Designing Hybrid SONET and DWDM Networks

Sunan Han, Fujitsu Network Communications

ABSTRACT

To take full advantage of SONET granularity and DWDM capacity, the two technologies must be combined to enable deployment of the most economic transport networks. The emergence of integrated SONET and DWDM platforms is also part of the effort to build a hybrid network to achieve this objective. It then poses a new challenge to network designers in designing networks mixed with MSPP, ROADM, and integrated platforms. This article provides guidelines on recognizing different types of hybrid networks and how to accomplish the design task by using existing design tools or procedures.

INTRODUCTION

Transport network design is so important to service providers that good design practices can save carriers millions of dollars in transport equipment and fiber costs. Synchronous optical network (SONET) was the dominant technology deployed in all metro and long distance networks for many years. Thus, the design of SONET transport networks has been practiced again and again, and the methodologies or algorithms adopted in SONET network design tools have constantly been improved. Regardless of the fact that the major optimization algorithms in routing and resource allocation all, unfortunately, fall into the NP-complete class, most network designers feel comfortable having their design tools create a suboptimal network design. SONET network design has already become a set of routine processes, rather than new challenges each time a new design task arrives.

The class NP is the set of decision problems that can be solved by a nondeterministic Turing machine in polynomial time. An NP-complete problem is defined as a problem in NP, and any other decision problems can be reduced to it by polynomial transformations. So NP-complete problems are the toughest problems in NP because if any NP-complete problem can be solved in polynomial time, so can all NP problems. For detailed definitions please refer to [1]. NP-complete problems are informally those that can be solved by a computer, which simulates a deterministic Turing machine (computable) but in an impractically long time (intractable). This is because the solution space of an NP-complete problem is too large to be searched exhaustively in a reasonable time to find an optimal solution. Compromises have been made in finding the algorithms that solve NP-complete problems by intelligently searching only part of the solution space in a reasonable time, but most likely with a suboptimal solution. This is why an expensive design tool sometimes delivers a very poor network solution.

For design of an optical-only network with dense wavelength-division multiplexing (DWDM) technology, the routing part of the design is very much like SONET design, but only deals with traffic at the wavelength level, such as 2.5 or 10 Gb/s wavelengths. Topological design should be different from that of SONET. Using a ring design as an example, a topological ring of the DWDM network should be extended to more network elements than in SONET to take full advantage of the bandwidth provided in a single pair of fibers that require just a single set of engineered optical amplifiers, dispersion compensation modules, and regenerators. Another important part of DWDM network design is dealing with the optical properties, such as power loss and dispersion, that are nonlinear variables of the transport distances. The optical properties are very equipment- and fiber-specific. Each vendor of different optical gear using a different type of fiber will need a separate set of rules to engineer the links of the network. But in any case, these rules are fixed once the hardware, and therefore the optical properties, of the equipment are determined. Thus, the design process is still quite routine.

A new network design challenge has become imminent only when carriers came to the realization that combining the fine granularity of SONET with the vast capacity of DWDM will bring the ultimate efficiency and economy into their transport networks. Literature in [2–4] has formal proofs that subwavelength grooming through SONET improves network utilization and economy. The challenge now is to design a hybrid network with both SONET and DWDM technologies where the intermixing is optimized in cost and utilization before any new design tools become available.

In the beginning, the technological platforms for the design of hybrid networks included the SONET add/drop multiplexer (ADM), also known as a multiservice provisioning platform

 0163-6804/06/$20.00 © 2006 IEEE

(MSPP) today, and the optical ADM (OADM) for DWDM or WDM. In recent years, new platforms that integrate SONET and DWDM into one system have emerged. They are the ADM-on-a-wavelength (AOW) platform and the centralized STS switch (CSS) platform, which were documented initially in [5]. Before the emergence of integrated platforms, the design of SONET and DWDM hybrid networks solely relied on an overlay architecture where the ADM was overlaid on top of DWDM gear. This overlay architecture was well documented in [6]. Hybrid network designs were conducted to achieve specific analytical results around this architecture [3, 4], where SONET and DWDM networks were designed independently by respective design procedures.

It is a new challenge to incorporate integrated platforms into design methodologies and best realize their benefits. This article intends to provide some general methodologies for the design of hybrid networks with integrated platforms, as well as standalone ADMs/OADMs, using existing SONET and DWDM design procedures. This article identifies two types of hybrid SONET and DWDM network architectures — vertically hybrid and horizontally hybrid architectures — and discusses methodologies to tackle each of them.

Technological Platforms for Transport Networks

The evolution of SONET is marked by the replacement of the legacy ADM, which handles one ring at a time and transports exclusively time-division multiplexing (TDM) traffic in a multishelf architecture, by the MSPP, which terminates and crossconnects multiple rings or mesh links and provides data services all in a single shelf [7]. This evolution has greatly reduced the per STS-1 end-to-end transport cost, as well as central office (CO) operation cost due to office space and power consumption reductions.

Meanwhile, the rise of DWDM technology has brought tremendous bandwidth and fiber relief to the transport network. DWDM was first adopted by long distance carriers because the spending in amplification, dispersion compensation, and regeneration made up most of the network equipment cost in regional and national SONET networks. DWDM became more and more popular in metro networks when the local exchange carriers grew their networks. Other than fiber exhaustion, traffic volume is the major economic factor for deploying DWDM technology in metro networks [8].

The basic architecture of a two-degree OADM includes a pair of wavelength multiplexers/demultiplexers (muxes/demuxes) and a set of transponders. Each transponder terminates a wavelength from a mux/demux and connects to client equipment for service delivery. A reconfigurable OADM (ROADM) is an enhanced OADM that crossconnects wavelengths and is capable of terminating more than two fiber degrees. The wavelength-selective switch (WSS) is a recent technology adopted by most ROADMs to dynamically route and terminate

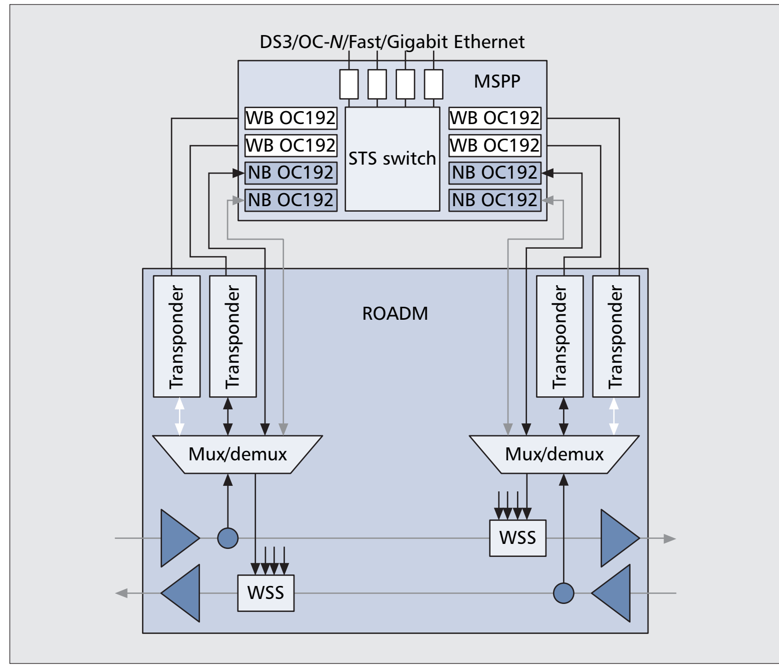


Figure 1. *The MSPP-ROADM overlay architecture.*

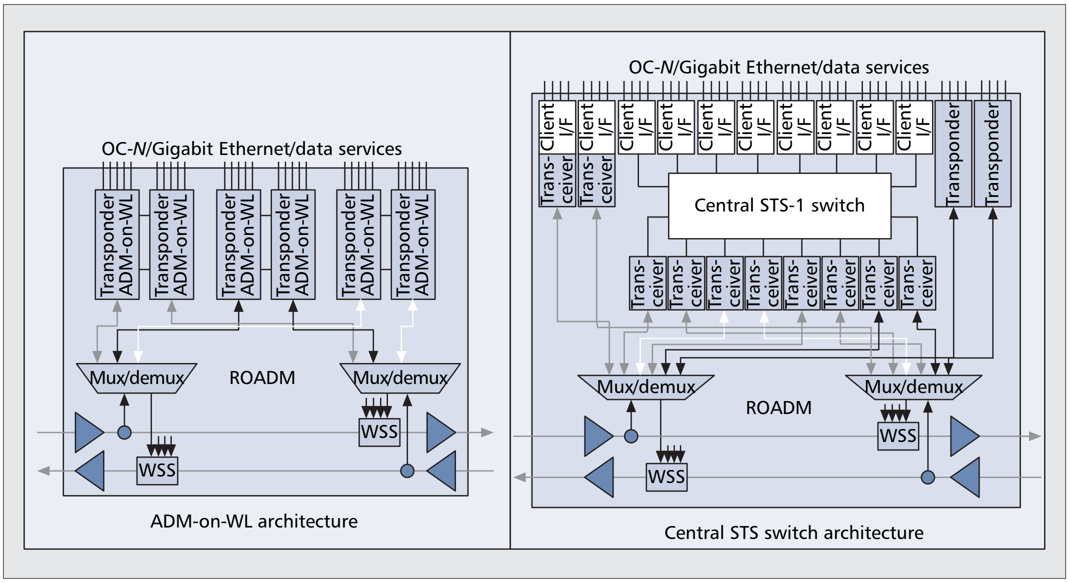
wavelengths due to better optical attributes than other technologies [9]. For the architecture of an ROADM, please refer to Figs. 1 and 2.

Original hybrid network designs utilized an overlay architecture [3, 4]. Figure 1 shows such an architecture with two different ways to interconnect the MSPP and ROADM platforms. When line cards with wideband optics (WB OC192 in the picture) are used in the MSPP, the interconnection must be through transponders in the ROADM to transform the "uncolored" optics into "colored" optics required by DWDM technology. Narrowband line cards (NB OC192 in the picture) can also be used in MSPP. They are already colored and can be directly connected to the optical mux/demux. They are usually more expensive than wideband cards, but frequently the economic choice in the one-for-two trade: each narrowband line card replaces a wideband line card and a transponder.

New integrated platforms have been developed in an effort to eliminate or reduce the cost incurred in the interconnection between MSPPs and ROADMs, as well as to enhance the power of aggregation. AOW is an implementation of SONET ADM or MSPP functionality directly into a transponder card. The left half of Fig. 2 shows a ROADM with the AOW architecture. A pair of ADM-capable transponder cards forms an MSPP that is capable of supporting a SONET ring with all of the standard features and STS-1 grooming capabilities. A 10 Gb/s card supports an OC-192 ring via a 10 Gb/s wavelength, and a 2.5 Gb/s card supports an OC-48 ring via a 2.5 Gb/s wavelength, from/to the west or east mux/demux. The tributary side of the transponder interfaces with multiple client services from OC-3 to OC-48 to Gigabit Ethernet.

The right half of Fig. 2 depicts the other integrated architecture that utilizes a CSS. In this architecture, the optical and electrical parts of a transponder are separated as transceiver and

New integrated platforms have been developed in an effort to eliminate or reduce the cost incurred in the interconnection between MSPPs and ROADMs, as well as to enhance the power of aggregation. AOW is an implementation of SONET ADM or MSPP functionality directly into a transponder card.



■ **Figure 2.** *The SONET-DWDM integrated architectures (AOW and CSS).*

client interface, respectively, and they are connected through the CSS. The breakthrough in this architecture is global, any-port-to-any-port, any-port-to-any-wavelength, and any-wavelength-to- any-wavelength aggregation and grooming. It implies the minimization of equipment ports by eliminating inter-ring crossconnect and client interface fragmentation. Please refer to [5] for detailed analysis of architectural and economic benefits of integrated architectures compared to the overlay architecture shown in Fig. 1.

SONET-DWDM Hybrid Network Design Building Blocks

The technological platforms surveyed above, together with the deployed fiber strands, are the basic components of a transport network. The fundamental building blocks of a design process are as follows.

Input data. The required data to warrant a correct network design when input to the design routines:

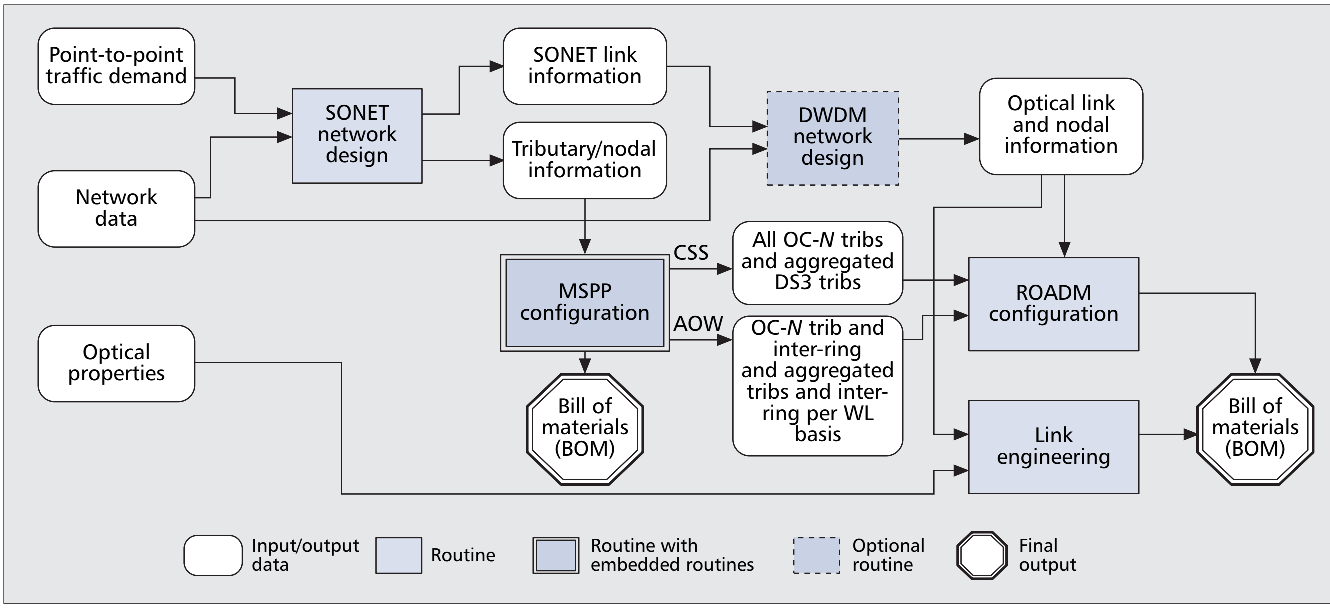
- Point-to-point traffic demand. There may be multiple types of demand. Each type of demand can be represented by an $N \times N$ matrix where the intersection of row i and column j represents a demand that originates from node i and terminates at node j.
- Network data. This includes a list of network nodes, their locations given in the form of coordinates or span distances or both, the fiber connectivity among the nodes, and, in multiperiod or growth scenarios, the existing network equipment lineup and configuration. Also, cost information for the spans (e.g., fiber) and equipment (e.g., line cards) is very important for optimization of the network. Network protection schemes have a big impact on the routing behavior of design routines. In SONET design the protection schemes are bidirectional line switched ring (BLSR), unidirectional path switched ring (UPSR), dedicated path protection mesh (DPPM), or shared path protection mesh (there are more varieties of mesh protection schemes than ring, but they lack standardization). DWDM design has comparable or BLSR/UPSR-like network protections.
- Optical properties. These are the optical characteristics of the optical transport equipment and the fiber types to be used in the network design.

SONET network design routine. This functional routine does the network topology design, such as construction of rings, routing of demand from origination to destination, grooming of traffic demand to efficiently share the transport facilities, and association of routed demand to the most appropriate SONET transport unit (e.g., OC-48 or OC-192), all on a optimization basis under the constraints given in the network data.

SONET network design output.

- Tributary and/or nodal information. On a per node basis, this describes in detail the terminating ports for each transport unit that stops by each of the nodes. For example, at node *X*, an OC-192 ring stops by and adds/drops 20 DS3s, 13 OC-3s, and 5 OC-12s; an OC-48 stops by the same node and adds/drops 15 DS3s and 8 OC-3s; and so on. It also gives information on how cross ring traffic goes, such as two OC-3s dropped from ring 4 and added to ring 2. This output information is also the input information for the MSPP configuration routine.
- SONET link information. It gives point-to-point SONET logical links in OC-N (N = 12, 48, or 192). This output information becomes the input as point-to-point wavelength traffic demand for the DWDM network design routine in SONET-over-DWDM scenarios.

SONET MSPP configuration routine. This routine uses the tributary/nodal information from the SONET network design routine to equip each node with the correct number or type



■ **Figure 3.** *SONET-DWDM hybrid network design flow chart.*

of MSPP shelves, cards, connectors, and cabling. In multi-period scenarios, existing free slots in the shelves and existing free ports in the interface cards need to be filled up first before adding new equipment. This routine actually has a decision to make regarding what tributaries are on the MSPP and what can be passed through to the ROADM based on the architecture of overlay, AOW or CSS. More details about the MSPP configuration routine are given later on. It is also responsible for the aggregation of low-speed interfaces into high-speed interfaces for the ROADM. The aggregation is necessary in that DS1 and DS3 cannot be the direct feed to the transponders and the number of ports on a transponder is limited.

MSPP configuration routine output.

- Bill of materials (BOM). Detailed list of the physical materials required to support the switch and transport of the given demand at each network node, including racks, chassis, fans, interface cards, control cards, processing cards, switch fabrics, timing units, filler cards, connectors, and cables. Pricing can easily be applied to the BOM.
- OC-*N* tributaries and aggregated tributaries in OC-*N*. This output is generated only for the input to the AOW and CSS integrated platforms. It includes optical tributaries that can be directly connected to the ROADM and aggregated OC-*N* from low-speed DS1/DS3/OC-*n* ($n < N$).

DWDM network design routine. This routine takes the SONET network link information from the SONET network design routine as the point-to-point wavelength demand, designs the best network topology, and routes the demand through the DWDM network.

DWDM network design output.

- Optical link and nodal information. This includes wavelength assignment and transmission distance on a per link basis, and the distribution of passing through and terminating wavelengths at each node. The actual add/drop demands for each wavelength, however, is not available in this output. They are associated to each SONET transport pipe, link, or ring at the SONET design stage. When a SONET transport pipe is allocated a wavelength at the DWDM design stage, the add/drops of that wavelength are automatically carried over.

ROADM configuration routine. This routine does the same procedure as the MSPP configuration routine, but allocates the ROADM equipment such as muxes/demuxes and transponder cards. The add/drops or tributaries for each wavelength are taken from the output of the MSPP configuration routine in the case of integrated platforms.

Link engineering routine. This routine engineers the optical links based on the optical properties associated with each optical component in the DWDM transport network. It may be merged with the configuration routine if the network covers a metro area with short spans between nodes so that no regenerators or in-line amplifiers are needed in the spans.

Output from the ROADM configuration and link engineering routines.

- BOM. Detailed list of the physical materials required to support the switch and transport of the given demand at each network node, including racks, chassis, fans, interface cards, transponder cards, control cards, processing cards, optical switches and mux/demuxes, timing units, amplifiers, dispersion compensation units, attenuators, filler cards, connectors, and cables.

SONET-over-DWDM Hybrid Network Design Procedures

In designing a hybrid SONET and DWDM network, the most common architecture is SONET over DWDM, where the underlying or core transport is DWDM while the SONET routing is

The best SONET design may generate a bunch of topologically different OC-48 and OC-192 rings, while the most economic DWDM transport network may consist of just a single DWDM ring. Therefore, there are two options in the topological optimization,

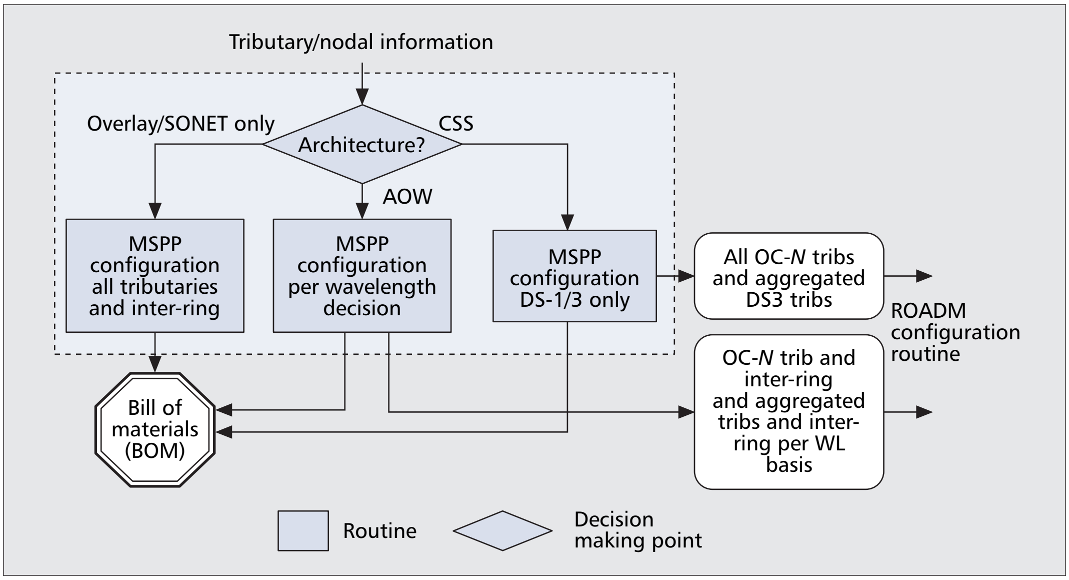


Figure 4. *Flow chart for the MSPP configuration routine.*

achieved by the overlaid or integrated MSPPs. The need of SONET granularity is due to the existence of low-speed service demands such as DS1/DS3 and the lack of subwavelength grooming in the DWDM platforms. The overlay, AOW, and CSS architectures all can be used in such SONET-over-DWDM network designs.

With all the necessary building blocks described in the last section, we are able to put together a complete picture of the process of designing a SONET-over-DWDM hybrid network. The best way to illustrate is to use a simple flow chart as shown in Fig. 3.

In the flow chart diagram, shaded blocks are routines that are standard procedures either implemented in a program or through a set of automatic or manual applications (e.g., spreadsheets, manual steps, and Visual Basic programs). The transparent blocks are data input and output to/from the routines.

DWDM networks take advantage of its ample bandwidth and let traffic bypass some intermediate nodes through provisioning of dedicated wavelengths between nodes to save interconnection or crossconnect costs. When compared to SONET topology, which is most efficient when it routes the traffic as near as possible from origination to destination, DWDM has a goal to carry the same traffic in as few topological structures (e.g., rings) as possible. DWDM does this at the cost of allowing some traffic to traverse longer distances than it does in SONET. For a simple example, the best SONET design may generate a bunch of topologically different OC-48 and OC-192 rings, while the most economic DWDM transport network may consist of just a single DWDM ring. Therefore, there are two options in the topological optimization, both of which need to be decided at the SONET design stage.

The first option is to design the SONET network the best way it can be, regardless of the DWDM topology. At the DWDM design stage, the SONET transport pipes will be rerouted as wavelengths on a different network topology that is optimized for DWDM design. The second option is to decide the DWDM network topology first, and then design the SONET network based on the predetermined DWDM topology. In the latter case, the SONET transport pipes do not need to be rerouted at the DWDM design stage. Our experience has proven that the second option often has better performance than the first in the combined design results.

The MSPP configuration routine has a very unique and delicate task to perform, depending on which DWDM transport platforms are in use. In the case of MSPP and ROADM overlay, all tributaries, inter-ring connectivity, and SONET transport pipes are configured on the MSPP shelves, just like a SONET-only design. However, in the integrated platform cases, AOW and CSS, the tributaries and interconnections are dealt with very differently, as shown in Fig. 4

In configuring a node with CSS architecture, no optical tributaries need to be accommodated on the MSPP, and all are passed along to the ROADM configuration routine. All inter-ring traffic will be handled in the centralized switch. Only DS-3 or lower-level tributaries need to be put on the MSPP for aggregation, with no need to differentiate which wavelength they end up with.

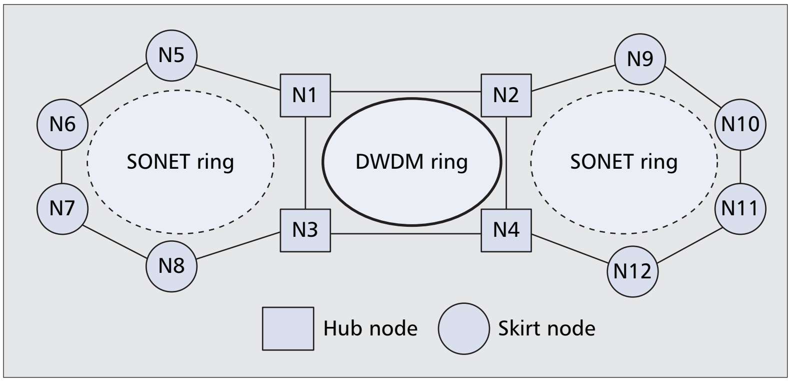
Things are quite different for the AOW architecture, though. Assume that the following two types of AOW cards are available: a 4-port 2.5 Gb/s card with each port being provisioned freely as OC-3, OC-12, OC-48, or Gigabit Ethernet (GigE), and an 8-port 10 Gb/s card with each port being able to handle OC-3, OC-12, OC-48, or GigE independently.

The first 12 columns of Table 1, except column 3, are the output from the SONET network design routine. For example, five OC-192 and two OC-48 SONET rings terminate at node *A*. Columns 13 to 19 are the MSPP interface cards that need to be configured based on the output. All SONET rings ride on a single DWDM ring called *R-1*. A pair of 2.5 Gb/s AOW cards is

				Add/drop or tributary port				Inter-ring port				MSPP interface card						
Node	SONET ring	DWDM ring	Band-width	DS3	OC3	OC12	OC48	DS3	OC3	OC12	OC48	DS3-8p	OC3 2p	OC3 4p	OC12 1p	OC12 4p	OC48 1p	OC48 2p
A	Ring1	R-1	OC192	15				12	4			0					2	
	Ring10	R-1	OC192	14	3			19	4			0					2	
	Ring11	R-1	OC192	15	4							0					2	
	Ring15	R-1	OC192	3	2							0			2			
	Ring2	R-1	OC192	29	1			2				0					2	
	Ring4	R-1	OC48	11	1			5				0			4	0		
	Ring5	R-1	OC48	16								21			4	0		
B	Ring1	R-1	OC192	20	15	2	1	3				0	0	6			0	2
	Ring11	R-1	OC192	12	4	3		13				0					2	
	Ring12	R-1	OC192	17	9	2	2	19	3			0	2	4			0	2
	Ring13	R-1	OC192	11	9	4		3	1			0		4			2	
	Ring14	R-1	OC192	4	1	1	1					0			2			
	Ring2	R-1	OC192	20	9			3				0	2	0			2	
	Ring3	R-1	OC48	10	4							0	2	0	4	0		
	Ring5	R-1	OC48	12	2							0			2	0		
	Ring8	R-1	OC192	16	8	3	1	2				0	2	2			2	
	Ring9	R-1	OC192	24	16		1	5	2			30	2	6			0	2
C	Ring1	R-1	OC192	15	3	6	2					0		2	2	0	2	
	Ring10	R-1	OC192	18	6	9	1					0	2	2	0	2	0	2
	Ring11	R-1	OC192	11	11	8	1	2				0		6		2	0	2
	Ring12	R-1	OC192	5	6	6	2	1				0	2	2	2	0	2	
	Ring13	R-1	OC192	14	7	13		1				0		4	0	4	2	2
	Ring14	R-1	OC192	3		5	2					0			2			
	Ring15	R-1	OC192	8	10	7	1					0	2	4	4	0	0	2
	Ring16	R-1	OC192	3	3	1						0			2		0	
	Ring2	R-1	OC192	23	17	5						0	0	8				2
	Ring3	R-1	OC48	2	1				1			0			2	0		
	Ring4	R-1	OC48	6	6	2						0	2	2	4	0		
	Ring5	R-1	OC48	9	7			2				0	2	2		2		
	Ring6	R-1	OC48	5	8	1		1	2			0	2	4		2		
	Ring7	R-1	OC48			4						0						
	Ring8	R-1	OC192	12	6	9	1					0	2	2	0	2	0	2
	Ring9	R-1	OC192	15	3	5	2	3	3			24	2	2			2	

■ **Table 1.** *SONET-over-DWDM network design.*

needed for each OC-48 ring (west and east), and a pair of 10 Gb/s AOW cards is needed for each OC-192 ring in the ROADM. DS3 ports have to go on the MSPP and then be aggregated to OC-*N* before connecting to an AOW card. OC-3 or higher-speed ports can be put either on the MSPP for aggregation or directly on an AOW card. In order to optimize the cost, we need to put as many OC-*N* ports on the AOW card as possible to avoid an extra layer of interconnection in the MSPP, under the constraint that the maximum number of ports cannot exceed four



■ **Figure 5.** *Network example for horizontally hybrid network design through hubbing.*

for a 2.5 Gb/s card and eight for a 10 Gb/s card. In node *A*, for example, *Ring1* is an OC-192 ring that terminates 15 DS3s, and drops another 12 DS3s and 4 OC-3s for the interconnection to other rings in node *A*. The corresponding AOW card in the ROADM is a 10 Gb/s one and has eight ports. We can put all 4 OC-3 on the AOW card. The remaining 27 DS3s are on the MSPP and aggregated into one OC-48. This is why there are a couple of one-port (1p) OC-48 cards (1 + 1 protected), but no OC-3 cards in the MSPP. DS3 cards are provisioned based on the total number of DS3 ports in the entire node. In total, the MSPP configuration routine sends five ports (one OC-48 and four OC-3) to the DWDM configuration routine. Actually, the MSPP configuration routine has done almost all the work. The DWDM configuration routine just needs to allocate a couple of AOW cards.

Let us look at a more complex example of *Ring1* at node *B*. The optimized configuration is to put one OC-48, two OC-12s, and three OC-3s directly onto the AOW card. The remaining 23 DS3s and 12 OC-3s are on the MSPP and aggregated into two OC-48s for the remaining two ports on the AOW card. This configuration process can be automated through a try-until-fail algorithm, which tries each port, highest speed first, on the AOW card until the remaining AOW ports are less than the OC-*N* ports that are MSPP aggregated from the remaining tributary ports. The blue-shaded area of Table 1 is the output of a macro program that implements such an algorithm.

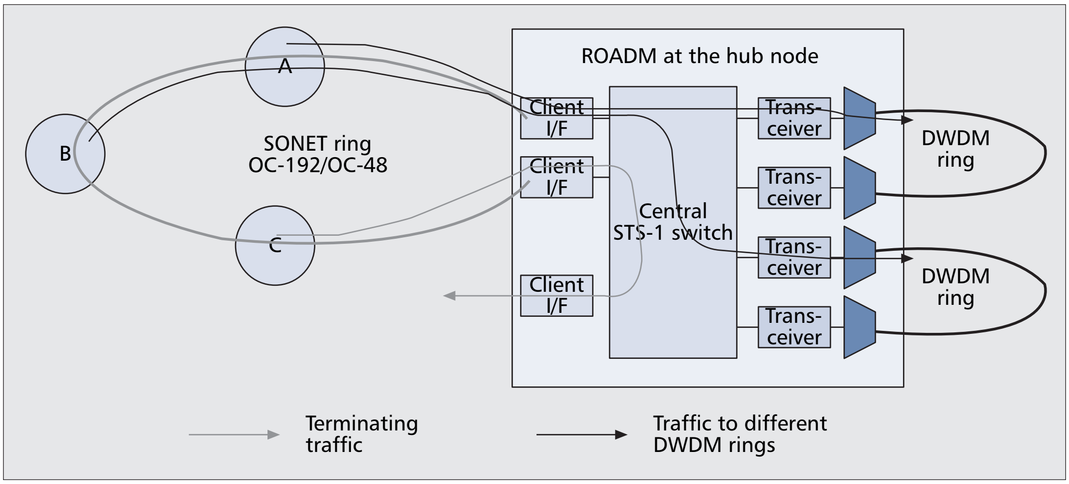
Horizontally Hybrid SONET-DWDM Network Design

If we view the SONET-over-DWDM architecture as a "vertically" hybrid network architecture, where SONET and DWDM coexist everywhere in the network, there are ways to design efficient SONET and DWDM hybrid networks "horizontally." In such a network parts of the core transport are on SONET and parts are on DWDM.

One simple approach is that before the SONET network design begins, the demand matrix can be screened to isolate the high-speed demand that is from the same origin to the same destination and whose total bandwidth is approximately 10 Gb/s, such as three to four OC-48s, six to eight GigE circuits, and so on. This type of demand can be applied directly to the DWDM network to save ports on the MSPP and thus excluded from the SONET design. At the DWDM design and configuration stages, this demand will be routed and assigned to wavelengths and low-cost transponders that have no AOW functionality. The rest of the network can be either SONET only (and therefore the SONET transport will coexist with the DWDM transport) or SONET over DWDM as discussed earlier, whichever is more economical.

A more advanced approach to optimize the transport network with both SONET and DWDM technologies is to use hubbing to collect traffic from the parts of the network that do not have enough traffic to justify DWDM deployment. The DWDM ring is only built over the hub nodes where the traffic concentrates the most, and the SONET rings are used to transport traffic between the hub nodes and skirt nodes. This approach creates three new technical requirements in the design process:

- Deciding on the hub nodes and homing the skirt nodes to their hub nodes.



■ **Figure 6.** *Hub configuration with CSS in horizontal SONET-DWDM hybrid design.*

- Splitting the single traffic matrix of any-node-to-any-node (ATA) into two matrices: a hub-node-to-hub-node (HTH) matrix and a matrix for the rest of the demand, which could be skirt-to-skirt or skirt-to-hub (STS/H). The HTH matrix is for the design of the DWDM network, and the STS/H matrix is for the design of the SONET network.
- Interconnecting the two technologies.

Let us use the example in Fig. 5 to discuss how the requirements can be met. The hub nodes can be predetermined or selected through an automatic procedure based on aggregated nodal traffic and network connectivity. After the hub selection, let's assume *N1*, *N2*, *N3*, and *N4* are selected to be the hubs in our example, and each of the other nodes, or skirt nodes, needs to find a home at a hub node. A shortest path homing should serve the purpose in most cases. Nodes *N5* and *N6* are homed at *N1*, and *N7* and *N8* are homed at *N3*, and so on. Any traffic demand from a skirt node will terminate at its homing hub first.

In splitting the traffic matrix, the demand originated at *N6* and terminated at *N11*, or *N6-N11*, will be split into *N6-N1*, *N4-N11*, and *N1-N4*, where the first two demands are for the STS/H matrix and the last is for the HTH matrix. When designing a network with a large number of nodes, manual calculation of the HTH matrix can create a problem. However, the following algorithm provides a simple solution. It is implemented in two nested loop statements of a BASIC-like programming language with the data structure being set up accordingly:

```
For i = 1 To number_nodes
    for j = 1 To number_nodes
        HTHmatrix(hub(i), hub(j)) = HTH-
matrix(hub(i), hub(j)) + ATAmatrix(i, j)
    Next j
Next i
where:
```

number_nodes is the total number of nodes in the network,

ATAmatrix is the any-node-to-any-node traffic matrix,

HTHmatrix is the hub-node-to-hub-node traffic matrix to be calculated, and

hub(*i*) is the hub or home of node *i*.

It is also not difficult to calculate the STS/H matrix by directing each demand from a node to its hub. Some unnecessary backhauling exists in the above approach. For example, demand *N6–N7* does not have to be sent to any hub because it can be handled within the SONET network. This type of traffic can be picked out from *ATAmatrix* and added directly to the STS/H matrix.

With a different set of traffic demands and network topologies, the SONET network (or networks) and DWDM network can be designed individually, where the DWDM network has more concentrated point-to-point traffic to fill up the wavelengths. After the design, special care is needed in configuring the hub nodes that interconnect the SONET and DWDM worlds. A straightforward approach uses MSPPs for the SONET part and ROADMs for the DWDM part. The cross-domain traffic is terminated first and then interconnected through client interfaces. This method, however, proves not to be the most efficient configuration because it introduces some extra interconnection cost. The AOW integrated platform can subtend SONET rings on its client interfaces and therefore can be used in some hubs as a single-platform solution. However, there are obstacles in using it for general cases when, for example, the SONET ring terminates traffic at the hub, or there is traffic from the SONET ring that goes to different DWDM rings. In the latter case, the pair of AOW transponders that take in the subtended ring form a single wavelength, which can only be transported in one DWDM ring. With the CSS architecture, however, all the obstacles no longer exist, as shown in Fig. 6.

This article has provided methodologies in designing vertically and horizontally hybrid networks involving the integrated transport platforms. These methodologies have been proven useful in real world network designs and studies.

FINAL WORDS

The introduction of both SONET and DWDM technologies in today's networks, and the emergence of integrated platforms create new challenges to network designers. This article has provided methodologies for designing vertically and horizontally hybrid networks involving integrated transport platforms. These methodologies have proven useful in real-world network designs and studies.

REFERENCES

[1] M. R. Garey and D. S. Johnson, *Computers and Intractability: A Guide to NP-Completeness*, W. H. Freeman & Co, Jan. 15, 1979.

[2] H. Zhu *et al.*, "Cost-Effective WDM Backbone Network Design With OXCs of Different Bandwidth Granularities," *IEEE JSAC*, vol. 21, no. 9, Nov. 2003, pp. 1452–66.

[3] R. Skoog *et al.*, "Metro Network Design Methodologies That Build a Next-Generation Network Infrastructure Based on This Generation's Services and Demands," *J. Lightwave Tech.*, vol. 22, issue 11, pp. 2680–92.

[4] O. Gerstel, P. Lin, and G. Sasaki, "Combined WDM and SONET Network Design," *Proc. IEEE INFOCOM '99*, vol. 2, 1999, pp. 734–43.

[5] S. Han, "Architectural and Economic Impact of the Integration of SONET and DWDM Platforms," Tech. Dig. OFC/NFOEC, Anaheim CA, Mar. 2006, Session NThA5.

[6] D. Cavendish, "Evolution of Optical Transport Technologies: From SONET/SDH to WDM," *IEEE Commun. Mag.*, June 2000, pp. 164–72.

[7] S. Han, "Economics in Deploying Next Generation SONET Equipment in Metro Networks," *Proc. NFOEC*, Dallas, TX, Sept. 2002, vol. 1, pp. 526–36.

[8] L. Steinhorst, S. Han, and E. Koopferstock, "SONET and DWDM: Competing Yet Complementary Technologies For The Metro Networks," Tech. Dig. OFC/NFOEC, Anaheim CA, Mar. 2005, Session NTuH1.

[9] B. P. Keyworth, "ROADM Subsystems & Technologies," Tech. Dig. OFC/NFOEC, Anaheim CA, Mar. 2006, Session OWB5.

BIOGRAPHY

SUNAN HAN (sunan.han@us.fujitsu.com) received a Ph. D. degree in computer science at the University of Texas at Dallas in 1992. From 1992 to 1996 he was an assistant professor of computer science at Adams State College in Colorado. He joined a systems engineering group at Nortel Networks in 1996, first as a member of scientific staff and then as manager of a voice and data network design team. Now he is a principal planner with Fujitsu Network Communications. His research interests include SONET and DWDM network design and analysis, voice, data, and transport network architectures, network optimization, economic analysis and modeling, and algorithm design and analysis.