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9 Designing Multipoint Logically Switched Optical Networks

Eric Bouillet

CONTENTS

9.1 INTRODUCTION

The huge potential of optical networks for satisfying the skyrocketing needs of broadband telecommunications services while meeting rigid quality of service requirements has long been acknowledged. However, although fiber has become the medium of choice in telecommunication networks, its vast resources are severely underused because of the much slower electronics that are interfaced with the optical medium. For instance, transceivers operate at speeds that are several orders of magnitude below the actual usable capacity of the fiber (several Gbps versus hundreds of Gbps). In order to achieve higher rates, wavelength division multiplexing (WDM) techniques have been widely suggested. The concept behind WDM is to partition the optical spectrum into multiple nonoverlapping λ channels, each assigned a wavelength and modulated at electronic speed. In parallel to WDM transmission, recent studies have enabled the realization of photonic routing and switching devices that perform elementary functions such as wavelength routing and switching. With those devices in hand we can envision all-optical transparent networks that carry traffic between distant users on single beams of light from end-to-end. The optical network has the capability to route the signal on specified fiber paths, thereby allowing wavelength reuse, in addition to wavelength multiplexing. Furthermore, as in the radio frequency paradigm, sources can multicast signals to multiple destinations.

While purely optical networks have very large capacity, they lack the processing power useful for many network applications, especially the ability to support high connectivity. For this reason, an electronic layer must be superposed on the optical layer. This hybrid combination of electronics with optics is depicted in Figure 9.1. We consider general transparent optical networks called linear lightwave networks (LLN) as the optical infrastructure for the hybrid network. LLNs are all-optical networks whose nodes are generalized switches called linear divider combiners (LDC). The LDCs are controllable photonic switches that can create multipoint optical connections in a waveband-selective manner. In the sequel a waveband is a bunch of adjacent λ-channels and its width depends on the discrimination capabilities of the LDC. More precisely, the waveband is the smallest segment of the optical

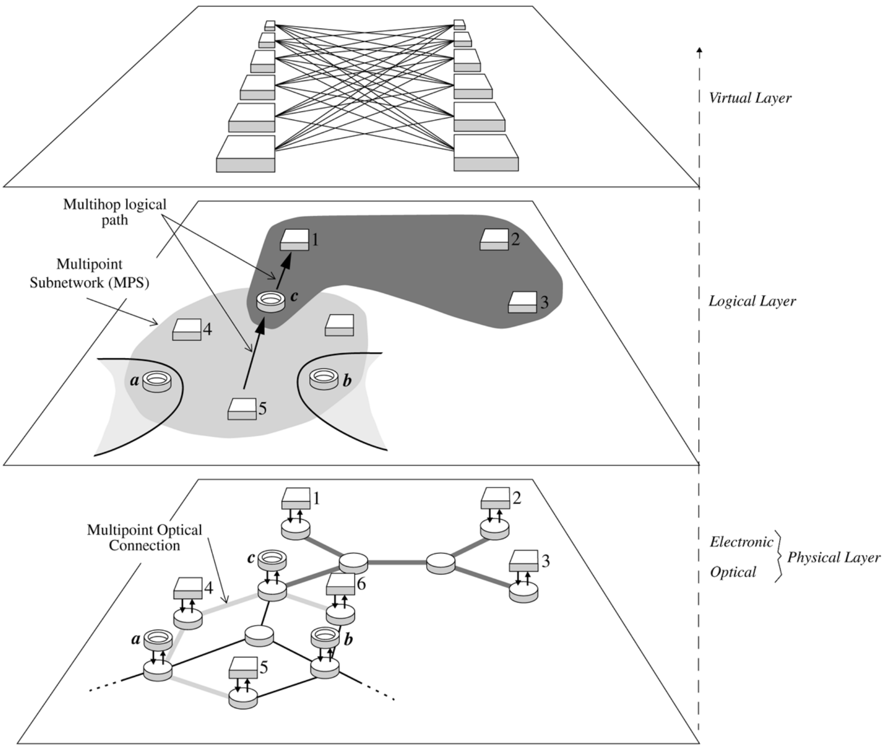


Figure 9.1 Hybrid Combination of Electronics with Optics

spectrum that is distinguishable in the LDC, while the λ-channel is the smallest unit resolvable in the access station by a tunable receiver. Typically, the spectral width of a waveband is much larger than a λ-channel. The LLN is accessed through network access stations (NAS) containing optical transceivers. Electronic equipment (either end user equipment or switches) accesses the network via external ports on the NAS. The connections between these external ports are called logical connections. The NAS are connected through access fibers to the LDCs, which in turn are set to create end-to-end paths between the access stations, either point-to-point or multipoint. In the latter the optical path is, de facto, a tree. Once an optical connection is set, it can carry one or more logical connections on it, using multiplexing protocols such as WDM, TDM, or CDM to avoid interference. In order to distinguish logical connectivity and optical connectivity, we lay a logical layer on top of the physical topology (PT). The role of the logical layer is to conceal the details of the optical paths and center our view on the logical connectivity.

There are four possible types of logical connectivities:

- *one-to-one* — one connection from one source to one destination
- *one-to-many* — multiple connections from one source to many destinations
- *multicast* — one connection from one source to many destinations
- *many-to-one* — multiple connections from many sources to one destination.

A fifth possibility, the many-to-many, combines one-to-many and many-to-one. We will call a set of NAS fully connected by a many-to-many connection a multipoint subnet (MPS). A MPS acts like a broadcast-and-select subnetwork of a larger network.

Even though the physical support is all-optical, it would be futile to attempt to establish full optical connectivity among all the NAS (or, in other words, to set up a MPS that covers the whole network). There are two reasons for this:

- The electromagnetic signal degrades as it propagates through a large transparent network. The degradation becomes even more evident when the signal is split for multicasting purposes in the LDC. Thus, a purely optical connection between distant NAS is sometimes impossible.
- To achieve a full connectivity among n NAS, $n(n - 1)$ simultaneous unidirectional connections must be established, and the purely optical approach soon reaches its limits when n becomes large.

Therefore, in order to maintain the connectivity between all NAS, the optical signal will sometimes have to be converted into an electronic form, processed, switched, and converted back to an optical signal, to continue on another optical path. This is the basic idea of multihop optical networks. In the networks proposed here, the key idea is to cluster the NAS into several MPS and let the electronic logical switches relay the traffic between stations that belong to different subnets, while the stations belonging to the same subnet communicate optically. Following this idea, we end up with a multipoint logically switched network (MSN) characterized by mutihop paths in a logical topology (LT). The difference between our

MSN and a multihop network is that the latter has an LT in the form of a graph, while the LT of the MSN is a hypergraph. The whole concept is illustrated in Figure 9.1, which shows a LT composed of two MPS and three NAS each, with the NASs numbered from 1 to 6. The link between the two MPSs is assured by the ATM switch *c*, which includes its own NAS to access the optical network. The figure also shows a multihop logical path from NASs 5 to 1. The capacity of the links in the virtual layer superimposed on top of the LT, must correspond to some prescribed traffic requirement between the NAS. The model for the traffic should include the notions of multicasting, time-scales (call level and bit rate), service classes, and Quality of Service (QoS).

The MSN architecture presented above relies on the optical resources to provide high throughput and electronic techniques to achieve higher connectivity. There is no free lunch, however, and by coupling optical switching with electronic switching, electronic bottlenecks are introduced. Nevertheless, intelligent electronics is essential to compensate for the lack of processing power in the optical layer.

9.1.1 Design of the Network

Broadband network design is usually aimed at satisfying a traffic requirement between NASs, taking into account their geographical location and without exceeding a maximum cost. In our case, we will assume that the virtual layer connectivity and capacity requirement and the PT of the optical infrastructure, described above, are given. The objectives, then, will be first to design the LT, and second to embed it into the PT. The design of the logical topology involves three operations:

- Pick an LT
- Map the NAS in the LT
- Route the traffic in the LT

Next, the LT is embedded in the PT, which requires two operations:

- Set up the optical path in the LLN such that the NAS in each MPS can see each other.
- Assign appropriate wavelengths to the connections among NAS.

In the next section, we will explain the value of a multipoint optical network. We then present the LT design and the embedding problems in Sections 9.3 and 9.4.

9.2 MOTIVATION

The properties of MSN come from the ability of the LLN backbone to support multipoint optical connections, thereby enabling higher connectivity with fewer electro-optic interfaces than in electronically switched networks connected by point-to-point fiber links. This is shown in Figure 9.2 with a comparison between a multipoint optical network and a standalone ATM network. The physical connectivity layer corresponds to the fiber deployment on the ground. This layer is fixed because

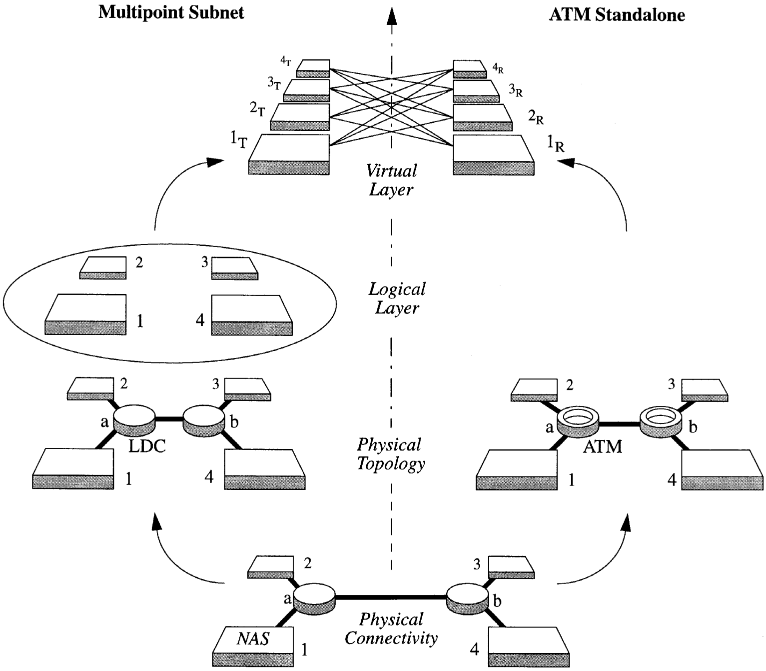


Figure 9.2 Comparison of Multipoint Optical Network and Standalone ATM

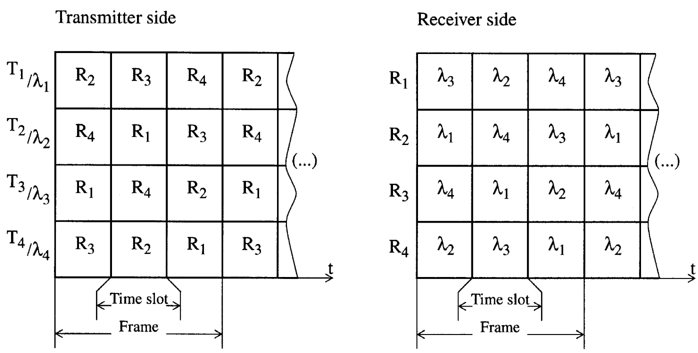
it is usually bound to geographical constraints. We consider bidirectional links with a unidirectional fiber for each direction. The two networks to be compared lie on top of the physical connectivity and must satisfy a traffic requirement represented in the figure by the virtual layer. We assume a uniform traffic with one unit of flow (*uof*) in either direction of the NAS pairs. In addition, we assume that all the transceivers have a same capacity *Cuof* that represents the maximum bit rate that can be carried through one λ-channel.

9.2.1 Standalone ATM Network

The standalone ATM network reposes entirely on a point-by-point connectivity. There is one optical transceiver per NAS and ATM port, thus a total of 10 transceivers (two per link). A trivial computation tells us that the traffic on any fibers from/to the NAS is 3*uof*, whereas the traffic on the inter-switch fibers is 6*uof*. Thus the utilization of the NAS fibers is $\rho = 3/C$, and $6/C$ for the inter-switch fibers. Furthermore, each ATM switch has to process 10*uof*.

9.2.2 Multipoint Optical Network

In the multipoint network version, the connections are realized on a broadcast and select basis. All the transceivers are tied together by one multipoint optical path which in turn supports the 12 logical connections. Thus all stations are included in a single MPS, and no logical switching is required in this case. A time wavelength division multiple access (T-WDMA) protocol is then used to multiplex the logical connections, with one optical transceiver in each station. In one version of T-WDMA the transmitter of each station is permanently tuned on a dedicated wavelength which is broadcast to all other stations. Each wavelength carries a one-to-many (one-to-three in the example) connection using TDM in the transmitters. The receivers select the information from a given transmitter by tuning on that transmitter's wavelength. In this scheme, an appropriate schedule is pre-arranged so that the information can be retrieved at the destination side. Figure 9.3 shows one appropriate T-WDMA schedule for the present example.



- Each transmitter T_i has a capacity C, and transmits on wavelength λ_i.
- The capacity C is divided into 3 time slots (one frame), one slot per logical connection.
- Capacity per logical connection is C/3.
- During a time slot transmitter T_i transmits to receiver R_j, and the receiver R_j is tuned to wavelength λ_i.

Figure 9.3 T-WDMA Schedule

9.2.3 Standalone ATM versus Multipoint Optical

In the ATM version, a signal from station 1 to station 2 goes through 2 links with utilization $3/C$, one link with $6/C$, and 2 ATM switches that must process $10uof$. Using the schedule of Figure 9.4, the same signal needs to go through only one logical connection with utilization $3/C$. Also, one transceiver per NAS is sufficient to achieve a full connectivity. Thus, there is a gain of 4 to 10 in terms of transceivers (an expensive component). A difference, however, is that the receivers must be rapidly tunable (order of microseconds) in the multipoint network.

In conclusion, the multipoint optical approach provides us with a higher throughput for a lower cost. This is the reward of a more efficient management of the fiber's resources. The standalone ATM uses only one λ-channel with a capacity limited by the electronic interface, whereas the optical approach uses 4 separate λ-channels. Another important feature of the multipoint architecture is its ability to dynamically assign the capacity among the logical links inside an MPS. In the example above, a nonuniform capacity assignment would be simply accomplished by allotting more time slots for some logical connections in the T-WDMA schedule. In the standalone ATM the capacity is fixed by the hardware.

9.3 DESIGN OF THE LOGICAL LAYER

The design of the LT involves three steps. The first step is to find a suitable target topology for the LT. This target topology is bound to the following constraints:

- The number of transceivers per NAS — This determines the degree of connectivity between the MPS
- The maximum admissible number of logical hops between any pair of NAS — Determines the diameter of the topology
- The maximum admissible number of logical connections per MPS — This determines the maximum number of NAS per MPS
- Optional constraints such as self-routing properties, k-connectivity for fault tolerances, etc.

In the second step, terminals are mapped into the target topology, with respect to the following:

- The physical locations, or more precisely the geographical distances between the NAS — We want to prevent optical connections between nodes that are too far apart.
- The traffic requirements — Fast purely-optical channels are reserved for the virtual connections with stringent requirements, whereas virtual connections with relaxed requirements can be routed through mutihop logical paths.
- Feasibility of embedding the LT into the PT.

The last step addresses the routing problem in the LT. This corresponds to the embedding of the virtual layer into the LT. In other words, we want to find the routes which satisfy the traffic requirements and minimize the delays and congestion. The details of what we have already done in this direction are given in the Preliminary Work section below.

9.3.1 Preliminary Work

In Section 9.2, we explored the potential of the dynamic capacity allocation offered by the MSN architecture, and compared two identical LTs. Both are regular Kautz hypergraph topologies,[12] with 252 NAS clustered into 42 MPS of 12 NAS each, giving a total of $12 \times 11 = 121$ logical one-to-one connections per MPS. One topology has static MPS with a fixed capacity for each logical connection, and the other has dynamic MPS thereby enabling dynamic capacity sharing among the logical channels of the MPS.

We evaluate the routes that maximize the throughout in each LT, using a flow deviation algorithm.[11] Briefly, this algorithm iteratively evaluates the direction of a gradient on the surface of some objective function and recomputes a new metric for the next iteration. Advancing step by step, and always following the steepest descent/ascent, the algorithm stops when it reaches a minima/maxima. We demonstrated that the congestion and the delay in a dynamic MPS depends only on the total capacity and the aggregate flow loading the MPS. Thus the dynamic MPS can be viewed as an atomic object with a given capacity. This approach allows a simplified view of the network and reduces the complexity of the problem by a factor of 121 (the number of logical links per MPS).

The results of the comparison are reproduced in Figure 9.4, which shows that the dynamic MPS converges to an optimal solution 100 times faster than the static MPS, and that it achieves a better throughput.

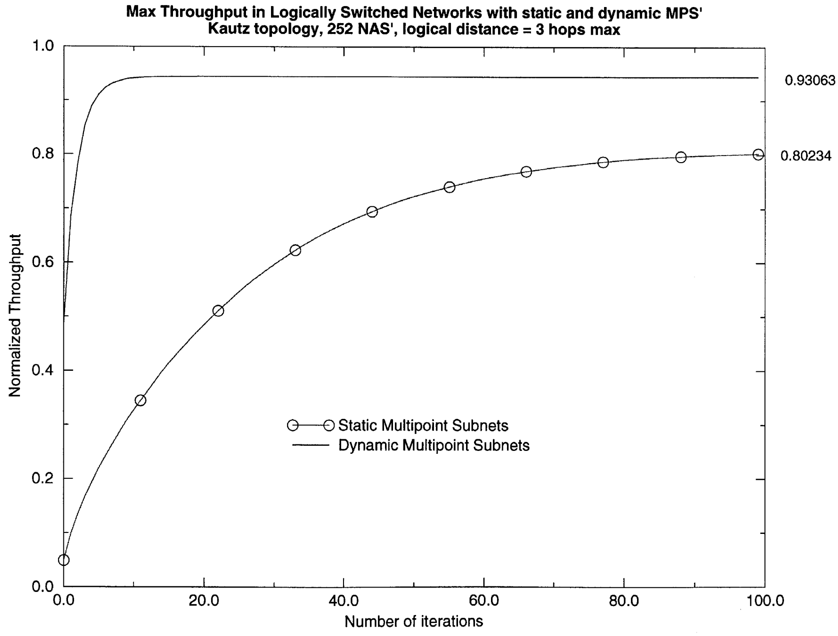


Figure 9.4 Dynamic MPS Compared to Static MPS

9.3.2 Future Work

The two first steps of the LT design problem, i.e., find a suitable target topology and map the NAS, have to be solved. Much has already been done in this area for graph topologies [8-9, 13] and we want to extend the results for the case of hypergraphs with the constraints presented above.

In the previous version of the algorithm, only point-to-point traffic requirements have been addressed. However, the MSN architecture is a natural candidate for multicast services, and we would like to modify the algorithm so that it also takes advantage of this additional ability.

9.4 THE EMBEDDING OF THE LOGICAL LAYER INTO THE PHYSICAL TOPOLOGY

Once a valid LT is found, it must be embedded in the physical topology. This is achieved by setting up optical paths in the form of trees for each MPS, so the NASs in each MPS can see each other by tuning their transceivers appropriately. All λ-channels used by NAS in the same MPS are grouped into a common waveband for ease of routing through the LDC. An example of embedding is illustrated in Figure 9.5. The combined action of setting the optical tree and tuning the transceivers is bound by some constraints, however, which are

- The optical trees must either by routed on separate fibers or WDM techniques must be used to avoid interference (different wavebands must be assigned to trees sharing the same fiber).
- The number of wavelengths is limited.

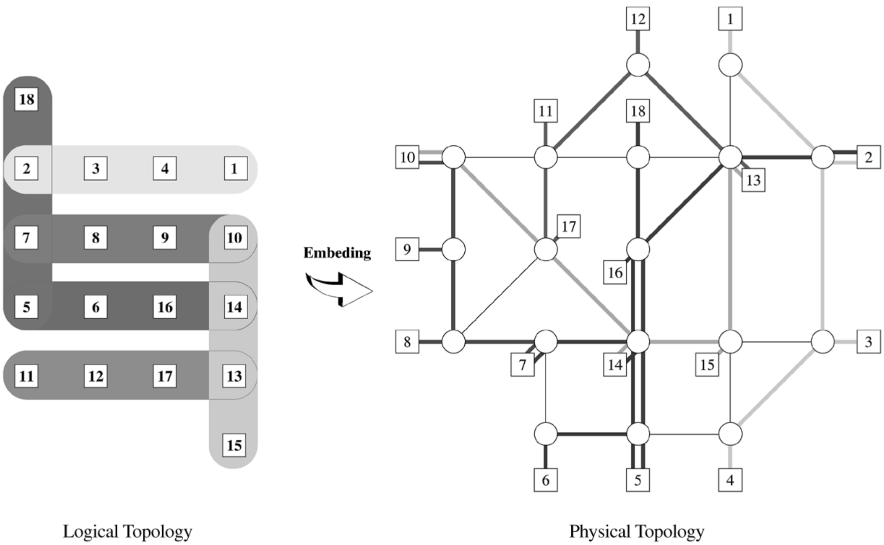


Figure 9.5 Embedding Logical Layer into Physical Topology

9.4.1 Preliminary Work

We have developed various Integer Programming (IP) formulations to solve this problem, with some variants in the objectives to be optimized. Typically, they concern the average point-to-point distance and the number of wavelengths. A selfexplanatory formulation of the IP used to solve the embedding shown in Figure 9.2 can be found in the appendix.

9.4.2 Future Work

- The IP formulation becomes intractable when the network becomes large (a hundred nodes or more). We therefore need to devise a heuristic that solves the embedding in large networks, with possible modifications of the LT when the embedding is unfeasible.
- We need to adapt the design techniques to networks carrying logically multicast traffic.

9.5 CONCLUSION

We have presented the concept of multipoint logically switched networks, a hybrid architecture that marries the speed of optics and the intelligence of electronics. This architecture is justified by the many advantages it offers:

- higher connectivity than either electronically switched networks or purely optical networks
- higher throughput
- logical multicasting is naturally supported
- lower cost
- dynamic capacity allocation is possible

In order to concretise this architecture, we will have to solve the challenging problems of designing a suitable logical topology and embedding this topology into a given physical topology.

REFERENCES

1. Stern, T.E., A linear lightwave MAN architecture, *Proc. of NATO workshop on High Speed Networks*, 1990.
2. Stern, T.E., Linear Lightwave Networks: How far can they go? *Proc. Globecom* 1990.
3. Stern, T.E., Linear Lightwave Networks, CTR Technical Report No. 184-90-14, Columbia University.
4. Bala, K. and Stern, T.E., Algorithms for Routing in Linear Lightwave Network, *Proc. Infocom*, 1991.
5. Bala, K., *Routing in Linear Lightwave Networks*, Ph.D thesis, Columbia University, 1992.
6. Jiang, S., Stern, T.E., and Bouillet, E., Design of Multicast Multilayered Lightwave Networks, *Globecom* 1993, Houston.
7. Sharony, J., *Architectures of Dynamically Reconfigurable Wavelength Routing/ Switching Networks*, Ph.D thesis, Columbia University, May 1993.

8. Jiang, S., *Multicast Multihop Lightwave Network: Design and Implementation*, Ph.D thesis, Center for Telecommunications Research, Columbia University, New York, 1995.
9. Ramaswami, R. and Sivarajan, K. N., Design of Logical Topologies for Wavelength-Routed All-Optical Networks, *Proc. Infocom*, 1995.
10. Ramaswami, R. and Sivarajan, K. N., Routing and Wavelength Assignment in All-Optical Networks, *Transactions on Networking*, October 1995.
11. Fratta, L., Gerla, M., and Kleinrock, L., *The Flow Deviation Method: An Approach to Store-and-Forward Communication Network Design.*
12. Bermod, J.C. and Peyrat, C., de Bruijn and Kautz networks: a competitor for the hypercube? In *Hypercube and Distributed Computers*, Elsevier Science Pub., North Holland, 1989.
13. Bienstock, D. and Günlük, O., *Computational Experience With a Difficult Mixed-Integer Multicommodity Flow Problem*, IEOR, Columbia University, 1993.

APPENDIX: A MIXED-INTEGER PROGRAMMING FORMULATION

In this appendix, we provide a mixed-integer programming formulation for the embedding problem given in Section 9.4. The objective of this formulation is to minimize the optical capacity requirement and the average size of the optical trees. Each optical connection Λ_w supports K logical connections $\lambda_{w,k}$, $k \in (1, \ldots, K)$, that connect K NAS-pairs tied to Λ_w. A boolean variable Λ_w^{xy} is set to 1 if Λ_w goes through a fiber between optical switches x and y, or 0 otherwise. Similarly, a boolean variable $\lambda_{w,k}^{xy}$ is set to 1 if $\lambda_{w,k}$ belongs to Λ_w^{xy}. Λ denotes the maximum number of optical connections in a fiber. The overall formulation is:

Minimize

$$m\Lambda + \sum_{xy}\sum_{w}\Lambda_w^{xy} \tag{9.1}$$

Such that

$$\sum_{y \neq x}\lambda_{w,k}^{xy} - \sum_{y \neq x}\lambda_{w,k}^{yx} = \begin{cases} 1 & \text{if } x \text{ is the source of } \lambda_{w,k} \\ -1 & \text{if } x \text{ is the destination of } \lambda_{w,k} \\ 0 & \text{otherwise} \\ & \forall w, k, x \end{cases} \tag{9.2}$$

$$\begin{aligned} \Lambda_w^{xy} &= \max_k(\lambda_{w,k}^{xy})\,\forall w, x, y \\ \sum_w \Lambda_w^{xy} &\leq \bar{\Lambda}\,\forall x, y \end{aligned} \tag{9.3}$$

$$\Lambda_w^{xy} \in \{0, 1\}, \lambda_{w,k}^{xy} \in \{0, 1\} \forall w, x, y, k \tag{9.4}$$

In the objective function 9.1, m is an appropriately large quantity. Equation 9.2 is a flow conservation equation. Equation 9.3 indicates that any logical connection must be supported by an optical connection, and Equation 9.4 is the optical capacity constraint.