Juniper ADVA Packet Optical Convergence

Reducing total cost of ownership in de-layered networks

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Executive Summary

Many enterprises and service providers are re-architecting the way they build their networks and asking for a converged architecture, which includes IP/MPLS elements and support for circuit switching and metro/long-haul dense wavelength-division multiplexing (DWDM). This converged solution enables optimal wavelength utilization for different packet and legacy services, as well as easing operations through multilayer integration.

Packet optical convergence ingredients are:

- Data plane integration, where colored optical line interfaces are moved from a separate transport shelf into the router, thus enabling CapEx savings by eliminating grey interfaces, transponder boards, and shelves; and OpEx savings on power consumption and footprint.
- Network management plane integration for end-to-end service provisioning and performance/alarm management of both packet and transport layer. Virtual integration of the router interfaces into the transport Network Management System (NMS) allows management in an identical way as for traditional external optical interfaces.
- Control plane integration, to enable multivendor networking scenarios that can be operated in a homogeneous manner across different packet-forwarding technologies. This provides the foundation for agile traffic engineering using a Path Computation Element (PCE) embedded in a software-defined networking (SDN) architecture.

This paper discusses packet optical market drivers, solutions, and the three areas of convergence in detail.

Introduction

Service provider infrastructure has changed significantly over the last 10-15 years. The three distinct network layers—packet, circuit switching, and optical transport—have evolved towards a model where only two layers remain in the majority of networks: IP packets (routers) being transported over wavelength-division multiplexing (WDM) (optical transport). Circuit switching has either been removed entirely as packet traffic has become the dominant traffic type, or its function has been subsumed into optical transport network (OTN) switching embedded into optical transport systems.

Today, the optical equipment market is worth an estimated $12.2 billion according to Infonetics Research, with the WDM segment, in particular, showing strong growth of some 11% mainly driven by the rise in spending on 100 Gbps technology.

Infonetics Research also forecasts that the service provider router and switch market will grow at a 7% CAGR from 2012 to 2017, when it will reach $20.2 billion. Again, much of this growth will be driven by the shift to using 100GbE packet ports on routers. "Operators expect 100GbE ports to grow from 5% of all their 10/40/100GbE router port purchases in 2013 to 30% in 2015."[1]

These two major service provider equipment markets are about to undergo further fundamental change as the two remaining network layers which they serve, IP and optical transport, converge over time to form a single homogeneous layer. The timing and rate of this convergence will vary depending on customer technical evaluation, customer organization realignment, and business adoption of new cloud-based services. Due to these and many other factors, the core backbone is most likely to be first to experience this transformation before it moves into access and metro aggregation layers.

Packet optical converged solutions have been an interesting topic for enterprises and service providers for a long time. However, there have been many reasons for a limited adoption of packet optical so far:

- Core router platforms are typically over engineered with full IP features. When these are used for applications that mainly only require MPLS, a high capital and operating expenditure (CapEx and OpEx) result.
- In the last 10 years, many overprovisioned 10 Gbps transport infrastructures have been deployed. Actual traffic growth has lagged the capacity of such systems for a number of years, with the consequence that the industry tried first to maximize as much as possible of this investment, thus slowing the introduction of new architectures.
- IP/data and transport teams and processes are still operating in separate silos in many enterprise and service provider organizations.

Transport and router vendors started a couple of years ago to develop integrated router and optical transport solutions for metro deployments and to redesign their core offerings, optimizing them for MPLS and high scalability/performance, while 100 Gbps dual polarization quadrature phase shift keying (DP-QPSK) coherent technology started to be demonstrated in different field trials.

[1]Source: Infonetics Research, Dec 2013

Meanwhile, enterprises and service providers started facing two conflicting trends. First, there has been a dramatic traffic increase due to the explosion of data services and video, reducing significantly the spare capacity in the deployed networks and making it necessary to introduce new routing/switching and optical network technology in the coming years to satisfy projected traffic demand. On the other hand, enterprises and service providers are experiencing a need to reduce their OpEx cost, in particular the effort needed to manage complex multilayer, multivendor networks. To simultaneously satisfy these two trends, future points of presence (POPs) need to integrate multiple routing/switching and transport functionalities while also providing a simple and automated way to manage the network.

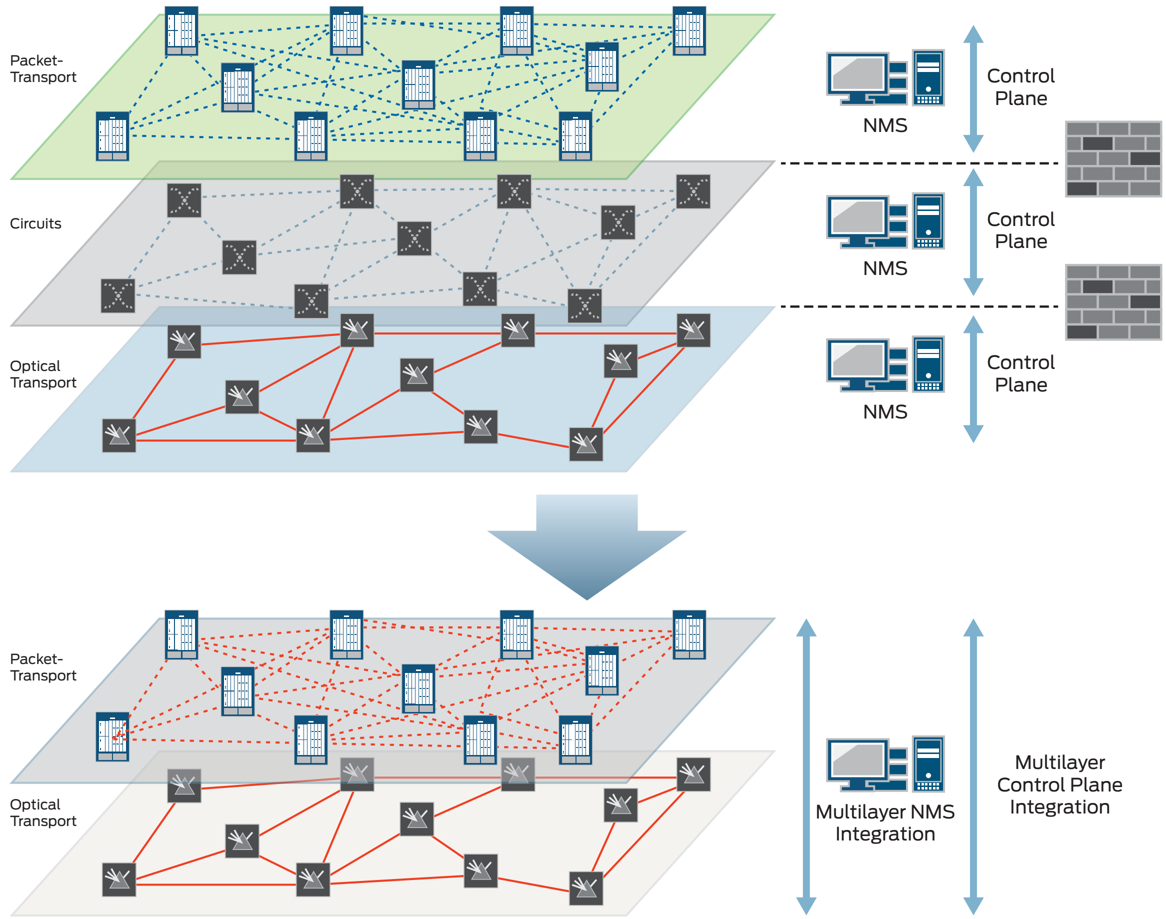

Figure 1: Multilayer integration

As a consequence, many enterprises and service providers are re-architecting the way they are building the network, and they are asking for a converged architecture, which includes both IP/MPLS elements and a metro/long-haul optical DWDM layer. This converged solution enables optimal wavelength utilization for different packet and legacy services. Moreover, it will enable a multilayer control plane and NMS, leading to a powerful multilayer management solution to ease provisioning, alarm correlation, and traffic engineering.

In summary, there is a clear trend pushed by many enterprises and service providers to overcome the traditional packet/transport separation by integrating multiple disparate layers and functionalities. However, there will be various routes to converged network-layer architectures depending on legacy network situations, organizational structures, traffic profiles, and processes.

Packet Optical Convergence

Juniper Networks and ADVA Optical Networking have developed a packet optical solution which is exploiting three convergence areas.

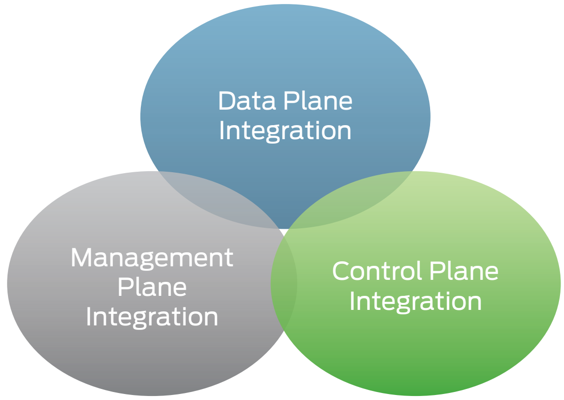

Figure 2: Juniper Networks and Adva packet optical convergence integration points

It should be noted that all three areas could be separately applied and are independent from each other to a certain extent. For example, the benefits of control plane integration could be leveraged with or without date plane integration. Or data plane integration could be used without an integrated network management solution.

Data Plane Integration

The integration of DWDM optical interfaces on both core and edge routers provides attractive CapEx savings compared to the traditional architecture using grey interfaces and dedicated DWDM transponders that are part of a separate transport system. The traditional DWDM transponder-based approach requires two grey short reach client optics in addition to the optics for the DWDM line side, one on the router and another one on the client side of the transport transponder. For an end-to-end connection, this adds a total of four additional optical interfaces in the transmission path. In addition, the transponder-based approach requires additional shelves with the associated power supplies, controllers, cooling fans, etc… to accommodate the supplementary transponder cards. Integration of the DWDM optics into the router, therefore, saves this additional capital expense. The integration of optics in the router also provides an additional level of operating expense savings, including a reduced footprint (by saving external transponder shelves) as well as reduced power consumption. Finally, reducing the number of optical components in the transmission path makes for easier troubleshooting and increases the overall reliability of the transmission link.

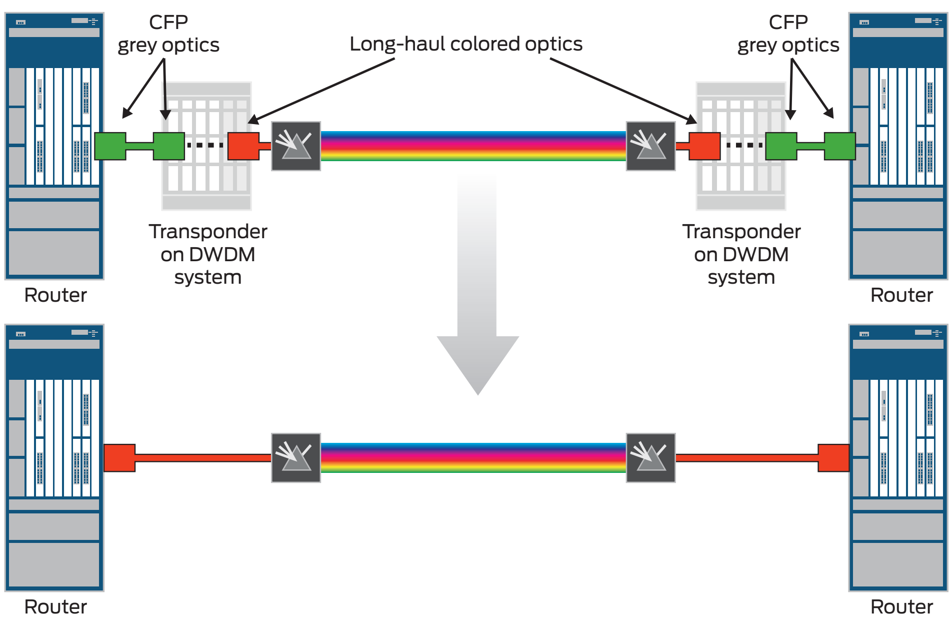

Figure 3: CapEx savings through packet optical integration

However, packet optical integration is about much more than just physical integration of the optical interfaces. The elimination of intermediate network management layers reduces operational complexity because the network design and provisioning processes are simplified. The combination of integrated network management and an interoperable control plane allow for improved optimization of the network in the multilayer design process, providing visibility into both the MPLS and optical layers and the possibility for joint optimization of both layers. This results in cost and performance optimized networks, faster service provisioning, and hence revenue generation.

Figure 4: 100GbE DWDM interface PIC for PTX Series Packet Transport Routers

Colored interface integration into routers can take advantage of the tremendous progress in miniaturization and commoditization of DWDM that has happened over the last couple of years. Optical 100Gbps DWDM interfaces make use of single carrier DP-QPSK modulation. This DP-QPSK modulation scheme is aligned to the Optical Internetworking Forum (OIF) implementation agreements for 100Gbps transceivers, which have established this modulation scheme as the de facto single technology of choice for long-haul 100Gbps transport across the industry. As 100Gbps DWDM optics use coherent transmission with digital signal processing (DSP) for compensation of chromatic and polarization mode dispersion (PMD), DWDM networks are becoming significantly easier to design and operate. 100Gbps coherent technology, therefore, makes it much easier to transport wavelengths from external sources such as routers over an optical line system while maintaining deterministic behavior and properties identical to native 100Gbps transponders, if those are being used.

Using state-of-the-art soft-decision forward error correction (SD-FEC), 100Gbps DP-QPSK interfaces in the router can be deployed on ultra long-haul transport links with a feasible transmission distance of 2,000 km and more over good fiber infrastructure. This requires the use of an FEC overhead of approximately 20%, which translates into a gross bit rate of around 128 Gbps (this also includes Ethernet and OTN framing overheads). 100Gbps DP-QPSK modulation encodes information in both the optical signal phase through quaternary phase shift keying, and polarization of the optical signal through polarization multiplexing. Combined, this allows the encoding of 4 bits per symbol (or time slot), and yields a symbol rate (or baud rate) of only around 32 Gbaud. As such, the 100Gbps DP-QPSK modulation format is compatible with the standardized 50 GHz channel spacing as defined in International Telecommunication Union (ITU) G.694.1, which scales DWDM transmission systems to a single fiber capacity of approximately 10 Tbps. The combination of integrating color interfaces for unsurpassed density in DWDM interfaces on the router, and 100Gbps technologies for unsurpassed capacity in the transport system enables a scalable and future-proof core network architecture. These advantages have created a big momentum for the integration of DWDM optics directly into router interfaces.

Table 1 details the technical specification of Juniper's 2-port 100GbE DWDM PIC for the Juniper Networks® PTX Series Packet Transport Routers product family.

Table 1: Specifications and Optical Signal Characteristics of the DWDM PIC

OTU4 DWDM PIC	
Port density per slot	PTX5000: 4 x 100GbE (32 x 100GbE per chassis) PTX3000: 2 x 100GbE (16 x 100GbE per chassis)
Modulation scheme	DP-QPSK
Optical connectors	LC, non-angled
Line rate	127.14 Gbps
Forward error correction	G.709 FEC SD-FEC with 20% overhead
Optical signal-to-noise ratio (OSNR) tolerance	14.5 dB EOL (back-to-back, 0.1 nm noise bandwidth resolution)
Chromatic dispersion (CD) tolerance	50,000 ps/nm
PMD tolerance	25 ps (80 ps DGD)
Tx optical output power	-2 dBm (minimum)
Rx optical input power	-18 to -5 dBm
Wavelength range	96 channel C-Band, 191.25 THz (1,567.54 nm) to 196.00 THz (1,529.55 nm)
Wavelength tuning grid	50 GHz granularity, acc. to ITU-T G.694.1
Power consumption	250 W typical, 311 W maximum for 2 x 100GbE ports

The PTX Series routers leverage all recent 100Gbps technologies and optical integration advances. Their ultra-long-haul 100 Gbps transponders are directly integrated into the PTX Series using a two-port OTU4 DWDM PIC. The 100Gbps DWDM interface on PTX Series routers allows for an unsurpassed slot capacity of 4 x 100GbE ports, and with 8 slots available per PTX5000 Packet Transport Router chassis, total capacity is 32 x 100GbE. The PTX3000 Packet Transport Router utilizes a 2 x 100GbE capacity per slot for a total capacity of 16 x 100GbE per chassis. The 100Gbps DWDM interface on PTX Series devices make use of state-of-the-art SD-FEC, which allows for deployment of the integrated transponder on ultra long-haul transport links.

Juniper's packet optical solution includes complete monitoring, provisioning, and management of the colored interfaces through Juniper Networks Junos® operating system. The onboard OTN framer of the two-port OTU4 DWDM PIC provides full access to ITU-T G.709 OTN overhead. Specifically, the following functionality is supported:

- All Junos OS CLI commands, including the ability to manage 100GbE OTU4 DWDM PICs
- SNMP v2c and v3 to monitor and manage the 100GbE OTU4 DWDM PIC
- RFC 3591—Definitions of Managed Objects for the Optical Interface Type
- Performance monitoring for all relevant OTN and optical counters and gauges, including 15 minute and 24 hour buckets and associated transverse chromatic aberrations (TCAs)
- GR-1093 based state management for OTN PICs and OTN 100Gbps ports
- Fault management and suppression based on ITU-T G.798 for the OTN layer

Outlook on Optical Integration and Low Power Digital Signal Processing

Both the form factor and power consumption of 100Gbps DWDM coherent solutions are rapidly shrinking due to an increased focus on optical integration and the development of low power digital signal processing (DSP) chips for chromatic dispersion and PMD compensation. This tremendous progress in optical integration will enable the integration of a complete 100Gbps coherent transmitter (Tx) and receiver (Rx) optical front end in a pluggable interface. Such pluggable 100Gbps Tx/Rx optics will fit into a C form-factor pluggable transceiver (CFP-2) form factor, but the DSP chip must be placed on the host board. The functionality of the pluggable 100Gbps Tx/Rx optics remains completely generic, as all of the specific and proprietary algorithms are contained in the DSP chip on the host board. This architecture allows interworking between the pluggable 100Gbps Tx/Rx optics of different vendors, thereby enabling many more vendors of pluggable optical modules to enter the 100Gbps line-side market.

Multiple vendors of pluggable optical modules are also currently working towards a 100Gbps DWDM CFP module that consists of Tx/Rx optics as well as the DSP chip, including forward error correction and OTN framing. The availability of such pluggable 100Gbps DWDM CFPs from multiple vendors will revolutionize the 100GbE transport market by allowing for a much higher degree of flexibility, which will truly drive 100GbE coherent into the metro transport space. Although the CFP-based solutions from different vendors will not necessarily interoperate due to differences in DSP algorithms and forward error correction (FEC), the same CFP module can be used in routers/switches from different system vendors, thereby at least realizing line-side interoperability on the transport layer. This architecture will therefore allow for packet optical transport independent of the transport layer infrastructure.

100Gbps coherent DWDM pluggable CFPs require the design of a coherent ASIC that can fit within the power budget of a CFP form factor. Using 28 nm or 20 nm complementary metal oxide semiconductor (CMOS) fabrication technologies for the coherent ASIC, this is feasible for a class-4 CFP with power consumption between 24 and 32 watts. In order to minimize the power consumption of a pluggable 100Gbps coherent CFP, some trade-offs are required in the optical performance of the Tx/Rx optics as well as turning off some of the functionality in the DSP ASIC. These trade-offs reduce the maximum feasible transmission performance of 100Gbps coherent pluggable CFPs when compared to an optimized solution using board mounted optics. As such, 100Gbps coherent pluggable CFPs will typically target applications with a maximum transmission distance of up to 1,500 km, which is well suited for core networks in most medium-sized geographies (e.g., the national networks of most European countries).

Pre-FEC Triggered Fast Reroute

There are a number of advantages to the router having direct access to the optical transmission performance parameters of the transport layer. For example, MPLS fast reroute (FRR) can be triggered by monitoring the pre-FEC bit error rate (BER). This enables the router to perform the switchover of the traffic to a predefined protection path before an actual outage occurs on the transport link. The direct visibility on the router of the transport layer optical performance allows for multiple orders of magnitude faster response to performance transients. For example, a typical failure scenario consists of the accidental disconnection of a fiber along a transport link, often at one of the patch panels. When using pre-FEC BER triggered FRR, such mistakes will no longer result in an outage. Other common failure scenarios in long-haul transport networks such as the breakdown of a laser in an inline optical amplifier can typically be considered as relatively “slow” events that are easily handled by pre-FEC BER triggered FRR.

Pre-FEC BER-based FRR allows a pre-FEC BER threshold to be set for switchover (and switch back after repair). This threshold setting allows for balance between transparent reach and the capability to switch in response to faster pre-FEC BER transients.

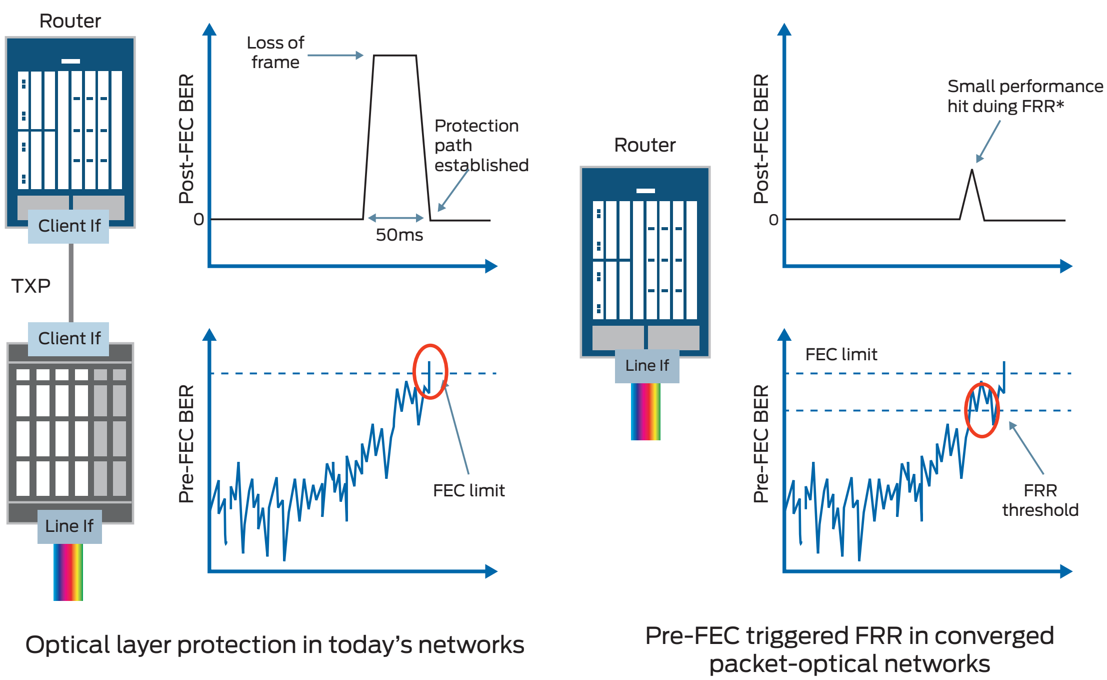

Figure 5: FRR triggered by pre-FEC BER increase

Alien Wavelength and Black Link Standardization

Because 100Gbps DP-QPSK modulation is now broadly accepted as the industry-wide standard for 100Gbps transport, it becomes much easier to mix-and-match best-in-class optical interfaces (clients and transponders) with best-in-class optical line systems (the multiplexers and amplifiers). Almost any modern optical line system can support the transport of 100Gbps DP-QPSK modulation with high performance and over long-haul distances, as the same features that give coherent its high performance (high gain, CD, and PMD tolerance) also make it less dependent on the optical line system used. Similarly, 100Gbps coherent DWDM optics that are integrated on core and edge routers are easily transported over any existing DWDM transport deployments, something that has been traditionally difficult to do with direct detect interfaces.

The specifications that are needed for industry-wide compatibility of optical interfaces (clients and transponders, whether integrated or not) with DWDM line systems (DWDM multiplexers, Reconfigurable Optical Add Drop Multiplexers or ROADMs, amplifiers, etc.) are described in the ITU "black link" standards. ITU G.698.2 currently specifies physical parameters that allow the optical signal from an integrated DWDM transponder on a router to be carried over an optical transport system without passing through an external transponder. Although the current ITU black link standard covers 10 Gbps line rates and below, work is ongoing in the ITU to extend this standardization framework to cover both 40 Gbps and 100 Gbps transmission rates. The transition of the optical transport industry towards a highly adaptive transponder using coherent detection and digital signal processing ASICs greatly simplifies the transmission performance prediction in optical transport networks, and is thus a key enabler of black link operation with high transparent reach.

Juniper and ADVA Optical Networking are also actively engaged in driving line-side interworking standards for 100GbE transceivers that would further simply interoperability between transport and routing platforms from different vendors.

The Evolution to 400GbE/1T

Beyond 100Gbps the tight integration of packet and optical transport will be a strong factor driving the industry to adopt 400 Gbps and 1 Tbps (1T) transport at a much faster rate than its predecessors. 400 Gbps and 1T will make use of so-called "superchannels," consisting of multiple optical carriers to transport the high bit-rate signals. The most straightforward implementation is the use of multiple 100Gbps DP-QPSK carriers to construct a 400Gbps (4 carriers) or 1T (10 carriers) format. In legacy transmission systems, these carriers can be spaced within an existing 50 GHz channel grid, but preferably flex-grid technology would be used to allow for a grid-less architecture. Using a grid-less architecture, channel spacing can be reduced to 37.5 GHz per carrier in the above example, increasing the total single fiber capacity to 12.8 Tbps.

Agile Optical Networks

Flexible optical networks are complementary to the integration of DWDM interfaces into routers, and vice versa. Figure 6 shows one such network.

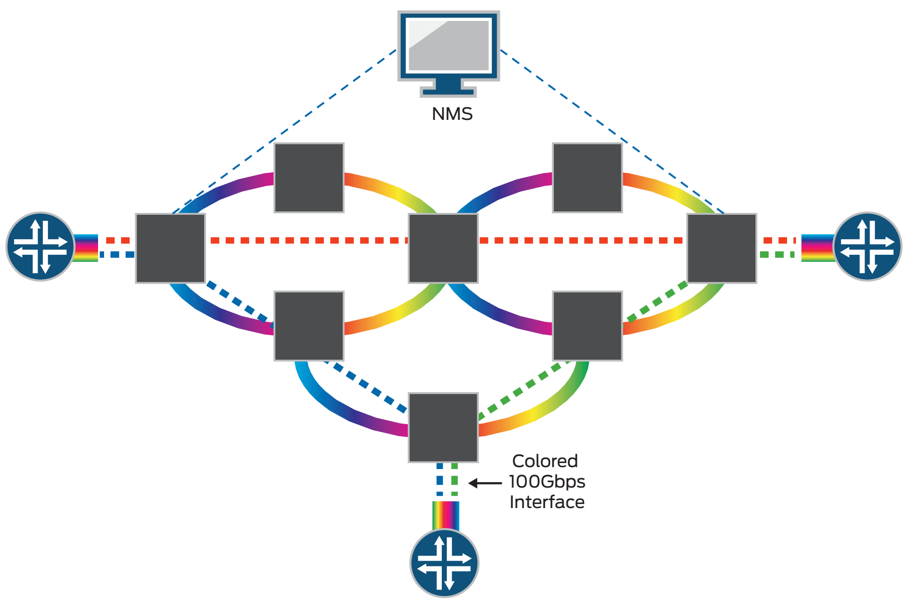

Figure 6: Dynamic optical network

In this case, core routers and MPLS switches are connected to the optical layer through optical add-drop multiplexers (OADMs). Because multiple optical paths are available between router ports, optical path protection and/or restoration is possible. The entire optical network is operated, managed, and monitored through a service and network management system (NMS). OADMs that can be remotely configured and reconfigured using an NMS via a control plane are called Reconfigurable Optical Add Drop Multiplexers (ROADMs). Key benefits of the ROADM-enabled networks are:

- The ability to add, drop, and pass-through wavelengths at a node without the need for additional cabling or a site visit
- The ability to reconfigure a network on-the-fly without the need to physically cable new pass-through connections
- Automated power leveling functionality across all channels in the DWDM grid, reducing the need for regeneration sites

Modern ROADM architectures such as those used by the ADVA FSP 3000 support colorless and directionless operations. In the case of ***colorless*** operation, wavelengths (or colors) of the DWDM interfaces in the add-drop path of ROADMs are not fixed but can be adjusted to any wavelength (hence the label "colorless"). This feature significantly decreases blocking in the network since the odds of finding an available wavelength when needed are much higher if the add/drop can be tuned. In ***directionless*** ROADMs, any add/drop port can be routed in any network direction. This feature significantly increases network flexibility which may, for example, be used for restoring optical paths. If we add a flexible cross-connect matrix to the add-drop port of colorless and directionless ROADMs, we achieve a fully nonblocking behavior which is then called ***contentionless***. In such a system, any client port can be connected to any add-drop port. Colorless, directionless, and contentionless (CDC) ROADMs enable the ultimate flexibility in optical networks and therefore efficient network automation.

As aforementioned, optical interface data rates of core routers and MPLS switches are in the process of increasing to 400 Gbps and 1 Tbps going forward. As also mentioned, these data rates will migrate to the use of grid-less channel spacing to improve efficient use of the available fiber spectrum. Future transport network designs that are independent of a particular wavelength grid will be supported by grid-less optical networks.

Optical service provisioning needs to take into account optical transmission's analog behavior, which produces a number of parameters to be considered. Some examples of these would be fiber attenuation, chromatic and polarization mode dispersion, and nonlinear transmission effects. When calculating the optimal optical path through a network, all of these constraints must be considered. The ADVA FSP 3000 optical network system's path computation engine uses a control plane for constraint-based routing of optical paths throughout a network.

Network Management Integration

A comprehensive multilayer network management solution is a key building block in converged packet optical networks. Requirements and features should be driven by operational aspects. Packet optical convergence unites previously separate operational teams of the packet and transport layers. From this perspective, an optimized multilayer network management strategy could look like the following:

1. Maintain analysis and maintenance tools for each technology to track down technology-specific issues by personnel with adequate know-how.
2. Leverage control plane interoperability to introduce end-to-end packet service provisioning and management across all layers based on shared knowledge about resources and topology.
3. Assign the network packet node with integrated interfaces as a gateway for the packet-to-optical transition, thus enabling multilayer fault correlation and provisioning.

The strategy above would not preclude separate expert teams operating each layer. Maintaining separate teams would be beneficial especially in the introduction phase of converged solutions. It would also support the possibility to deploy best-in-class network management systems for each layer.

Many of today's network operational models are still based on separate IP/MPLS and optical transport teams. Therefore the strategy described above seamlessly fits into such scenarios, since IP/MPLS and optical layer NMS are still separate. However, service provisioning time can be significantly reduced through control plane interworking between the layers, thus increasing overall network efficiency through automated multilayer interoperability.

Fully converged network elements supported by one integrated NMS will be the next evolutionary step towards fully integrated packet optical solutions supporting all kinds of transport services. These next-generation systems will lead to new converged network operational concepts where a single team will be responsible for the entire multilayer transport network covering IP/MPLS, time-division multiplexing (TDM) leased lines, and wavelength services.

As already pointed out, two key features of operationally optimized multilayer network management solutions are end-to-end service provisioning and end-to-end optical layer management. Service provisioning is supported by control plane interoperability and described in the next chapter. Integrated optical layer management is discussed below.

A key enabler as well as operational requirement for packet optical integration is the integration of a router's DWDM interfaces into the transport NMS. The concept of "virtual transponders" (VXPs) enables the integration of optical interfaces from one router vendor into a differing vendor's DWDM management system. The transport NMS has access to all monitored parameters of the optical interface in the router and can control parameters such as switching the router interfaces on/off and tuning the optical wavelength. In this way, the DWDM NMS keeps control over the optical parameters of the integrated optics, which appears to that network management system in a similar way as an external DWDM transponder. This targeted function is supported by Internet Engineering Task Force's (IETF) black link MIB standardization.

Typical features and parameters of such an integrated solution are:

- Automatic discovery of routers and optical network elements with the graphical display as icons on a network map
- Inventory information about all discovered network port modules and shelves
- Alarm, performance, event values, and reports
- Display of end-to-end services

Figure 7 shows ADVA FSP Network Manager (NM) managing Juniper Networks PTX5000 Packet Transport Router and ADVA FSP 3000 as an example of an integrated end-to-end optical layer management solution.

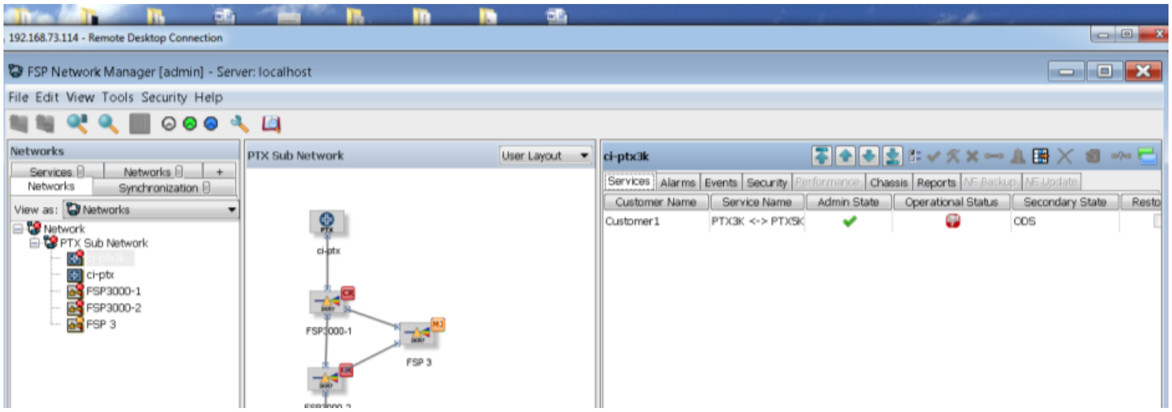

Figure 7: FSP Network Manager end-to-end optical layer management

External wavelength services support in optical layer NMS is an important prerequisite, especially in multivendor environments. This concept is used for creation of optical layer tunnels in the case of colored router interfaces. The optical control plane that follows the same procedures and protocols as the router control plane can then establish tunnels between those interfaces as well as between real transponder cards. From an optical system perspective, external wavelength services start and end on client ports of wavelength filter modules in DWDM terminal nodes or colorless modules in ROADMs. External channel profiles need to be provisioned containing a set of parameters like data rate, FEC, line coding, launch power, TX OSNR, and Rx required OSNR. Figure 8 shows a typical use case for packet optical network management integration.

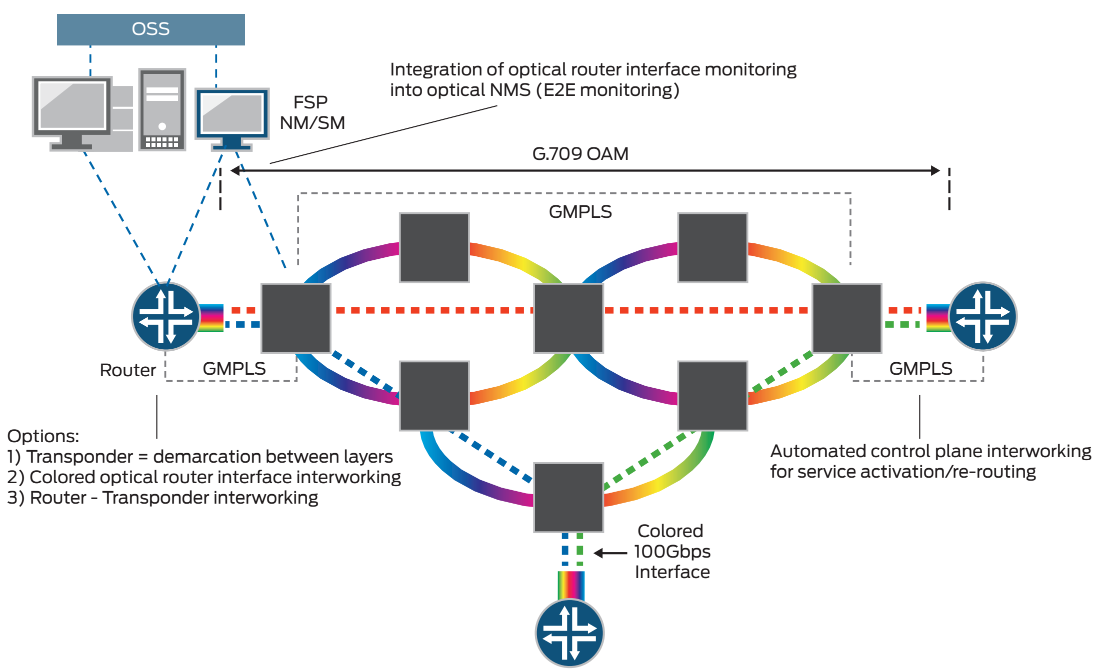

Figure 8: Packet optical convergence overview

In this example, the optical layer operational team is managing and monitoring the network end-to-end through the transport network management system. Since optical paths start and end at router ports in the case of integrated colored router interfaces, the router line interfaces need to be integrated into the transport NMS. This concept works just as well as the case of grey router ports with transponders located in the DWDM system. The concept would be applied in situations where topology challenges could be addressed by using specialized transponders. Operational teams can either be part of the transport division, in the case of "integrated" service providers or enterprises, or they could be teams of external operators who offer managed services for service providers or enterprises.

IP/MPLS services are set up in the packet layer through IP/MPLS network management systems. Thanks to a shared routing view, the packet NMS has sufficient information to engineer packet traffic considering available packet and optical routes. Since optical networks have evolved from simple point-to-point architectures to more sophisticated flexible mesh topologies, Generalized MPLS (GMPLS) control planes are used to configure the optical layer. This approach eases operations of complex optical network elements like directionless and colorless remote configurable add-drop multiplexers, and it paves the way for an integrated operation paradigm for the network as a whole.

Control Plane Integration

Traditionally, packet and optical networks have been operated independent of one another, preventing IP routers from having visibility of the actual fiber. Vice versa, the optical network has been unaware of the packet topology and hence actual use of fiber resources. This model is in essence an overlay model. For over a decade, there has been discussion in the industry about enhancing that model with a signaling interface between routers and the optical network called "user-to-network interface" or UNI. These kinds of overlay models have successfully been deployed for mass services with ubiquitous reachability such as telephony networks or the Internet. Hence it is a service model, where the only service is connectivity between two endpoints, and the route through the network is unimportant to the clients. Yet in routed networks, this model was not successful due to the lack of visibility from the client devices about potentially available options to route traffic.

When we now look at operating a packet/optical network, the service model no longer fits. First, there is no single ubiquitous connectivity of an optical layer but rather a set of optical islands from various vendors that are interconnected on several access points. Second, the connectivity services are provided by IP routers, which bundle them to route them jointly through a server network in order to reduce differential delay. Third, routers use the optical connectivity just as a means to transport data. In other words, the purpose of the optical topology is to support the IP network topology in providing services but not to provide services by itself to an end user. To do so, packet resiliency must not be compromised by unconscious routing of wavelength. These facts call for a different modeling approach than the classical node-based overlay model.

A *link-based* overlay model abstracts the underlying network as a set of links rather than a single node (black box). Hence, the server network exposes itself as a set of nodes interconnected with an abstract link to the client network attached to it. Using this approach, all the internals of the optical network are hidden by the abstract link construct. For the link-based overlay, an "abstract link" is used to expose topological information in a virtual network topology (VNT) which is valuable to the client network. While such a link-based overlay is relatively uncommon in telecommunications, it is actually well-known in computer networks:

> *"An* overlay network *is a computer network which is built on the top of another network. Nodes in the overlay can be thought of as being connected by virtual or logical links, each of which corresponds to a path, perhaps through many physical links, in the underlying network."*

In the case of the virtualization model, the server network serves the needs of the client network to understand where traffic is going. Taking a closer look at the foundation principles of IP networking allows a better understanding of what is expected to be supported by the underlying server infrastructure:

1. **Distributed routing:** Routers have the ability to determine the next hop based on network topology information.
2. **Network resiliency:** IP networks are built in a redundant manner. Dual-homed connections and link diversity are essential. Inbuilt mechanisms provide resilience to packet services, and Shared Risk Link Group (SRLG) information is used to select redundant connectivity.
3. **Shortest path:** Packets follow the shortest path between source and destination whereby the term "shortest" is usually a combination of bandwidth/latency product and number of hops.

The first point reflects the distributed nature of the Internet, which does not match well with the centralized approaches that are often favored in optical networks. The requirement is to inject reachability and routing information from the optical subnetwork into the traffic engineering database of the routers so that the potential connectivity and reachable endpoints of the optical network are available in advance. One method of choice is to use an interior gateway protocol (IGP) such as IS-IS or OSPF between router and adjacent optical switching element. This method doesn't impose the usage of IGP inside the optical subnetwork. Indeed, optical subnetworks may rely on a centralized SDN controller as a source of topological data. Only the protocol speakers at the border of the optical network should be distributed to satisfy the nature of Internet routing. This answers the question of "how" optical topology information can be leaked to the IP network.

A second question to be concerned with is "what" needs to be exposed. IP routing aims to keep traffic flowing even in the case of resource outages. For fast convergence, resiliency mechanisms need to rely on predicting which resources have a high likelihood to fail contemporaneously to correctly assign redundant routes. In a simple IP network, a node or a link between nodes may fail due to a local failure. However in a packet/optical network, a single fiber cut of a DWDM link would affect all wavelengths transported. Moreover, each individual wavelength may connect different pairs of routers such that a single fiber cut in the optical network appears to be a triple or quadruple failure in the IP topology.

To cope with such situations, the notion of Shared Risk Link Groups has been introduced. An SRLG or a set of SRLGs is a link attribute. By comparing the SRLG attributes of links, the path computation algorithm in routers can correctly compute diverse failure routes in advance. Again, the crucial point is to expose SRLGs of the optical domain into the packet domain to avoid provisioning packet services on joint risk label-switched paths (LSPs). By using the link-overlay model, SRLG attributes can easily be communicated from the optical domain into the packet domain such that it has an accurate view about the risk topology and can correctly calculate bypass routes to protect packet LSPs. Indeed, SRLG is the key to the synchronization of routing decisions between layers in multilayered networks. The nature of SRLG information is layer independent and can therefore be used as common reference information for routing at any layer.

The third point is about finding the shortest path. For a single network layer, this is pretty much covered by least cost routing using link metrics. However, the optical layer can alter the optical route in a multilayer network, and this introduces latency changes where IP routers still see the same link between IP nodes, hence erroneously using the same outdated metrics.

Viable Packet/Optical Model

A way to cope with this problem is to derive the packet metric from the metric of the optical route. In other words, a virtual link should carry a metric meaningful to the packet network route calculation. For example, the latency of a virtual link can be coded as a metric. It would then be up to the IP router to multiply the optical latency with the bandwidth information that is locally known to get to the usual bandwidth/latency metric used in today's IP networks. As a by-product, the optical network offers enough information to the attached routers to understand if lower latency paths are possible and which redundancy constraints need to be considered. In many cases, for example, it is preferable to use two redundant paths which do not differ much in metrics rather than choose an optimum path in which a metric changes dramatically in case of failover. The option which is ultimately chosen should be up to the discretion of the IP network operator who is charged with providing reliable services to the end user.

So to address the needs outlined in the previous section, we consider the following entities for the purpose of a viable packet/optical network model:

1. **IP router**: A node capable of switching and forwarding packetized traffic in the form of IP packets.
2. **Optical cross-connect (OXC):** A node that is capable of switching wavelength-sized traffic without looking into packets.
3. **Access link:** Connects an IP router to an adjacent OXC. An access link is a real link that isn't virtualized.
4. **Abstract (TE)-link:** Connects two OXCs that host access links to adjacent routers. An abstract link abstracts the network in between the two OXCs while maintaining the characteristics of the route: latency, metric, SRLG.
5. **Real link:** A potentially amplified fiber connection between two OXCs.

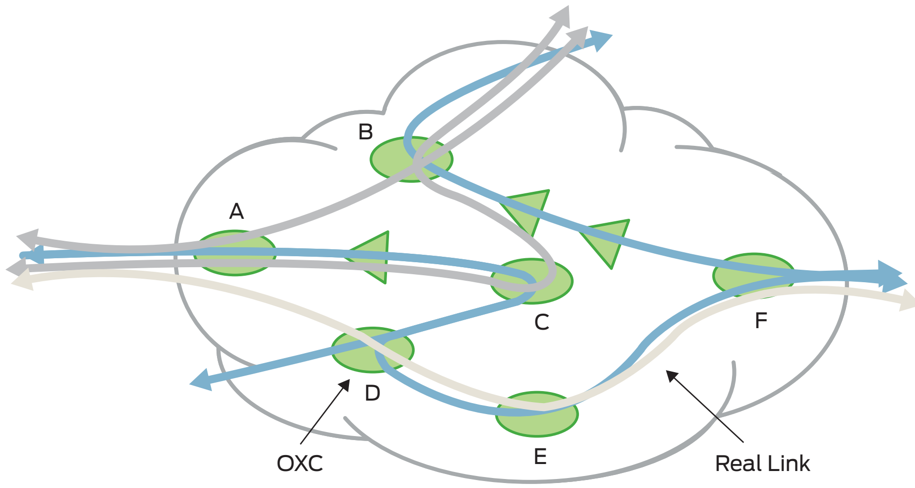

Figure 9: Abstract topology

Optical Cross-Connect

Each optical subnetwork connects OXCs with real links and hooks them up to routers with access links. While the term OXC suggests switching capabilities, DWDM transport gear may also be considered as a specific instantiation of an OXC, even though DWDM terminals only have the capability to switch wavelengths on/off. Wavelengths can be set up starting from access links, utilizing network capacity, and terminating at an endpoint of the remote access link. With all of these ingredients, an abstract model can be developed that satisfies the demand of an IP network.

Instead of applying the overlay model for the optical network as a whole, we apply it on a reachability basis. In other words, for each OXC connected to a router, there exists a list of potentially reachable border OXCs taking into consideration optical impairments, switching, and fiber limitations. Those OXC-OXC reachability pairs are called an "abstract TE-link" or in short an "abstract link." It is also possible to expose more than one abstract link between the same OXC pair, for example, to provide the IP network with information about different potential connectivity. In this case abstract links have the same endpoints but differ in SRLG information or metrics.

The existence of an abstract link allows the IP network to compute routes through the optical network taking into consideration the access links, while the abstract links represent an abstraction of the underlying fiber topology. This architecture not only supports distributed path provisioning but is also well suited for a Path Computation Element (PCE)-based approach. A PCE is a central device in the router domains that assists routers in calculating LSPs. To do so, a PCE needs to learn about the IP and abstracted optical topology and then use this knowledge for path computation. Yet virtual links express only the possibility to connect two OXCs. That doesn't necessarily mean that traffic does indeed already pass between those routers, as wavelengths may not have been provisioned yet. Hence, a PCE still needs to distinguish between ***potential*** connectivity and ***actual*** connectivity (adjacencies) between routers.

To achieve this, access links play an important role. While they expose a packet switching capability on one end, the OXC end has only lambda switching capabilities. So once access links get populated into the traffic engineering (TE) database of routers, they do not automatically attract packet traffic due to the difference in switching capabilities. This is actually desirable behavior, as the availability of virtual links expresses only the possibility to connect two OXCs using the abstract link resources.

Reachability, Latency, and Diversity

Upon request, a border router can initiate the establishment of a wavelength path along a triple hop route specified by access link, abstract link, and access link. When this path is established, a packet-IGP adjacency between two routers is created that triggers the packet control plane to update its packet topology information.

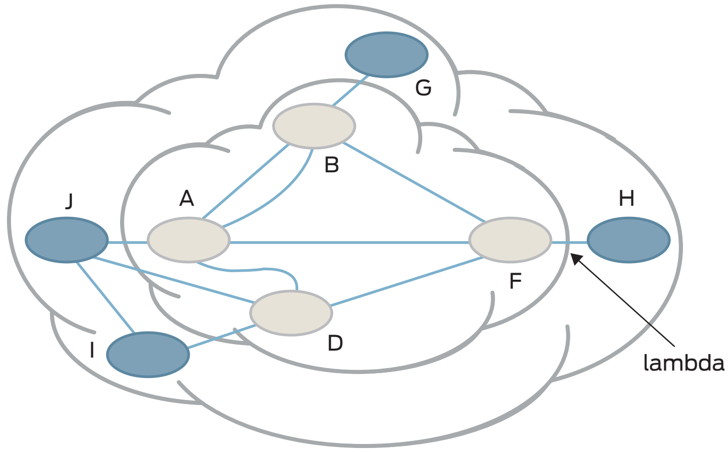

Figure 10: Virtualized topology

Based on this protocol architecture, reliable network services are provided, and three attributes are important: reachability, latency, and diversity. Networking as such is only possible if there is a way to understand which node is actually reachable. It relies on the fact that the source router by some means understands or assumes that the destination router is connected to the same underlying network and this network is available. However, without further information a router has no means to understand the latency of its connection before it is established. Dialing up a wavelength without further qualification would be like rolling dice; for example, you might get a submarine connection or a terrestrial connection.

This situation changes with virtual links, since they carry critical latency and SRLG information. In a digital network, the number of possible abstract links is pretty high. However, optical networks tend to be fragmented and wavelengths are subject to signal degradation and can only travel a certain distance before they need to be regenerated. Consequently, the number of potential paths through the optical network is limited. Also fiber connectivity is limited. Hence, the number of OXCs that can be reached from any given access link is typically quite low.

This allows the precomputation of abstract links in the optical subnetwork. An abstract link can be considered as a soft-forwarding adjacency that follows a defined sequence of real links and nodes. It inherits the SRLG values from those real links and can sum up the latency attributes as well as metric information. Thus, an abstract link is a spur in an optical network. A redundant abstract link can be calculated the same way by excluding SRLG identifiers from the first abstract link. In this way, an abstract link is pinned to a sequence of real links in the optical domain. Once the route is pinned down, available wavelengths can easily be calculated by adding up the free spectrum along the abstract link.

Packet Optical Planning Tool

Key targets of network planning tools are simplification of the network planning process and time savings during preparation of network configurations. Benefits should be:

- Hiding the complexities of large systems
- Allowing for cost-effective network building
- Promoting error-free configuration and installation
- Allowing for several solution options for each network

Similar to multilayer network management systems, planning tools need multilayer functions like overall capacity planning and layer-specific functions (like MPLS path or optical link planning).

The following section shows an example of an optical layer-specific planning tool—the ADVA FSP Network Planner. Key functions include:

- Support of various network topologies (ring, linear-add/drop, point-to-point, mesh)
- Support of various protection options
- Calculation of optical conditions (dispersion, optical budgets, optical signal to noise ratio, etc.)
- Generation of Bill of Materials (BoMs)
- Supplying cabling and placement plans

A typical planning process workflow would start with a requirements definition phase where parameters like topology, network configuration, and a traffic matrix are entered. As a next step, the tool would suggest a network design that matches the defined targets. Finally, optimization of the suggested network configuration could be conducted during a post processing phase. The sequence of steps in the workflow may vary, depending on the type of network being designed.

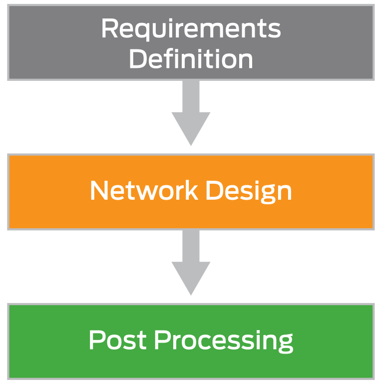

Figure 11: Optical network planning process workflow

Figure 12 shows a result page of the FSP Network Planner. It displays a graphical view of the network topology, as well as information about fiber type, distance, and available budget for each fiber. It is possible to select optical services and view their path through the network.

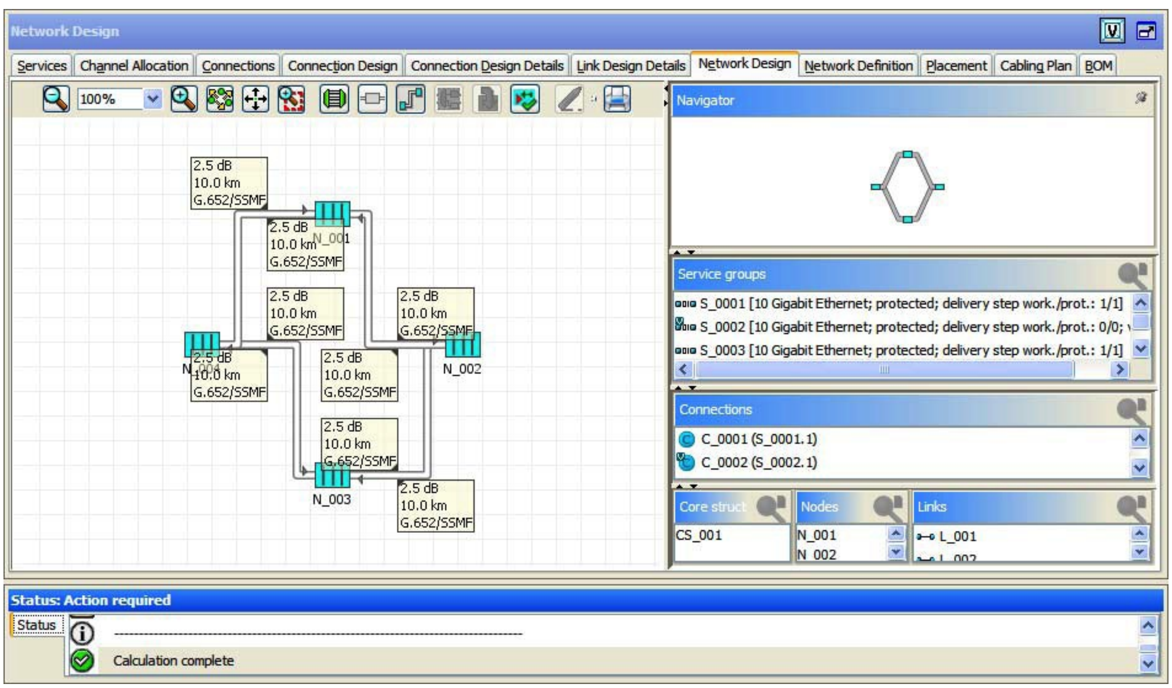

Figure 12: FSP Network Planner result page

Benefits and Total Cost of Ownership (TCO) Reduction

Packet optical converged solutions enable enhanced service offerings and deliver operational and capital benefits through the three integration areas discussed in this paper.

Data plane integration

- TCO advantages through colored interfaces in the routers, i.e., elimination of external transponders
- Evolution towards pluggable, interoperable optical modules at 100Gbps (e.g., upcoming standards for 100Gbps coherent pluggable modules)
- Increased connectivity options between router ports through flexible optical layer

Management plane integration

- End-to-end packet service provisioning and management across all layers based on shared knowledge about resources and topology
- Packet service setup, which is fully aware of optical topology without human intervention
- Avoidance of network-level traffic loss in case of service affecting maintenance work by proactive and automated traffic rerouting

Control plane integration

- Uses automated, optically constraint-aware control plane to conduct the optical path computation and setup process, eliminating human error and maximizing connection reliability
- Requires substantially reduced time to provision capacity (from days to seconds)
- Allows adjustments to bandwidth "*on the fly*" as demands vary, enabled by extended transmission reach such that no intermediate manual equipment provisioning is necessary
- Delivers mean time to repair (MTTR) improvements with current availability objective through multilayer coordinated restoration

Conclusion

Operators have been asking for a simpler, less complex, more cost efficient network architecture enabling them to concentrate on innovating revenue-generation services. Together, Juniper and Adva have provided such an architecture by leveraging best-in-class routing in the PTX Series Packet Transport Routers from Juniper Networks and industry-leading optical systems in the FSP 3000 from Adva into a packet optical convergence architecture. In this innovative converged architecture, the data plane, NMS, and control plane are all tightly coupled together into a single homogeneous system. This gives service providers a holistic view of the network, and it reduces complexity in provisioning, maintenance, and troubleshooting events. The partnership between Juniper Networks and Adva is enabling a revolutionary and innovative solution for today that will be scalable and agile into the future.

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About ADVA

At ADVA Optical Networking we're creating new opportunities for tomorrow's networks, a new vision for a connected world. Our intelligent telecommunications hardware, software and services have been deployed by several hundred service providers and thousands of enterprises, helping them drive their networks forward. For more information, please visit us at: www.advaoptical.com.

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