CWDM and GFP in the Metro Core

Abstract
The metro core - the heart of the public telecom network - is becoming critically important to the performance of the overall network. On the one hand, it is sending and receiving data from the huge long-haul pipes, while on the other it is being taxed on the access side by an increasing stream of voice, data and video appearing in a variety of formats. It is no wonder that this area is often the troublesome bottleneck that is inhibiting full traffic throughput. Attempts to remove this bottleneck with long-haul technologies such as Dense Wavelength Division Multiplexing (DWDM) and proprietary "sub-lambda" multiplexing have proved too expensive. Recent market realities have increased the need for new lower-cost technologies and standards that offer viable cost-efficient solutions to the growth of the metro core infrastructure. This paper outlines how products based on the new Coarse WDM and Generic Framing Procedure (GFP) standards can solve these problems at much lower cost and with much greater efficiencies than previous solutions.

1 Introduction

1.1 Metro Core Definition

With the decentralization of Central Office equipment to remote switching centers, Central Business District (CBD) buildings, underground vaults and curbside cabinets, it is becoming less clear where the boundary lies between the metro core and the metro access networks. Similarly, the geographical differences between metro core and long haul are starting to blur due to urban sprawl and the formation of satellite cities. The term metro-regional is sometimes used to differentiate the extended metro core from the long haul. In this paper, we will define the metro core network in terms of its functionality, distance and capacity and how it interfaces to the long haul and the metro access networks.

1.2 Functionality

The metro core adapts, multiplexes and grooms traffic from the access network and transports this aggregate traffic to other metro nodes - generally Central Offices (COs) - where it is demultiplexed and switched or routed to co-located service providers, other access networks, or to the long haul network. The multiplexing, switching/routing and grooming may be performed at the circuit level and/or packet level to meet differing service requirements. Circuits can be provisioned in the time-domain (TDM) or the wavelength domain (WDM).

1.3 Distance

Generally, the individual link distances between COs can range from intermediate reach (< 40 km) to long reach (< 80 km) and the overall extent of the metro core network (eg, a metro-ring perimeter) can vary from kilometers for small cities to hundreds of kilometers for large cities (up to 300 km for example). In contrast, metro access networks are much smaller in size (mostly less than 40 km).

1.4 Capacity

The capacity of metro core networks can be defined in terms of switch/router capacity and transmission link capacity. The transmission links meet their capacity requirements using more fibers and/or more wavelengths and/or higher data rate channels. Today, most transmission channels have a data rate less than or equal to 2.5 Gbit/s (OC-48/STM-16). Higher capacity channels, up to 10 Gbit/s (OC-192/STM-64 and 10 Gigabit Ethernet) exist but are not being deployed as quickly as expected.

1.5 Long Haul Interface

The long haul transmission network comprises multiple fiber pairs and multiple DWDM wavelengths, with each wavelength transporting either a 2.5 Gbit/s or a 10 Gbit/s SONET/SDH channel. Consequently, for most carriers, these are the only two interfaces between the metro core and the long haul. A large STS-1 switch is often installed at this interface to groom traffic between the metro core and long haul channels. This interface is called "opaque", since it involves Optical-Electrical-Optical (OEO) conversion between the metro core and long haul optical networks. There is generally no transparent (all-optical) wavelength interface between these two networks, since the cost of using long haul quality lasers throughout the metro core network is at this time prohibitive.

In some cases, the 10 Gbit/s traffic is transported across the long haul by inverse multiplexing onto 4 x 2.5 Gbit/s SONET/SDH channels. This is done to reduce dispersion and increase the un-repeatered transmission distance. This is especially important where there are many fibers and wavelengths involved, since for long haul applications multi-channel repeaters can be very expensive. At major OEO switching centers, equipment vendors also use inverse multiplexing to adapt the optical transmission channel to a circuit switch fabric – since most large electrical switch fabrics are optimized to handle 2.5 Gbit/s streams only.

1.6 Metro Access Interface

The interface between the metro access and the metro core is very different to that described above for the long haul. The metro access networks comprise a plethora of protocols, each optimized for a particular service and customer need. Both legacy and new protocols must be supported and the evolution to a ubiquitous access protocol is about as likely today as it was 10 years ago (the undelivered promise of ATM being a case in point).

For all the protocols supported at the metro core to access interface, there are multiple ways of transporting and switching each of these across the metro core network. Examples include:

a) Via a dedicated dark-fiber physical layer network with optical patching at a Main Distribution Frame (MDF);
b) Via a WDM physical layer network with OOO or OEO switching;
c) Via a SONET or SDH transport and STS-1 circuit-switched network;
d) Via a SONET or SDH transport and ATM cell switching network;
e) Via a Gigabit Ethernet (GbE) or Fibre Channel (FC) packet switched network; and
f) Via any of the above lower-layer protocols with MPLS and IP packet routing.

Multiple equipment vendors support each of these transport and switching options and each vendor can provide very good reasons why their solution is the best. The reality is that each is more suited only to certain types of traffic and to different applications.

In all cases, the traffic can be transported as is within the metro core but it must be adapted to 2.5 Gbit/s or 10 Gbit/s SONET/SDH before transmission across the long-haul interface. Traffic that is already in this format will clearly require no adaptation or cost burden at the long haul interface. The ratio of traffic that crosses over to the long haul, to the traffic that stays within the metro area, will influence the optimum metro network solution. The challenge for the carriers is to build a metro core network that provides the best compromise for handling all customer protocols, service requirements and traffic patterns. An even greater challenge arises as these parameters vary from one metro area to another.

1.7 Cost Considerations

The metro core network provides the "glue" connecting the long haul network, numerous metro access networks, co-located carrier equipment, service provider equipment and end-customer equipment. It should provide transparent switching and transport where possible to reduce costs, with adaptation from one form of transport to another only when necessary. This is because every conversion from one protocol to another adds cost to the network.

For example, the 10 Gbit/s transmission, switching and interfacing issues mentioned in section 1.5 above may be contributing to the slower than expected rollout of 10 Gbit/s transmission channels in the metro core network. There are fewer conversions if all channel rates are capped at 2.5 Gbit/s and - for the time being - this keeps the metro core network costs down. This is unlikely to change until there is greater price erosion of the network equipment needed to support seamless 10 Gbit/s multiplexing, transmission and switching.

2 Metro Core Network Architectures

2.1 Existing Infrastructure

2.1.1 Transport and Switching Equipment

To cater to the diverse needs of service providers, private enterprises and end-customers, a mix of broadband and narrowband transport and switching is required. As outlined below, WDM transport and optical switching enables broadband growth, but it alone is insufficient to achieve the narrow bandwidth granularity required by millions of metro customers. To support the full spectrum of broadband and narrowband services, WDM equipment must be complemented by TDM circuit switching, packet switching and routing equipment.

TDM circuit switching is increasingly performed by Digital Cross-connect Systems (DCS) with narrowband Virtual Tributary (VT 1.5, 2 & 6) and broadband STS-1 (51.84 Mbit/s) channel granularity. The DCS supports n x STS-1 concatenated channel capacities, where n = 1, 2, 3, 6, 9, 12,…192 (ie, 51.84 Mbit/s to 9.95 Gbit/s). When combined with multiplexer products conforming to the recently approved GFP Standard (ITU-T G.7041 / Y.1303 dated Dec'01), STS-1 switching in the metro-core is expected to enable seamless end-to-end transport of digital voice, data and video services, from the metro access to the long haul.

While TDM circuit switching is most suited to channelized services, such as leased line private networks and time-critical services such as voice and video, packet switching and routing are more suited to bursty data traffic associated with virtual private networks and the Internet. Carrier-grade Gigabit Ethernet switches and IP packet routers are installed in the metro core to handle this type of traffic. For improved Quality of Service (QoS) for packet services, Multi-Protocol Label Switching (MPLS) is growing in support. For Storage Area Network (SAN) applications requiring low-latency, bulk packet data transport, Fibre Channel, FICON and ESCON networks and switches (called “directors”) are often used.

Within the metro core, IP routers often have low cost GbE interfaces for transporting data to other IP routers and to network servers. However, such GbE networks are not extended across the long haul in their raw 1.25 Gbit/s format. This protocol and rate does not fit with the metro-core to long haul interface options discussed in section 1.5. Instead, more expensive Packet over SONET (PoS) interfaces running at the OC48 rate are currently used to transport IP traffic between metro core routers over the long haul network.

2.1.2 Predominance of SONET/SDH Transport Rings

Synchronous Optical Network (SONET) and Synchronous Digital Hierarchy (SDH) were introduced in the late 1980s as standards-based multiplexing and transmission protocols for fiber optic networks. These replaced the proprietary fiber optic implementations of Plesiochronous Digital Hierarchy (PDH) networks, which had preceded them.

Over the past 10 years, SONET and SDH networks have spread to just about every part of the telecommunications network, from the long haul through the metro core to the metro access networks. When they were first introduced, the predominant traffic type was telephony and for this reason, their design was optimized for handling hundreds to thousands of narrowband 64 kbit/s PCM voice channels, although hooks were included for eventually handling higher-capacity services.

Advantages

SONET and SDH can be configured as point-to-point, bus or ring topologies with typically five and up to 16 add/drop multiplexer (ADM) nodes per bus or ring. Protected SONET and SDH rings have dominated in all parts of the network due to their simple, self-healing capability in the event of fiber cable breaks or equipment failure.

SONET/SDH rings implemented with ADMs having TDM switching capability for Virtual Tributary (VT) and STS-1 payloads have enabled multiple logical mesh networks of almost arbitrary sub-rate capacity to be configured between nodes in the ring. This results in greater utilization of the ring capacity and supports the rapid provisioning of private networks for service providers and enterprise customers.

Built-in performance monitoring capabilities with Bit Error Rate (BER) analysis enable faulty links and channels to be identified quickly, thus supporting Service Level Agreements (SLAs) for private network services and enterprise customers.

Perhaps the most important advantage of SONET/SDH is that it (like Ethernet) is ubiquitous throughout the network.

Disadvantages

Initially, SONET/SDH was focused on the transport of narrowband voice and data services. Standards for mapping T1/E1 streams into Virtual Tributaries (VT1.5/VT2) enabled seamless end-to-end transport of customer voice and data traffic. Mapping DS3/E3 into a STS-1 payload and ATM into OC-3/STM-1 and OC-12/STM-4 provided some relief for transporting higher bandwidth data services. However, lack of standard mapping and multiplexing procedures for native data-centric protocols (such as GbE) has until recently thwarted their integration with the existing SONET/SDH infrastructure. In the absence of standards, proprietary TDM multiplexers (also called "sub-lambda multiplexers" in WDM systems) have been deployed to transport native data-centric protocols over SONET/SDH.

The Packet over SONET (PoS) specification defined by the Internet Engineering Task Force (IETF – RFC 2615) is an interim solution to the above broadband data transport problem. However, this is targeted primarily at IP packet networks and associated routing equipment. GFP - being an ITU standard - offers a more flexible solution for transporting multiple data-centric protocols in their native packet format.

In all the above cases, a disadvantage of SONET/SDH transport is that extra adaptation layers are required between the native data protocol and the SONET/SDH network. This is further exacerbated when ATM adaptation layers are included in the transport chain. This adds cost and increases the end-to-end transmission latency, which for some data applications can significantly reduce the effective data throughput.

2.2 Adding New Services

2.2.1 New Services & Protocols

In the early 1990s, the transition of the Internet from the ARPANET to the World Wide Web led to the vast array of data services and associated bandwidth demands that we have today. For service providers and enterprise customers, Internet technology has extended to private Intranet and semi-private Extranet applications. Since these are all computer-centric technologies, it stands to reason that Fast Ethernet (FE) and Gigabit Ethernet (GbE) based Local Area Networks (LANs) are popular as low cost data transport and switching solutions for interconnecting computers, servers and workstations, both within and between offices and campuses. The latter are sometimes referred to as Metropolitan Area Networks (MANs).

Gigabit Ethernet and native 10 Gigabit Ethernet are also suitable for data transport across vast (long-haul) distances, although the OC-48/STM-16 and OC192/STM-64 interface between the metro core and the long haul requires some form of adaptation. In the case of 10 GbE, OC-192/STM-64 has been defined by IEEE 802.3ae as an alternative transport option, thus reducing cost and transmission delays associated with the protocol mapping process.

While LANs and MANs based on the Ethernet standards are most suited to bursty, transaction oriented and client-server data traffic, Storage Area Networks (SANs) based on Fibre Channel, FICON and ESCON are more suited to handling bulk packet data transfers between servers and disk arrays for example. These SAN standards need to co-exist with the Ethernet-based standards, since the transport and switching requirements are different. For example, SAN applications are more sensitive to end-to-end transmission latency. ESCON, for example, starts to become inefficient for distances and associated delays greater than 10 km (50µs delay). ESCON is thus limited to smaller metro-core networks. In contrast, Fibre Channel (FC) and FICON are more suited to remote storage and disaster recovery applications. These protocols start to become inefficient for distances greater than 100 km (500µs delay). Computer equipment can, however, use "buffer credits" to permit greater efficiency over extended transmission distances and through switching and conversion delays.

In addition to new broadband data services, the 30-year old promise of video on demand (VoD) services is now finally coming to fruition due to low cost MPEG compression technology and the increasing availability of affordable server capacity and network capacity - all the way to the end-customer.

Metro access networks that provide greater capacity to the residential customers include HFC-cable networks and fiber-fed remote terminals (RTs) with DSL. The RTs typically interface via DS3/OC1, OC3 or OC12 SONET to telephony and ATM switches at the access edge of the metro core network. The HFC networks interface to the metro-core via transmultiplexers with digital video distribution networks based on ATM/OC12, DVB-ASI and GbE standards.

Where broadband wireline networks are too difficult or too slow to deploy, MMDS wireless networks are yet another means of delivering video, voice and data services to business and residential customers. These metro access networks interface to the metro core via remote (base-station) multiplexers, with ATM/OC-n and Gigabit Ethernet backhaul options. Figure 1 below illustrates the various protocols that support new services in the metro area.

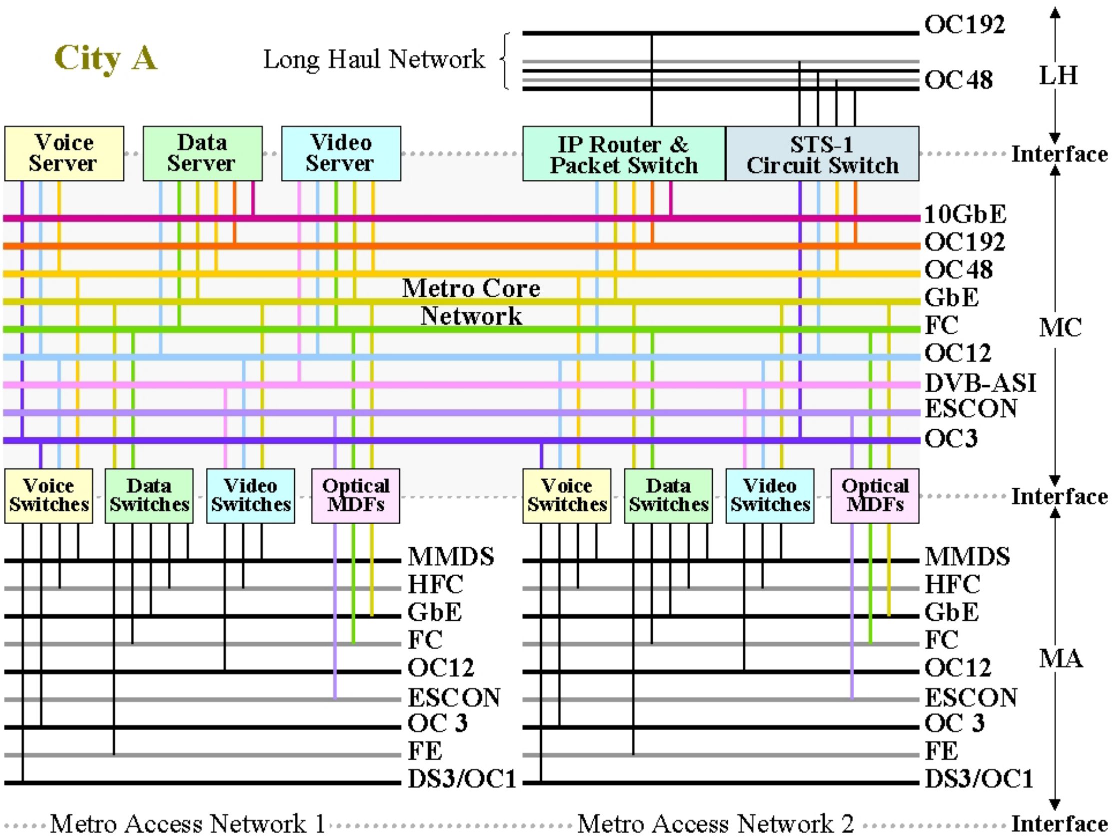

Figure 1 Metro Access, Metro Core and Long Haul Transport and Switching Options

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As shown in Figure 1, in most cases, there are voice, data and video switches at the edge of the network, which hand off traffic between the metro access and the metro core. In some cases, service providers and enterprise customers require either dark fiber or clear wavelength connections for low end-to-end latency and lower equipment cost. This is shown in Figure 1 for the case of GbE, FC and ESCON connections. Figure 1 also accentuates the interfacing differences between the long haul and metro access edges to the metro core network.

2.2.2 Broadband Service Requirements

Provisioning broadband networks for service providers and enterprise customers is always an expensive proposition (only the definition of broadband changes – not the price). Service Level Agreements (SLAs) are therefore required between the carrier and the customer. SLAs define the price and the Quality of Service (QoS) and typically take the following customer requirements into account:

- Interface protocol (eg, GbE, FC, OC12 etc);
- Security (eg, dedicated fiber/wavelength, circuit-switched or shared packet network);
- Peak Information Rate (applicable to shared packet networks or channels);
- Committed Information Rate (applicable to shared packet networks or channels);
- Protected vs Unprotected (including path and equipment protection options); and
- Minimum Bit Error Rate (BER) – requiring performance monitoring.

2.2.3 Fiber Exhaust Issues

In the early 1990s, a large amount of fiber was deployed in metro core networks; however, unexpected and unevenly distributed demand has resulted in pockets of congestion. Pulling and plowing-in new fiber can be expensive and time-consuming - especially in the metro-area where road closures are required. Congestion relief can be provided by forklift upgrades to the existing transmission equipment, or by adding a WDM overlay to provide fiber pair gain. The latter option is preferred since service disruption is avoided; the existing transmission equipment can see out its service life; and new equipment, such as Metro Ethernet switches or Next Generation (NG) - SONET ADMs can be deployed where and when needed.

In contrast to previous expectations, the actual number of wavelengths required per fiber in the metro core is generally less than eight and mostly less than 16. With 20-20 hindsight, this makes sense if you consider that for simple fiber pair-gain applications, the number of wavelengths needed depends on the wavelength-capacity growth rate and the residual fiber life. For example, for 10 years residual fiber life and 20% p.a. growth rate, then $1.2^{10} \Rightarrow 7$ wavelengths required. For 30% growth rate, this equates to 14 wavelengths.

2.3 Latest Architectures & Protocols

2.3.1 Metro DWDM Networks

In the late 1990’s, DWDM networks diffused from the long haul to the metro-core, providing a quick solution to a rapidly growing fiber exhaust problem. The legacy long-haul requirements were stripped away, such as distance (< 300 km instead of 3,000 km) and number of channels (typically 4-32 channels instead of 160 channels), eventually resulting in lower cost network implementations. New metro-specific requirements were added, such as the need for multi-protocol support (instead of just 2.5 Gbit/s and 10 Gbit/s SONET/SDH).

The new protocols to be supported are illustrated in Figure 1. The metro-core also required any-any channel connectivity between COs using “true-ring” topologies - in contrast to hubbed topologies with traffic switching and grooming at each hub. Support for existing SONET/SDH metro-ring networks with no downtime was a must, with the new protocols and services added unobtrusively at the wavelength layer.

Notwithstanding the rationalization of DWDM technologies for metro-core applications, they, like their long-haul counterparts, are still hampered by fiber dispersion and optical power management complexities associated with up to 300 km ring perimeters and the losses associated with multiple optical add/drop nodes and associated fiber links. High cost externally modulated lasers and/or low dispersion fiber are required to overcome the dispersion issues and expensive erbium doped fiber amplifiers (EDFAs) are required to overcome the accumulated losses associated with all-optical add/drop multiplexers and fibers.

Given the above issues, suppliers developing all-optical DWDM products for the metro-core market would generally agree that the “holy grail” of metro-ring designs is a “digital-optics” solution comprising reconfigurable optical-add/drop multiplexers with built-in optical amplification at each node and flexible power management providing a “unity-gain” system. In this way, wavelengths can be selectively dropped and added under local or remote network management control, while the optical power of all wavelengths exiting each node is the same for all nodes in the metro-ring. Digital optics overcomes the complex and costly analog-like design problems of existing all-optical WDM networks – enabling a truly “plug & play” SONET-like solution that many SONET-centric carriers will appreciate. Unfortunately, digital optics is still very expensive when implemented with all-optical DWDM technology and it does not reduce the complexity and cost of managing accumulated dispersion problems.

2.3.2 Metro CWDM Networks

By 2000, it was clear that neither the growing long haul nor the metro-core network capacities could be fully utilized until the metro access bottleneck was removed. However, DWDM was far too expensive as a technology solution for the metro access market segment since the distances were much shorter, fewer channels were required and the WDM network cost had to be amortized across fewer end-customers. It was at this time that CWDM re-invented itself, emerging from what was predominantly a low cost LAN technology to what is now an accepted telecommunications technology with ITU standards support.

CWDM technology employs much wider wavelength spacing than DWDM. For example, CWDM wavelengths are specified by the International Telecommunications Union (ITU) to be spaced 20nm apart, with up to 18 wavelengths between 1270nm and 1610nm inclusive. This includes 2-5 wavelengths that might not be useable due to a water-peak in the E-band for the installed base of ITU-T G.652 fiber. Newer G.652.C fiber removes this water peak, thus guaranteeing that all 18 wavelengths can be used.

For comparison, 18 DWDM wavelengths in the optically amplified C-band would be spaced approximately 1.6nm (200GHz) apart. To achieve this tight wavelength spacing, DWDM lasers require power-hungry and space-consuming thermo-electric coolers to maintain their wavelength accuracy. This results in large DWDM equipment racks with extensive fan-forced cooling. In contrast, CWDM lasers can operate without cooling and still maintain their 20nm wavelength accuracy across a wide ambient temperature range. This results in significant space and cost reductions for CWDM solutions. CWDM filters also require less stringent manufacturing tolerances than DWDM filters, further reducing the cost of CWDM [2].

Figure 2 illustrates how 8-wavelength CWDM technology can be applied to transform a single G.652 fiber strand to the equivalent of four bi-directional channels supporting different protocols and rates. This approach is ideal for situations where metro fiber is leased by the strand. In this case, a single fiber strand performs the same function as 8 dedicated fibers.

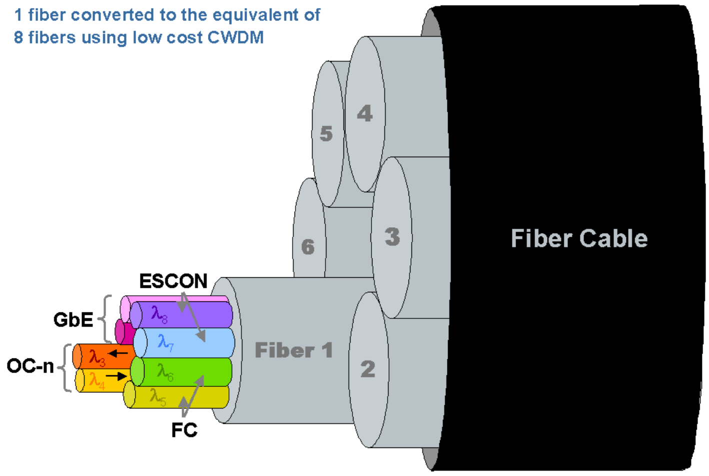

Figure 2 8x Pair-Gain using CWDM

Loss-Limited CWDM Networks

All-optical metro CWDM networks comprise multiple optical add/drop multiplexer (OADM) nodes connected in a bus or ring topology. For such networks, accumulated optical power losses will limit the network size to typically 67 km less 8 km per OADM node installed (assuming 70 km dispersion limit at 1610nm and 2.5 Gbit/s, 20 dB link loss margin - laser output to receiver input, 2.4 dB OADM insertion loss and 0.3 dB/km fiber loss). Such networks are considered “loss-limited.” As an example, a six-node all-optical CWDM network will have a maximum end-to-end transmission distance of only 19 km. This is nowhere near adequate for metro core applications.

Dispersion Limited CWDM Networks

Through the addition of new Semiconductor Optical Amplifiers (SOAs), metro CWDM networks with many optical add/drop nodes can now be extended up to their 70 km dispersion limit, which is adequate for the smaller metro core applications. Unfortunately, the flip side to the use of SOAs is increased provisioning complexity due to the same analog-like design and optical power management problems that burden the all-optical metro DWDM networks.

A low cost, band-aid solution to the dispersion limit problem is to constrain the available protocols and rates to GbE and below. However, this approach is not attractive to carriers who need a “plug & play” solution that at least handles all metro protocols up to OC-48/STM-16. Another solution is to 3R regenerate (re-amplify, reshape & retime) each wavelength whenever it is approaching its dispersion limit for the protocol being carried. A disadvantage of this approach is even greater power management and provisioning complexity.

2.3.3 Regenerative CWDM Networks

Node Architecture

A legacy of the long haul DWDM network design experience has been the accepted premise that full 3R-regeneration of all WDM channels will always be too expensive. However, for metro applications where the number of channels is not large (eg, 4 growing to 16) and the inter-node distances are less than 70 km (at 2.5 Gbit/s), the premise that full 3R regeneration of all wavelengths at each node is too costly no longer applies. In fact, the low cost of wideband CWDM components (up to 2.5 Gbit/s data rate) combined with the availability of multi-rate, protocol agnostic electronics, such as programmable clock & data recovery (CDR) devices and wideband cross-connect switches, has created the opportunity to turn conventional WDM network design wisdom on its head.

As shown in Figure 3, a regenerative CWDM node demultiplexes all optical channels. The data in each channel are optically to electrically converted and amplified (1R), re-shaped (2R) and optionally retimed (3R). Each channel is electrically switched to either a local tributary interface and/or to an outbound CWDM port for transmission to another regenerative CWDM node. Both point-to-point and broadcast channels are supported. Since all wavelengths are fully regenerated, the result is a "digital optics" solution, but without the costly optical amplification, power management and accumulated dispersion problems associated with all-optical metro WDM solutions.

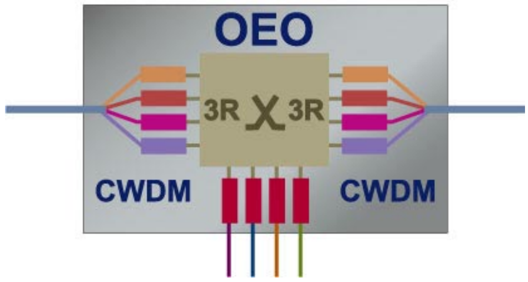

Figure 3 Regenerative CWDM Node

Network Architecture

As shown in Figure 4, regenerative CWDM nodes may be connected to form linear (bus), hubbed and true-ring networks. Their any-to-any, multi-channel transmission & switching capability supports multi-protocol logical mesh and broadcast networks, paralleling the capabilities of existing SONET/ SDH networks. As a digital optics solution, regenerative CWDM networks are managed and configured just like SONET/SDH networks. Network designs require simple linear calculations involving only the link budget, added jitter per node and the number of nodes.

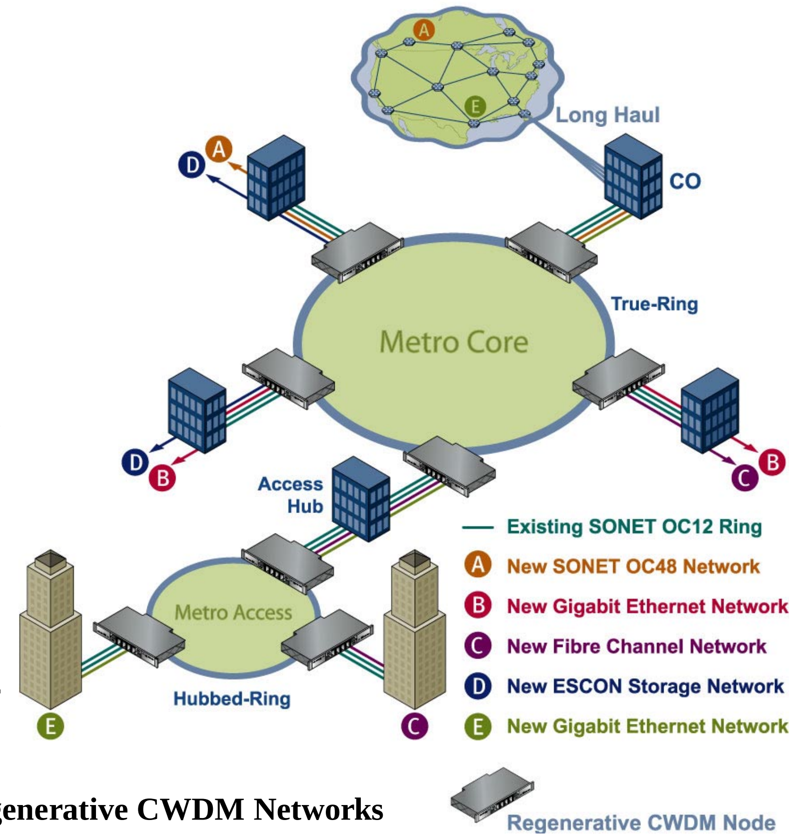

Figure 4 Regenerative CWDM Networks

With just 4 bi-directional CWDM channels and a conservative 40 km between each regenerative CWDM node in a 5-node ring, it is easy to see that this digital optics technology easily meets the capacity growth, end-to-end transmission distance, logical mesh connectivity and multi-protocol needs of metro core applications. What is not expected is that this regenerative CWDM technology meets these needs at much lower cost, space and power consumption than comparable all-optical metro DWDM solutions.

Regenerative CWDM can be applied as a ubiquitous solution to many metro applications encountered by a telecommunications carrier. This results in economies of scale for both the supplier and for the customer. Applications include both metro core and metro access using just about any form of single-mode fiber, including dispersion-shifted fiber (DS fiber). For the metro access segment, the low power and space benefits of CWDM has now enabled multi-channel, multi-protocol WDM technology to be applied to Outside Plant (OSP) applications [1]. For metro core applications where DS fiber has in places been deployed, regenerative CWDM is an ideal, low cost solution to the four-wave mixing problem that until now has limited the use of WDM to the more expensive L-Band DWDM products.

For all metro WDM applications, regenerative CWDM offers an efficient network architecture that is simple to design, install, maintain and upgrade. Network designs employ simple SONET/SDH intermediate-reach (IR) or long-reach (LR) design rules rather than complex optical power management and dispersion calculations. Installation and maintenance are both simplified by the elimination of wavelength-specific interfaces, thus reducing spare holdings. Improved network diagnostics are enabled by remotely managed loop-backs on a link-by-link and channel-by-channel basis. When upgrades are required, extra channels and nodes can be added without any need to rebalance the existing optical links and wavelength channels. Both protected and unprotected channels are supported with optical UPSR and BLSR protection options. A mix of protected and unprotected services with channel re-use enables more services to be supported than the number of CWDM wavelengths available. More efficient wavelength utilization is yet another factor in favor of regenerative CWDM as a low-cost solution to the increasing demand for new multi-protocol metro services.

In summary, regenerative CWDM provides the same functionality and operational simplicity for wavelength-multiplexed services as SONET/SDH provides for TDM multiplexed services. The two technologies go hand-in-hand, supporting a wide range of broadband and narrow-band applications, with complementary features. Examples include low latency and cost for intra-metro services (such as SANs) and ubiquitous OC-48 transport for inter-metro services.

2.3.4 Metro Ethernet

While SONET/SDH networks are all-pervasive, they do not interface to the actual users of the network. In the case of data applications, this interface is one of the Ethernet family. As more services are transported over IP networks (including voice and video), it is apparent that these services are starting and ending their journey on an Ethernet network. Given the assumption that end-to-end networking costs will be reduced if unnecessary protocol conversions are removed, it is easy to understand why the Metro Ethernet Forum was formed to promote an evolutionary path that would result in a ubiquitous Ethernet network that ultimately replaces the existing SONET/SDH networks in the metro access and metro core [4]. The convergence of 10GbE and OC-192 is consistent with such an evolution.

In a Metro Ethernet world, SONET/SDH ADMs are replaced by Ethernet Switches with improved QoS features that support the SLA requirements listed in section 2.2.2. Transport interfaces between switches are generally GbE or 10GbE. Improved path protection switching is achieved using reconfiguration algorithms that converge faster than existing Ethernet networks. Latency issues for time-critical services such as telephony, video-conferencing and storage networks are addressed with priority packets and improved flow control mechanisms.

One of the main deficiencies of Metro Ethernet is that it only supports packet data transport and switching. Customers requiring circuit switched services for low latency and guaranteed security are instead offered virtual circuits - which is not always acceptable to their specific application. A combination of Metro Ethernet and regenerative CWDM may overcome this problem for broadband applications. Metro Ethernet still has a long way to go in meeting all SLA requirements and its competition is fighting back. The recent GFP standard is giving new life to what were considered legacy SONET/SDH networks. Such networks already meet the SLA requirements listed in section 2.2.2.

2.3.5 Generic Framing Procedure (GFP)

The GFP standard is defined in ITU-T G.7041 / Y.1303 (dated Dec'01). It defines new frame formats and procedures for mapping broadband data protocols onto multiple concatenated STS-1 payloads in a SONET/SDH frame. Examples include ESCON, FICON, Fibre Channel and Gigabit Ethernet (all of which are 8B/10B coded at the physical layer). As illustrated in Figure 5 both narrow-band VTs and GFP-mapped broadband data streams can co-exist in the same SONET/SDH stream, which can then be transported over WDM wavelengths.

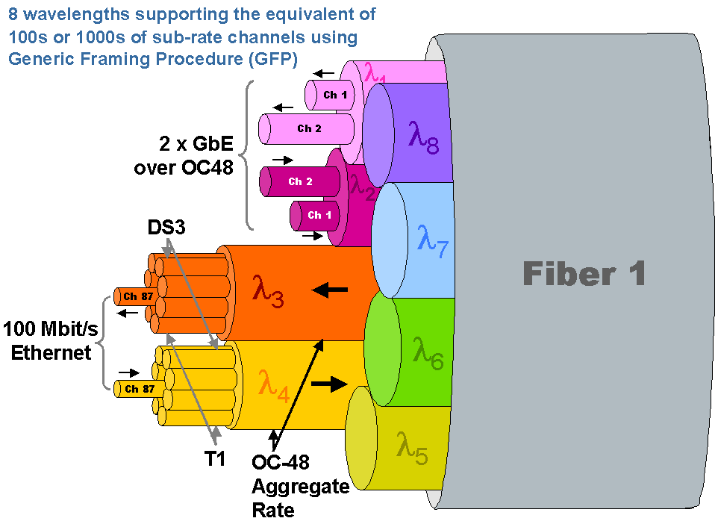

Figure 5 Improved Wavelength Utilization through GFP-based Multiplexing

Two adaptation modes are defined. These are: Frame Mapped GFP and Transparent GFP. Frame Mapped GFP is optimized for packet switched applications. In the case of Ethernet over SONET (EoS) applications, it transports data link layer packets (frames) between Ethernet bridges and other Ethernet bridges or forwards higher layer frames to IP routers. Frame Mapped GFP can potentially take the place of existing PoS networks defined by the IETF and exploits the same Point-Point Protocol (PPP) approach.

Transparent GFP operates on the 8B/10B block-coded physical-layer data stream used by most broadband data-centric protocols. Since it does not operate at the frame level, there is less delay in the adaptation process, thus being more suited to circuit-switched applications requiring low end-to-end latency. Other 8B/10B coded streams, such as DVB-ASI video are also supported by the new breed of GFP compliant chip-sets being introduced in early 2003.

2.3.6 Resilient Packet Ring (RPR)

The emerging IEEE 802.17 standard, referred to as Resilient Packet Ring (RPR), enables the efficient transmission of bursty data traffic between multiple nodes connected to a SONET ring (generally OC48 or OC192). RPR is in part based on the Spatial Reuse Protocol (SRP), a Cisco-developed MAC-layer protocol for ring-based packet networks (specified in IETF RFC 2892). Like Metro Ethernet, RPR offers the advantages of statistical multiplexing, fine granularity bandwidth provisioning, channel re-use and broadcast transmission.

Compared to Metro Ethernet and SONET, additional benefits of the RPR protocol include:

- **Bandwidth utilization:** Both rings are used for transporting and switching traffic, with lowest priority traffic dropped in the event of fiber cable damage or equipment failure. The benefit of this feature is a virtual doubling of capacity compared to existing SONET based TDM networks.
- **Sub-50ms protection switching:** RPR overcomes the current limitations of Metro Ethernet by utilizing carrier-class SONET-ring based algorithms for rapidly detecting and correcting ring faults. Note that if Metro Ethernet was specified for ring configurations, then it too could apply these same algorithms, thus resulting in faster convergence.
- **Multiple physical layer options:** RPR is focused on optimizing the MAC-layer protocol rather than the physical layer protocol. As such, both SONET and GbE physical layer options are supported, as is an underlying WDM network option.
- **Real-time traffic support:** Constant bit rate services such as voice and video are supported at the packet-layer through advanced QoS features and in the case of the SONET-ring option, through synchronization to the 8kHz stratum timing provided at the physical layer. This enables virtual circuit channels to be provisioned with lower latency than Metro Ethernet networks.
- **GFP-mapping option:** Support for GFP offers a “best-of-both-worlds” solution for metro area networks. RPR packets can be mapped into part of an OC-48 or OC-192 SONET frame, leaving the remainder of the SONET frame for TDM based circuit-switched services. The ratio of RPR to TDM bandwidth could in principal be adjusted dynamically in 155.52 Mbit/s (STS-3) increments, thus creating up to 16 dynamically provisionable wideband channels in the case of an OC-48 ring.

Compared to Metro Ethernet and SONET, disadvantages of the RPR protocol include:

- **Extra adaptation overheads:** RPR is a new MAC protocol – which is different to the Gigabit Ethernet MAC protocol. As a result, extra packet processing overheads are incurred in converting from one protocol to the other.
- **Not (yet) a standard:** While Ethernet and SONET have been standardised for many years, the RPR standard is not yet complete and has suffered further delays.

2.3.7 Next Generation SONET Networks

The term NG-SONET seems to have been in use longer than the terms GFP, however, it is expected that GFP will be the standard that truly differentiates NG-SONET from legacy SONET networks. Prior to GFP, proprietary solutions for TDM multiplexing of data-centric services into OC-48 and OC-192 streams were developed and are still being deployed today. These are often marketed by WDM product vendors as "sub-lambda multiplexers." Some may argue that both GFP and RPR are what will differentiate NG-SONET from legacy SONET. However, this is speculative until RPR is ratified as a standard and widely adopted.

Figure 6 illustrates the ubiquitous transport benefits of NG-SONET multiplexers that comply with the Transparent GFP option. Shown in this figure are two metro WDM rings interconnecting COs, each separated by a long haul network. Attached to each WDM ring are TDM multiplexers from three equipment vendors. Each multiplexer combines two GbE streams into a SONET OC-48 stream. The multiplexers from vendors 1 & 2 comply with the GFP standard. The sub-lambda multiplexer from vendor 3 is proprietary. These SONET multiplexers may be co-located in the CO with the WDM multiplexers or they may be remote from the CO (eg, in a CBD building). In either case, they may connect to the CO via a point-point link, or as part of a SONET ring connected to the WDM ring via OC48 interfaces.

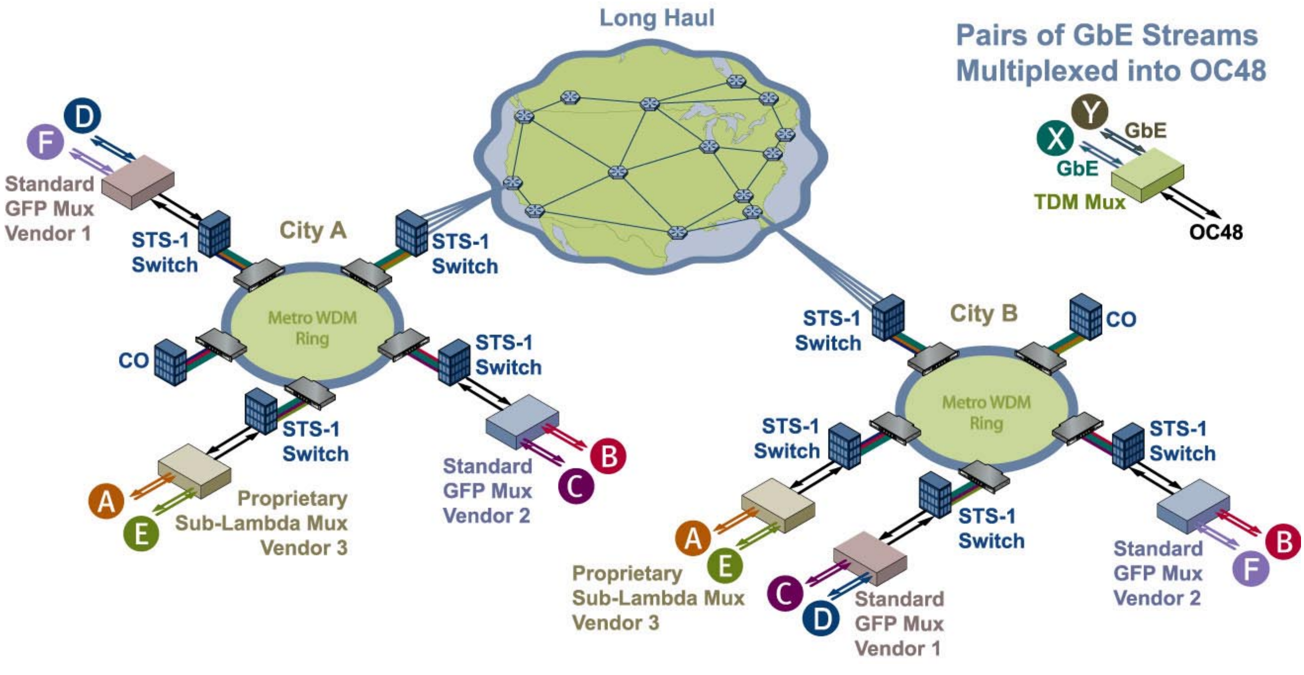

Figure 6 Ubiquitous GbE Networking via GFP Standard Multiplexers

As shown in Figure 6, the two GbE streams labeled A & E that are multiplexed into OC48 by Vendor 3's equipment, can be switched via a STS-1 switch as a aggregate OC48c stream (like PoS) but cannot be demultiplexed by any other vendor's equipment. As a result, it is not practical for the STS-1 switches to separate and groom the two GbE payloads into other outbound OC48 streams (even if they could) and consequently the two GbE channels must always go to the same destination and to the same type of proprietary multiplexer.

In contrast, Figure 6 also shows the mix and match benefits of GFP-standard SONET multiplexers. In this case, the four GbE channels B,C and D,F originating from the multiplexers of Vendor 2 and Vendor 1, respectively, can be separated and groomed into different outbound OC48 streams by the STS-1 switches. Figure 6 shows these GbE streams arriving at different destinations (paired-off as B,F and C,D).

As a result of the Transparent GFP-based NG-SONET multiplexers, individual GbE private networks can now be provisioned across the metro access, metro core and long haul in the same way that T-1 and DS-3 based private networks have been provisioned to date using legacy SONET equipment.

NG-SONET multiplexers that support Frame Mapped GFP offer yet another option for ubiquitous packet data transport. In this case, GbE frames can be bridged from Ethernet LANs into NG-SONET metro access networks and then at the CO connected directly to an IP router interface that supports Frame Mapped GFP.

The above scenarios involving central STS-1 switches and routers are hubbed packet network applications. Frame Mapped GFP can be applied in other ways to support distributed packet networks, including the integration of Metro Ethernet switching into the NG-SONET multiplexers. This option would compete with distributed RPR based metro networks.

In summary, GFP-compliant NG-SONET multiplexers enable ubiquitous packet and circuit transport of data-centric services such as GbE and FC with no geographical barriers other than those defined by specific applications and associated higher-layer protocol efficiencies.

3 Sorting through the Network Puzzle

3.1 Comparison of Protocols & Architectures

3.1.1 All-Optical CWDM vs Regenerative CWDM vs DWDM vs New Fiber

For metro core networking, 16-wavelength all-optical CWDM networks combined with SOAs to compensate for OADM node losses will find some niche opportunities in the smaller cities where metro ring perimeters are less than 70 km. This is because CWDM technology is dispersion limited to 70 km at 2.5 Gbit/s over existing G.652 fiber infrastructure.

Regenerative CWDM overcomes the distance limitations of all-optical CWDM and thus increases its applicability to metro core applications. Regenerative CWDM has the same 70 km dispersion limit, however, this now only applies to each link in a metro ring, rather than the metro ring perimeter. For the rare situations where a link is greater than 70 km, a regenerative CWDM node can be installed as a repeater – for about the same power, space and cost as an EDFA gain block in a DWDM network.

Compared to DWDM, a perceived deficiency of CWDM is its lack of support for 10 Gbit/s transport at this time. However, for CWDM applications requiring 10 Gbit/s transport, the following options may be used:

a) Inverse multiplexing 4 x 2.5 Gbit/s streams, as sometimes used in the long haul; or

b) Deploy all sub-10 Gbit/s services on CWDM wavelengths and all 10 Gbit/s services on spare fibers made available due to the CWDM pair-gain.

For those niche metro core applications requiring greater than 16 wavelengths, DWDM networks are the better option at this time.

One of the reasons for using CWDM and DWDM in the metro area is to defer the installation of new fiber. However, regenerative CWDM offers additional benefits when fiber exhaust is not an issue. For example, the added value of remotely managed electronic cross-connect switching at each node provides another good reason to defer the installation of new fiber. New fiber does not have this dynamic provisioning functionality, nor does it have loop-back testing, optical-layer protection switching and the performance monitoring features that can be provided by a regenerative CWDM solution.

3.1.2 Metro Ethernet vs RPR vs EoS vs PoS

The jury is still out regarding Metro Ethernet vs RPR, however, Metro Ethernet has a strong case based on its ubiquitous availability and associated low cost. Ethernet is the source and destination LAN for most data traffic, so it makes perfect sense to extend this network equipment into the metro area, thus reducing costly protocol conversions. On the other hand, RPR applies the same argument – being that SONET is a ubiquitous metro transport network and should be exploited.

To add further complexity to the argument, Frame-Mapped GFP offers a compromise for Metro Ethernet [3] – providing an alternative EoS solution without the extra MAC-layer overheads of RPR. In both cases, GFP enables a hybrid-switching option – supporting both packet and circuit switched services. The winner at the end of the day will be determined by the cost and efficiency with which Ethernet LAN data traffic is extended over the metro area, more so than their support for real-time services such as voice and video. Existing circuit switching and SONET transport can look after these real time services quite well. In this light, Metro Ethernet switching and EoS transport using Frame Mapped GFP could be the winning combination. This is an interesting contradiction given that the original intent of the Metro Ethernet Forum was to employ native GbE based transport. Delays in ratification of the RPR standard have increased the likelihood of the combined Metro Ethernet and EoS outcome.

As another EoS interface option, Transparent GFP combined with STS-1 switching within the carrier networks enables the ability to create private GbE paths among packet switches, routers and remote customer equipments.

In the absence of a GFP standard, PoS was introduced to solve a packet transport problem in the metro and long haul networks. Frame Mapped GFP offers much the same capabilities as PoS and thus is a likely substitute for PoS in new installations.

3.2 Low Cost Metro Core Architecture

Both CWDM and NG-SONET technologies are lower cost alternatives to dense wavelength division multiplexing and proprietary sub-lambda multiplexing technologies. Furthermore, NG-SONET networks implemented at the 2.5 Gbit/s OC-48/STM-16 rates are complementary to an underlying regenerative CWDM network. In this case, the regenerative CWDM topology (number of nodes, distances between nodes, etc) maps 1:1 to the regenerative NG-SONET topology, whether this is a ring, bus or simple point-to-point link. Additionally, the NG-SONET network adds finer channel granularity to the CWDM channels and the CWDM technology enables multiple NG-SONET or other protocol networks to co-exist on the same fiber or fiber-pair. Operationally, the regenerative CWDM and NG-SONET networks are installed, configured, managed and spared in much the same way. This benefit is greatly appreciated by the carriers that are already trained to install SONET based metro networks.

4 Conclusions

The key take-aways provided by this paper are:

- The 2.5 Gbit/s and 10 Gbit/s SONET/SDH interfaces between the metro core and the long haul, combined with STS-1 cross-connect switching in the metro core, and at the edges of the metro network, have driven the need for standards based mappings of data-centric protocols such as Gigabit Ethernet into SONET/SDH transport systems.
- Within the metro core, the need for low cost fiber relief and low-latency transport of native protocols such as Gigabit Ethernet, Fibre Channel, FICON and ESCON, has driven the demand for CWDM transport networks.
- Compared to all-optical CWDM networks requiring analog-like design rules, regenerative CWDM networks offer a "digital optics" solution that better meets the 300 km transmission distance requirements and SONET-like operational requirements of carrier-class metro core applications and at a much lower cost point than equivalent DWDM systems.
- NG-SONET networks conforming to the new GFP standard combined with regenerative CWDM networks meet the above needs at low cost for both multi-protocol broadband and narrowband services delivered to hundreds or thousands of customers.
- NG-SONET is more likely to use Metro Ethernet than RPR to inter-connect distributed Ethernet LANs in a metro area. This is because there are fewer protocol overheads and lower costs associated with adapting Ethernet into SONET using the new GFP standard. This assumes that existing real-time services such as voice and video are mapped into TDM circuit channels as they have done for the last decade, rather than attempting to packetize them into Ethernet or RPR.

5 References

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6 About RBN

RBN is a designer and developer of optical transport and switching products for the access and metro markets. RBN has identified and addresses a key issue—an imbalance between carrier revenues and costs. RBN addresses the issue by designing and developing products that enable carriers to offer lower cost broadband services. Designed for simplicity and flexibility of use, small form factor, low power usage and low cost of ownership the company pushes the boundaries of optical networking closer to the end user.

RBN was the first to market with a reconfigurable optical add/drop multiplexer that is outside plant hardened for use in the central office, enterprise environments and remote terminals. More specifically the platform can be used in a variety of applications including fiber pair gain, SONET upgrade avoiding truckrolls, Digital Loop Carrier (DLC) network upgrade and integration of new services into existing infrastructure

The company's flagship product, the RBNi 8200, uses the simplicity and low-cost features of CWDM and is multi-protocol enabling the integration to transport voice, video and data.

RBN's business model is to market and distribute its product through leading communications manufactures and solution providers.

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