CROSS-LAYER, DYNAMIC NETWORK ORCHESTRATION, LEVERAGING SOFTWARE-DEFINED OPTICAL PERFORMANCE MONITORS

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Abstract

The coherent revolution has signalled in a new era for optical networks. Flexible transceivers (TRx) able to adapt a wide range of transport layer parameters such as modulation format, symbol rate, center wavelength, forward error correction (FEC), etc., are the key enabling components that will finally deliver on the promise of dynamic network operation. With flexibility comes the potential for a more optimized network, leading, in turn, to increased network efficiency and capacity. To be subject to optimization, an optical network has to first be observable, and this is what the ORCHESTRA project aims to introduce. Physical layer status monitoring with an unprecedented level of detail, enabled by the digital signal processing (DSP) in the deployed digital coherent receivers that will function as software-defined optical performance monitors (soft-OPMs). Novel OPM algorithms will be developed and combined with a novel hierarchical monitoring plane, cross-layer optimization algorithms and active-control functionalities. ORCHESTRA's vision is to close the control loop, enabling true network dynamicity and unprecedented network efficiency.

1. Introduction

High rate optical transmission with coherent detection has emerged as the most promising approach toward addressing the challenges arising from the explosive and continuous growth of Internet traffic. Multi-rate, multi-flow optical interfaces are under development to overcome the capacity limit of fixed grid dense wavelength division multiplexed (DWDM) networks, allowing more efficient use of the optical spectrum. Elastic optical networks with configurable multi-carrier optical super-channels and flexible optical nodes are being proposed as a mean to improve network scalability, flexibility and end-to-end performance of optical connections [1][2].

Taking for example an optical network that serves as the backhaul to a number of access providers, fully dynamic networking technologies will be able to support the gradual expansion of end-user line-rates (or end-user coverage) by means of flexible connections whose line-rates increase in an adaptable manner, and with fine granularity. In such a scenario, the network may have to cope with the issue of overcoming a transmission-reach limit without introducing regeneration, or with the issue of a capacity crunch towards a particular destination that is already provisioned with several randomly allocated legacy channels.

Optimization processes are therefore needed to avoid waste of resources and deployment on new massive or unnecessary investment [3]. These optimization processes involve also traditional provisioning in legacy networks. Often deployed 3R regenerators or high performance systems are not strictly necessary at the time and under the conditions revealed during the set-up. Abundant operating margins are added beyond what is required for a given optical reach in order to avoid to need for future interventions over data channels affected by component aging, polarization-dependent loss (PDL), unpredictable degradation due to non-linear interference (NLI) from neighbouring channels, or other events (e.g. maintenance operations during the channel lifetime).

The combination of flexible TRxs, frequent software-defined performance monitoring, and an efficient mechanism for control plane reaction allows for the adaptation of physical link parameters (e.g. modulation format, FEC, or even the path) in order to maintain the required signal quality at any given moment during the lifetime of the channel, in the face of varying impairments [4]. Such an approach yields two important benefits. Firstly, operating margins can be significantly reduced from the current paradigm where they are considered at the Beginning of Life (BoL), since the impairments are measured in real-time and their varying effects on signal quality known; optical channels can therefore be operated near the 'zero margin' regime, with significant network efficiency improvements and associated savings in cost [5]. As much as 25% spectrum efficiency and 20% lower cost was forecast to be achieved by 2024, using a flexible network simulation and near-zero margins in [6]. Secondly, it is possible to monitor degradations due to, for example, component aging. Rather than immediately replace equipment or install new regenerators along a path to recover a channel that no longer meets the required quality of transport (QoT), the control plane may reduce the modulation format or change the symbol rate to reduce the required optical signal-to-noise ratio (OSNR) and avert a hard failure, therefore prolonging the life of the channel; new equipment need only be bought and installed much later on, when existing components have further degraded to the point where they can no longer be compensated by link parameter changes.

However, before an optical network can be subject to any kind of optimization, it first has to be observable. Coherent interfaces and reconfigurable optical photonic nodes have the possibility of reporting a huge amount of data related to the physical links; these data, however, are currently not fully exploited. Dealing with the amount of data produced by the DSP-based impairment monitors and reacting appropriately, poses a huge challenge for current control and monitoring infrastructure, since a central-management approach is normally adopted. The amount of data can overwhelm the network controller, and the monitoring functionality envisaged by ORCHESTRA cannot be adequately supported in a cost-effective and scalable way. To deal with these limitations we propose a new, hierarchical control and monitoring architecture that relies on the information provided almost for free by the coherent transceivers, which are operated as software-defined multi-impairment optical performance monitors (soft-OPM).

2. General Concept and Vision: the ORCHESTRA Architecture

ORCHESTRA is a dynamically controlled and managed optical network that relies on information provided by coherent optical interfaces (Figure 1). It is aimed at core and backbone optical networks, where high capacity DWDM systems are employed and coherent detection is adopted; however, exploitation of ORCHESTRA paradigm could also be found in future metro networks using sample coherent line-cards as soft optical monitors, also for low rate and low cost direct detection interfaces.

Currently, hardware monitors (mainly providing power, chromatic dispersion (CD), differential group delay (DGD) and Q^2 values) are used in coherent WDM line-cards for failure and fault recovery purposes. Obtaining accurate, real-time physical layer monitoring information will facilitate correlation analysis between different measures.

In addition to algorithms for measurement and mitigation of chromatic and polarization mode dispersion (PMD), ORCHESTRA will work on OSNR, and self-phase modulation (SPM) monitoring algorithms, and will take on the challenge of estimating inter-channel linear and nonlinear effects such as cross-phase modulation (XPM) and crosstalk. Emphasis will be placed on developing DSP schemes that are hardware-efficient, to minimize node controller computation load and power consumption. The latter will also be achieved using a modular implementation approach. The control and monitoring plane will be able to make efficient use of hardware resources by engaging and disengaging impairment monitoring and mitigation functional blocks of the transceivers, as dictated by changing conditions and network-wide operational goals (i.e. trading off estimation accuracy vs energy efficiency).

It will also enable, through cross-layer optimization algorithms, the interaction among different entities, such as bandwidth variable transponders, optical amplifiers, and flex-grid colourless and directionless ROADMs. FEC coding gain, Raman pump power, super-channel spectral width, could all be adapted to network needs by predicting the quality of service (QoS) of new connections (in case of new provisioning), and become self-reacting (self-adjusting, self-organizing and self-healing) in case of degradation, faults and congestion [7].

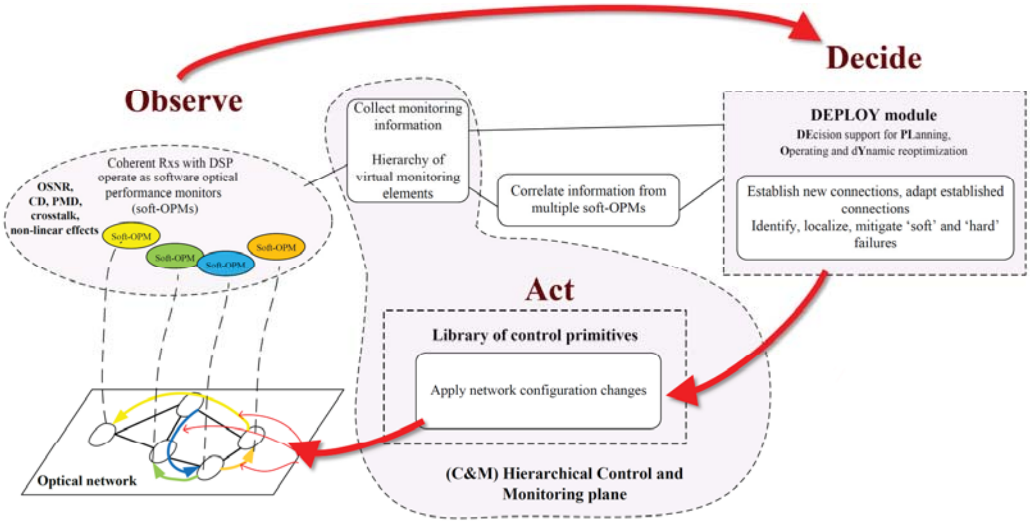

Figure 1. ORCHESTRA's Observe-Decide-Act loop enabling observability, dynamicity and unprecedented efficiency.

3. A hierarchical monitoring control and management plane

In ORCHESTRA, the control plane is organized as a hierarchy of virtual monitoring entities (Figure 2). The virtual entities at the bottom of the hierarchy (leaves) correspond to individual light-paths, while entities at higher levels include ingress nodes, nodes corresponding to regions, and others, which are related to several (subsets of) light-paths.

The operations, administration and management (OAM) handler will enable effective processing of monitoring information (filtering, correlation) and fault management, avoiding bottleneck issues related to centralized approaches. Active control plane functions will be organized in a library of control primitives that will be enforced at the different levels of the hierarchy by the virtual monitoring entities. By appropriate choice of the best primitive within the library, solutions are employed at a local level; therefore, single connection's parameters and properties are adjusted and escalate, following the hierarchical structure, to include multi–connection actions in a more global manner, keeping the complexity and the intervention to the network as low as possible and avoiding overwhelming the central network controller.

The hierarchy's root is the central Application Based Network Operations (ABNO) controller under which all lightpaths in the network reside [6]. Each monitoring virtual entity can take configuration decisions for all the light-paths under it in the hierarchy. The decisions pertain to several control-dimensions, and in particular: (i) transmission configuration parameters, such as the modulation format, the baudrate, the FEC, filter guardbands, (ii) resource allocation parameters, such as the path, the spectrum and the regenerators used.

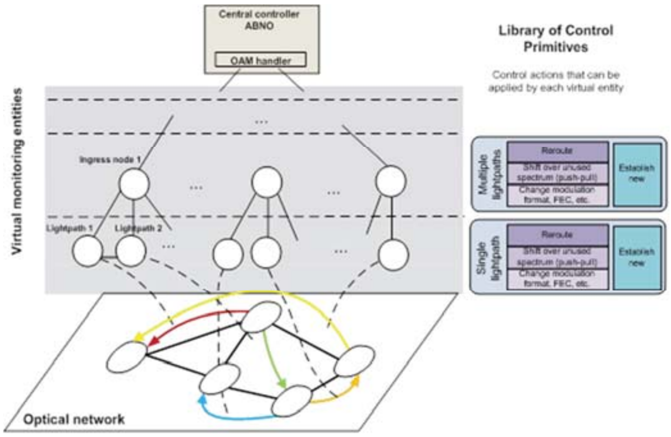

Figure 2: ORCHESTRA's hierarchical control and monitoring (C&M) infrastructure

The hierarchical control plane will handle various types of tasks, such as establishing a new connection, adjusting the transmission rate, or resolving performance deterioration alarms, handling failures of links or nodes. Depending on the specific task the control plane will follow certain procedures to solve the problem and optimize the network, interacting in various ways with the physical layer and the soft-OPMs.

According to the hierarchal structure the control plane starts by running procedures at a leaf node, i.e., taking local decisions about the transmission configuration of the connection that is involved. In a second step and in case the problem is not resolved or the network is not effectively optimized, the problem is handled over to a higher level where actions on more light-paths are allowed: the problem of passing control to higher-level entities continues until the problem is remedied, with the network controller being the final level that can interact with all connections.

4. Dynamic optimization procedures and use-cases

The introduction of optical flexible networking is prompting the emergence of new types of optimization problems, given the dynamicity and flexibility of the networking infrastructure and the support of sub-wavelength granularity and grooming at the optical domain (via multi-flow transceivers). However, the algorithms designed up till now completely neglect the physical layer or, in the best case, are based on worst-case physical layer estimates and gross margins: interference effects, full load and aging of equipment are two typical issues for which worst-case assumptions are applied.

Cross-layer optimization is the key to unleashing the full potential of flexible transceivers. Previous studies in WDM networks demonstrate that cross-layer optimization can reduce the number of wavelengths required in a WDM network by 10% [7], while even higher spectrum savings of up to 60% were reported for flex-grid case [8].

ORCHESTRA aims to achieve true cross-layer optimization enabling the interaction with the physical layer to obtain any parameter of interest with high accuracy. ORCHESTRA's advanced cross-layer optimization functions will be compiled in a library module called the Decision support for PLanning, Operating and dYnamic reoptimization (DEPLOY). True cross-layer optimization lowers the margins of the transceivers, enabling them to use their capabilities to the fullest extent, from day one, to end of life.

In fact, systems upgrade is not always an "all in one" process. The upgrade process may begin with a single links/node and further progress can be deferred during particular events (such as the Olympic Games, the Milan Expo, etc). In such cases, a failure which is facilitated by the upgrade itself, can cause huge damage in terms of data loss or brand value. This can potentially lead to a network that, for a certain period of time (longer than one night), is provisioned with "hybrid" optical paths, i.e. composed of links adopting different technologies. Clearly, this intermediate and rare situation can benefit from the impairment monitoring and fast network reaction capability of the ORCHESTRA mechanism.

"Hybrid" path are also defined as those crossing different network domains. This could refer to the case of a single operator's network employing equipment from multiple vendors (multi-vendor domains), or the case of alien wavelengths in a multi-operator/multi-vendor domain.

Typically, optical domains are islands where everything is managed and controlled by a single operator. Enabling the direct access of the domain to clients is not widely followed, since it opens the back door to the outside world. The former case is usually dealt by OTN transparent framing. Some limited digital performance monitoring is embedded in OTN but is not enough to cope with multi-vendor domains of different sizes, as in the scenario shown in Figure 3.

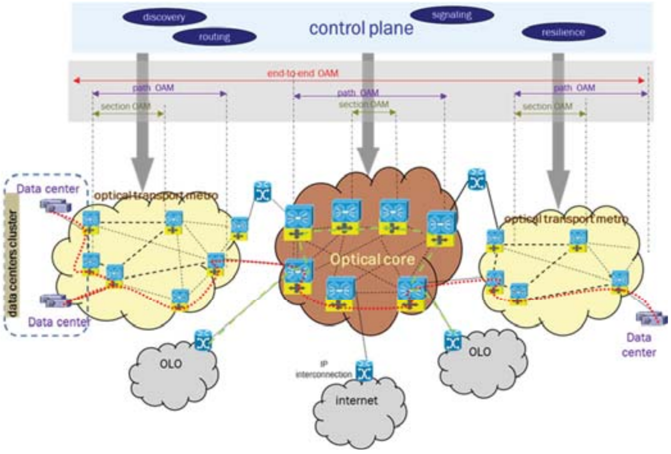

Figure 3. Illustrating hybrid optical paths composed of different technologies in a multi-domain environment. Domains shown include metro, core, Other Licensed Operators (OLOs), and data center clusters.

The friendly light-paths (i.e those of the network operator) can be affected by any technological/physical misalignment of the alien light-paths (i.e those coming from other operators domains). It is challenging for the alien operator to ensure that its wavelengths will have sufficiently good QoT/QoS over an unknown domain, as well as for the actual operator to provide such guarantees unless it has perfect knowledge of the transmission parameters of the alien channels. The issue has been compounded with recent advancements, where connections can use different modulation formats, and where the spectrum gap between optical channels is getting smaller with the adoption of flex-grid technology; dynamic provisioning of alien channels may therefore looks like an unfavourable feature. However, the potential advantages offered by successful handling of alien wavelengths make them an exciting challenge for operators to take on: they enable the sharing of equipment and resources among operators, allowing for the emergence of new business models similar to those found in wireless networks; they offer increased revenues, increased reliability and service speed across networks. ORCHESTRA aims to leverage its advanced monitoring capabilities to provide efficient solutions to a number of quality of transmission issues arising when dealing with alien wavelengths. By correlating impairment information from friendly (known) light-paths through the use of algorithms such as network kriging, it is possible to estimate the QoT of alien channels which are not being sensed by the soft-OPMs. Therefore, the operator can make appropriate adjustments to its network to ensure the alien QoS that has been agreed upon is maintained.

5. Conclusions

ORCHESTRA relies on information provided by coherent transceivers that can be extended, almost for free, to operate as software defined optical performance monitors (soft-OPMs). Novel advanced DSP algorithms for real-time multi-impairment monitoring will be developed and combined with a novel hierarchical monitoring plane to handle monitoring information in an efficient and scalable manner. Impairment information from multiple soft-OPMs will be correlated, to provide an even better understanding of the physical layer. The advanced monitoring functions used in optimization procedures will enable true cross-layer optimization, yielding unprecedented network efficiency and higher network availability.

Acknowledgements

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