IP-optical convergence: a complete solution

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The shift to software-defined networking (SDN) architecture for transport networks has given a new lease on life to the IP-over-optical solution that has been around for nearly two decades. Converging the IP and optical network layers to centralize network control is an excellent way to increase service velocity and lower total cost of ownership (TCO) for network operators.

Changes have occurred. For example, IP router products are now offered with DWDM interfaces for aggregation and metro networks, which reduces the number of fibers needed to deliver a given traffic volume. This kind of approach has generally been referred to as IPoDWDM – meaning DWDM interfaces integrated into the router line cards. As well as reducing network complexity, this approach reduces the need for network components such as shelves, which in turn makes opex reductions possible.

Another approach to converging IP and optical has been used on the multilayer control plane. Developments in this area conducted by standards organizations such as IETF have resulted in the GMPLS protocol suite. The protocols in this suite enable automated provisioning for services that use resources. Like many other issues that operators face today, this causes costs to rise and lowers the ability to evolve with changing business environments.

The problem with separate IP and optical transport networks is the unnecessary resource overhead it creates. Basically, each network has its own control and management mechanisms, which not only increases the number of resources needed to reach a given performance target, but also makes networks more complex than they need to be. The current SDN movement in the telecoms industry offers a much-needed solution to attain the high levels of automation that modern networks demand – for both IP and optical systems. In parallel, and to some extent related to this, service providers are moving away from the independent operation of IP and optical transport toward a converged approach, with joint operation.

The challenge – which is not entirely new – is to bring these two transport networks together. Looking back to the late 1990s, when the volumes of IP traffic started to rise significantly, dense wavelength division multiplexing (DWDM) technology raised the capability of fiber optic communications close to their full potential. At this point, the telecoms industry identified the need for a way to combine IP and optical transport technologies. Protocol layering was one of the first converged approaches that had the right balance of traffic control, multi-service support, payload efficiency and low operational complexity. As a result of this early work, several equipment changes have occurred. For example, IP router products are now offered with DWDM interfaces for aggregation and metro networks, which reduces the number of fibers needed to deliver a given traffic volume. This kind of approach has generally been referred to as IPoDWDM – meaning DWDM interfaces integrated into the router line cards. As well as reducing network complexity, this approach reduces the need for network components such as shelves, which in turn makes opex reductions possible.

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**Terms and abbreviations**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASIC</td>
<td>application-specific integrated circuit</td>
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<tr>
<td>BGP-LS</td>
<td>Border Gateway Protocol Link State</td>
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<td>CPE</td>
<td>customer premises equipment</td>
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<td>CFP</td>
<td>100Gbps small form-factor pluggable</td>
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<tr>
<td>CLI</td>
<td>command-line interface</td>
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<tr>
<td>DWDM</td>
<td>dense wavelength division multiplexing</td>
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<td>EDFA</td>
<td>erbium-doped fiber amplifiers</td>
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<td>EON</td>
<td>elastic optical networks</td>
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<tr>
<td>FCAPS</td>
<td>fault, configuration, accounting, performance, security</td>
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<tr>
<td>FEC</td>
<td>forward error correction</td>
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<td>FW</td>
<td>forwarding</td>
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<td>GMPLS</td>
<td>generalized multi-protocol label</td>
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<td>IETF</td>
<td>Internet Engineering Task Force</td>
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<td>IPoDWDM</td>
<td>IP over DWDM</td>
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<td>LH</td>
<td>long-haul</td>
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<td>ML</td>
<td>multilayer</td>
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<td>MP-BGP</td>
<td>multi-protocol BGP</td>
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<td>MPLS</td>
<td>multi-protocol Label Switching</td>
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<td>Mpx</td>
<td>muxponder</td>
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<tr>
<td>NE</td>
<td>network element</td>
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<tr>
<td>NMS</td>
<td>network management system</td>
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<td>OF</td>
<td>OpenFlow</td>
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<td>O&amp;M</td>
<td>Operation and Maintenance</td>
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<td>OLA</td>
<td>optical line amplifier</td>
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<td>OTN</td>
<td>optical transport network</td>
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<tr>
<td>PCE</td>
<td>path computation element</td>
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<td>PCEP</td>
<td>PCE protocol</td>
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<td>PDEF</td>
<td>protocol definition language</td>
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<tr>
<td>ROADM</td>
<td>reconfigurable optical add/drop multiplexer</td>
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<td>SDN</td>
<td>software-defined networking</td>
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<tr>
<td>SFP+</td>
<td>small form-factor pluggable for up to 10Gbps</td>
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<tr>
<td>SR</td>
<td>Segment Routing</td>
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<tr>
<td>TCO</td>
<td>total cost of ownership</td>
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<td>TDM</td>
<td>time division multiplexing</td>
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<tr>
<td>TNC</td>
<td>transport network controller</td>
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<td>Tpx</td>
<td>transponder</td>
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<tr>
<td>VPN</td>
<td>virtual private network</td>
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<tr>
<td>VM</td>
<td>virtual machine</td>
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<tr>
<td>WSON</td>
<td>wavelength-switched optical network</td>
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<tr>
<td>XFP</td>
<td>10Gbps small form-factor pluggable</td>
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in several network layers, and is the first standard control plane for wavelength-switched optical networks (WSONs).

Since then, network operators have introduced reconfigurable optical add/drop multiplexers (ROADMs). These components simplify the operation of large numbers of DWDM channels and reduce the number of signal regenerators needed in metro and core networks.

To date, however, there have been only a few deployed networks in which control plane integration of IP routers and optical transport systems has been implemented using DWDM and ROADMs. One reason is the typical organizational division of IP and optical operations. Add to this the fact that IP routers have limited support for GMPLS and that data plane (DWDM layer) interworking has presented a significant challenge. The result is low-level adoption of the technology.

Today, the optical industry is trending toward using independent 100Gbps coherent DWDM ASICs. These chips simplify data plane interoperability (at the DWDM layer) among the different network element vendors — a factor of paramount importance when it comes to combined control.

**Closing the gap**

While some steps have been made to integrate the two transport networks, a fully integrated solution that includes logical integration of all planes — data, control, and management — is still needed. This article outlines such a solution, referred to as IP-optical convergence.

**Taxonomy**

Both the IP and DWDM layers are multi-domain technologies that include various planes. Each plane can be implemented using one of several architecture variants. This organization is illustrated in Figures 1 and 2, where Figure 1 shows the overall taxonomy, and Figure 2 details the data plane.

**Data plane**

In the 1980s, coherent receivers and coherent technology were the focus of much study. Unfortunately, the technology never took off due to the complexity of polarization and phase stabilization. Some 30 years later, however, these initial problems have been overcome by advanced digital signal processing, allowing coherent technology to open up new ways of utilizing the bandwidth of optical fibers.

When combined with technologies such as flexible grid allocation

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**FIGURE 1** IP-optical taxonomy overall

**FIGURE 2** Data plane taxonomy

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However, this integrated approach has several disadvantages, including the fact that long-haul optics are bulky, power-hungry and temperature-sensitive, which impacts the router line card density and capabilities.

Furthermore, a multitude of different router line cards are needed to cater for many kinds of optics such as 10G, 100G and 400G covering distances from 10km to over 2000km. To overcome the cost of developing a range of different line cards, pluggable optical modules can be used instead. These modules come in several variants to cater for the different data rates and distances. A drawback of this solution, however, is that it typically offers advanced optical capabilities later than is possible with solutions integrated on the line cards.

Another level of complication is added by the pace of evolution: packet-forwarding hardware and fiber-optics hardware may not develop in a synchronized manner, and so a combined card may not be able to take advantage of the most up-to-date technology.

So the questions that need to be answered are: when is it desirable or necessary to keep operations and perhaps ownership of IP and optical transport separate, and when should operation be integrated?

From a pragmatic and a technical point of view, the best solution would be to integrate optics on the router line card if doing so does not negatively impact IP router cost or size capabilities, and then use a separate optical transport shelf/box for all other cases. Such an additional box may be needed anyway to host optical amplifiers, such as erbium-doped fiber amplifiers (EDFA), or Raman amplifiers for improved reach, as well as for DWDM mux/demux and ROADM components.

For joint operation, the existence of two boxes should not be an issue as the separate optical transport box can be seen as an extension of the IP router backplane.

Figure 3 illustrates both approaches, where option 1 is the separated approach and option 2 the integrated one. The illustration shows the optical components without placing any assumption on how they are assembled in an actual network element.
Control plane

There are several ways to implement the control plane in a converged architecture. It can be implemented as a pure GMPLS with all the control plane functions, signaling and routing distributed in the network. Alternatively, the control plane can be implemented as a centralized implementation with centralized PCE, with no routing or signaling in the network. There are several alternative architectures between these two extremes, as summarized in Figure 4.

An IETF initiative, Segment Routing (SR), offers some advantages, including operational simplification and improved scalability.

For a converged IP-optical control plane in the core network, SR together with SDN is a good solution, while for the aggregation/metro network a single SDN controller with standard OpenFlow for the southbound interface is probably best.

A perfect fit

By leveraging source routing and tunneling, SR improves network scalability and provides a set of tools to implement traffic engineering without requiring any changes to the MPLS data plane.

Using SR, the ingress node basically steers a packet through a controlled set of instructions, called segments, by prepending the packet with an SR header. A segment can be a topological or a service-based instruction. It can use semantics that are local to an SR node or use global semantics that are applicable within an SR domain. Applying SR guarantees that packets follow a predetermined path through any network topology and that a given service chain is applied while at the same time maintaining the per-flow state at the ingress node of the SR domain.

The beauty of the SR architecture lies in the fact that it can be applied to the MPLS data plane directly without making changes to the forwarding plane, and requires only a minor extension to the existing link-state routing protocols.

As shown and summarized in Figure 5, the centralized intelligence of SDN with its multilayer ML-PCE capabilities together with SR protocols and architecture are the best fit for converged core networks, together with its multilayer ML-PCE capabilities.
for business-related functions such as and inventor y, as well as prov iding data by the SDN controller), fault correlation and restoration functions performed (including the control plane protection software management, performance example, include the application of automation and dynamicity. be capable of dealing with all aspects of it – including the control plane – and be able to run in real time with high levels of automation and dynamicity.

The operation and maintenance functions carried out by an NMS should, for example, include the application of security measures, configuration tasks, software management, performance management, fault management (including the control plane protection and restoration functions performed by the SDN controller), fault correlation and inventory, as well as providing data for business-related functions such as analytics and billing (BSS).

A management system that can provide a consolidated view of a network simplifies the many types of network operations. As such, an NMS needs to be scalable to support high-capacity networks; it needs to be highly capable to handle complex multilayer connectivity; and it needs to be able to support multi-vendor environments.

A unified NMS should provide full network evolution support for both existing O&M features as well as new features such as integration of multi-standard small cells, and support for Wi-Fi, 4GIP networks, SDN and cloud environments. It provides a single interface to network elements and makes relevant network data available through northbound interfaces. A unified NMS can help operators to reach set network-performance targets and improve productivity by enabling increased coverage, more widespread automation, higher network availability and by supporting best-in-class usability. Such high-quality and efficient O&M not only reduces TCO of network equipment but also helps improve operator perception with existing and potential subscribers.

Planning
Planning is a fundamental part of efficient networking. It is a cyclical process that starts with network monitoring: traffic matrices and/or events are simulated, the impact is assessed and appropriate actions are taken to assure that the set performance targets are still achievable. The overall network planning cycle from initial deployment to maintenance.

The best way to plan a converged network is adopt a multilayer approach and retrieve data from the management system, from the controller, or from both. The result of the planning activity can then be used to purchase any additional equipment needed such as units, nodes or cards, or to initiate a cycle of network optimization.

Use cases and benefits
The main issue with dual operation of IP and optical transport systems is that it creates an unnecessary overhead in both time and resources. To a great extent, optical transport layer resources – wavelength and spectrum – are provisioned when transport bandwidth is lacking. So, with the trigger in the packet layer, operators can save a lot of time by automating provisioning of the optical transport layer. In other words, what is needed is an implementation for single-step, multilayer provisioning.

Use case: time to market
An operator needs to provision a business Layer 2/Layer 3 VPN service on IP Edge on customer premises equipment (CPE). To enable rapid provisioning in this scenario, multilayer operation is a requirement – separate provisioning for each layer of the transport network would simply take too long.

Use case: planning
Multilayer planning can save resources in terms of deployed equipment, time and expertise. To maximize equipment savings, the path computation algorithm of the planning tool should be the same as the one used by the network controller. Planning tends to be carried out offline using updated snapshots of the network, with cycles ranging from a couple of months to several years.

Use case: optimization
Optimization is similar to planning but is carried out online. As the network evolves and becomes more complex, multilayer resource optimization can make intelligent use of resources.
Optimization is performed through a specific application that sits on top of the network controller, allowing the carrier to specify policy and metrics.

**Use case: protection/restoration**
Applying multilayer protection/restoration removes the need to duplicate protection resources across several layers, and eliminates the conflicts that arise as a result of protection/restoration mechanisms working individually in the different layers.

Overall resource availability can be further improved by combining protection in the IP/MPLS layer—which can be engineered for fast protection—with restoration in the optical layer (which is better suited for this task due to slower ROADM switching times and longer optical amplifier settling times as a result of transients).

**Use case: calendar**
Dynamic time-sharing of resources may be of interest for, say, data-center interconnects. These links need to support scheduled large-volume data transfers but do not require permanently assigned resources.

**Converged architecture**
The IP-optical convergence solution offers significant operational gains as it permits the different layers of a network to operate in a single step. This in turn leads to improved service, reduced time to market and optimized utilization of resources.

The technical considerations of each of the planes addressed in this article are summarized below:

**Data plane**
An integrated approach—optics on router line cards—brings benefits in terms of fewer system components and simplified system management.

Some optical transport components such as ROADMs and optical amplifiers require an additional shelf; placing the optical port on the same shelf improves flexibility and supports the case for separated—yet still automated and centrally managed—optics.

**Control plane**
Centralized control brings benefits in terms of better utilization of resources and simplified operation. The SDN approach, combined with SR for the IP/PMP/LS layer, improves scalability and simplifies operation. Well-defined application interfaces to the controller are a significant factor in the automation of application resource requests—such as the resources to set up a VPN with a data center interconnect.

**Management plane**
A unified management system capable of handling all the IP and transport layers and equipment end-to-end is key to an efficient converged network. Overall, as such networks are typically multi-vendor, it is important that the unified management system has support for multi-vendor environments, multilayer and multi-domain scenarios.

The complete IP-optical convergence solution with its architecture and key components is illustrated in Figure 7.

Overall, a converged architecture makes the most of the current industry shift toward SDN, driven by a need for lower costs, faster services, shorter time to market as well as reduced operational complexity.

Commercially available cutting edge IP-optical convergence offerings encompass emerging protocol suites such as SR and best-of-breed architecture, without forgetting the need for more traditional tools such as planners and management systems. The converged solution described here has the right mix of revolutionary and traditional approaches.

Such an integrated approach offers a viable migration path from the installed base, as well as being an attractive proposal for meeting the IP and transport network requirements for the foreseeable future.
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