New Transport Services for Next-Generation SONET/SDH Systems

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ABSTRACT

SONET/SDH systems have been the preferred transport technology over fiber optics for almost two decades now. Carriers have developed extensive expertise in operating, managing, and developing business models for these systems. Manufacturers' technical expertise in such systems has increased to a deep understanding of what transport over fiber is about. In short, SONET/SDH can be called a mature transport technology. Out of this mature expertise, new techniques for bettering transport over fiber services have recently appeared. These techniques are likely to considerably reshape the next generation of SONET/SDH systems in many aspects: new transport techniques, new transport services, new management systems and business models. In this article, we describe several new transport techniques, and discuss their impact on the creation of new transport services for next-generation SONET/SDH systems.

INTRODUCTION

For the last 15 years, synchronous optical network/synchronous digital hierarchy (SONET/SDH) has been the main transport technology over optical fibers. SONET/SDH systems allow the transport of constant bit rate clients, through synchronous transport modules (STMs) and virtual tributaries (VTs), as well as variable-rate packet-oriented clients, such as asynchronous transfer mode (ATM)/IP/frame relay, and others. These signals are transported over a synchronous frame, which is used to modulate a single wavelength channel. Current SONET/SDH interface speeds range from 51 Mb/s to 10 Gb/s.

SONET/SDH legacy equipment were designed primarily for the transport of constant bit rate applications. This is evident in many characteristics of the transport technology; for instance, bandwidth is provisioned via a rigid hierarchy of bit rate signals (STS-3, STS-12, STS-48, etc.).

However, with the explosion of datagram applications allowed by IP and other packet switch technologies, solutions for the transport of data over SONET/SDH systems were developed. For Internet traffic, for instance, IP packets are framed using packet over SONET (POS) [1], and placed into the synchronous payload envelope (SPE), the SONET/SDH frame payload area. Another example is multimedia traffic, with stringent quality of service (QoS) requirements. In this case, ATM is used as a way to access optical fiber, providing a predictable end-to-end transport service much needed by this type of application. ATM cells are placed into the SPE according to standardized optical interfaces (e.g., [2]).

Even though POS and ATM have been widely used as means of data adaptation into SONET/SDH payload, neither of these is recognized to be the best for data transmission purposes, as far as bandwidth usage and high-speed processing capability are concerned. POS uses HDLC framing that becomes difficult to implement in high-speed processing of 10 Gb/s or even 40 Gb/s. ATM has a well-known cell tax that consumes an extra 10 percent of bandwidth.

On the other hand, although SONET/SDH has been the single technology for Internet transport over fiber, it has limitations of its own. For instance, each transport path has a fixed bandwidth (time-division multiplexing, TDM, model), which is defined over a rigid rate hierarchy. Moreover, there is a lack of fine granularity to accommodate all potential clients' stream rates, especially data applications. Finally, because SONET/SDH nodes have limited network management functionalities, each transport path takes a long time to set up, typically weeks for U.S. coast-to-coast.

New techniques, however, are currently being developed to address many of these limitations. Generic Framing Procedure (GFP) has been developed as a new framing for data accommodation into SONET/SDH and optical transport network (OTN). Virtual concatenation has been standardized for flexible bandwidth assignment of SONET/SDH paths. Link Capacity Adjustment Scheme (LCAS) has been discussed for dynamic bandwidth allocation in support of virtual concatenation. One of the most important objectives of these new technologies is to enable flexible and reliable data transport over SONET/

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SDH, which is referred to as data over SONET/SDH (DoS). This article is aimed at describing these new technologies, elaborating on DoS architecture for new transport services, together with considerations of implementation aspects.

In the next section we introduce a DoS network architecture. A discussion ensues on upcoming transport services enabled by this architecture, including network scenarios and implementation aspects of these services.

Data over SONET/SDH Network Architecture

DoS is a transport mechanism that provides a means to accommodate various data interfaces (e.g., Ethernet, Fibre Channel, ESCON/FICON) into SONET/SDH efficiently. In particular, DoS is effective to accommodate Gigabit Ethernet (GbE), which has been widely deployed for WAN interface application.

DoS utilizes three technologies: GFP [3], virtual concatenation [4], and LCAS [5]. These technologies are being standardized in the International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) and T1X1.5.

Generic Framing Procedure

GFP was first discussed in T1X1.5; now ITU-T is working to standardize it as G.7041 [3]. In G.7041, GFP is defined as a framing procedure to delineate octet-aligned variable-length payloads from higher-level client signals for subsequent mapping into octet-synchronous paths. The mapping procedure for the client signals into octet-synchronous paths is also defined in the standard document.

GFP is generic in terms of two stack directions: at the layer below it, with respect to transport services used by GFP; and at the layer above it, with respect to mapping services provided to applications by GFP. At the layer below it, GFP allows the use of almost any type of transport technology, although in the standards body the focus is mostly on SONET/SDH and OTN. The only requirement for the transport layer is to provide an octet-synchronous path for GFP.[1] At the layer above it, GFP supports various types of packets, including IP packets, Ethernet frames, and HDLC frames such as PPP. The only requirement for the upper layer is that packets should be octet-aligned. This unique generic feature comes from the fact that GFP provides a simple packet delimitation scheme.

GFP has two mapping methods to accommodate client signals into SONET/SDH payload: frame-mapped GFP and transparent GFP. These two methods are designed to be suitable to several new applications and services coveted by carriers.

Framed-Mapped GFP — The advantage of frame-mapped GFP is its simplicity and effectiveness. In order to transport packets over a serial transmission line, some means of framing is necessary for packet delineation purposes. Frame-mapped GFP is a simple and effective way to provide packet delineation. GFP frame delineation is based on a header error correction (HEC) hunting method, a well established technique used in ATM cell delineation. However, as opposed to ATM, GFP allows variable-length payloads, which enhances the effective bandwidth for packet transport. For example, in current Ethernet over ATM over SONET/SDH framing, 1500 bytes of Ethernet frame is first encapsulated with ATM adaptation layer 5 (AAL5) [6], resulting in 1536 bytes with appropriate padding and CPCS-PDU trailer. These bytes are then divided into 32 pieces of 48 bytes each. Finally, a 5-byte header is added to each 48 bytes of data, resulting in a total of 1696 bytes for 1500 bytes of Ethernet data. Overall, as much as 13 percent cell tax for ATM transport is added.

Another well established framing method is PPP/HDLC, used for framing IP packets. In PPP/HDLC framing, a special character (0x7E) needs to be inserted at packet boundaries as a delineation flag. If the application data happens to contain the flag character, this character is escaped in order to remove ambiguity about packet delineation. This technique, called byte stuffing, is said to cause an overhead (also called bandwidth expansion) of less than 1 percent for random data. This overhead, however, depends on the application data content, and could go up to 50 percent (i.e., 50 percent of the link bandwidth could be wasted in the worst case). Bandwidth expansion causes problems of budgeting and managing fiber bandwidth, since the bandwidth available to an application ultimately depends on the application's data content.

Transparent GFP — A unique feature of GFP is a transparent means of transporting block-coded signal, namely transparent GFP. At this moment, mapping for 8B/10B coding only is defined. One application envisioned is the support of storage area network (SAN) over WAN. Transparent GFP reduces the necessary resources for constructing a distributed storage system over a wide area. Since latency is important to achieve stringent performance requirements for storage-related applications, transparent mapping is designed to map individual code words rather than receiving an entire frame and mapping it into a GFP frame. An extra added value is that transparent GFP mapping is more bandwidth efficient than 8B/10B mapping.

Virtual Concatenation

Virtual concatenation is a mechanism that provides flexible and effective use of SONET/SDH payload. Historically, SONET/SDH was first defined as a (worldwide) unified digital hierarchy for the transport of 64-kb/s-based TDM service. The capacity of payload was rigidly defined for plesiochronous digital hierarchy (PDH) service accommodation. However, the disadvantages of such a rigid SONET/SDH rate hierarchy, especially when data applications such as Ethernet are considered, were soon realized. Virtual concatenation breaks the limitation incurred by this rigidity via the definition of payloads with flexible bandwidth. It "virtually" concatenates several payloads to provide a payload with flexible bandwidth, appropriate for data service accommodation.

GFP has two mapping methods to accommodate client signals into SONET/SDH payload: frame-mapped GFP and transparent GFP. These two methods are designed to be suitable to several new applications and services coveted by carriers.

[1] *A bit-synchronous transport system is not precluded from using GFP.*

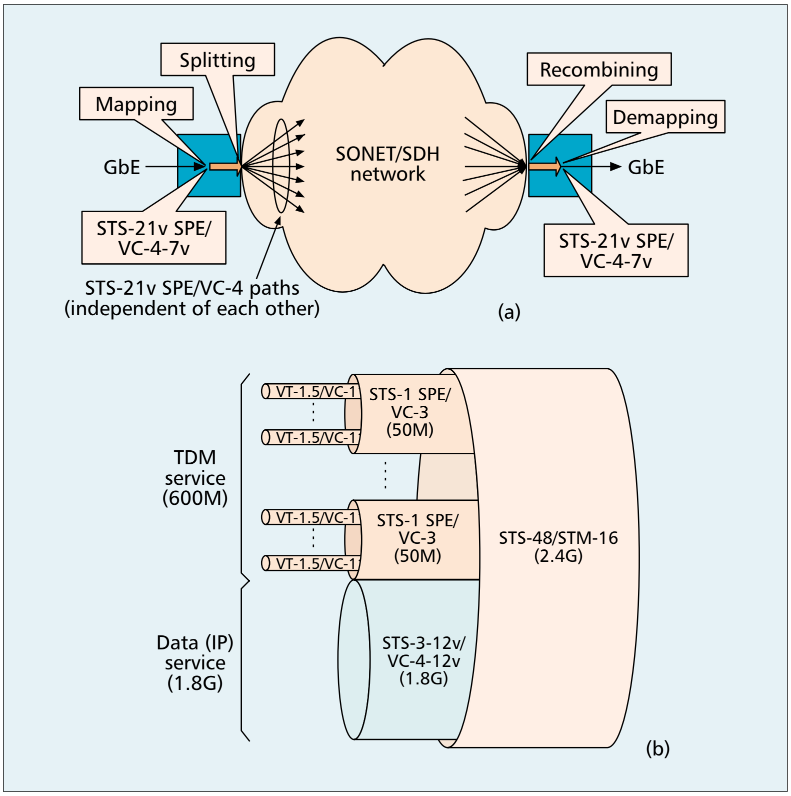


Figure 1. *SONET/SDH virtual concatenation: a) the virtual concatenation concept; b) bandwidth partitioning with virtual concatenation.*

Consider the case of GbE transport by SONET/SDH. According to the conventional SONET/SDH specifications, STS-48c SPE/VC-4-16c must be used to accommodate GbE signals at full speed. Since STS-48c SPE/VC-4-16c capacity is 2.4 Gb/s, however, 1.4 Gb/s capacity is wasted. If STS-12c SPE/VC-4-4c is used to avoid bandwidth wastage, full-speed accommodation cannot be achieved. GbE could be suitably accommodated if a contiguously concatenated payload STS-21c SPE/VC-4-7c with 1.05 Gb/s capacity were defined. In such a case, however, every node in the network would need to handle this newly defined STS-21c SPE/VC-4-7c signal, which would not be practical because such a concatenated payload is not supported by legacy SONET/SDH equipment. Using the virtual concatenation technique, seven independent STS-3c SPE/VC-4 payloads are virtually concatenated to provide STS-3c-7v/VC-4-7v payload (suffix v stands for virtual) with 1.05 Gb/s bandwidth, which is perfectly suitable for GbE accommodation. This solution is viable because the implementation of virtual concatenation is limited to multiplexing nodes; there is no need to add virtual concatenation capability to every node of a SONET/SDH network. For instance, for GbE accommodation into STS-3c-7v/VC-4-7v, at the origination point, GbE is mapped into a STS-3c-7v/VC-4-7v payload, which is constructed with seven virtually concatenated STS-3c SPEs/VC-4s. There is no restriction on which OC-*n*/STM-*N* signal(s) should be used. The seven payloads may or may not reside in the same OC-*n*/STM-*N* contiguously, or may even reside at different OC-*n*/STM-*N* interfaces. Within the network, they are treated as seven separate and independent STS-3c SPE/VC-4 payloads. At the destination, the seven payloads are combined to construct the original STS-3c-7v/VC-4-7v signal using inverse multiplexing, and GbE is subsequently demapped from it. This means that the intermediate nodes, through which each STS-3c SPE/VC-4 travels, do not need to handle STS-3c-7v/VC-4-7v at all, so that STS-3c-7v/VC-4-7v need to be understood at both end nodes of the path only. Thus, carriers are free to introduce the virtual concatenation function without any serious impact on the existing network. Moreover, an element management system (EMS)/network management system (NMS) of today can easily support virtual concatenation. Figure 1a illustrates the virtual concatenation technique for a SONET/SDH system.

Another valuable feature of virtual concatenation is that the bandwidth of a SONET/SDH interface can be divided into several subrates. In POS, the whole payload of OC-*n*/STM-*N* must be dedicated to IP packet accommodation. Therefore, it is not possible to accommodate IP services into some portion of the SONET/SDH bandwidth. Virtual concatenation provides a way to partition SONET/SDH bandwidth into several subrates, each of which being capable of accommodating different services. Figure 1b illustrates the issue. The figure shows an example of bandwidth partitioning over an STS-48/STM-16 signal. 600 Mb/s are dedicated to TDM (fixed rate) services using VT1.5/VC-11 paths, and the rest of the 1.8 Gb/s portion is virtually concatenated to construct a STS-3-12v/VC-4-12v payload assigned for data service. In such a manner, virtual concatenation can be used for partitioning an OC-*n*/STM-*N* bandwidth to accommodate various services within a single frame.

LINK CAPACITY ADJUSTMENT SCHEME

As described in the last section, virtual concatenation can be applied to construct payloads with various capacities. Although the number of concatenated payloads can be determined in advance for most applications, it may be useful to allow the number of concatenated payloads to be changed dynamically. LCAS is defined for this purpose. In LCAS, signaling messages are exchanged between the two VC endpoints to determine the number of concatenated payloads. For instance, assume STS-5v SPE/VC-3-5v (250 Mb/s payload capacity) is currently used. According to user requirements, the number of concatenated payloads, currently five, could be increased to obtain STS-6v SPE/VC-3-6v, or reduced to obtain STS-4v SPE/VC-3-4v. Furthermore, LCAS makes sure that this process is done in a hitless manner (i.e., without any bit errors during the process). Therefore, LCAS allows carriers to assign and utilize bandwidth more efficiently and flexibly. This feature is very useful, for instance in adjusting bandwidth requirements on a time-of-day basis, across certain routes for which traffic variability is predictable and seasonal. Another application is the rerouting of traffic due to current network conditions, such as failures or maintenance procedures.

DATA OVER SONET/SDH ARCHITECTURE

GFP, virtual concatenation, and LCAS provide the fundamentals for the creation of a truly integrated data services over SONET/SDH transport system, or DoS. DoS has the following features:

- Flexible bandwidth assignment with 50 Mb/s granularity
- No modification required for intermediate nodes
- Efficient framing scheme, with small overhead
- Accommodation of any type of data service, including IP packet, Ethernet Datagram, ESCON, and FICON
- Coexistence of legacy service and data service in a single SONET/SDH frame
- Dynamic bandwidth control
- Network management through an existing, quality-proven NMS

Figure 2 illustrates the concept of integrated data accommodation of DoS. Figure 2a shows current packet transport over SONET/SDH. Various framing methods are used, which segregate these applications from the transport service up to management level. Figure 2b, on the other hand, depicts an integrated data transport service over SONET/SDH based on DoS. Notice how GFP glues various applications into the same transport technology. This allows for the implementation of several new network level techniques, such as load balancing, multiprotocol label switching (MPLS), protection, and multiplexing, which can be developed for all applications seamlessly. These techniques are integrated into a powerful, efficient, and flexible NMS, bringing additional revenue to carriers.

LAYER 1/2 HYBRID NETWORK VIA DOS

One of the most important DoS applications is a layer 1/2 hybrid network. DoS realizes coexistence of TDM and data services in a single SONET/SDH frame. For TDM services, layer 1 handling is required. For data services, packet handling is necessary in the GFP layer, which can be regarded as layer 2 in some sense because it is above the physical layer and below the IP layer. Hence, if DoS is introduced in a transport network, the nodes should handle both layer 1 (TDM) and layer 2 (GFP) simultaneously. This means that the network element can be layer 1/2 hybrid when DoS is applied.

Currently, SONET/SDH rings are widely used transport networks. If DoS is applied to one such a ring, network nodes should perform GFP frame add/drop as well as conventional SONET/SDH path add/drop. Such a network is in fact a layer 1/2 hybrid ring, realized by layer 1/2 hybrid nodes. Figure 3 shows a layer 1/2 hybrid add/drop function. The bandwidth for data traffic is assigned in SONET/SDH section by section, according to the client bandwidth requirements. Note that a ring protection scheme, such as 2F-UPSR (SNCP ring) or 4F-BLSR (MS SPRING), can be applied to a layer 1/2 hybrid ring, because the network is still based on SONET/SDH.

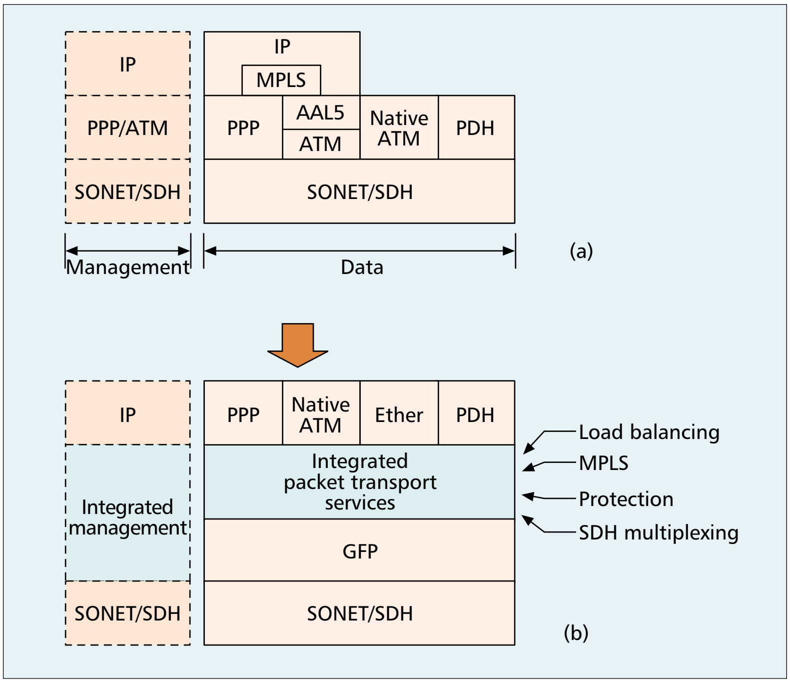


Figure 2. *Transport services over SONET/SDH: a) current packet transport; b) integrated transport services.*

NOVEL SONET/SDH TRANSPORT SERVICES

As described in the last section, DoS allows coexistence of both TDM and data traffic in a single OC-*n*/STM-*N*. In addition, it is also possible to configure the ratio between TDM and data traffic flexibly. These features lead to bandwidth on demand (BoD) services supported by Data Over SONET/SDH architecture.

BoD service has the following characteristics, according to current carriers needs:

- Billing based on usage and SLA requirements, as well as length of contract.
- Point-to-point,OC-*n*/STM-*N* bandwidth pipes, with flexible holding times.
- Provisioning realized in near real time (seconds to minutes).
- Multiple classes of service based on protection and restoration.

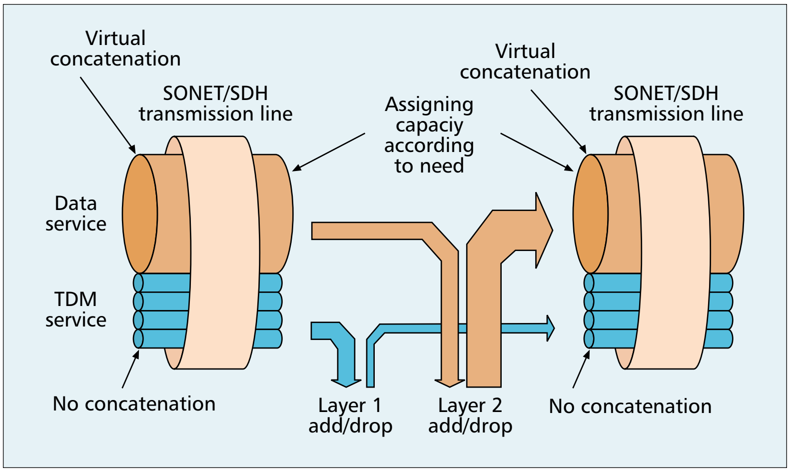


Figure 3. *Layer 1/2 hybrid add/drop.*

OIF is currently working on the signaling specification as UNI 1.0 between client and network. However, the bandwidth modification is out of the scope of that document, and will be discussed only in a future UNI 2.0 document.

A unique feature of BoD service based on DoS is best effort service provisioning under network failure condition. In general, path failure leads to immediate service unavailability. In contrast, service can continue, albeit with some degradation, in BoD based on DoS, if the failed member of the virtual concatenation group is removed from the group.

BoD service can be deployed under both distributed and centralized control. In distributed control, user–network interface (UNI) [7] and generalized MPLS (GMPLS) [8] based path setup is used. In centralized control, EMS/NMS-based network control is applied. An example of the distributed control scheme is depicted in Fig. 4a. The end user requests bandwidth adjustment from the network provider (step #1, additional 50 Mb/s, in Fig. 4a) through the UNI. Next, the network provider routes the additional member path and sets up the path based on GMPLS (step #2, additional VC-3, in Fig. 4a). Every node in the network advertises its timeslot usage using OSPF-

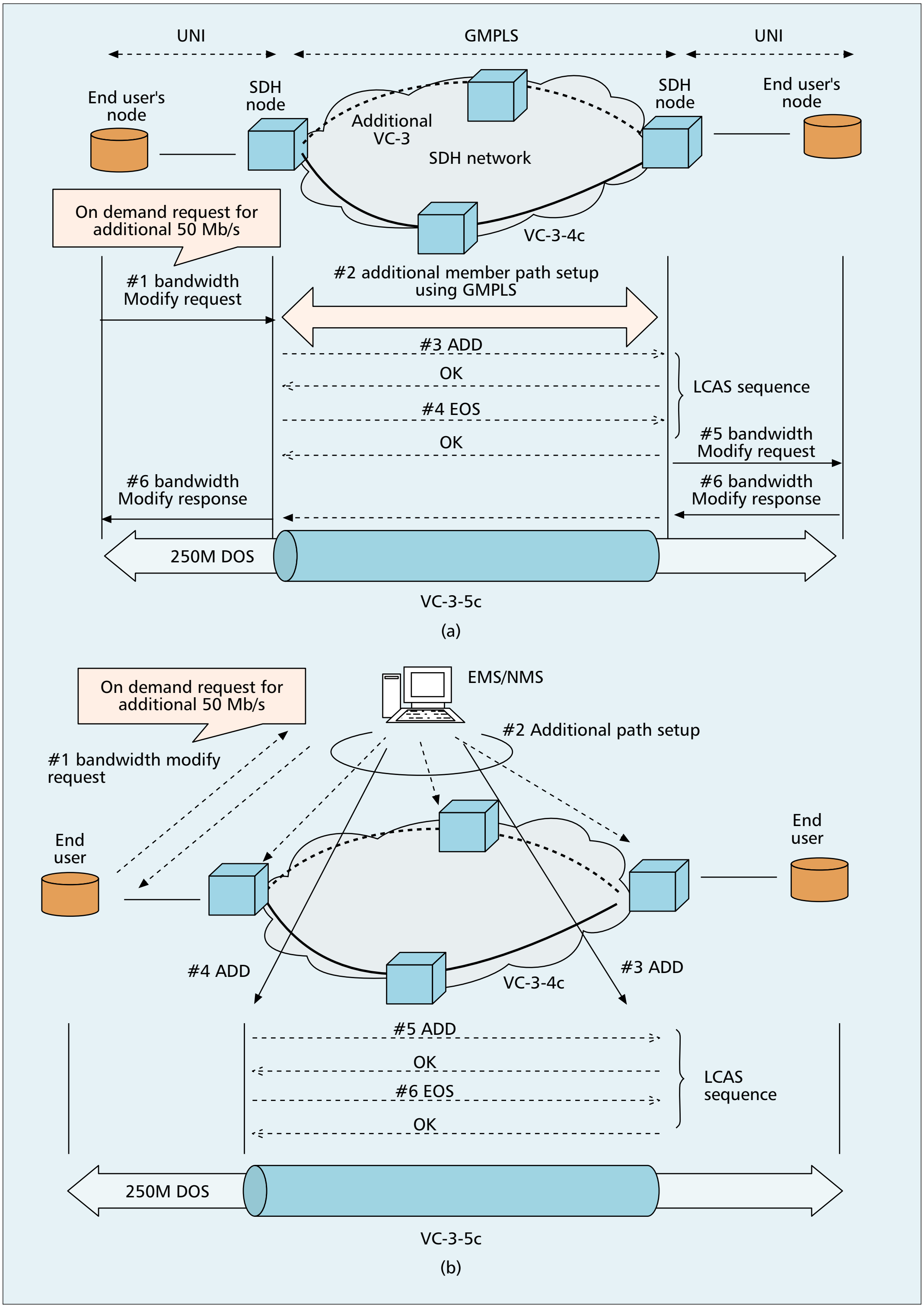


Figure 4. *Examples of BoD setup: a) UNI/GMPLS-based; b) EMS/NMS-based.*

TE or IS-IS [9], so the edge node can determine the end-to-end route for the additional member path using the advertised information. Next, the additional path is configured using RSVP-TE [10] or CR-LDP [11] signaling. After that, the LCAS protocol gets triggered and the additional member path is accommodated to the path group (steps #3 and 4 in Fig. 4a) in a hitless manner. The network provider is then able to start provisioning new bandwidth service, satisfying the current end user's bandwidth requirements.

OIF is currently working on the signaling specification between client and network — UNI 1.0 (end user and network provider interface in Fig. 4a). However, the bandwidth adjustment feature is out of the scope of that document, although expected to be present in a future UNI 2.0 document.

Figure 4b shows an example of EMS/NMS-based on a centralized control scheme. In this case, the EMS/NMS receives a bandwidth modification request from the end user (step #1, additional 50 Mb/s, in Fig. 4b). The EMS/NMS then routes the end-to-end path (additional VC-3 in Fig. 4b) in order to increase the end-to-end capacity and set up the path using a local command such as TL-1 (step #2 in Fig. 4b). After that, EMS/NMS starts LCAS procedure at the edge nodes (steps #3 and 4 in Fig. 4b) so that hitless bandwidth increase be performed (steps #5 and 6 in Fig. 4b). Once these steps are completed, the network provider can provide the requested bandwidth to the user.

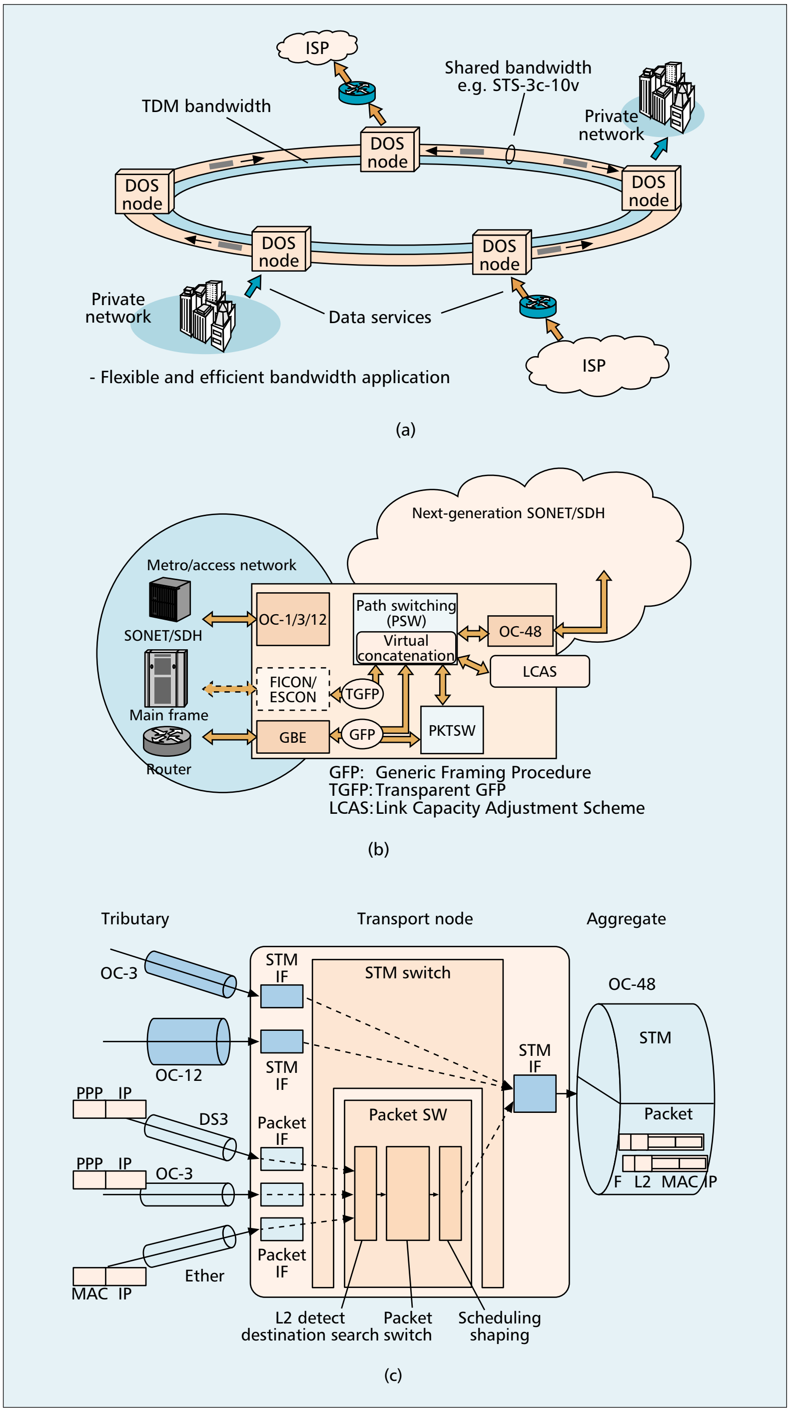
DoS Transport Node: Architecture and Applications

In this section, DoS transport architecture and network applications are considered.

DoS Node Architecture

Figure 5a illustrates an example of a novel transport network using DoS nodes. The network is a ring that provides hybrid services: TDM and shared data transport. In this example, TDM service is realized via dedicated bandwidth across the ring. In the same network, some shared bandwidth is used to provide efficient and reliable data transport applications. Notice that this transport network differs from a recent resilient packet ring (RPR) initiative (IEEE 801.17), in the sense that the latter is focused on data transport only (Ethernet directly over fiber is currently the interface of choice) for metro area applications. In contrast, besides data applications, the hybrid services support TDM applications as well, and can be used in both MAN and WAN scenarios. Note that the channel identifier field in GFP linear frame structure can be used to distinguish 256 data streams within a single SONET/SDH path (Fig. 6).

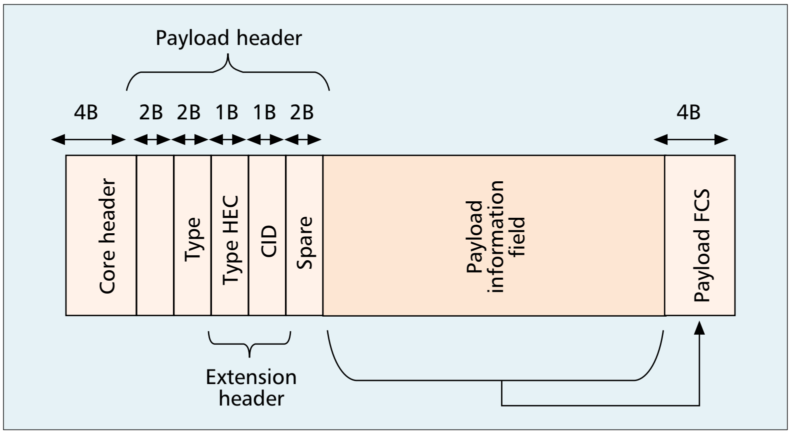
Figure 5b shows a typical functional architecture of a DoS node. The node provides transport interfaces, such as legacy SONET/SDH, ESCON/FICON, and GbE, for a wide range of applications. The DoS node uses virtual concatenation and GFP as enablers to efficiently pack application data into SONET/SDH frames. It also uses LCAS to regulate the amount of bandwidth assigned to transport the client data.



■ **Figure 5.** *A DOS node: a) an example of network architecture using DOS; b) functional architecture; and c) hardware architecture.*

DoS nodes are designed to provide a wide variety of line interfaces so that new services can be launched without deployment of new nodes. New line interface cards are installed as need arises. Interfaces for a data center (e.g., ESCON, FICON, Fibre Channel) and digital video (e.g., DVB-ASI) are also utilized. Figure 5c illustrates the hardware architecture of a DoS node with layer 1/2 hybrid switch capability. The node is composed of the following modules.

Switch modules:
- STM switch
- Packet switch



■ **Figure 6.** *The GFP linear frame structure.*

Aggregate interface cards:
- OC-48/STM-16
- OC-192/STM-64
- OC-768/STM-256

Tributary interface cards:
- Ethernet (10M/100M/1G)
- Fibre Channel, ESCON/FICON
- DVB-ASI (video interface)
- POS (OC-3/STM-1, OC-12/STM-4, OC-48/STM-16)
- ATM (OC-3/STM-1, OC-12/STM-4, OC-48/STM-16)
- TDM (OC-3/STM-1, OC-12/STM-4, OC-48/STM-16, DS1, DS3, etc.)

Node-to-node trunks are terminated on an aggregate interface card. On the receiver side of the aggregate interface, TDM traffic continues to be switched to either the tributary interface cards or aggregate interface cards, while the data traffic on virtually concatenated channels are routed to the packet switch. The packet switch performs termination of virtually concatenated payload to produce GFP streams at the switch input ports. At the output ports of the packet switch, the virtual concatenation function maps the GFP streams into virtually concatenated payloads, which are sent to the STM switch. The packet switch performs the switching of GFP frames between ports, some connected to tributary interface cards and the rest to aggregate interface cards, through the STM switch. At the tributary interface card, GFP frames are terminated to extract the original data stream, which is then mapped to the appropriate layer 1 and 2 protocols.

In the data transmission direction, the incoming layer 1 and 2 protocols are terminated, and data streams are encapsulated into GFP frames at the tributary interface cards. If the line interface card happens to have several ports, the GFP frames from the various ports are aggregated together and sent to the packet switch. The packet switch then switches GFP frames, maps the frames into virtually concatenated payloads, and sends them to the aggregate interface cards.

GFP Point-to-Point Frame Application

The structure of a GFP linear (point-to-point) frame is depicted in Fig. 6, as specified in [3]. A typical application of GFP linear frame is point-to-point connection and concentration. For example, data streams from multiple tributary interface cards can be aggregated into a same aggregate interface card. The 8-bit channel identifier (CID) in the GFP extension header is used to indicate one of 256 data streams. If the available bandwidth of the aggregate interface is below the sum of peak traffic of all data streams, statistical multiplexing is introduced to achieve concentration.

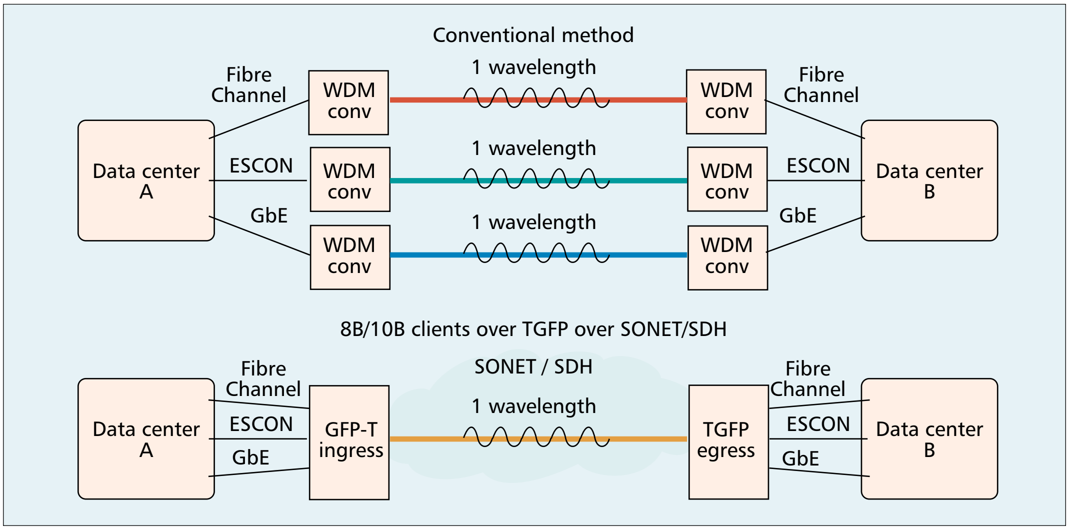
The optional payload FCS field in the GFP frame can be used for performance monitoring of an end-to-end GFP path. The area covered by FCS is the payload information field only, which contains the user data. Therefore, at intermediate nodes, recalculation of FCS is not necessary, so that FCS is retained throughout the path.

The end-to-end path monitoring can be used for path quality management as well as for triggering protection mechanisms.

SAN Interconnection by Transparent GFP

SAN deployment for disaster recovery applications has recently received a lot of attention. This application requires direct connection of SAN interfaces to a WAN in an efficient manner.

The conventional method for supporting this



■ **Figure 7.** *Application of TGFP.*

application is to simply assign one wavelength to each SAN interface. This method is inefficient in terms of bandwidth usage because the SAN bit rate is generally much less than the wavelength modulation rate. Better efficiency is achieved by multiplexing several SAN signals into a SONET/SDH modulated wavelength. Transparent GFP (TGFP) allows transparent transport and multiplexing of 8B/10B clients such as Fibre Channel, ESCON, FICON, and DVB-ASI (digital video), as mentioned earlier. Transparency means that data and clock rate received at the TGFP ingress node can be recovered at the egress node over a SONET/SDH network. TGFP can be seen as a kind of sub-lambda technique for 8B/10B interfaces over SONET/SDH (Fig. 7).

An additional benefit of this solution is that TGFP provides 6.25–16.25 percent bandwidth reduction from the original 10B rate. Table 1 shows typical VC path capacity required for SAN client transparent transmission.

Protocol	10B based rate	8B based rate	VC path size
ESCON	200 Mb/s	160 Mb/s	STS-1-4v
DVB-ASI	270 Mb/s	216 Mb/s	STS-3c-2v
Fibre Channel, FICON	1062.5 Mb/s	850 Mb/s	STS-3c-6v
GbE	1250 Mb/s	1000 Mb/s	STS-3c-7v
Infiniband	2500 Mb/s	2000 Mb/s	STS-3c-14v

Table 1. *Bandwidth reduction by use of TGFP.*

Conclusion

In this article, we have introduced several emerging techniques currently under development for next-generation SONET/SDH systems. Based on these new techniques, we have elaborated on new SONET/SDH transport services likely to become reality within a few years. Data over SONET/SDH, using GFP, virtual concatenation, and LCAS, is likely to become the dominant transport method over SONET/SDH transport networks.

Looking ahead, flexible transport services, combined with virtually unlimited bandwidth availability brought by WDM transport techniques, will ensure that sophisticated and bandwidth-hungry Internet applications of the future can be deployed. These yet to be seen applications will likely change computer and human communications in a revolutionary/unprecedented way.

Acknowledgment

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References

[1] W. Simpson, "PPP over SONET/SDH," IETF RFC 1619, May 1994.
[2] ATM Forum Tech. Comm., "2.4 Gbps Physical Layer Specification Draft," PHY WG, BTD-PHY-2.4GB-01.04, Apr. 1999.
[3] ITU-T Rec. G.7041, "Generic Framing Procedure (GFP)," Oct. 2001.
[4] ITU-T Rec. G.707, "Network Node Interface for the Synchronous Digital Hierarchy," Oct. 2000.
[5] ITU-T Rec. G.7042, "Link Capacity Adjustment Scheme (LCAS) for Virtual Concatenation," Oct. 2001.
[6] J. Heinanen, "Multiprotocol Encapsulation over ATM Adaptation Layer 5," IETF RFC 1483, July 1993.
[7] OIF, "User Network Interface (UNI) Signaling Specification" Oct. 2001.
[8] P. Ashwood-Smith *et al.*, "Generalized Multi-Protocol Label Switching (GMPLS) Architecture," IETF Internet draft, Nov. 2001.
[9] K. Kompella *et al.*, "Routing Extensions in Support of Generalized MPLS," IETF Internet draft, Nov. 2001.
[10] P. Ashwood-Smith *et al.*, "Generalized MPLS Signaling — RSVP-TE Extensions," IETF Internet draft, Nov. 2001.
[11] P. Ashwood-Smith *et al.*, "Generalized MPLS Signaling — CR-LDP Extensions," IETF Internet draft, Nov. 2001.

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