monitoring the quality of the optical circuits, and it consists of a high-resolution integrated Optical Spectrum Analyzer, the electronic interface, the data conversion from analog-to-digital, and a micro-power DSP. The spectrum produced by the micro-OSA is processed by the transmission models to provide meaningful information to the PPO node management and control module.

The micro-OSA accomplishes a number of key monitoring tasks. First, it monitors optical amplifier gain, gain bandwidth, and noise figure, by comparing the spectra of transmitted and received optical signals. Similarly, with the micro-OSA, it is possible to characterize optical fiber loss between PPO nodes, by comparing power levels of transmitted and received signals. The micro-OSA can determine the existing number of wavelengths used at each link, wavelength allocation status on each link, e.g., channel spacing, data rate and transmitted power, equal or unequal channel spacing, and optical signal-to-noise ratio at each wavelength. To provide all these functionalities, the micro-OSA at the PPO node must have sub-GHz resolution. This device can be realized with the same technological steps used for integrated circuits fabrication. Future technologies will enable the growth of thick reflective layers and their carving by anisotropic etching to achieve linear or curvilinear array of micro-needles with thickness (in the hundreds of nanometer range), height (in the tens of micron range), and spacing suitable to realize a dispersive grate, that is capable to operate on a focused laser beam (10 μm). The system includes on the same substrate fixed and mobile mirrors and a linear array or a matrix of integrated photodiodes. It is expected that the entire spectrometer will be as small as 1.5 cm^2, fully integrated with a batch manufacturing methodology. The fabrication cost is expected to be lower than 4$ US. Measures produced by the spectrometer are then elaborated by a microprocessor as indicated by the transmission models. In the foreseen prototype the DSP and the associated memory will be state-of-the-art micro-power product available on the market.

1.2 Expected Advantages of the PPO Node Concept

If proven feasible, the proposed architecture based on PPO nodes will provide a self-configuring solution that continuously determines a cost effective way to employ (optical) network resources throughout the lifetime of the network, i.e., 1) it determines the most cost effective solution by using all-optical transmission and/or O/E/O (through routers) at selected nodes on a per flow basis; 2) it provides dynamic bandwidth provisioning to adjust to traffic changes, i.e., as traffic patterns change, the network can set up new lightpaths, and tear down old ones, thus avoiding the problem of burning wavelengths (fixed reservation of wavelengths); 3) as new PPO nodes and fibers are added to the network, it discovers them automatically, without requiring the manual redesign of the network, similarly to today "plug-and-play" network nodes in LAN technology; 4) it provides a continual and timely monitoring of the signal quality on each optical circuit to inform the control and signaling protocol; 5) it provides a convenient design by integrating optical components and sensors together in the PPO node.

The self-configuration capability of the architecture based on PPO nodes makes it possible to reduce the design, installation, and maintenance costs, because no-human intervention is required to perform such complex tasks. However the success of the deployment of self-configuring networks, highly depends also on the possibility of developing high performance, compact, and easy-to-install PPO nodes.

In conclusion, it is interesting to notice that some similarities between the proposed ad-hoc optical networks and the dynamic nature of ad-hoc wireless networks can be found here. New PPO nodes can be deployed by the user as needed, and connected to existing fiber cables. A user's interface may migrate physically from one PPO node to another. A user's interface may migrate logically from one router to another, by simply requesting a new lightpath. All these unknowns, combined with the complexity of handling optical signals quality at high transmission rates, constitute a challenging open problem that will be tackled by the PIs.

[2] The PPO node can fulfi ll this request by either increasing, if possible, the transmission rate of the outgoing lightpaths or by creating additional lightpaths.

2 Previous work

To the PIs' best knowledge, no previous publication has addressed or studied the proposed PPO node concept. However, a number of papers is available on related subjects. Such published results will form the stepping stones for the research activities of the proposed project. This section provides a short survey of previously published results and state of the art in the fields of optical networking, transmission and optical integrated components.

In optical networking, a number of projects and papers have studied the problem of provisioning resources in WDM networks. The (new) MONET test-bed [57, 2, 3], sponsored by DARPA, carries out experimental testing of advanced optical technology and more generally it explores the intrinsic capabilities and limitations of transparent and reconfigurable optical networks. Experiments include high speed transmission of SONET and non-SONET rates (including Gigabit Ethernet) over optical circuits. Prototypes generated from other parallel efforts [74] are integrated and tested using the MONET test-bed.

The MIT ONRAMP project [59, 27, 26, 28] focuses on novel higher layer protocols that take advantage of the optical layer reconfigurability, huge bandwidth, and transparency. In addition, new technologies for facilitating bandwidth provisioning, protection, and other optical-layer capabilities are studied and implemented in the test-bed that consists of a *feeder ring* architecture.

Protocols, that provide auto-configuration/discovery and traffic engineering capabilities have been proposed and studied. Neighbor discovery and address auto-configuration capabilities have been included in the IPv6 protocol [48, 60]. In addition, the protocol addresses the possibility of tunneling. However, such capabilities are based on a network architecture of routers and terminals, communicating among themselves using inband signaling. The design of control planes for Optical Cross-Connects (OXCs) and in hybrid networks consisting of OXCs and Label Switching Routers (LSRs) is contemplated by the GMPLS protocol [6, 5]. Such protocols do not provide any auto-discovery, nor auto-configuration capability to the OXC. Moreover, both IPv6 and GMPLS do not take into account optical layer transmission impairments.

When the span of the optical circuit is not sufficient to connect the source to the destination node with a single-hop lightpath, traffic demands are transmitted using multiple concatenated optical hops. With the advent of Optical Add-Drop Multiplexers (OADMs) and OXCs the interest of multi-hop network has shifted to the optimal design of multi-hop SONET rings and mesh networks. A large literature is available that studies multi-hop ring designs and good surveys can be found in [56] and in [77]. Multi-hop networks with arbitrary topology, also referred to as mesh, have been the topic of recently published papers: [80, 9] study the problem of optimally design multi-hop mesh networks; [79, 78] focus on network performance in the presence of dynamic allocation of lightpaths.

A common assumption in all these papers is the same transmission rate on every optical circuit. However, [33] shows that the ADM total cost can be reduced in a multi-wavelength ring if single-hub SONET OC-48 rings are combined with SONET OC-12 rings. This design could be considered as a particular case of the multi-rate approach applied to entire rings (as opposed to individual optical circuits). The same concept has been analyzed in more detail in [50].

A considerable amount of results is available in the literature on multi-rate networks [39, 55]. Most of these results are derived for conventional first generation multi-rate networks. An exception is the ongoing effort led by a DARPA-sponsored Telcordia Technologies (previously Bellcore) consortium [74] that has developed Variable Bit Rate Interfaces and Adaptive Rate Line Cards. The transmission rate of these interfaces can be controlled to select the preferred rate between node pairs.

As this list of relevant previous work indicates, most of the published results deal with one aspect of circuit transparency at a time, i.e., multi-rate on multiple rings, or multi-hop and multi-span at a single rate in hierarchical architectures. The study and simulation of the impact of the transmission problems and physical layer performances in the network design are attracting a growing interest in the community [4, 62, 37, 1, 34, 73, 46]. The activities in the IETF groups attest such interest [23]. Paper [62] combines the event-driven simulation of the user's request for an optical circuit with the evaluation of the Bit Error Rate (BER) along the chosen route for the circuit. In order to maintain a satisfactory BER, the blocking probability of the circuit request is higher than the ideal case in which transmission impairments are assumed to be negligible. A similar approach based on the BER evaluation is used in [46]. In this paper regeneration of the (single rate) signal at some intermediate nodes (multi-hop approach) may be required to set up the end-to-end connections that would not be possible otherwise, due to low signal quality. The aim of the algorithm proposed in this paper is to maximize the utilization of transmitters and receivers. Recently, another paper [1] has considered the impact of polarization mode dispersion on the design of all-optical networks.

In optical transmission, system performance evaluation has been an important issue in the telecommunication industry as well as a subject of intense research. So far, the most popular method to evaluate the performance of a WDM optical system is to solve a nonlinear Schrödinger equation using the split-step Fourier method. This numerical simulation automatically takes into account all the nonlinear effects, such as Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), and Four Wave Mixing (FWM). Commercial simulation packages based on split-step Fourier method are also available. However, because of the numerical algorithms involved, a simulation typically takes a few minutes to several days depending on the number of WDM channels, channel spacing and the total simulation bandwidth. It is well known that many processes in an optical communication system are random because of the randomness of the data pattern as well as the random nature of the noise. Each run of a numerical simulation gives only one specific sample of this statistic process. Therefore, the system performance predicted by a numerical simulation is rather qualitative than quantitative. In principle, to precisely evaluate a system performance at the bit error rate level of 10^{-12}, trillions of simulation runs have to be made, which is virtually impossible.

In order to understand the mechanism of various factors that determine optical signal degradation, a number of analytical or quasi-analytical models have been developed. Each model deals with a specific source of degradation [42, 45, 71, 25, 43]. Since distinct analytical models use distinct approximations and have different limitations, combining them into a simple and unified analytical model is not straightforward. Therefore, a unified analytical approximation of optical system performance evaluation is a major part of the transmission study in this proposal.

In the field of integrated optics, different techniques are currently used to build compact optical spectrum analyzers. They are based on Fabry-Perot interferometer scheme or on dispersive elements that spatially spread the signal to its optical spectrum. The most advanced instruments have no moving parts and use a dispersive grating and a photodiode array to measure power versus wavelength. The grating density depends on the wavelength range under analysis and is around 500/mm (2 μm pitch).

Advanced products are portable but too bulky to obtain the foreseen high level of miniaturization. Moreover, they have a limited frequency sensitivity that eventually can be mechanically tuned. They use discrete expensive components and require considerable power consumption in the interface and processing electronics.

The integrated circuits technology trends for the next 10 years will lead to ten of million of transistors integrated on the same chip and, at the same time, to technology capabilities that will permit to integrate optical components, interfaces and signal processing. Having optics and electronics on the same substrate will significantly reduce costs and, for the electronic part, will increase the processing power and will reduce the power consumption.

In summary, a number of technical advances are now available in the field of optics applied to telecommunication and data networks. These advances and related results will be revisited in this proposal and applied to create the foundations for the proposed self-configuring optical network infrastructure based on the PPO node.

3 Proposed Research

This section consists of two parts. The first part describes some initial results obtained by the PIs' research teams. The second part describes the tasks and deliverables of the project.

3.1 Preliminary Results

The preliminary results presented in this section illustrate the nature of the problems that will be addressed in this project. Examples of techniques that may be used to solve such problems are described too.

3.1.1 Advantages of Multi-Hop Networking

This section presents possible cost and performance advantages of designing an optical network architecture based on multi-hop (MH) and multi-rate transmissions. The MH network is compared against first generation (FG) and single-hop (SH) networks, assuming the same physical (mesh) topology and offered traffic load. The network topology consists of 19 nodes, the average link length is 64 km [14].

The comparison is carried out assuming a simplified scenario in which the electronic layer offers fixed traffic multiplexing, e.g., SONET STS-1 tributaries. It is assumed that every node consists of a PPO node connected to a Digital Cross-Connects (DXC). Similarly to what described in Section 1, Optical Line Terminals (OLTs) perform O/E and E/O conversion at the DXC input and output ports, respectively. OLTs provide variable bit rate receivers and transmitters, that can operate between minimum and maximum given rates. Eight nodes are equipped with OLTs that can operate between OC-3 and OC-768, while the remaining nodes are equipped with OLTs that can operate between OC-3 and OC-192.

The network cost is determined by the sum of two factors: the cost associated with the required number of wavelengths, and the cost associated with the required electronics. The wavelength cost is assumed to be linearly proportional to the total wavelength mileage. The electronic cost is assumed to be proportional to the number of OLTs, and their transmission/reception rates. The OLT cost is assumed to double as the transmission/reception rate quadruples.

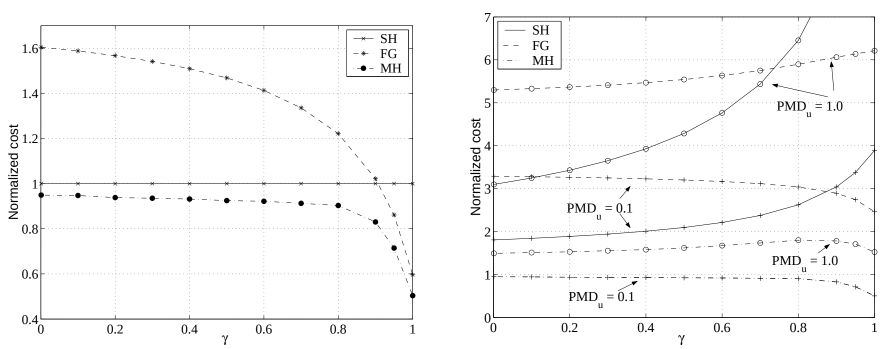
In choosing the span and the rate for each lightpath, the minimization of the wavelength cost does not necessarily lead to the minimization of the OLT cost. Similarly, the minimization of the OLT cost does not necessarily yield minimum wavelength cost. Therefore, the design of a MH mesh with minimum total cost is not a trivial problem and requires an optimal trade-off between the two cost factors. In order to consider all possible wavelength-to-OLT cost ratios, parameter γ [15], is introduced. When $\gamma \rightarrow 1$, the OLT cost is assumed to be negligible. When $\gamma \rightarrow 0$, the wavelength cost is assumed to be negligible. Values of γ in the range $(0, 1)$ represent all possible intermediate wavelength-to-OLT cost ratios.

The cost comparison is carried out in the presence of static traffic (off-line problem). The off-line problem consists of optimally providing network resources in order to fulfill a set of given tributaries, while minimizing the overall network cost.

The performance comparison is carried out in the presence of dynamic traffic (on-line problem). The on-line problem consists of provisioning network resources to newly generated tributaries that are characterized by an arrival rate and a duration interval. The objective is to minimize the blocking probability, i.e., the probability that a tributary cannot be accommodated because of lack of resources.

Both problems are considered in the presence of an ideal optical medium, i.e., in which transmission impairments are negligible, and in the presence of Polarization Mode Dispersion (PMD) as the main transmission impairment. PMD is one of the most serious impairment for transmission rates at 10 Gb/s and above.

The off-line problem can be solved using the Integer Linear Programming (ILP) formulation given in [14]. Since the problem can be demonstrated to be NP-hard, ILP-based solutions can be found only for small size topologies. Thus, efficient algorithmic approaches must be designed that run in polynomial time and yield sub-optimal solutions [14].



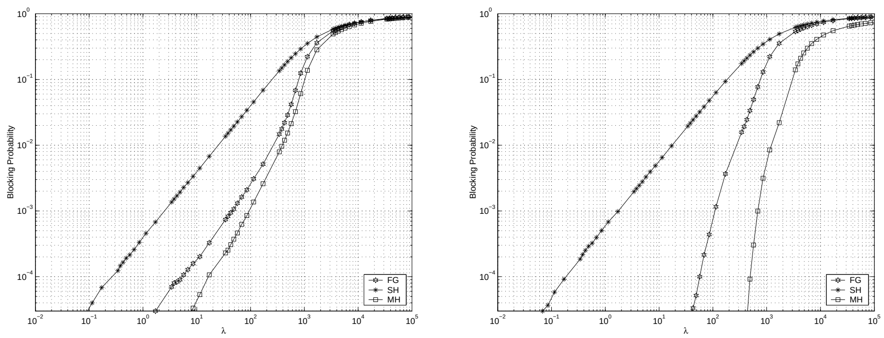
(a) Ideal medium (b) $PMD_u = 0.1, 1.0$ ps/$\sqrt{\text{km}}$

Figure 3: Normalized cost in MH, FG, and SH networks

Fig. 3 reports two sets of curves that plot the network cost versus γ for the three networks (SH, FG, and MH). The network cost is normalized to the SH network cost obtained in the presence of ideal medium. Curves are obtained assuming that each source-destination pair requires 400 STS-1. The network costs are obtained using the algorithmic approach proposed in [14] in the presence of an ideal medium (Fig. 3(a)) and in presence of PMD (Fig. 3(b)) Two values of PMD, $PMD_u = \{0.1, 1\}$ ps/$\sqrt{\text{km}}$, are considered. The first value is within the ITU recommended range. The second value is typical of fibers manufactured and deployed a few years ago. In accordance with the power tolerance recommended by ITU-T G.691, the maximum probability to exceed a 1 dB power penalty due to PMD is set to $4.2 \cdot 10^{-5}$. With such outage probability, the allowed maximum accumulated Differential Group Delay (DGD) is three times its mean value.

Curves reveal that both FG and SH network costs are significantly affected by PMD, even in the presence of fibers with only $PMD_u = 0.1$ ps/$\sqrt{\text{km}}$. The MH network cost is less affected by PMD. The curves also show that the MH network is more cost effective than the FG network, even when the OLT cost is negligible ($\gamma = 1$). The reason for this counter intuitive result can be found by observing that optical transparency enables to bypass lower speed electronics. These results demonstrate the cost-effectiveness of the MH approach applied to static traffic.

The on-line case is studied considering three networks (SH, FG, and MH) that have the same cost. The networks are designed to serve a uniform traffic distribution, using the same optimization algorithm adopted for the off-line case. Newly generated tributaries are accommodated until network resources are available. In this simplified scenario, the optical layer is static, while the electronic layer accommodates the arriving tributaries dynamically. Results are obtained assuming that tributaries are generated according to a uniform traffic distribution. Tributaries are generated according to a Poisson process, and the holding time is exponentially distributed with a mean value $\mu = 1$.



(a) Ideal Medium

(b) $PMD_u = 0.1, 1.0$ ps/$\sqrt{\text{km}}$

Figure 4: Blocking probability of MH, FG, and SH networks

Figures 4(a) and 4(b) plot the blocking probability in the presence of the ideal medium and in presence of PMD impairments, respectively. The plots show a clear advantage, in terms of blocking probability, gained by using the MH network. The advantage is more pronounced in the presence of PMD impairments. An even more significant gain is anticipated by allowing the optical layer to be dynamic as well. This topic will be the subject of further investigation.

3.1.2 Modeling Optical Transmission System Performance

The previous subsection focused on PMD effects and their impact on the design cost and network performance. The results have been obtained under the assumption that the other impairments are negligible, or equivalently, that countermeasures can be taken to make them negligible. Real optical transmission systems are however affected by a number of transmission impairments, including interference effects between signals on different wavelengths. Some models that take these facts into account have been previously studied by one of the PIs.

The impact of Cross Phase Modulation (XPM) in optically amplified WDM systems has been studied in [42]. The proposed analytical model has been widely adopted by industry in the link design. The model is based on a modulated pump and CW probe approximation and it calculates the variance of XPM-induced crosstalk. This model is effective only for NRZ modulation format in which eye closure in the vertical direction is the dominant effect.

Another important source of nonlinear crosstalk in WDM systems is Four-Wave Mixing (FWM), which is sensitive to WDM channel spacing and system dispersion map. In [71], an analytical model has been proposed to represent FWM, and the statistical nature of FWM has been analyzed.

Another nonlinear fiber effect is modulation instability (MI). An analytical model to evaluate the effect of MI on amplified fiber-optical systems is proposed in [43].

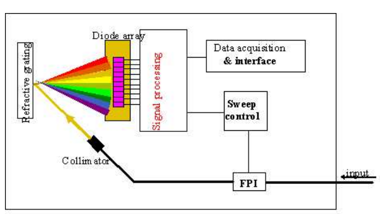
It is worth noting that the different analytical models mentioned above use different approximations. Each approximation has its own assumptions and limitations. Combining various analytical models into a simple and unified analytical transmission performance evaluation package is not straightforward. While at Nortel Networks, one of the co-PIs (Hui) developed an analytical model that combines the effect of noise and waveform distortion in WDM system [44]. Similar methods will have to be developed during this proposed project to combine additional existing models.

The sources which contribute to system performance degradation will be first identified. They will be ranked by decreasing relevance. Based on a good understanding of all the existing analytical models, we will simplify them based on a common system assumption and a unified base of approximation. The results will be combined together to find the overall system performance. Because each source of degradation has its unique statistic nature, special roles will have to be defined when adding them up.

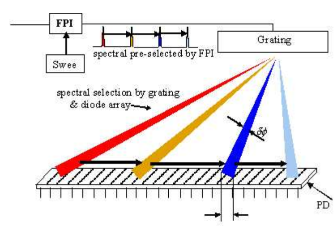
A peculiar aspect of this research area is the fact that the devised models will have to produce real-time results to be used by the PPO node management and control module. Therefore, such models will have to be simple. Their numerical implementation should require contained processing and memory capabilities: these resources at the PPO node are limited and must be available for other tasks too, e.g., RWA algorithm, advertisement protocol, etc. Another innovative aspect of the proposed research here, is the fact that the transmission models will have to be created in such a way that the measurements produced by the high-resolution micro-OSA can be efficiently used to provide useful information to the PPO node management and control module.

3.1.3 High-resolution Optical Spectrum Analyzer

The design of optical link performance monitor is based on an optical spectrum analyzer (OSA). The use of conventional OSAs permits to measure parameters like optical power at each channel, signal wavelengths and optical Signal-to-Noise Ratio (SNR). However, due to the limited bandwidth resolution, a conventional OSA does not give relevant information such as signal data rate, modulation format, and detailed structure of the signal optical spectrum. The availability of high resolution OSAs is extremely important for the automatic self-calibration of optical nodes. This necessity motivated a preliminary research at the University of Kansas on high resolution spectrum analyzers. Experimental preliminary results with a novel OSA structure demonstrated an ultra-high resolution as good as 1 GHz (0.008 nm) and measurement wavelength range of 32 nm. With this resolution, in addition to the monitoring of wavelength, power, and SNR per wavelength channel, the OSA will be able to recognize signal data rate, modulation format (RZ, NRZ or soliton), and to estimate signal distortion penalty due to PMD and chromatic dispersion.



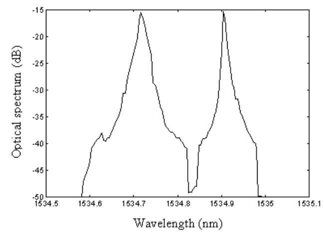
(a) Block diagram



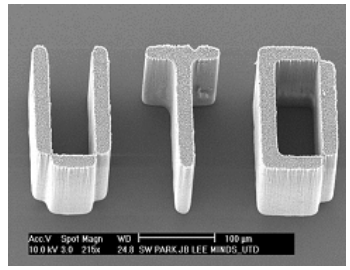
(b) Operation principle

Figure 5: High-resolution OSA

Fig. 5(a) shows the optical configuration of the novel OSA. It is the combination of a scanning Fabry-Perot interferometer (FPI) and a dispersive grating that together with a photodiode array provide both ultra-high spectral resolution and wide measurement bandwidth. The operation principle is illustrated in Fig. 5(b). The high resolution FPI makes a pre-section of the signal optical spectrum, which may be continuous in the wavelength domain, into discrete narrow-band slices. Due to the refractive grating, each wavelength slice is dispersed into a light beam at a certain spatial angle.



(a) Measured optical spectrum



(b) UTD processing capabilities

Figure 6: OSA features

Fig. 6(a) shows a measurement in which the left peak represents a wavelength channel modulated by a 10 Gb/s SONET data stream and can be easily distinguished from a CW optical signal directly received from a tunable laser (right peak).

The ultra-high resolution OSA was made by discrete components and has volume and cost that are far away from what is expected for a future PPO node. In order to achieve the target volume and cost, it is necessary to use micro-fabrication techniques that enable at the same time the co-integration of optical and electrical components and cost-reduction batch manufacturing methodology. The fabrication facilities available at the University of Texas at Dallas will permit the fabrication and experimental tests of many optical microstructures. Fig. 6(b) shows an example of processing capabilities. The figure shows the three letters U, T, and D obtained by anisotropic etching of a 50 μm thick gold layer.

The co-PI, Dr. Maloberti and his co-worker Dr. S. Gregori gained a wide experience in the area of microelectronics and the fabrication of optical sensor arrays [54, 41, 22, 40, 53]. The co-PI participated as general technical coordinator to a European funded Esprit Project (MINOSS) that aimed at the design of various sensor systems, incorporating linear arrays and 2D matrix of CMOS photodiodes. The results of the research activity that included the design of the readout interfaces are presented in many publications [70, 67, 51, 52, 69, 49, 36, 7].

Assuming that the micro-OSA under study will use a linear array of 1024 photodiodes, it will be necessary to define the most suitable charge amplifier and data converter. Even for this issue, the past experience and many experimental implementations will significantly support the research activity of this proposal [66, 68, 35, 65].

3.2 Research Plan and Statement of Work

To efficiently realize the self-configuring optical network architecture proposed by the PIs, the research efforts will focus on three fundamental research areas. The next three subsections describe in more details the deliverables for each research area.

3.2.1 Research Area 1: Network Protocols and Architectures

This research area aims to study the network protocols and to optimize the use of the available network resources in the presence of dynamic traffic demands. A novel aspect that characterizes these tasks is the fact that a cost-effective PPO node is expected to have limited signaling rate, storage capacity, and processing capability. In addition, processing capabilities and memory space will have to be efficiently shared among protocols, algorithms and transmission models, all running at the PPO node.

The following tasks will be carried out:

- **Task 1.1**: Advertisement protocols: in this task the protocol informing the nodes of the available resources is considered. Different advertisement protocols need to be studied for the following cases:

  - Optical layer: PPO node auto-discovery. This advertisement protocol is required at PPO nodes, to gather and to send information to the other PPO nodes within the optical transparency island.
  - Electronic layer: router signaling. This task will produce an efficient way to create the two routing tables that each router must have according to the proposed network architecture (Sec. 1).

  For each case, it is necessary to establish which information has to be advertised and to which nodes the information must be sent to, — information does not need to be sent outside the optical transparency island — how the protocol should operate, how to efficiently store the advertised information, how often advertisement is required, and how often dummy lightpaths must be created to maintain accurate information about transmission impairments.

- **Task 1.2**: Provisioning: in this task, the resource provisioning protocol and algorithms are taken into consideration. Provisioning is required for both the lightpaths and the end-to-end connections and involves:
  - algorithms, needed to optimize the selection of the routing, the transmission rate, the intermediate nodes where O/E/O conversion is performed;
  - protocols, responsible for allocating the required resources.

  Study of efficient algorithms and protocols for resource provisioning that is tailored to the PPO node network is essential to obtaining high performance networks.

- **Task 1.3**: Integration of transmission models and measurements. Advertisement and provisioning protocols, and algorithms will take into account results produced by numerically solving the transmission models (developed in Task 2.1, 2.2, and 2.3) and measurements obtained by the micro-OSA (studied in Research Area 3).
- **Task 1.4**: Scalability of network design and management. A scenario where a large number of PPO nodes is interconnected is anticipated. Scalability of advertisement and provisioning protocols and algorithms will be addressed, with special attention paid to processing and memory capabilities required at the PPO node.
- **Task 1.5**: Implementation of recovery mechanisms in the PPO node network. Concepts developed in a previously funded NSF project (see Section 5) will be applied to the proposed network architecture to provide a recovery mechanism that survives component failures, i.e., both hard and soft failures.
- **Task 1.6**: Network demonstrator. The advertisement and provisioning protocol module will be tested on the OMEGA (Optical Mesh network for Emerging Gigabit Application) test-bed (see Section 5), with emphasis on convergence and synchronization of the proposed protocols and distributed algorithms. The OMEGA test-bed is the result of an ongoing collaboration between UTD and CPqD, Campinas, Brazil. Additional nodes are planned to be added to further expand the test-bed.

3.2.2 Research Area 2: Transmission Models for Optical Signal Quality Estimates

In this research area, each of the sources which contribute to system performance degradation are identified and ranked by priorities. Models will rely on measurements produced by the PPO node micro-OSA.

The specific tasks include:

- **Task 2.1**: Nonlinear crosstalk: Develop or extend simplified analytical models for nonlinear crosstalk in WDM systems such as XPM and FWM. For example, for XPM the analytical model presented in [42] need to be modified for the case of RZ modulation, when time jitter (or equivalently horizontal eye closure) is the dominant effect.
- **Task 2.2**: Dispersion measurements: 1) verify the possibility to characterize chromatic dispersion in fiber links, and locate and characterize dispersion compensation units (usually referred to as dispersion map) by analyzing the relative fading effect of the two RF tones on lightpaths, 2) measure the accumulated dispersion [61, 64] and 3) measure PMD effects, by analyzing the degree-of-polarization (DOP) of the RF tones [47].

- **Task 2.3**: Transmission performance: Develop a simple algorithm for evaluating transmission performance taking into account both linear effect (such as accumulated ASE noise, receiver noise and other noise sources) and nonlinear effect (such as waveform distortion introduced by nonlinear crosstalk and PMD). Each of the sources which contribute to system performance degradation has to be identified and ranked by priorities. Based on a good understanding of all the existing analytical models, we will simplify them based on a common system assumption and a unified base of approximation. The results will be combined together to find the overall system performance. Because each source of degradation has its unique statistic nature, special roles have to be defined when adding them up.

- **Task 2.4**: Validation through numerical simulation. The proposed transmission analytical models will be tested and verified against numerical simulations. The validation of proposed approximations used in the analytical model is fundamental to ensure its accuracy. Full numerical simulation packages are commercially available which solve nonlinear Schrödinger equations using split-step Fourier methods. Although a numerical simulation package cannot be used directly at the PPO node, that requires quick estimates, it can be used as a reference for comparison.

- **Task 2.5**: Demonstrator. An experimental test-bed will be set up to verify our analytical model. When a system is subject to various linear and nonlinear degradations, in addition to formulate individual sources of degradations, it is essential to predict their combined effect on the system performance. Because several sources of system performance degradation are statistical and cannot be directly verified by numerical methods quantitatively, experimental verification is necessary to assure accuracy of the analytical model. The test-bed will be a WDM optical system with multiple in-line optical amplifiers. The data rate will be variable from 100 Mb/s to 10 Gb/s. For long distance transmission experiments, optical recirculating loop will be used. Receiver Q degradation due to various linear and nonlinear effects will be measured and compared with the analytical model. The test-bed will utilize the equipment available at the University of Kansas lightwave communication laboratory and the installed fiber connection from the KU lightwave communication laboratory, Lawrence to north Lawrence and then to Toepka. The round-trip length of this link is approximately 90 km. A small scale field trial will be conducted using this real fiber link.

The success in the development of the simplified analytical model will enable us to conduct fast optimization of the optical network performance through the following processes:

- predict transmission performance for lightpaths between different clients;

- identify the maximize data rate which does not deteriorate the signal quality.

3.2.3 Research Area 3: On-Chip Micro-Optical Spectrum Analyzer for Real-Time Measurements

This research area aims at the following goals:

- verify the feasibility of the required micro-integrated sensors and the readout electronics;

- design and prototype critical parts of the system.

The progress in the microelectronics field, driven by system-on-chip applications, will make available many of the components or functional blocks required by the PPO node. Namely, high-resolution A/D converters, power management circuits, low-power high speed DSP cores, high-density memories. The technology will evolve from a set of specific-applications (CMOS analog, Bipolar, CMOS digital, Power management, Radio BiCMOS, Non Volatile and DRAM memories) into a single technology. The level of business generated by the proposed optical network architecture will not be (at least at the beginning) capable to direct the technology evolution. Therefore, it will be necessary to continuously monitor the evolving scenario, exploit the available components, and design the system architecture that require a minimum custom design (and determine the best cost-benefit). Moreover, the research area will study the post-processing needs for on-board micro-optics, will analyze the impact on the overall reliability, and will examine the associated packaging and testing requirements.

The research activity is divided into the following tasks.

- **Task 3.1**: Dispersive grating. The dispersive grating will be obtained with microelectronics photolithography on the same substrate used for the on-board electronics. Post-process steps will grow the reflective material with a width in the order of ten of microns; anisotropic etching will produce the required patterns, including mirrors to focus the dispersed signal into a linear array of CMOS photodiodes. The micro-spectrometer will be used for:

  - monitoring of the number of wavelength used at each link;
  - monitoring the wavelength allocations at each link (channel spacing and possibly data rate at each wavelength);
  - measuring signal-to-noise ratio at each wavelength;
  - measuring optical amplifier gain, gain bandwidth and noise figure.

  These functions require a significant bandwidth resolution. Therefore, an important part of the research will be devoted to obtain a very large level of dispersion while using a small area.

- **Task 3.2**: Photodiodes array, readout channels, and temperature sensors. This task will address the design, the integration and the experimental verification of a linear array of 1024 photodiodes, and a temperature sensor. The photo-diode pitch will be 4 μm (or less) to ensure the best trade-off between system sensitivity and spectral resolution. The system will include 32 readout channels used to measure the signal of 32 passive pixels. The use of dynamic matching of the readout channels and digital correction techniques will minimize the possible fixed-pattern noise caused by the electronic section.

- **Task 3.3**: Data Conversion and Signal Processing. The aim of this task is to specify the signal processing needs and identify the proper architecture and functional cells necessary for the implementation. Specific interfaces between the readout channels and data-converter(s) will be outlined.

- **Task 3.4**: OSA demonstrator. In order to prove the feasibility of the integrated optics and sensor module, a micro-board will be realized including a custom chip for photo-detection and readout channels, a dispersive grating and commercial parts to prove the specific solutions resulting from this project and provide the interface with the laboratory measurement equipment. The demonstrator will allow the characterization of single blocks (photodiodes array, readout channels, ...) and of the complete system with different signal processing algorithms, eventually implemented by an external microprocessor.

3.2.4 Field Trial Demonstrator

The PIs, in conjunction with Dr. Alberto Paradisi, of CPqD, Campinas, Brazil, plan to further demonstrate the advantages of the proposed PPO node concept and self-configuring optical network by means of a field trial. Additional funding will be required for this last task, that is not included in the current NSF proposal.

A promising opportunity is the experimental environment provided by the National Brazilian Optical Internet project, called Giga. The aim of the Giga project, which will start by the end of 2002, is to establish a field trial fiber optic network between Campinas, Sao Paulo and Rio de Janeiro. Such network will be used for experimentation and research, as well as for business and educational services. This initiative pulls together researchers of various universities, R&D centers, and companies. The objective is to create a shared field trial which would not be affordable for a single participant. The field trial, firmly based on the most advanced technology available, is of fundamental importance to allow testing and experimenting, steps that are necessary for the technological development of the Country. The field trial will be used to carry out research on optical networking technologies and next-generation-networks, including full IP-over-WDM integration, use of Gigabit Ethernet, dynamic and automated provisioning and restoration at the optical layer. The physical size of the network (a few hundreds kilometers) will enable the participants to develop experimental solutions for long distance interconnection, using channel rates that range from 2.5 to 40 Gbps.

It is expected that by using such field trial, it will be possible to find possible deficiencies of the PPO node demonstrators developed in the laboratory, and find appropriate solutions that will circumvent them.

3.2.5 Project Coordination

The research activities in the three areas will be coordinated by the PI with the help of Dr. Isabella Cerutti, who will participate in the project as a Post-Doctoral Fellow. Three meetings will be organized each year in which personnel working in the three areas will present results and jointly plan future research activities. Weekly interaction among the three USA teams and the CPqD team in Brazil will be possible using conference calls. Similar ways of interaction have been used in the past with successful results and joint publications [29, 16, **?**, **?**].

4 Expected Impact and Dissemination Plan

The multi-disciplinary nature of the proposed study has the potential to reveal unexpected, and perhaps controversial results similar to the one illustrated in the proposal (see Section 3.1). The transmission models, network optimization techniques, and software modules that will be identified, designed, and developed in the course of the proposed study will provide valuable instruments to practitioners who will design optical networks in the years to come. The prototyping of the micro-Optical Spectrum Analyzer will represent a valuable benchmark for assessing the ability to create compact and cost-effective sensors that are required at the PPO and other optical network nodes. If proven viable, the PPO node concept will offer a new way to design high speed network in the access, metro, and perhaps even wide areas.

Results originating from this research effort will be made available to the community by means of presentations at international conferences and symposia, Lab open-house visits offered to telecom industry local to the participating Universities (which includes most of the manufactures and some of the major service providers in the USA), and publications in prestigious technical journals and magazines.

Finally, the realization of the three demonstrators will provide an hands-on environment for graduate and undergraduate students who will have the opportunity to work on state-of-the-art networking software, transmission equipment, and integrated circuit design. The collaboration with the CPqD in Brazil will not only bring state-of-the-art modeling of the Optical Layer to the project, it will also expose students to international collaborative work which will require planning and coordination between geographically distant groups: skills that are becoming increasingly important in today's globalized economy.

5 Previous NSF Work

One NSF project, currently funded at UTD, entitled Differentiated Reliability (DiR) in Multi-Layer Optical Networks, started on 01/01/01. With this project, introduced by one of the PIs, the concept of differentiated Reliability, or DiR for short, is introduced in high speed optical networks. The most relevant publications resulting from the award are [19, 11, 18, 32, 75, 29, 76, 21, 12, 30, 13, 10, 31, 17, 20]. The project is briefly described next. Current networks typically offer two degrees of service reliability: full (100%) protection (e.g., in presence of a single fault in the network) and no (0%) protection. This reflects the historical duality that has its roots in the once divided telephone and data environments, in which the circuit oriented service required protection, i.e., provisioning readily available spare resources to replace working resources in case of fault, while the datagram-oriented service relied upon restoration, i.e., on dynamic search for and reallocation of affected resources via such actions as routing table updates. The current trend, however, is gradually driving the design of networks toward a unified solution that will support, together with the traditional voice and data services, a variety of novel multimedia applications. The problem of designing cost effective multi-layer network architectures that are capable of providing various reliability degrees (as opposed to 0% and 100% only), as required by the applications, is addressed in this NSF project. The concept of Differentiated Reliability (DiR) is for the first time formally introduced and applied to provide multiple reliability degrees (classes) in the same layer using a common protection mechanism, e.g., path switching. According to the DiR concept, each connection in the layer under consideration is assigned a minimum reliability degree, defined as the probability that the connection is available at any given time. The overall reliability degree chosen for a given connection is determined by the application requirements. In a multi-layer network, the lower layer can thus provide the above layers with the desired reliability degree, transparently from the actual network topology, constraints, device technology, etc. The cost of the connection depends on the chosen reliability degree, with a variety of options offered by DiR. The NSF DiR grant was leveraged by the PI to launch an international collaboration with the Brazilian CPqD and produce a network demonstrator, called the OMEGA test-bed. The OMEGA test-bed consists of 5 nodes, interconnected to form an arbitrary mesh, that run DiR protocols to ensure the desired degree of reliability [29, **?**].

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