Introduction

For years, core networks received little attention while operators focused their investments on upgrading their metro core, aggregation and access networks to deal with IP traffic growth and new services on both the wireline and wireless side.

Over the past couple years, however, we have seen a core network renaissance begin. With upgrades in metro and access networks complete, operators are finding that the core network has become the bottleneck. As operators invest in the next round of core networks, they will take advantage of the latest technologies available in order to squeeze the greatest efficiencies out of their finite bandwidth and to future-proof their networks against continued traffic growth. The first move in this direction is being seen as super-channel line card implementations beginning to address the emerging 100G market, and competing directly with non-integrated implementations of 100G.

This paper looks at the evolution of core networks, with an emphasis on the following technologies:

- 100G transport
- Switched OTN
- Super channels
- Photonic integration

In particular, we focus on photonic integration as enabling and/or improving the other technologies.

The New Era of Super Channels

Overview & Definitions

As suppliers look to 100G and beyond, we are hearing an increasing consensus among them that the super channel is the best solution. A super channel is an evolution in DWDM in which several optical carriers (or lasers) are combined to create a composite signal of the desired capacity. A super channel differs from simply sending multiple wavelengths down a fiber in two key ways:

- The spacing of optical carriers within a super channel can be packed tighter than the ITU-T WDM grid, thus enabling higher spectral efficiency, a key driver for using super channels;
- Super channels behave as a single unit of bandwidth, are brought into service in a single operational cycle, and therefore allow service providers to scale operations without scaling costs.

Greater spectral efficiency is achieved via tighter spacing between sub carriers. For example, while today’s long-haul DWDM systems are based on 50GHz channel spacing, super channel implementations will remove the guard band between carriers currently defined by ITU-T wavelength grids, enabling tighter spacing of carriers and higher spectral efficiency. The combination of greater channel rates and tighter spacing yields more bit/s per Hz, meaning more bit/s per fiber.

As a point of reference, today’s 100Gbit/s transport systems using DP-QPSK modulation achieve 2bit/s/Hz, while 10Gbit/s NRZ systems achieve up to 0.4bit/s/Hz
Both of these implementation options have an optical reach of 2,500-3,000km. Using prototype super channel systems, suppliers have been able to achieve 4bit/s/Hz using DP-16QAM modulation, which allows increased spectral efficiency but only metro-regional reaches in the range of 400-600km. In more forward-looking “hero experiments,” which may be many years away from commercial viability, results of greater than 11bit/s/Hz have been reported using super channel techniques.

Significantly, super channels also occupy the same amount of spectrum as a single laser being used for a given transmission rate and the same modulation technique, e.g., 10 DP-QPSK sub channels at 100G each, versus a single DP-QPSK channel at 1 Tbit/s. Figure 1 illustrates two super channel implementations compared with a single channel implementation, all occupying the same amount of spectrum.

Beyond greater spectral efficiency, there is another critical advantage of super channels versus traditional single carrier transmission. Super channels enable the industry to get to higher bit rates five or even 10 years sooner than would be possible with single channel technology. The reason is that optical transmission is far ahead of electronic processing. Today, while 100G transport is moving into the mainstream, the state of the art in electronic analog-to-digital conversion is only at 32 GBaud. Terabit-speed processing is more than a decade away.

Furthermore, even on the optics side there are time-to-market and economics advantages in using super channels. There are no commercial modulators today that operate at 11bit/s rates, yet 11bit/s super channels can be created using multiple sub-carriers. Even when 11bit/s modulators do come to market, they will be far more expensive than 100G optics.

A final significant point about super channels is applicable to long-haul DWDM transmission. Some suppliers are achieving high bit rates through alternative modulation formats, particularly 16 QAM and 64 QAM modulation. At OFC/NFOEC 2012, both Alcatel-Lucent and Ciena announced the ability to transmit at 200G single channel rates, in both cases using 16 QAM modulation format. However,
higher bit rate QAM modulations involve a physics trade-off of data rate and reach, so the higher data rates come with a distance penalty. In fact, 16 QAM modulation formats are being aimed at regional transmission distances, in the range of 600 km or less, and are not suitable for implementing long-haul and ultra-long-haul transport super channels.

Here again, super channels shine. Suppliers building super channels from multiple DP-QPSK modulated sub carriers can achieve distances beyond 2,000 km. For example, Infinera, using its 500G photonic integrated circuit (PIC)-based super channel, has reported up to 3,000km transmission and up to 6,000km using 250G BPSK super channels (trading capacity for greater distance).

Industry Support for Super Channels

Industry support for super channels as the best means of achieving bit rates beyond 100G for long-haul transport is nearly universal. (We are referring specifically to long-haul DWDM as metro and regional transmission may also have single carrier systems, as noted above.) Given the many competing approaches offered at 40G and even the debates around the best approach for 100G, this industry harmony is a welcome change for participants up and down the supply chain.

This section details just some of the industry support around super channels.

- In January 2012, Cisco demonstrated a 400G and 1Tbit/s super channel prototype. The prototype included two 1Tbit/s super channels composed of 10 100G channels using 16 QAM modulation and one 400G super channel composed of four 100G channels using 16 QAM modulation.
- In March 2011, ZTE was awarded a post-deadline paper publication for achieving a 10Tbit/s data rate over 640 km using a single-source super channel. The super channel consisted of 112 optical sub-carryers, each running at 100G, and each spaced at 25 GHz.
- Infinera has commercially launched a DWDM system based on 500G long-haul super channels. The system, called the DTN-X, aggregates five 100G channels for up to 500G aggregate capacity per super channel. The 500G long-haul super channels are contained on a PIC and single system line-card.
- In March 2012, Verizon and NEC published results of a field trial in which the operator transmitted 21.7 Tbit/s over 1,503 kilometers (934 miles) of standard single mode field fiber on the telco’s network in the Dallas area. To achieve the 21.7 Tbit/s of fiber capacity, the companies used a combination of advanced modulation and super channels. Most notable about this trial was that Verizon used existing fibers to show what’s achievable in real-world network conditions. The 2012 trials follows a 2011 collaboration in which Verizon and NEC teamed up to demonstrate 450G and 1.15Tbit/s super channels running alongside a single 100G channel. This field trial was also conducted on Verizon’s Dallas-area network.

Integrated Switching & DWDM

Core networks are migrating away from traditional architectures based on separate DWDM transport and switching elements to new architectures based on DWDM transport and switching integrated into a single network element. At the
same time, the switching function in these new converged elements is moving away from Sonet/SDH switching of the past to OTN-based switching for the future.

The Old Way: Muxponders

Point-to-point optical networks based on muxponders are inherently inefficient. Muxponders are used when the client service rate is less than the line side wavelength rate, such as when 2.5G services are mapped into 10G wavelengths. In an all-optical network architecture, ROADMs are used to re-route wavelengths at intermediate nodes along the way, but there is no bandwidth management (or grooming) performed at these ROADM nodes, as sub-wavelength bandwidth grooming or correcting for wavelength blocking requires an OEO conversion.

In a muxponder-based network, if there aren’t enough client services to fill the line side, bandwidth is wasted as the unused line side capacity is not available for any other services. Thus, in the case of the 4 x 2.5G muxponder, if there are only two services on the line, 50 percent of available capacity is wasted (i.e., two 2.5G channels remain empty).

The industry’s move to 40G and particularly 100G line side optics exacerbates the “muxponder tax” problem as the mismatch between client side and line side rates has become far greater. For example, even as client side interfaces move up to 10G, there is still a 10x mismatch between the line side and client side on a 100G network. While operators around the world are eager to benefit from capex and opex advantages of 100G, those benefits will be more than offset by the bandwidth-wasting disadvantages of the point-to-point muxponder-based network architecture of the past.

All-optical ROADMs increase network flexibility and reduce opex for operators, but, as noted, on their own they do not address this muxponder tax challenge at all, since they cannot provide the sub-wavelength bandwidth management that is needed.

Furthermore, market research shows that the mismatch between client rates and line side rates is here to stay for the foreseeable future. See Figure 2 for Heavy Reading’s core client side interface forecast for 2015.

![Figure 2: Projected Core Network Client-Side Interface Share, 2015](image)

Source: Heavy Reading, 2012
The Rise of Switched OTN

OTN has rapidly risen as the bandwidth management and grooming technology of choice for the next generation of core transport networks. Several trends have converged to make OTN the consensus choice for core networks:

- **Reducing the cost per bit for transport.** Operators globally are pushing the concept that the lower bits are processed in OSI stack, the less it costs in terms of both capex and operex. All-optical transport is the least costly form of transport, but sub-wavelength switching and grooming can’t be performed at this level. As a Layer 1 technology, OTN is seen as a suitable choice for lowest cost transport, grooming, and switching, replacing the need to do some of these functions at Layer 2 and Layer 3.

- **Continued Internet traffic growth.** It is widely understood that IP/packet traffic is the driver of both traffic and revenue growth today and in the future. OTN was created as a universal transport protocol to handle TDM traffic and packet traffic, much more efficiently than legacy Sonet/SDH. Standards advances such as ODU0 (for Gigabit Ethernet) and ODUflex have further adapted OTN for the packet transport and switching role.

- **OTN addresses the massive legacy of Sonet/SDH.** This legacy calls for a transition technology to handle both the packet and the TDM side – and OTN handles Sonet/SDH much better than Ethernet in its current form, based on operator feedback. While it has been adapted for packet traffic, OTN is still a TDM technology.

The New Way: Integrated Switching and Transport

Initially, some suppliers began building external OTN switches that would sit alongside DWDM transport gear in networks. This approach is not surprising since Sonet/SDH-based optical crossconnects were deployed in this same manner over the past 12 years. However, for this next-generation equipment, network operators are demanding much greater efficiencies. Side-by-side network elements require additional space and power and also require many short-reach optics on both ends of the connection in order to link the DWDM gear with the switching gear. In addition, there is added operational complexity in managing two separate elements.

To address the short-reach interconnect issue operators are demanding integrated transport elements that combine OTN switching with DWDM transport. Far from being the “God Box” concept of the early 2000s, these new elements are focused on transport with a tight coupling of OSI Layers 0 and 1. As Layer 2 also becomes a transport technology, some operators are also interested in integrating Layer 2 functions into these devices as well, typically for future architectures. Benefits of integrated transport and switching are:

- Eliminating hundreds of short reach interconnects;
- Reduction in space, power and capex costs;
- Reduced operex in managing one element instead of two;
- A single network element for the control plane.

**Figure 3** is an illustration of a wavelength-based muxponder and ROADM network architecture. **Figure 4** shows a transport network architecture based on WDM transport and OEO switching for sub-wavelength level grooming. It shows WDM transport and switching in separate elements and integrated in a single element.
Industry Support for Switched OTN/DWDM

Switched OTN and particularly switched OTN with integrated DWDM transport is taking off in the core. Heavy Reading now counts 10 vendors that are either shipping or have announced products that fit this new category, including Alcatel-Lucent, Ciena, Huawei, Infinera, Nokia Siemens Networks and others.

Figure 5 shows Heavy Reading’s core packet-optical switching forecast through 2015. This new category combines OTN switching with DWDM transport and, optionally, packet switching functions as well.

The need for integrated OTN/DWDM will also be driven by the fact that super channels have different capacities depending on the modulation technique used. OTN standards already include a flexible container option in the form of ODUflex, which allows OTN multiplexing containers to be created with a granularity of ODU0 (1.25Gbit/s). At the end of 2011 a proposal initially dubbed “OTUadapt” was put forward to ITU-T Q11 for a similar flexible container, at a much higher level of granularity to suit super-channel capacities. This proposal was initially made by Infinera and Verizon, but has gained more widespread support in subsequent ITU-T meetings, and now ITU-T Q11 has adopted it as part of its “living list” of proposals for beyond 100G technologies.

While the proposal is still in the very early stages of the ITU-T process, the basic idea for OTUadapt is that larger OTN containers can be built dynamically in units of 25Gbit/s; note that this granularity may change as the standard evolves, but 25Gbit/s is the current proposal. Thus a 500Gbit/s long-haul super channel could be built with 20 of these units, or a 400Gbit/s metro super channel could be built using 16 of these units.

So the question that is often asked – “what is the next data rate after 100G?” no longer has a single answer. Instead, service providers can choose the data rate that is most appropriate for their application.
Photonic Integration in Next-Gen Core Transport

We have seen an increasing role for photonic integration used in optical transport over the past decade. The most significant case of photonic integration to date has been Infinera’s use of large-scale PICs as the basis of its widely deployed DTN DWDM systems. These systems have been deployed commercially since 2004. Beyond Infinera, small scale PICs have also become widely deployed with JDSU’s integrated laser Mach-Zehnder, for example. This JDSU chip monolithically integrates five optical functions in indium phosphide. As another example, for the 168-pin 100G LH DWDM Multi-Source Agreement (MSA), the OIF specifies photonic integration. Such integration is needed to achieve the specified footprint and power consumption.

Photonic Integration in Super Channels

Heavy Reading believes that the optical industry will enter a new phase of photonic integration as it moves to 100G and beyond to the era of super channels, as described earlier in this paper. Significantly, the large-scale PIC, by its design, fits nicely into a super channel model that requires multiple carriers/lasers.

To create a 1Tbit/s super channel composed of 10 channels, a module requires roughly 10x the number of optical components that a single-channel (non-super channel) module would require. As we have discussed, however, a single channel 1Tbit/s module is more than 10 years away based on the current electronics trajectory.

This electronics is required, of course, to enable the coherent processing and impairment compensation that delivers the incredible increase in capacity seen in recent years. All modern coherent implementations are based on sophisticated ASIC chipsets, such as Ciena’s WaveLogic, Alcatel’s Photonic Services Engine or Infinera’s FlexCoherent Processor. Commercial differentiation in coherent implementations can either come from the integrated electronics or from integrated optics (or some combination). While coherent ASIC implementations are not yet commoditized, all vendors have access to electronic integration, whereas only a small subset of vendors have plans to develop their own coherent photonic integration, most preferring to rely on merchant MSA devices.

The goal, therefore, must be to reduce the number of discrete optical components on a card in order to make the super channel implementation practical and economical, and to avoid reliability issues that would arise with such a complex discrete component implementation. This is where photonic integration shines.

We expect that super channels will steer industry PIC implementation toward large-scale, multi-laser PICs, such as those developed by Infinera. PICs that combine multiple lasers on a chip play into the “fluid bandwidth” prospects of super channels. With super channels, operators will be able to throttle bandwidth up and down, depending on needs, by adding and subtracting carriers, as well as by tuning into different modulation formats that trade-off between capacity and reach.

While supporting “fluid bandwidth” applications, multi-laser PICs will provide a greater level of integration than possible with single-channel PIC implementations. Infinera’s new 500G PIC pair, for example, replaces 600 discrete optical functions with two indium phosphide chips – a transmit PIC and a receive PIC. The transmit PIC contains 10 lasers, initially capable of 50G each, but ultimately moving to 100G per laser.
We can't say that all suppliers will move to 10 channel PICs, but we believe that long-haul DWDM PIC development will shift to multi-channel, driven by super channels. Components and systems suppliers will seek the greatest balance between high integration and high yields – something that will likely vary from supplier to supplier.

**Photonic Integration in Integrated Switching/DWDM**

In addition to enabling efficient super channels, PICs also have a role to play in next-generation transport systems that integrate switched OTN and DWDM transport on a single chassis. Benefits here are:

- Reducing overall system footprint;
- Increasing system density;
- Enabling full access to input/output (I/O) switch capacity.

Certainly, reduced footprint and increased system density are important for any optical system. When transport and switching are integrated, however, the stakes become higher because system capacity and footprint are limited. Today's long-haul DWDM cards typically occupy more space than short reach 100G optics. So, while an integrated transport/switching system fully equipped with short-reach optics may have full access to the system's switching capacity (for example, 4 Tbit/s of a 4 Tbit/s switch fabric), the same system filled out with double-slot long-haul DWDM cards only has access to half the potential capacity (2 Tbit/s of the total 4 Tbit/s of capacity cited above).

The newest generation of 100G long-haul cards is single slot (aided, in part, by the use of photonic integration). These new-generation single slot 100G cards are just hitting the market, which is a positive development. As systems suppliers move to super channels implemented on integrated transport and switching systems, the issue of access to available switch capacity will arise again. Operators will require full-switch capacity access as line rate increase beyond 100G, and systems suppliers will have to comply. This too will drive greater need for photonic integration on the line side.

**Conclusions**

Core networks are in the midst of a transformation aimed at dramatically increasing capacity while also maximizing transport efficiency to reduce the cost per bit for transport. Core optical networks are at the beginning of a transport rate migration from 10G to 100G, the first step-up in channel rates since the migration from 2.5G to10G in the late 1990s.

As operators embark on the 100G migration, they seek to maximize their 100G network efficiency by inserting OEO grooming functions between DWDM wavelengths in order to pack these channels as full as possible and avoided stranded capacity. Operators believe that OTN as a universal transport protocol built to handle both packets and TDM is the best technology to perform this grooming function. Furthermore, by integrating OTN switching within the same elements that perform the WDM transport, operators can reduce short-reach interconnect costs and simplify management and provisioning. Heavy Reading believes that the vast majority of operators will choose this integrated approach.
Finally, as operators place new 100G systems into their networks, they want to ensure that these new systems will be future-proof for eventual bit rates beyond 100G. There is tremendous industry momentum supporting super channel to enable transport rates of 400G, 1T and beyond. Parallel photonic integration is the best fit for these super channels, which, by definition, require multiple carriers, and so we see renewed industry interest in PICs.

While photonic integration becomes a must in the super channel era, we also see application for PICs at 100G – whether using small scale serial integration to support the OIF 100G MSA or using large-scale parallel integration for 100G transport, as is the case with Infinera. As we move to the 100G era and beyond, the use of photonic integration becomes more pervasive and, ultimately, mandatory.