Cost Effective Optical Networks:
The Role of Optical Cross-Connects

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1. Introduction

1.1. The need

Communications and metallurgy have been at the heart of progress in human civilization since the beginning. This was true of stone-age cultures, it was true of Greek and Roman civilizations, it has been true in the modern world, and it is going to be true in the future. Introduction of new technologies, or new communications routes and media, has traditionally been one of the forerunners of societal revolution and we are in the midst of such a revolution at this moment. Our new “metallurgy” is the silicon chip and its gallium arsenide cousins. Our new communications routes and media are those of the Internet and telecommunications networks.

With an ever decreasing cost of transmission, and the seemingly endless ability to offer broader and broader bandwidth transmission and switching, applications and services designers are using up that bandwidth as fast as it can be created.

In addition, the economic opportunities for telecommunications have produced a very chaotic market with both the creation of new telecommunications carriers and the mergers and acquisitions of old ones at a rate hitherto unimaginable.

All of this will result in one singular need: the ability to flexibly manage that bandwidth, to be able to rearrange it, to interconnect it, to restore it in case of failure, and to provision new services transparently and efficiently. With the fundamental unit of bandwidth rapidly approaching 2.5 Gbit/s in the core of the network, the need for high-speed restoration and protection switching takes on a whole new meaning.

In this environment, it is efficient to introduce into the physical layer of the network an optical sublayer with cross-connects at the nodes that provide for reconfiguration of the connectivity of the high-speed channels in their entirety: adding them, dropping them, switching them between incoming and outgoing ports, and providing access to them as may be needed

In this paper, we present the arguments for the introduction of cross-connects in the optical layer, and the results of economic modeling of introducing optical cross-connects into both metro and long-haul networks. The cost-savings are shown to be significant in both cases without even considering the operations savings achieved by what amounts to the automation of the physical layer network.

The introduction of such capabilities into the network will be an essential part of realizing the full potential of the bandwidth of fiber, and will be essential to carriers in their drive to be competitive as well as to be able to provide the flexible connectivity in this world of rapid churn and change.

In short, optical cross-connects enable the building of networks and networks of networks, not just providing more bandwidth.

1.2. The approach

In traditional networks, the physical layer is regarded as unchanging unless a person is dispatched to reconnect or reconfigure the connections of fibers. There are three obvious reasons why this is a bad idea: first, it is expensive, second, it takes much longer than can be tolerated, and third, it is error-prone. What is not so obvious is that we no longer can trust our abilities to predict what the network should look like even
two or three years in the future. We do not know what speeds it will need to carry, we do not know what services it will carry, and we certainly have no idea what the traffic distributions will look like.

The answer to all of this is to provide the flexibility of switching high-speed optical channels in the core of the network.

One means for doing this now is to use large port-count digital cross-connect switches (DCS) and large numbers of time division multiplexers. This is an expensive approach as will be demonstrated in the examples to be presented. It also is difficult to perform restoration and protection switching in reasonable time limits in large networks because the switching action is done on sub-rate channels, one at a time, sequentially, rather than at the high-speed channel rate. And, configuration or provisioning of high-speed interconnection paths requires the coordinated switching of all of the sub-channels and re-assembly, a cumbersome process at the least.

The alternative discussed here is to deploy cross-connects at the optical layer. In this approach, the cross-connect switches at the line rate of the channels on the input ports, providing restoration and protection switching on a full OC-48 channel in one operation and avoiding the need for large banks of TDM multiplexers. The size of the required cross-connect is also commensurately reduced, both in port count and in physical dimension. Management of the optical layer is done at the optical layer and directly on each of the optical channels.

These optical cross-connects, so called because they operate at the optical line rate and on whole optical channels at a time, require a significant amount of information about the optical channels in order to perform fault management, protection switching and restoration, and to verify connectivity through a switch. This is done by accessing the various overhead bytes of the SONET carrier.

The use of SONET in the evolving network is to provide the overhead and framing structure. Internet Protocol (IP) routers and switches, Asynchronous Transfer Mode (ATM) switches, traditional SONET add-drop multiplexers and digital cross-connect switches (DCS) all use the SONET framing structure to provide the necessary overhead structure for transporting and switching their payloads. To access these overhead bytes requires the detection and processing of the SONET signals in the optical cross-connect, which means high-speed electronics. This leads to the use of electronic switching fabrics as the most cost-effective way of implementing the cross-connect switch function.

All-optical switching fabrics have been proposed as a means of cross-connecting signals regardless of bit rate or data format and therefore providing a degree of “future proof” design. These would be designed as optically transparent switches. One major benefit of an all-optical design would be an opportunity to significantly reduce the dc power consumption within the switch. However, there is a considerable cost. The actual state of the art of all-optical switches is that they are expensive, and they are of insufficient port count to be competitive with electronic fabrics at the moment. New technologies may change that but not for several years.

So, the architecture of preference for an optical cross-connect at this time is that of an electronic switching fabric consisting of a multistage switching fabric, with input and output interface boards that provide optical detection and regeneration, SONET framing and overhead processing. All of these functions are performed at the line rate of the optical channel, most commonly at OC-48 (SDH-16) rates. Extensions to OC-192 interfaces and switching will be developed soon.

1.3. The benefits

The most noticeable benefit of using optical cross-connects is a lower network cost and higher fiber efficiency. A typical traffic pattern at a node in the core of a network is that somewhere between 50 percent and 75 percent of the traffic is “through” traffic. Such through-traffic can be routed straight through a cross-connect without a need for any additional processing or switching. Instead of having to devote high-cost ports on DCSs or IP Switches to such traffic, much lower cost optical cross-connect switches can be used to express route the trough traffic. Cost savings of 30 to 40 percent are projected, as discussed later.

Operations costs are also reduced because of the automated and remote control functions available. Testing and provisioning can be performed on the entire network from a single remote location. Optical cross-connects also enable ring network interworking and the building of networks of complex ring and mesh
architectures. Networks can be configured in the same cross-connect on a wavelength-by-wavelength basis. For example, in a single cross-connect, several wavelengths, or channels, can be configured as self-healing rings, while other channels are connected as meshes. Protection and restoration protocols are selectable on a wavelength-by-wavelength basis, and mesh restoration times of the order of 50 to 100 milliseconds are achievable in a nationwide network.

Another benefit includes the removal of signal impairments that would otherwise accumulate in a cascaded transparent network. This is important because it allows the nearly limitless scalability of the network.

1.4. The Tellium Solution

Tellium believes that the need for more efficient restoration and protection networks will result in core networks being constructed as meshes because of the efficiency of shared-protection-resources that meshes allow. This places a premium on the availability of high-speed optical cross-connect switches and mesh restoration algorithms.

Tellium also believes that the fundamental building block of core network capacity will be the OC-48, 2.5 Gbit/s optical channel. This implies switching at OC-48 rates in the fabric of the switch, without demultiplexing into lower-rate signals.

We believe that SONET framing is essential to producing a manageable intelligent layer-one network.

We believe that regeneration and retiming (full 3R) is required to build extendable networks rather than just transmission pipes, and that the proper place in the network to perform that regeneration is in the optical cross-connect nodes. An all-optical transparent network must be designed to maintain signal integrity over its worst case path. Regeneration obviates that need.

The optical layer must be a managed layer to provide survivability. Survivability in the optical layer is key to providing service independent protection.

2. Evolving METRO and CORE Optical Network Architectures

The evolution of the Metro network is proceeding according to Figure 1, below. SONET rings, so popular because of their fast protection switching, have become the metro networks of choice for most network operators. Protection switching in less than 50 ms using industry-standard SONET add-drop multiplexers has achieved a level of network survivability unavailable heretofore. However, the economics of SONET rings are not as attractive as desired. To increase capacity, rings are stacked up on each other, and require digital cross-connect switches to interconnect them and to manage the traffic flow into the backbone network. Ring architectures also require protection bandwidth essentially equal to the service bandwidth and therefore use a lot of additional fiber.

In addition, OC-48 SONET ADMs do not have any OC-48 add-drop interfaces, and therefore direct connection of OC-48 traffic from routers and data networks is not possible.

The bandwidth problem is currently being addressed by adding DWDM overlays, each of which is managed separately, avoiding deployment of additional fiber, but still requiring all the SONET ADMs and not providing direct OC-48 add-drop ports. Transparent optical ADMs are possible on a limited number of channels, which would allow direct OC-48 add-drop, but the industry hasn’t yet been able to decide how important flexibility in the add-drop channels is and how many are needed. Optical switches are still expensive. And, the protection bandwidth problem would still be there.
Mesh architectures can provide protection much more efficiently than rings by sharing the protection bandwidth for several service paths. Instead of 100 percent protection overhead, perhaps only 30 or 40 percent is possible. For this reason, mesh architectures are being examined for deployment in both backbone long haul applications and in the metro networks of our large cities. Not only is the fiber cost reduced, but the use of optical cross-connects also provides significant cost savings.

Such a network architecture is shown in the following figure.

Mesh/Ring Network

Simplified Protocol Stack

= Aurora Optical Cross Connect
= WDM Terminal
= IP Router

Fig. 1 Stacked SONET Rings

Fig. 2 Future mesh and ring architectures based on optical cross-connect switches and network architecture configuration on a wavelength-by-wavelength basis.
Here, the optical cross-connects provide a protected, restorable optical layer network of wide flexibility. Interconnection to the network can be at essentially any SONET rate and IP Routers, ATM Switches, and SONET add-drop multiplexers all become essentially peer processes, flattening the architecture and the protocol. There is no inherent need to use SONET ADMs to transport IP or ATM traffic, for instance.

Mesh restoration is more complicated than ring protection switching, and in the past restoration times have been excessively long. Using the OC-48 channel as the basic building block of the core network allows mesh restoration in less than 100 ms, and algorithms for doing that are in development.

3. Applications for Optical Cross-Connects

The following are several examples of applications for optical cross-connects and the benefits they provide the network operator.

3.1. Automated Optical Layer Provisioning

![Diagram of automated optical layer provisioning and dynamic wavelength management](Fig. 3)

Optical layer provisioning is automated through the use of an optical cross-connect at the interconnection nodes for one or more DWDM systems. Here we show three DWDM terminals, all potentially from different vendors, being interconnected in an optical cross-connect. The interconnection between the cross-connect and the other network elements and terminals is done via standard short reach 1.3 \( \mu \text{m} \) fiber interfaces. This is an “opaque” network architecture in which the DWDM systems utilize transponders to convert the 1.3 \( \mu \text{m} \) signals to the desired DWDM channels in the 1.55 \( \mu \text{m} \) band. This facilitates interoperability between different vendors’ DWDM systems as well as the ability to interconnect channels that are assigned to different wavelengths. This is a particularly important feature when going between systems that have differing sets of wavelengths.
This Figure also shows the interconnection with a digital cross-connect switch (DCS), or equivalently, an IP router, which enables local traffic to be accessed and / or groomed.

Spare or vacant capacity can also be accessed by this system to provide additional service capabilities or for protection or restoration.

3.2. Automated Patch Panel Replacement

**Benefit:** Enables remote optical cross-connect function; operations savings

![Diagram](image)

Fig. 4 Automated Patch Panel Cross-connect Application

The optical cross-connect may be used effectively to provide automated fiber patch panel functionality. Here is shown the use of the cross-connect to interconnect channels from several DWDM systems, some traditional TDM transmission equipment, and providing connection to a broadband or wideband digital cross-connect switch (DCS). The use of standard 1.3 μm optical interfaces enables interoperability with virtually all SONET and DWDM network elements and systems. This application provides cost savings in operations and maintenance, where manual operations are often error prone, and facilitates record keeping.
3.3. Automated Remote Test Access

**Benefit:** Enables centralized remote optical testing; savings of $75K per saved Test Set.

The Tellium optical cross-connect has a multicast capability that permits any input port to be bridged to both its intended destination port and to a specially assigned Test Access port. Using this test port, and supporting test gear, the network performance can be monitored and tested remotely, including such traditional functions as continuity, loopback, and error-rate testing of out-of-service fiber or wavelength channels. The operations savings here are due to both a serious reduction in the amount of test gear required and in the ease of testing remotely from a central location.

3.4. OC-N Switching

Grooming of SONET traffic, and switching of IP and ATM traffic, may require granularity finer than the OC-48 line rate found in the core of the network. Coupled with the characteristic of 50 percent or greater pass-through traffic found in most core networks, the optical cross-connect can be used to efficiently route such traffic at any node to its respective switching element and to connect the resultant groomed or switched traffic to the outgoing fiber or WDM system. This application is illustrated in the two following figures, the first showing subrate channels being switched in an OC-48 system, and the second showing the grooming and switching of OC-48 and lower channels in an OC-192 system.

Both of these applications provide operations savings through optical layer automation of provisioning and restoration. Dynamic optical switching and routing in the core of the network and grooming at the edge using optical cross-connects in combination with higher layer network functions will provide the most cost-effective solution while providing a smooth evolution to a manageable broadband network.
**Benefit:** Operations Savings through optical layer automation, enables OC-N restoration & switching

Fig. 6  OC-N Switching: Grooming and switching of various traffic types in OC-48 networks using optical cross-connects.

Dynamic Optical Networking in the Core
Grooming At the Edge

Fig. 7  OC-N Switching: Grooming and switching within an OC-192 network using optical cross-connects.
A summary of these and other potential applications for optical cross-connects includes:

- Fiber Patch Panel Replacement
- Automated Optical Layer Provisioning
- OC-N Switching
- Remove Cascaded Optical Impairments (Optical 3R Regeneration)
- Remote Test Access
- Video Broadcast / Multicast
- Multiple Carrier Bandwidth Access
- Protected Optical Services
- Ring Interworking
- Optical Ring & Mesh Restoration


The fundamental economic driver for the application of optical cross-connects is that the cost of a port on an optical cross-connect can be as low as one-quarter the cost of an equivalent port on a DCS, and perhaps one-half the cost of the equivalent port on a high speed router. It therefore makes good sense to groom the traffic so that through-traffic can be switched through a node in an optical cross-connect rather than to perform that function in a DCS or a router.

In order to illustrate that benefit, we have modeled both a metro network and a national network to show the economic benefits of using optical layer cross-connects to provide restoration and interconnection flexibility. For comparison, we have used several scenarios utilizing various combinations of DWDM, all-fiber, restoration and no restoration, and digital cross-connects (DCSs), in addition to the use of optical cross-connects. Needless to say, these are simplified examples, but the results are significant enough to be convincing.
4.1. **Metro Network Optimization Example**

- 11 - node Metro network
- 1 - 16 mile spans
- Optical Cross-connects, DWDM, and DCSs modeled

**Five Scenarios:**
1. OXC & WDM/ Rest.
2. OXC & WDM/ No Restoration
3. OXC and Fiber
4. DCS & WDM
5. DCS & Fiber

Figure 8 shows an example 11-node Metro network having spans of 1 to 16 mile lengths. The use of DWDM, Optical Cross-connects, and Digital Cross-connect switches is optimized to minimize cost of building the network from scratch. Five scenarios are studied:

1. OXC and DWDM with Restoration
2. OXC and DWDM without Restoration, as a baseline
3. OXC and Fiber with Restoration
4. DCS and DWDM with Restoration
5. DCS and Fiber with Restoration

It should be noted that there are no optical amplifiers required for this network example.

The results are shown in the following chart.
Fig. 9 Capital costs for the Metro network of Figure 8

It is clear that the costs are much higher for the two DCS cases than for those using the optical cross-connect, whether DWDM is used or not. We also see that the use of the optical cross-connect and DWDM is the least expensive means of providing 100 percent restoration capability in this example of a Metro mesh network; a cost saving of approximately 60 percent. The use of additional fiber to provide the restoration capacity in place of the DWDM is in between. The cost of the OXC is about 20 percent that of the DCS.
4.2. Backbone Network Optimization Example

A national backbone network optimization model is shown in Fig. 10. This model includes 17 major network nodes, and the optimization studies the use of DWDM, optical cross-connects, and digital cross-connect switches to minimize the cost. Four scenarios were studied: 1) pure DWDM without OXCs and without any restoration, 2) DWDM and OXCs but without restoration, 3) DWDM and DCSs with restoration, and 4) DWDM with OXCs and with restoration. The traffic matrix for this example was a highly interconnected mesh.

The results of the optimization are shown in the Figure 11.

Fig. 10  Long-haul national network optimization interconnection network example
The most striking result shown in the resulting network costs is that the Tellium solution using optical cross-connects and DWDM with restoration is roughly half the cost of when DCSs (digital cross-connect switches) are used. Since there will be additional operations cost savings with the OXC model due to a reduced number of managed elements, it is believed that these projected cost savings are conservative.

It is also seen that in the case of no restoration, the addition of the optical cross-connect results in small savings due to improved grooming of DWDM channels. This alone is a highly interesting feature of the optimization because it says that adding cross-connects to a network design does not necessarily add cost while at the same time it adds a great deal of flexibility and manageability to the network.

National scale mesh networks are more cost-effective using optical layer cross-connects, but they make it imperative that the optical layer be self-protected. High-speed mesh restoration becomes a necessity, and this is made possible by doing the restoration, at least in part, at the optical layer using optical cross-connects. Such restoration can be performed in times of 50 to 100 milliseconds, compared with minutes to tens of minutes in the DCS-based restoration of today.

It is clear that the use of optical layer cross-connection and mesh restoration will be one of the key factors in providing manageable backbone high-capacity networks.

5. The Tellium Aurora Optical Cross-Connect Solution

Tellium offers a line of scalable optical cross-connects that are based on an internal electronic switching fabric that switches at the OC-48 full line rate of 2.5 Gbit/s. These are fully non-blocking switches that use low-cost short reach 1.3 µm interfaces, 3-R regeneration, have internal dual redundancy, and are scalable to very large sizes. Current products include the Aurora 32 and the Aurora 512. The Aurora 32 is the first optical cross-connect product to reach the marketplace. These are both fully managed network elements with management interfaces developed to meet a wide variety of application needs.
In addition to the cost savings discussed above, optical cross-connects require a much smaller installation footprint. The Tellium Aurora 512 provides 512 ports in a three-bay installation, including the internal dual redundancy of the switch matrix and all management interfaces.

The Aurora 512 Optical Cross Connect System is the highest capacity optical layer switching element available in the industry today. Its primary function is to cross-connect high speed (up to OC-48c) optical signals while bypassing the entire SONET/DCS layer. The Aurora 512 also performs restoration, dynamic wavelength management, and network gateway functions.

Fig. 12 The Aurora 512 Optical Cross-connect

Features and capabilities of the Aurora 512 are:

- 512 bi-directional ports, up to OC-48 line rate
- Up to 2.5 Gb/s per port (OC-48/STM-16) for a total switching capacity of 1.28 Terabits per second
- Scalable up to 400 Terabits per second capacity
- OC-192 ready with OC-48 grooming
- SONET performance monitoring
- Broadcast and multicasting through switch matrix
- Fully redundant switch architecture
- I/O port protection 1:n user programmable
- Optical line protection switching under 50 msec
- Optical ring restoration (UPSR and 4F BLSR)
- Optical mesh restoration

6. Conclusions

Optical cross-connects will become a cost-effective cornerstone of broadband networks at both the metro and national levels, providing cost-savings, bandwidth manageability, and application flexibility throughout the network. As the network migrates from time division multiplexing and traditional telephony to a data-centric optimized network, optical cross-connects will be necessary to perform management, restoration, provisioning, and optimization of the optical layer in the network. This is a rapidly developing product and
application, with small cross-connects available today, cross-connects in the 512 port class available in the year 2000, and larger versions soon afterward.