Chapter 4

Communication network engineering

4.1 Multi-level network model

A hub node is defined as the network node through which local network nodes obtain connectivity to remote network nodes, while a cluster is defined as a hub node and the network nodes local to it. The term *remote* refers to network nodes outside the current cluster, whereas *local* refers to networks nodes within the current cluster. Each cluster thus contains its own network nodes of which one is the hub node that provides connectivity to the network nodes of other clusters through their respective hub nodes.

A multi-level network model is presented, where lower network levels are defined as being closer to the physical network nodes than higher network levels. Each network level, except the top-most, contains network nodes as well as hub nodes, where the network nodes are defined as the hub nodes of the network level below, and the hub nodes are defined as the network nodes of the network level above. Clusters that are connected to each other through equal numbers of hub nodes are defined to be on the same network level, where connectivity is achieved by traversing upwards through the multi-level network model.

A wide-area network, or backbone network, is defined as the top-most level of the multi-level network model, whereas an often unclear mixture of distribution, metro and access networks make up the lower levels. Figure 4.1 shows the multi-level network model, with the lowest level being the physical network nodes and the top-most level being the backbone of the wide-area network. Clustering of network nodes is used to determine the hub node to represent a cluster on the next level of the multi-level network model. Each level of the multi-level network model is defined by the satisfaction of a criteria such as the desired intra/inter-cluster traffic ratio [17]. Figure 4.2 is another representation of the multi-level network model, where the two top-most levels and inter-subnetwork links are shown. In this figure the term *crown* subnetwork refers to the backbone network of the top-level in figure 4.1. Some of the nodes on the lower level are shown to be equipped with wavelength-selective cross-connects (WSXCs) and wavelength add-drop multiplexers.

4.2 Topologies

When a network architect is faced with the task of designing a network, one of the most important considerations is the topology of the network. Aspects such as network management, reliability and the services that will be enabled by the network are all influenced by the topology of the network. The responsible design of a network topology is such an important topic that most of the initial research in optical network

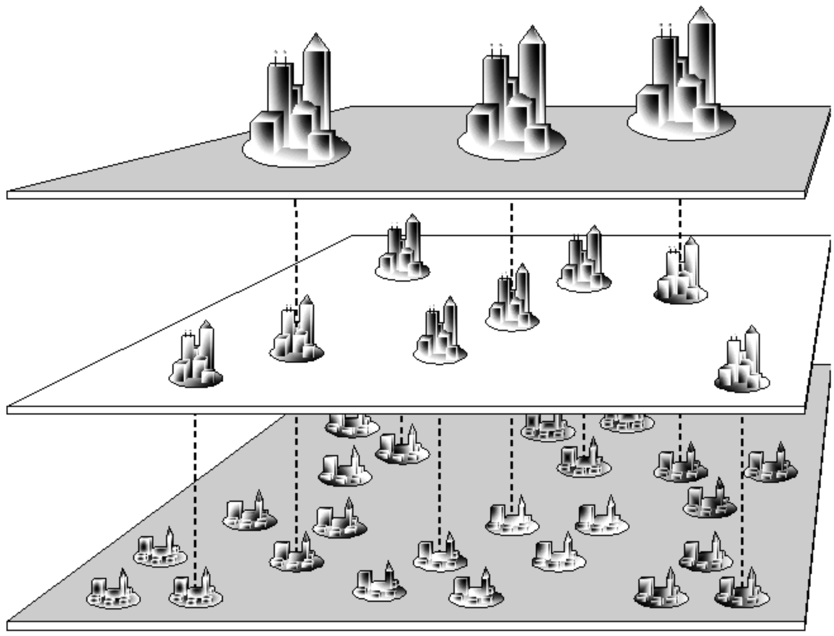


Figure 4.1: The multi-level network model.

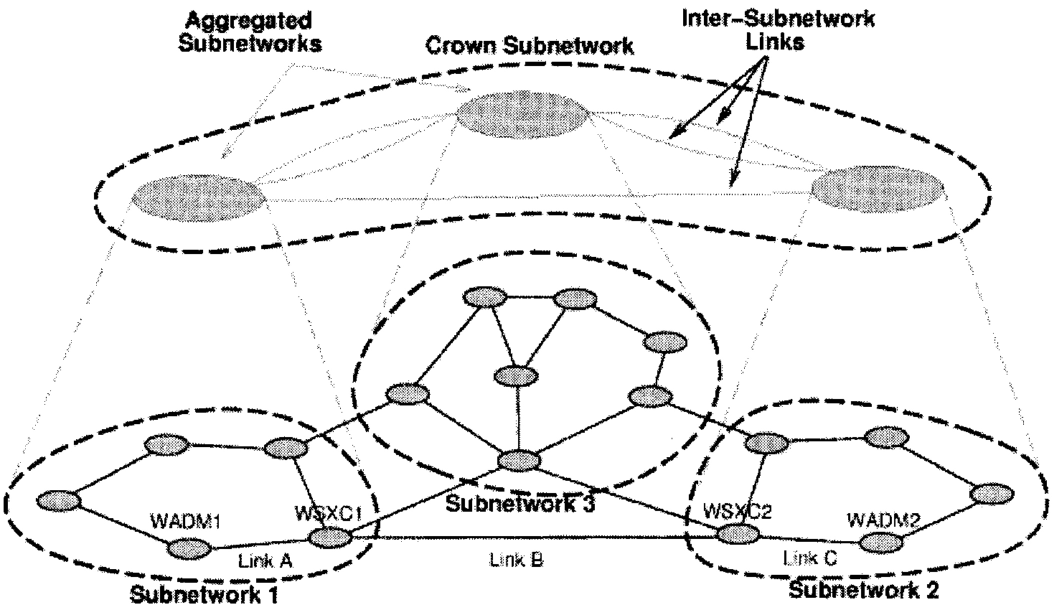


Figure 4.2: Representation of the multi-level network model showing the partitioning and aggregation of subnetworks [37].

design focused on addressing the issues that are similar and different in optical and conventional network topologies.

A network topology can be defined as the mapping of all sources of information to all destinations of information in the network. Communication between any two points in a network is achieved by the interconnection of nodes through the physical links that provide connectivity in the network. In optical networking the wavelength domain provides a new type of connectivity that did not exist for conventional networks. Local versus express routing of wavelengths over a shared physical infrastructure are challenging new concepts that optical network designers have to consider.

The physical topology is what we normally refer to when using the word topology on its own. Besides the physical topology, the logical and virtual topologies are also types of topologies that apply to optical network design. Physical topologies are defined as being the information about the geographical positions of network nodes and lengths of fiber links that connect them. Logical topologies are described by the flow distribution, demand and traffic matrices that serve as mathematical representation of the logical connections that have to be satisfied by the network under design. A virtual topology is the deliverable of the whole design process, a mathematical representation of the soon to be implemented network.

4.2.1 Physical topologies

There exists two often indistinguishable approaches to the design of a physical topology. The one approach is to design the topology based on an algorithm employing statistical metrics and mathematical relationships, while the other approach is through the utilisation of existing topological building blocks and configurations. From a mathematical point of view the employment of a mathematically exhaustive process considering numerous parameters and factors seems very attractive. Proving optimality of such an approach is however a very difficult and often impossible feat. It is therefore that network designers tend to prefer heuristic approaches that harness both the power and repeatability of an algorithm together with the insight and subjectivity of human intervention or artificial intelligence.

For physical topologies the traditional optimisation parameter is that of total fiber length. The length of fiber used in the physical topology of a network directly impacts on the cost of the network, due to the fiber cable cost as well as the installation cost. It is a well-known fact that the cost of installing optical fiber cable far outweighs the cost of the optical fiber cable itself. The role of these cost components in the total cost of a network has been changing due to dropping fiber cable costs and innovative new techniques that assist in the fiber cable installation process.

The shortest possible way of connecting all network nodes was thought to be the most cost effective, thus motivation for the ring topology. Such an approach did however require several fibers per cable, or several wavelengths per fiber. In the pre-WDM era of optical communication these requirements did not make the ring topology attractive. A total opposite design philosophy serves as motivation for the star topology. In the star topology a single node is identified as a hub node through which all inter-node traffic pass. All nodes are connected to this hub node by its own fiber, thus leading to a very high total fiber length which greatly increases the total cost of the network. Performance parameters such as hop distance is however very low in a network with a star physical topology.

If the hub node is equipped with very intelligent switching functionality and the network under design is not required to carry great volumes of traffic, and more specifically rapidly changing and competing sources and destinations of traffic, the star topology might appear quite adequate. These prerequisites are however not characteristic of typical communication networks, hence resulting in limited application of star physical topologies in typical communication networks. One example where the star topology has however found a niche is in the modern Ethernet local area network (LAN).

Increasing complexity at fiber terminals have contributed to the situation where total fiber length is rapidly losing importance compared to other topological design parameters. Even though the star topology offers some advantages, the disadvantages that it introduces also make it an unpopular candidate as physical topology for wide-area optical networks. The mesh physical topology has been defined as a general physical topology that can embody any other physical topology as one of its special cases. The fully connected mesh topology is an impractical case, where all nodes are connected to all other nodes by exclusive fiber cables. This results in a minimum, average and maximum hop distance of one at the expense of very high total fiber length. *Modern thinking seems to suggest that non-fully connected mesh topologies do offer the best compromise between all the parameters that determine performance and cost in optical network physical topologies.*

The number of wavelengths required to satisfy the requirements of a given logical topology differs depending on the candidate physical topology. Requirements such as blocking probability and multi-cast also influence the number of wavelengths for a specific physical topology, as shown in table 4.1 where the number of wavelengths required for wide-sense nonblocking multi-casting is shown for various topologies. In this table N is the number of network nodes, p is the number of rows and q the number of columns in the simplified grid mesh, and n is the number of dimensions in the hypercube. These formulas have been found [38] to be different for WDM networks incapable of multi-cast connections, resulting in more wavelengths being required to obtain multi-cast functionality.

Formulas such as shown in table 4.1 are useful since it is important for a network designer to known the number of wavelengths required in a network. It does not only impact on the cost of the network, but also determines the ease with which the RCA problem can be solved. Equations that can predict the number of required wavelengths for any specific physical topology do however not exist. A powerful tool in solving this problem is a metric known as the connectivity of a topology, which is defined as the normalised number of bi-directional links with respect to a fully connected mesh topology, expressed mathematically in equation 4.1 [39] with α being the connectivity, L the number of links in the network, and N the number of nodes in the network.

$$\alpha = \frac{L}{L_{\text{fully connected}}} = \frac{2L}{N(N-1)} \tag{4.1}$$

Figure 4.3 shows how the number of wavelengths required to satisfy full logical connectivity is determined by the level of connectivity that exists in the physical topology, and not by the number of nodes in the network as traditionally thought. *It is interesting to observe that for the same level of connectivity, a physical topology with a lower number of nodes requires more wavelengths than a physical topology with a higher number of nodes.* It can be attributed to the greater relative wastage that occurs in terms of unused wavelengths on the links of a network that has a lower number of network nodes. As the number of network nodes increase, the number of possible routes between any two nodes in the network also increase, which allows for more efficient wavelength assignments during the RCA process.

The parameters of an optical network's physical topology are mathematical representations of its various characteristics. A thorough parametric analysis of a physical

Physical topology	Number of wavelengths
N node linear array	$N-1$
N node uni-directional ring	N
N node bi-directional ring	$\lceil \frac{N}{2} \rceil$
$p \times q$ mesh	$p \times (q-1)$
$p \times q$ torus	$p \times \lceil \frac{q}{2} \rceil$
n dimensional hypercube	2^{n-1}

Table 4.1: The number of wavelengths required for wide-sense nonblocking multicasting in various physical topologies [40].

topology can supply the network designer with all the necessary information to evaluate the performance, cost and survivability of the specific physical topology. Table 4.2 shows the parametric analysis of various benchmark networks, with JON a representation similar to the existing topology in Japan, ARPANet a government network in the USA, UKNet a representation of the British Telecommunications (BT) network in the United Kingdom, EON the experimental European optical network, and NSFNet the National Science Foundation's experimental network in the USA. The network diameter parameter D is defined as the maximum number of optical hops between any two network nodes in the network when a shortest path routing approach is followed. $\bar{H}$ represents the average number of inter-nodal optical hops, where a hop is defined as the traversing of a single optical fiber link from one network node to another.

Physical topologies of benchmark networks

When researchers want to evaluate their theories against existing approaches, the use of a neutral and objective benchmark network physical topology is often required. These benchmark physical topologies are well studied and documented, which make them

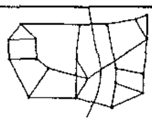
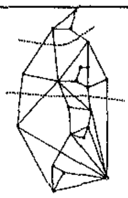
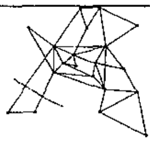
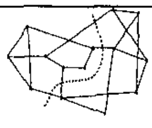
Network	N	L	α	$\overline{H}$	D	W_{LL}	N_{λ}
 JON	50	84	0.07	5.39	14	209	221
 ARPANet	20	31	0.16	2.81	6	33	33
 UKNet	21	39	0.19	2.51	5	19	22
 EON	20	39	0.2	2.36	5	18	18
 NSFNet	14	21	0.23	2.14	3	13	13

Table 4.2: Topological parameters of benchmark optical networks [41].

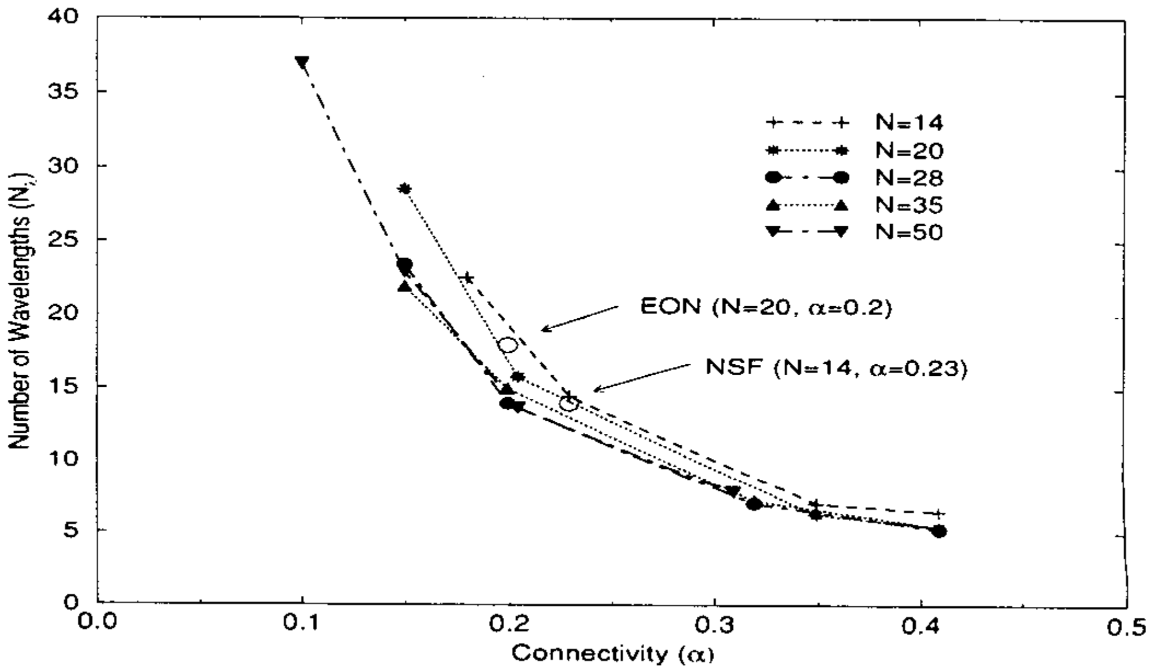


Figure 4.3: The number of wavelengths required in a network as a function of physical connectivity [39].

very important to any contributers in the field of optical networking. Figure 4.2 shows the topological parameters of several benchmark physical network topologies.

The NSFNet is probably the most well-known and documented network utilising optical links in the world. It was developed in the mid-eighties under the auspices of the United States' National Science Foundation (NSF) to replace the aging ARPANet, but was itself decommissioned in 1995 to make way for a commercial Internet backbone. When the NSFNet project was concluded the NSF commenced work on an experimental backbone network named very-high speed backbone network service (vBNS). It was designed to serve as platform for experimentation with new Internet and communication technology developments. Figure 4.4 shows the physical topology of the late NSFNet which spanned the surface of the continental United States of America. The physical topology has 16 network nodes located in several states ranging from

California in the west to New York State and Florida in the east.

NSFNet's predecessor ARPANet is another North American network topology that often receives attention from researchers in the field of optical networking. It has 20 nodes covering roughly the same geographical areas as the NSFNet. ARPANet, with its physical topology shown in figure 4.5, is widely regarded as the progenitor of the Internet and was created by the Advanced Research Projects Agency (ARPA) of the US Department of Defense to enable the network research community to experiment with packet-switching technologies.

Another prominent benchmark network of interest to researchers and academia is the European Optical Network, also known as EON. This network connects the most prominent European cities including London, Paris, Berlin and Milan, as well as outlying regions with nodes at Lisbon, Oslo, Athens and Moscow. Figure 4.6 shows the physical topology of the EON with an indication of the different populations of the regions served by the respective network nodes, as well as the link capacities in gigabits per second (Gbps). The nodes of the EON were mostly taken to be the capitals of the respective countries, with the population of the whole country or region used to determine the relative importance and subsequent weight of the network node. The weighting of network nodes is a very important topic since this determines the required connectivity and traffic that should be provisioned for at the respective network nodes.

4.2.2 Logical topologies

The flow distribution matrix was introduced in section 3.2.3, where modified gravity models were used to determine the relative weights of the respective network nodes. A methodology for determining how many network nodes there are supposed to be

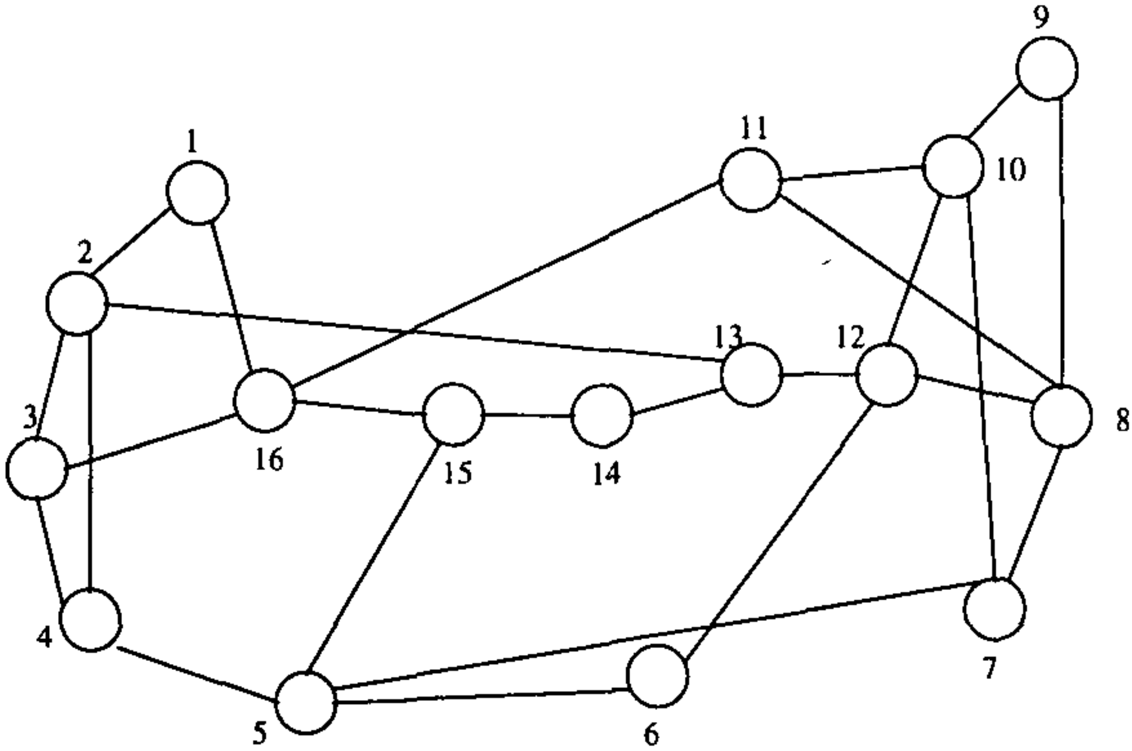


Figure 4.4: Physical topology of NSFNet [42].

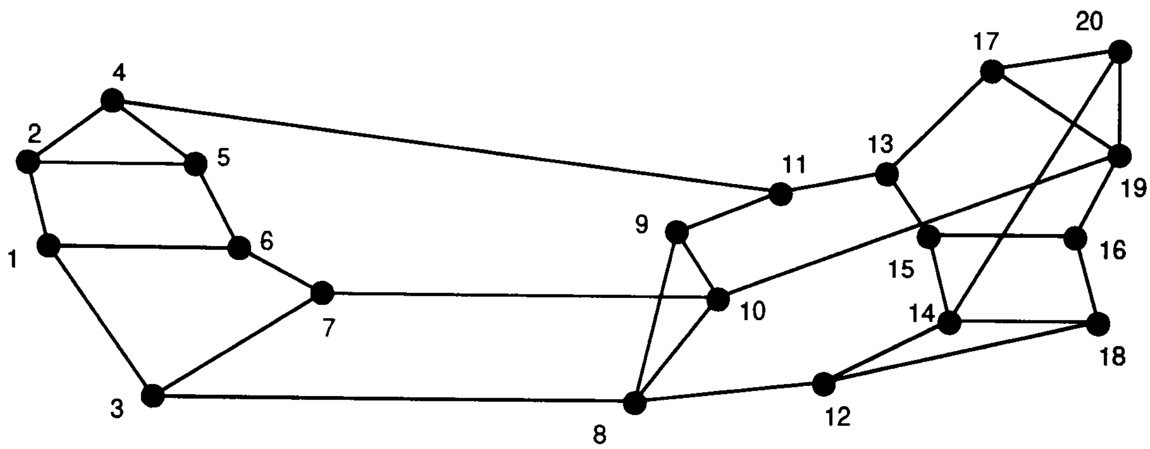


Figure 4.5: Physical topology of ARPANet [24].

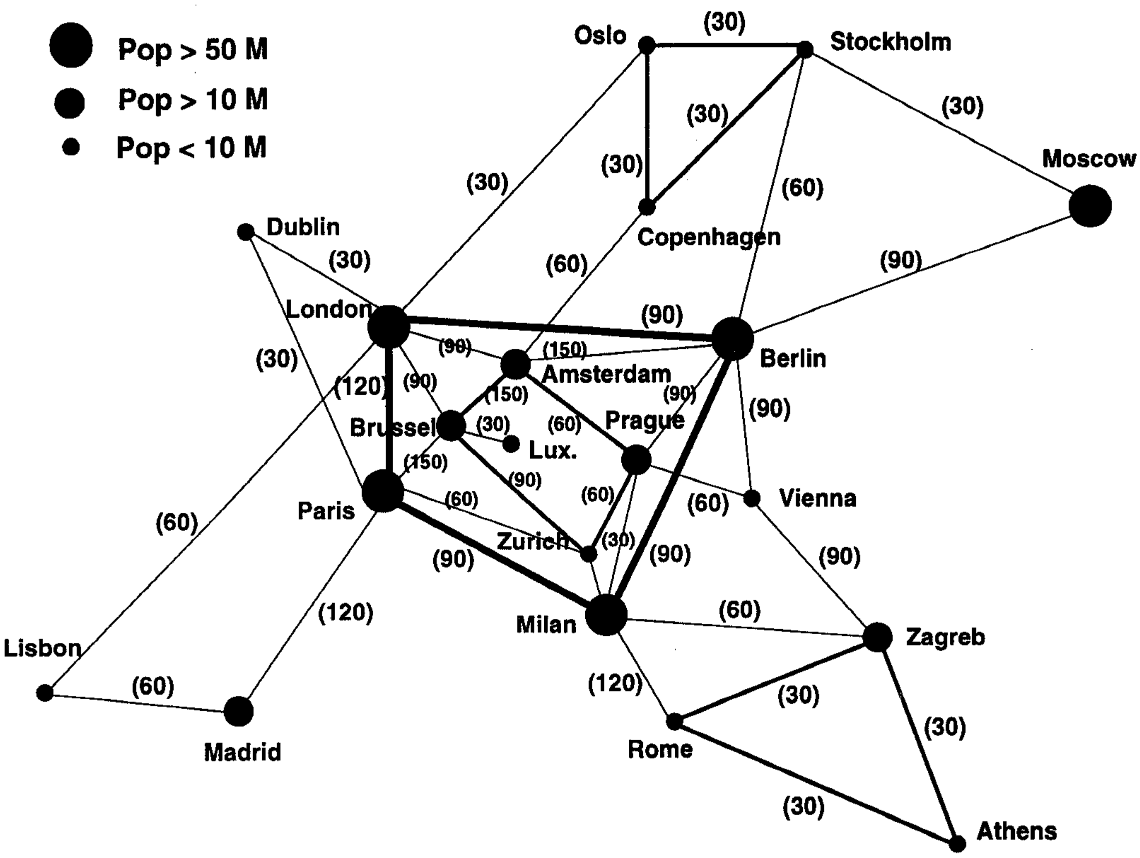


Figure 4.6: Physical topology of EON with link capacities in Gbps indicated in brackets [16].

and where these network nodes should be located, is presented in section 5.3. For the purpose of developing a logical topology it is assumed that the number and position of network nodes has been determined and that the relative weighting of the network nodes has been completed.

When a flow distribution matrix is presented for the development of a logical topology, the first primary deliverable is known as a demand matrix. The demand matrix is found by multiplying the flow distribution matrix with the estimated aggregate traffic of the whole network. For example, if a specific source destination logical connection has a relative weighting of 1%, as indicated in the flow distribution matrix, the demand for the logical connection in question would be 1% of the estimated aggregate traffic for the whole network.

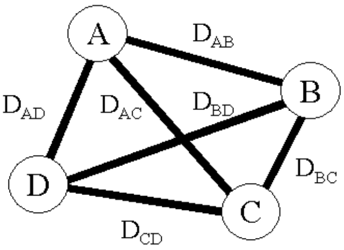
For the development of a demand matrix from a flow distribution matrix it is essential that a reliable estimate for the aggregate traffic of the whole network exists. This is however not a trivial issue, since where the network edge is defined, has a great impact on the aggregate traffic of the network under design. Communities of interest are very strong between adjacent network nodes, and it is important to only consider traffic that travels through a network node when estimating the aggregate traffic of the network levels under design.

The concept of demand symmetry, as introduced in section 3.2.1, applies to logical topologies. Figure 4.7 shows a logical topology describing the demand between four network nodes. Due to symmetry of the symmetrical demand matrix, only the upper right half of the demand matrix is populated. The asymmetrical demand matrix is fully populated and it should be noted that the demand between nodal pairs is allowed to be different for the two source-destination configurations.

The demand matrix is however only a theoretical representation of the traffic requirements to be satisfied by the network. Commercial optical networking equipment understandably does not allow for the transmission of arbitrary amounts of traffic, due to the quantised way in which standards such as SONET/SDH provide for bandwidth allocation. For this reason there is a quantisation difference between a demand matrix and a traffic matrix, where a traffic matrix contains entries indicated in units such as OC-x, STS-x or STM-x, not bits per second (bps), as in the case of a demand matrix.

Traffic matrices can be divided into two categories, namely matrices of provisioned traffic and actual traffic. A provisioned traffic matrix indicates the maximum traffic that can be satisfied by the network under design on a per logical link basis, whereas a post-implementation analysis of traffic distribution is presented in an actual traffic matrix. The collection of network statistics to construct real-time dynamic traffic matrices is not a trivial task. Network tomography techniques using link counts at router interfaces [43] can be employed to solve this inverse problem.

An actual traffic matrix will typically contain entries that are less than the corresponding entries of the provisioned traffic matrix. Under extreme conditions of logical link re-routing, known as restoration, individual entries of the actual traffic matrix may exceed the corresponding entries in the provisioned traffic matrix. Such an situation would however not exist for a long period, since it is a technique employed for fault toleration through the balancing of traffic load over the shared physical infrastructure.



	A	B	C	D
A		D_{AB}	D_{AC}	D_{AD}
B			D_{BC}	D_{BD}
C				D_{CD}
D				

Symmetrical

	A	B	C	D
A		D_{AB}	D_{AC}	D_{AD}
B	D_{BA}		D_{BC}	D_{BD}
C	D_{CA}	D_{CB}		D_{CD}
D	D_{DA}	D_{DB}	D_{DC}	

Asymmetrical

Figure 4.7: Logical topology with symmetrical and asymmetrical demand matrices.

4.2.3 Virtual topologies

The virtual topology of a network contains information about how wavelengths are to be routed over a physical topology, in order to satisfy the requirements described by the logical topology. Figure 4.8 gives an example of how a virtual topology can be presented, in this case according to a configuration known as the eight station ShuffleNet. The ShuffleNet was one of the first popular virtual topologies for easily achieving full logical connectivity over a less than fully connected physical topology. Other algorithmic approaches to virtual topology construction include the Kautz and deBruijn topologies, which have even inspired the development of network topologies capable of irregular scalability [44], something that is typically not possible for these algorithmically routable virtual topologies.

It has been demonstrated [7] that approaches based on unpredictable operators such as simulated annealing and genetic algorithms, can result in a network design superior to that of an exact and rigid algorithm such as ShuffleNet. Figure 4.9 shows average

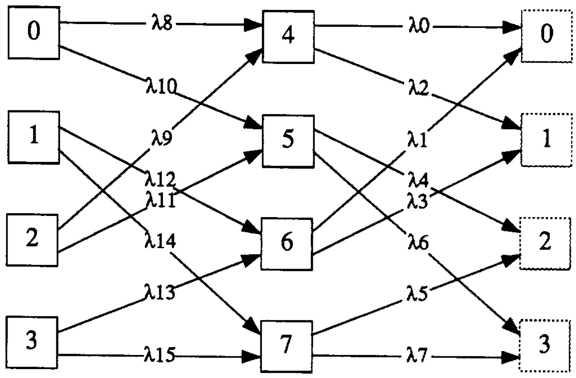


Figure 4.8: A representation of an eight station ShuffleNet virtual topology [7].

propagation delay as a function of traffic load for a ShuffleNet, compared to a virtual topology designed by simulated annealing. Figure 4.10 shows how networks, with various numbers of nodes, of which the virtual topology is designed through simulated annealing, approach optimality with regards to average propagation delay when compared to the theoretical lower bound for networks with uniformly distributed physical and logical topologies.

To determine a virtual topology, the fundamental problem to be solved is that of RCA. The routing part of the problem being that of finding paths in the physical topology to satisfy the logical topology, while the channel assignment part of the problem relates to the exploitation of multiple wavelengths on an optical fiber. It is this wavelength dimension, with its new possibilities and inevitable complexities, that makes optical network design so fundamentally different from the design of conventional communication networks.

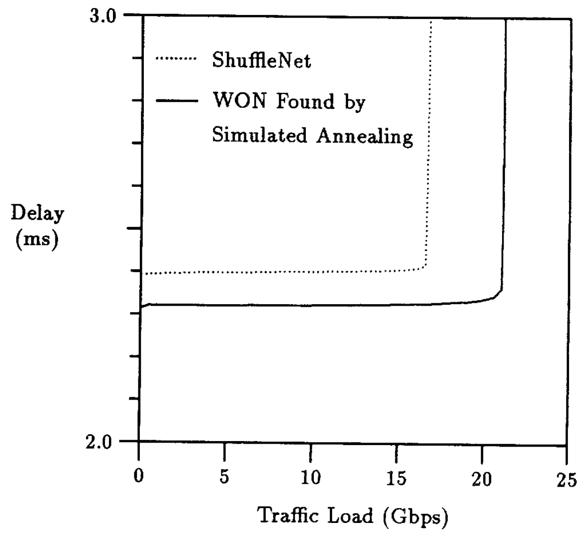


Figure 4.9: Average propagation delay as a function of traffic load for virtual topologies found through ShuffleNet and simulated annealing techniques [7].

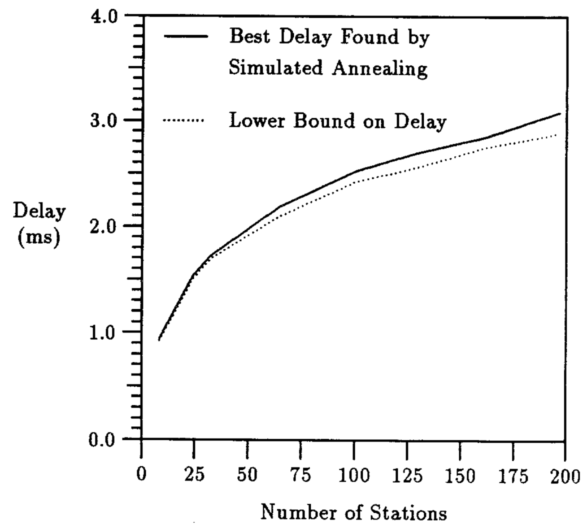


Figure 4.10: Average propagation delay as a function of the number of network nodes for virtual topologies designed through simulated annealing [7].

4.3 Network management

Optical networks utilising several wavelengths are expected to play a major role in what is known as next generation networking (NGN). Technological advancements now make it possible for these networks to be implemented, but the issue of how these networks will be managed has not been resolved yet. Requirements such as reconfigurability, in order to dynamically adapt to changing traffic loads, and survivability, to enhance reliability in the event of network faults or malfunctions, make the control and management of these networks crucial. Network management should not only be considered as an afterthought, but be regarded as an integral part of the network, influencing various aspects of the design process.

The concept of a transparent optical network refers to a scenario where dynamic reconfiguration of a network occurs without any form of optical-electronic-optical (OEO) regeneration. Ever-increasing data rates supported on optical fiber wavelength channels and the electronic bottleneck resulting from OEO conversion are the main motivators for a transparent optical network. The equipment required to make switching decisions based on information contained in the switched data itself presently still require electronic processing of header information, thus making the optical router nothing more than a theoretical concept. The network management principles employed in the management of these semi-transparent optical networks differ substantially from that of conventional communication networks that merely utilise optical fibers on its links. The expected evolution to fully transparent optical networks should thus play an important role in formulating the values and principles that will be the foundation of optical network management.

Traditional implementations of optical fiber technology in communication networks have limited functionality with regards to switching and routing of traffic over the network. Static wavelength allocations and spatial switch mappings allow for the exploitation of optical fiber's immense bandwidth on a per-link basis. The concept of optical networking does however require the dynamic control and management of all aspect of the network, including switching and routing functions in both the spatial and wavelength domains. Software overlays capable of managing the physical layer of optical network equipment constitute the sensor and actuators of the control systems described under the heading of optical network management. Configuration management is achieved through the centralised processing of information gathered through discovery protocols, describing the functionality and status of all the network components. Load management and restoration management are specialised functions responsible for maintaining network performance during periods of varying traffic distributions and in avoidance of or in reaction to faults or malfunctions in the network.

In a commercial optical network the need also exists for the management of security and accounting functions. Security management refers to the function responsible for maintaining security on both the physical layer and the information layer. With cable theft, sabotage and vandalism being unfortunate realities it is essential that a mechanism exists for detecting and avoiding security breaches on the physical layer. Even though security on the information layer is traditionally the responsibility of the higher level non-optical transmission protocols, wavelength level security is required to minimise the possibility of industrial espionage and protect information of a national security nature. Management of billing information for accounting purposes is also of great importance for commercial network installations. Technology now makes it possible for big corporations to obtain exclusive rights to individual wavelength channels in a commercial optical network, thereby bypassing the traditional network service provider with its audited billing systems, thus demanding more comprehensive and detailed accounting functionality at the network management level.

Figure 4.11 shows the network management architecture used in the multi-wavelength optical networking (MONET) program [37] sponsored by the Defense Advanced Research Project Agency (DARPA) of the U.S. Government Department of Defense, with participation from Telcordia Technologies, AT&T, Lucent Technologies, several government agencies and regional Bell Operating Companies. Its aim was to demonstrate the viability of using transparent reconfigurable WDM optical networking technology for NGN. The management architecture consists of three layers, namely: the network management layer, the element management layer, and the element layer. Graphical user interfaces (GUIs) serve as interfaces between the network and the managers of the network, who utilise the management functions of configuration management, connection management, performance management, and fault management to manage all aspects of the network, right down to the network elements (NEs) themselves.

4.3.1 Physical layer management

The physical layer of an optical network comprises the various components that are responsible for the transport and routing of data over the network. WADMs allow for individual wavelengths or wavebands to be added or dropped at a network node from an optical fiber carrying multiple wavelengths simultaneously. A network management function would be responsible for selection of the wavelengths or wavebands to be added or dropped from an optical fiber, as well as ensuring that conflicts do not arise due to interference from different data streams attempting to occupy the same spectral region. Carrier bandwidths and stop-bands should be taken into consideration when several wavelengths are multiplexed onto a single optical fiber. In commercial implementations it is customary to only allow data streams of the same SONET/SDH

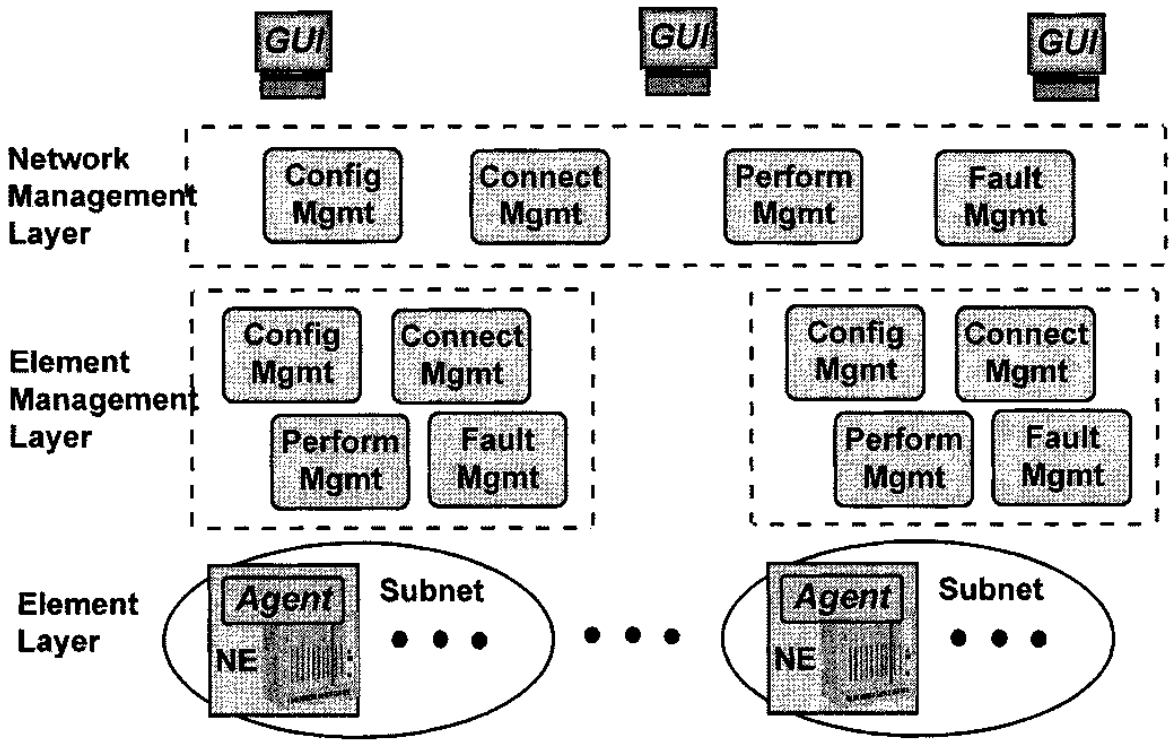


Figure 4.11: MONET network management architecture [37].

level to be multiplexed onto the same optical fiber, which simplifies the management of the process at the cost of capacity wastage. Developments in management techniques will enable the WADM of the future to allow for the multiplexing of different kinds of data streams onto the same optical fiber.

The optical network node introduced in section 2.1.5 has at its core the optical cross-connect (OXC). A cross-connect has as its defining function the ability to switch light from an input fiber to an output fiber. The relationship between input and output fibers can be referred to as the spatial mapping of the cross-connect. The optical cross-connect has two more optional functions, namely the ability to refine the input to output fiber relationship from a purely spatial mapping to a spatial and wavelength mapping, and secondly the ability to not only map wavelengths to output fibers but also to change the carrier wavelength of a data stream. The wavelength selectivity function is referred to as wavelength-selective cross-connect (WSXC), while the wavelength-interchanging function is referred to as wavelength interchanging cross-connect (WIXC). It follows intuitively that network management is very important in the ONN where such a complex spatial and wavelength selective and interchanging mapping is performed. Providing for the dynamic alteration of this mapping without incurring wavelength clashes or negatively impacting on the performance of the network is a challenging problem that requires innovative new network management solutions.

Management of optical amplifiers is required to achieve an optimal SNR at the receiver, thus minimising the BER of the system. Optical amplifiers, like the EDFA, have non-flat gain curves that cause the various wavelengths channels of a WDM system to be amplified unequally. A data stream can traverse several network nodes, be amplified at various places and have its carrier wavelength converter several times. Unequal gain for different wavelengths is unacceptable due to the increased dynamic range and variable sensitivity required at the receivers. The problem of unequal gain is best overcome by equalisation of the power levels of the various wavelength channels after the amplification process. Network management plays a role in ensuring that channel equalisation is performed adequately. *It can even be postulated that a network management system that is cognisant of all power levels across all wavelengths in all parts of the network might be able to require less channel equalisation and consequently reduce the unnecessary wastage of optical power resulting from a general channel equalisation policy.*

4.3.2 Configuration management

The physical layer management functions discussed in section 4.3.1 are aimed at the management of the individual components of a network, whereas the configuration management function has the network as its focus and considers the network components to be mere enablers for the satisfaction of the network requirements. Core to a configuration management function are automatic discovery protocols and mechanisms capable of gathering information regarding the status of all network parameters and features of all network components. Discovery of the network physical topology is essential for the efficient management of a network configuration. The complex nature and geographical distribution of network nodes make the manual configuration of a wide-area network virtually impossible. Various mechanisms and approaches exist for automatically configuring the various layers of the network [45].

Another important responsibility of the configuration management function is connection setup. This responsibility is so important that it is often regarded as a management function on its own [37]. The physical layer components involved in the establishment of a logical connection between two network nodes rely on the centralised coordination that only the configuration management function can provide. Since the configuration management function exists on a higher level than the physical layer management function, if is inherently objective with regard to requests for service provisioning on the physical layer.

Two schools of thought exist in connection establishment theory, the first coming from a traditional circuit switched paradigm proposing the use of signalling-based circuit setup and the second opting for a centralised approach involving provisioning for connection establishment based on statistical probabilities and resource availability. The signaling-based approach has as advantages the rapid establishment of connections purely based on demand, whereas a provisioning approach has the ability to allocated resources more efficiently in congested network scenarios. Factors such as quality of service (QoS) play an important role in new multi-service networks, which is why the provisioning approach tends to be more popular for implementation of optical networks in the short to medium term. Signalling protocols have however proven their worth in traditional circuit-switched telecommunication networks and surely deserve consideration for the predominantly packet-switched future optical networks.

4.3.3 Load management

Conventional theory describes Internet traffic as exhibiting pervasive long-range persistent behaviour. The long-range persistence of Internet traffic has formed the foundation of recent network traffic analysis, utilising the vehicle of self-similar processes for the creation of time series models. Accurate methods for the real-time measurement of statistical parameters in communication networks are critical [46] to avoid unrealistic traffic forecasts or estimations. Recent research [47] suggests Internet traffic to be non stationary with similar pervasiveness as demonstrated by the long-range persistence of Internet traffic. Although academia and industry alike are still unsure about what to make of these new findings, the importance of traffic distributions in the management of wide-area optical network remains undoubted. It is a well-accepted principle that the balancing of traffic load over the resources of a network increases the performance of the network under conditions of rapidly changing traffic patterns as well as in the event of network faults. For these reasons a load management function is performed by the optical network management entity.

In order to make the adjustments required for the balancing of network traffic, the load management function depends on the availability of information regarding actual traffic as well as traffic capacity on all the physical links of the network. The logical connection requirements described by the logical topology of the network provides a level of abstraction that assist the load management function in objectively evaluating the traffic demands on the network. In the event where an imbalance is detected, alternative routing options are considered and, if found superior to the current network configuration, applied by means of the network configuration management function discussed in section 4.3.2. The provisioning of network capacity to satisfy dynamic traffic demands should be evaluated against a framework of statistical probability based on a combination of theoretical analysis, experimental estimates and real-time indicators. The boundary between load management and restoration due to network faults is often vague due to their inherent inter-dependence.

4.3.4 Restoration management

The topic of restoration is discussed at length in section 4.4 where its role as high level provider of reliability is explained. The restoration management function is responsible for evaluating information describing faults or malfunctions in the network. The information is made available for presentation to operators as well as input to the restoration algorithms that attempt to solve the problem of routing traffic over a crippled physical infrastructure. As in the case of the load management function, any measure of intervention recommended by the restoration management function is channelised through the configuration management function, which on its part interfaces to the physical layer management function to affect the required changes.

By moving the restoration intelligence to a higher level the rapid development of restoration algorithms is encouraged. The responsibility of sporadic network testing resides with the restoration management function. Sporadic testing should be performed in a random fashion, thus minimising the occurrence of non-representative results. Fault isolation and diagnostics enables the restoration management function to identify individual pieces of equipment that require maintenance or replacement, thus not only saving money in the form of time of maintenance technicians but also ensuring shorter recovery cycles and even the avoidance of performance debilitating faults. *It might be difficult to identify and isolate faults in transparent optical network components due to the absence of digital electronics in positions where unobtrusive monitoring can be performed.* A practical solution employed in modern network is to limit transparency to manageable subnetworks and provide for electronic monitoring ability at the network edge.

4.4 Reliability

The concepts of reliability and survivability are very closely related. When reliability of a communication network is considered, the emphasis is on the network's ability to ensure that requirements with regard to performance and service delivery can be satisfied in an environment characterised by continuous attempts to disrupt this process. A communication network's survivability is a related concept that focuses on a network's ability to absorb these continuous attempts to degrade its performance and service delivery, especially through factors of a physical fault or malfunction nature. In addition to these fault-type factors that challenge and consequently define the survivability and resultant reliability of a communication network, factors related to the statistical nature and geographical distribution of communication traffic, as discussed in section 3.1, are also important when considering a network's reliability.

Although the concept of QoS mostly applies to communication systems in a physical-level performance context, its relevance to network reliability is undeniable. The users of a communication system normally have an expected level of service quality that can be expressed in terms that fundamentally boil down to minimum data rates and maximum propagation delays. Under normal network operating conditions these parameters can be maintained within acceptable margins with relative ease. When the network experiences unexpected load fluctuations the task of ensuring the expected QoS becomes more difficult. The same argument holds for the situation where a communication network experiences faults or malfunctions that require restoration techniques. It can therefore be concluded that the end-user's perception of network reliability is often in the form of either an expected, demanded or even tolerated QoS.

Network survivability and subsequent reliability is addressed on various levels. Figure 4.12 shows the survivability hierarchy for optical networks with the various levels that contribute to the reliability of a network. Protection techniques operate close to the physical equipment and have the benefit of rapid restoration times at the cost of a more highly connected physical topology. Re-routing techniques are employed on the higher levels of the hierarchy and have the benefit of being implemented in software, which is not only economical but also customisable. Corrective action originating from these higher levels of the hierarchy do however take longer to result in restoration of

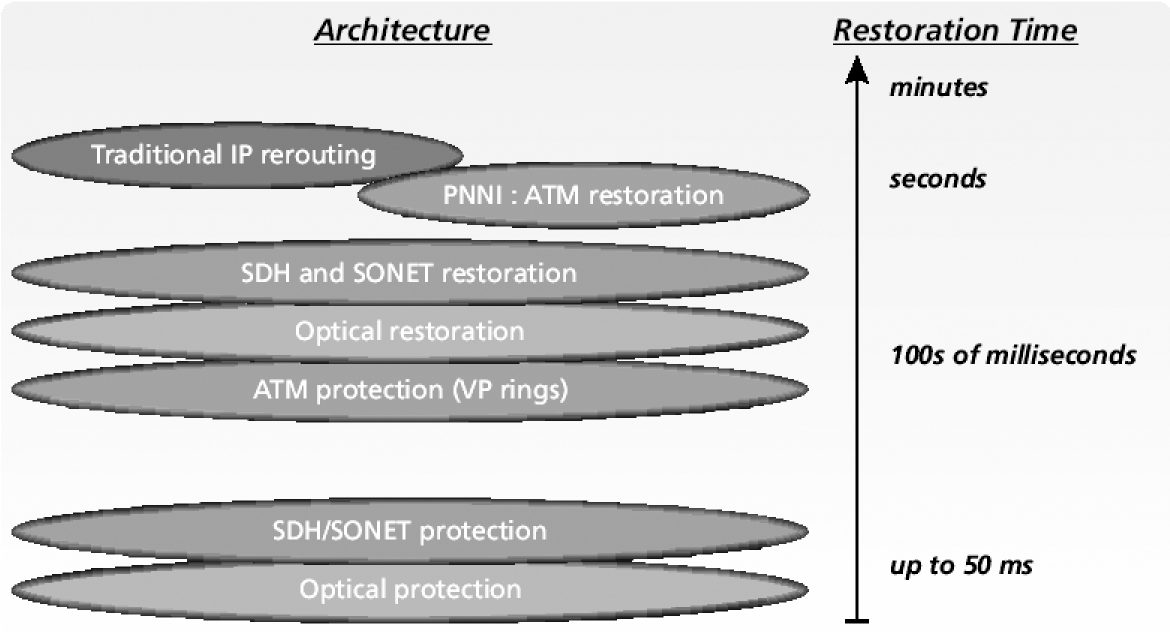


Figure 4.12: Survivability hierarchy for optical networks with relative restoration times [49].

normal network performance.

SONET provides built-in protection through what is known as APS. A formal definition of the protocols and algorithms involved in the APS mechanism is provided in the particular ANSI document related to protection in SONET systems [48], where approaches such as the dedicated and shared allocation of network resources are presented for use in SONET networks. The three architectures for protection in SONET networks exist namely: linear, ring and nested APS. Principles embedded through standards such as SONET and SDH can be generalised for consideration in a theoretical investigation of communication network reliability. These principles, as well as others relevant to the topic, are presented in the following sections.

4.4.1 Reliability through protection and restoration

There are two approaches to achieving increased reliability in a communication network. These approaches can be compared to the health anecdote that states that prevention is better than cure. The optical networking equivalent to prevention is known as protection, where measures are employed to protect a network from the factors that can negatively impact on its reliability. Restoration is the optical network's cure to alleviating a situation where the reliability of the network has been threatened and where neglecting to react expediently would surely result in a degradation of the network's performance and/or service delivery capability.

The methods whereby network reliability can be maintained reside on two planes, namely the hardware and software planes. Since the boundaries between hardware and software are often very vague it is more fitting to rather differentiate between these two planes as being either network infrastructure and network intelligence. Reliability of a network infrastructure is a function of the installed equipment, being electronic, photonic and material science technologies, as well as the design of the physical topology that determines the interconnection of the equipment and the physical connectivity of the network. Section 4.3 discusses network management and encompasses all functions of network intelligence, where restoration management and the connection setup function play an important role through their routing responsibility.

Of the various factors that impact on protection, that of physical topology is of most interest to the network designer since this is where a largely technology independent difference can be made. Protection, although many times referred to in the context of protection routing, is fundamentally about designing the physical topology of a network in such a way as to provide for the availability and exploitation of alternative routes between all the nodes of a network [50]. A basic requirement of any network that desires an acceptable level of reliability is to provide for protection by ensuring that no network node is connected to the rest of the network through a single physical link, even on a cable that contains several fibers. It is imperative that physical separation exists between the alternate routes between the nodes of a network. Algorithms such as the disjoint alternate path algorithm have been proposed [51] for ensuring that the risk and subsequent impact of physical faults or malfunctions on network reliability is spread across the physical topology.

Restoration routing differs from protection routing with regards to their approach to solving the problem of maintaining network reliability despite the failure of equipment of damage to the network links. Protection routing is a pro-active technique that introduced redundancy into the transmission process through various techniques, whereas restoration routing is a reactive technique that attempts to restore logical connectivity in the network through the re-routing of traffic to avoid problem areas in the physical topology of the network. It can thus be concluded that a network's restoration potential is largely dependent on the level of protection accommodated for in the network's physical topology.

Protection methods

There are two different approaches to the provisioning of protection paths for increasing the reliability of optical networks. The first approach is through the dedicated allocation of system resources for protection purposes during the connection setup phase for the exclusive use of the particular logical connection in question. The second approach is to allocate resources for the protection of several logical connections in a shared fashion. Various algorithms have been developed for utilisation in dedicated and shared protection resource scenarios [52]. Table 4.3 compares the characteristics of these two

Protection	Routing	Restoration speed	Routing flexibility
Dedicated	Path	fast	medium
	Link	fastest	low
Shared	Path	slow	high
	Link	medium	medium

Table 4.3: Comparison between protection approaches with their respective routing decisions.

approaches by considering the re-routing approach, as discussed in section 4.4.1, with regard to protection speed and routing flexibility. The dedicated allocation of resources for protection purposes is known as $1 + 1$ protection. This form of protection has as advantage simple management and quick restoration performance. As a matter of fact, typical $1 + 1$ protection schemes do not even require the use of restoration through re-routing since it is customary to transmit the protection data stream in conjunction with the conventional data stream. In the event of a fault or malfunction in the network the receiver will simply disregard the incoming data stream that was influenced by the failure and continue the uninterrupted delivery of service.

When shared resources are used for protection against network failures, it is inevitable that a protection path can only be utilised after the fault or malfunction occurs in the network, consequently leading to longer restoration times and requiring the retransmission of lost data. The shared allocation of protection resources is known as $1 : N$ protection, where N is the number of logical connections sharing the single protection path. It is theoretically possible to share more than one protection path between a number of logical connections, thus resulting in what can be termed $M : N$ protection, where M is the number of shared protection paths. The shared protection method has the attractive advantage of requiring drastically less network resources than the dedicated approach. When the statistical probability of network failure is considered it is justifiable to opt for a shared protection scheme purely based on the immense saving in network resources involved.

Restoration methods

A re-routing algorithm responsible for the restoration of a logical connection between two edge nodes previously connected through several intermediate network nodes has to follow either a global or local approach to solving the problem. A global approach to the restoration of a logical connection would evaluate the connection as if it did not exist prior to the failure of the intermediate physical link or network node and determine the most suitable route for the connection accordingly. Another approach would be to only consider the physical segment of the logical connection where the failure occurred and re-route the logical connection around the area in question without disturbing the connection status of the other physical segments utilised in the logical connection.

Following the local approach to re-routing has the advantage of quicker network restoration at the cost of introducing complex logical connection paths that can negatively impact the network's ability to establish subsequent connections or satisfy future restoration requests. Figure 4.13 shows the difference between global and local re-routing approaches to the restoration problem. The global approach to re-routing for restoration purposed is also known as the optical-path switching method, whereas the local approach is referred to as the optical-link switching method.

Whether the re-routing process should take changing network parameters into consideration has been investigated by researchers [42]. In the case where a protection path has been employed, its influence on the possible protection paths available for future restoration effort is often not considered. A dynamic algorithm, as opposed to a static

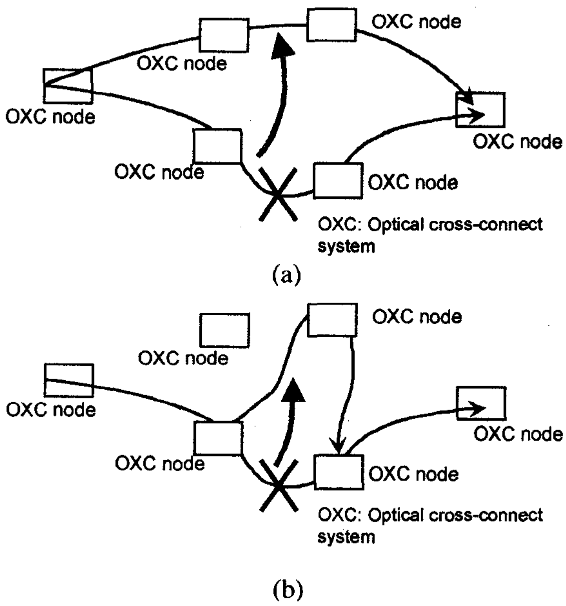


Figure 4.13: The difference between (a) global path switched re-routing and (b) local link switched re-routing in a basic optical network [53].

algorithm, would continuously attempt to manage the assignment of protection paths in such a manner as to minimise the impact thereof on future restoration attempts.

4.4.2 Relative cost of providing for network reliability

The level of physical connectivity has been identified in section 4.2.1 as an important parameter in determining the number of required wavelengths in an optical network. Figure 4.14 shows the influence that the number of wavelengths available in an optical network has on the ratio of optical links required to provide for network reliability. The ratio of optical links is defined here as the number of optical links required for restoration for a chosen approach relative to the number required when a shared resource optical-path switched approach is employed. The two approaches compared here relative to the shared resource optical-path switched approach are the dedicated resource optical-path switched and the shared resource optical-link switched approaches. Although the dedicated resource optical-link switched approach is not implicitly evaluated, interesting observations can be made regarding the relative cost of systems employing shared versus dedicated resources and optical-link versus optical-path switching.

With reference to figure 4.14 it can be seen that the cost of employing optical-link switched re-routing increases relative to optical-path switched re-routing as the number of available wavelength increases. This would motivate for a preference towards optical-path switched re-routing. When the ratio between the required number of optical links is interpretted for dedicated versus shared resource allocation it is noted that the cost-premium of dedicated resource allocation as opposed to shared resource allocation diminishes as the number of available wavelength increase. It should however be remembered that the very nature of dedicated resource allocation define an unavoidable residual cost penalty incurred for blocking characteristics superior to that of a shared resource allocation approach.

The dependence of a network's restoration ability on the protection accommodated for by the physical topology results in a relationship between network reliability and physical connectivity [54]. The relative cost of providing for network reliability is greatly influenced by the number of optical links demanded by the required level of network protection. Figure 4.15 shows the number of optical links required in a optical-path switched re-routing approach as a ratio of dedicated versus shared resource allocation schemes for various levels of physical connectivity at either a single or four wavelengths. As expected from the observations made in figure 4.14, an increase in the number of available wavelengths in the network resulted in an improvement of dedicated versus shared resource allocation. It is also relevant to comment on the observed dependence of highly connected physical topologies on an increased number of wavelengths [55].

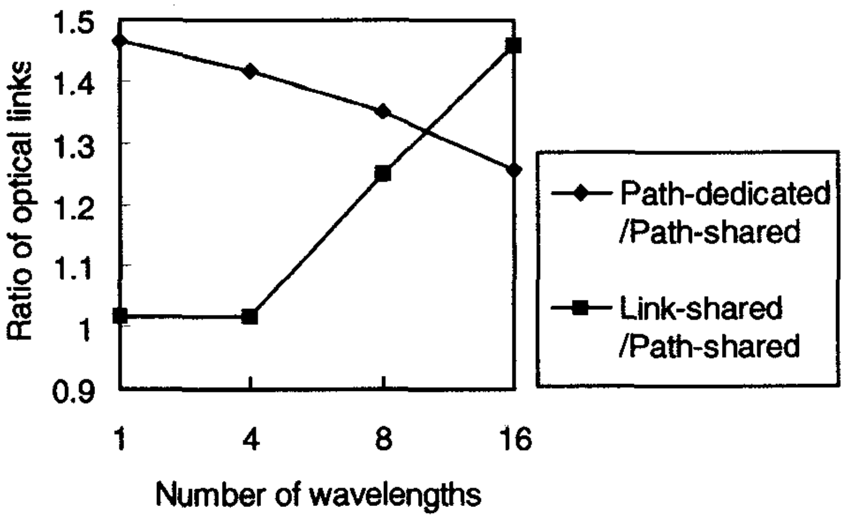


Figure 4.14: Ratio of required optical links as a function of the number of wavelengths [53].

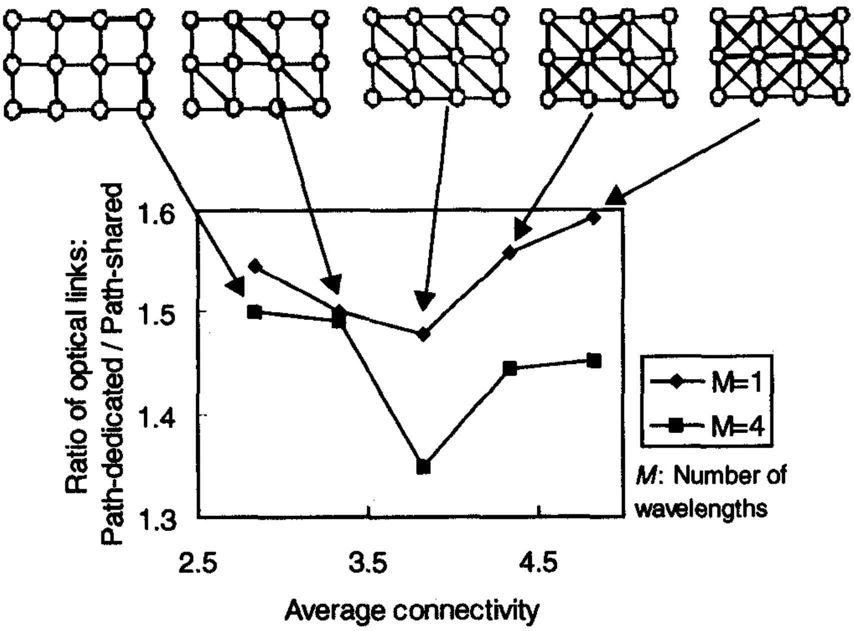


Figure 4.15: Ratio of required optical links as a function of the physical connectivity [53].

4.5 Business modelling

In the field of optical networking there are two main angles from which business modelling principles are applied. The first angle is the evaluation of optical networking technology in comparison to other more conventional communication technologies. This angle applies to greenfield scenarios where no or very limited communication infrastructure already exist. The second angle where business modelling plays an important role in optical networking is with regards to the techniques employed to maximise revenue generated by an existing optical network.

Factors such as the greater capital investment required for the deployment of an optical network weigh up against its enormous bandwidth benefit above conventional communication technologies. Whether investors should opt for proven traditional SONET/SDH optical networking technology or more advanced but young DWDM technology are also influenced by the classic performance cost trade-off. Reliability and interoperability are often the deciding factors when proprietary standards and unproven technologies compete in the marketplace.

The operators of existing optical networks, whether of the traditional or more recent variant, have to survive in a competitive market where new services and changing user requirements continuously disrupt the *status quo*. Factors such as economy, season and even sports events can influence what users expect from a communication network. It is a common practice of network operators to implement changes in their networks in peak holiday periods when it is expected that the public will generate large amounts of communication traffic without demanding or expecting the usual QoS level, the perfect conditions for a stress test of a communication network.

4.5.1 Financial aspects of the optical networking business case

In the context of new communication networks the spiraling bandwidth phenomenon can be explained as follows. Technological advances lead to decreasing unit capacity costs, which encourage network operators to invest by expanding their networks. Since more capacity now exists in the network their is a motivation for the stimulation of greater demand through the lower of prices and creation of new products and services. The resultant new demand profiles requires adjustments to the routing of traffic through the network. *The relationship between costing and routing for maximum return on investment (ROI) should be managed in such a way as to ensure growth over the short term, profit over the medium term as well as sustainability over the long term.*

In a multi-service communication network like that which optical networks are evolving to, the end-user defined requirements are in terms of services. The two opposing forces here being the quality of the service versus the pricing of the service. The problem of service pricing is not as simple as one tend to think, since the billing units of a service differ based on the service's underlying nature. Traditional circuit switched communication traffic was billed based on time, whereas more recent packet switched communication networks enable billing to be performed based on generated traffic. However, things like connection management and the related overheads provide justification for a fixed cost component, referred to as link shadow cost in mathematical discussions on the topic [56].

In an environment where communication networks are continuously growing, not only with regards to coverage but also with regards to capacity, the measures employed by network operators to ensure steady and growing revenues is often the crucial factor that determines survival. Judging end-users' willingness to pay more for new services is not easy, especially when considering that network operators are constantly offering more to their customers and many times undercutting each other in an attempt to secure elusive market share. It is important to notice that the amount of money available in the marketplace to pay for all the products and services offered by various communication network operators is not unlimited. Many people, especially in South Africa, already spend a relatively large percentage of their income on communication related expenses, which should prompt network operators to realise that their market is rapidly approaching saturation.

4.5.2 Elasticity as market manipulation tool

A concept known as the *price elasticity of demand* plays a very important role in how network operators attempt to manage the balance between the amount of traffic generated on their networks and the tariffs at which traffic is billed. It is analogous to the principle of economy-of-scale where it is possible to deliver a product or service at a lower cost when the number of resultant sales is greater. The relationship between volume and unit cost has however been found to be non-linear, thus providing the foundation of elasticity theory.

Elasticity in a multi-service communication network is best described as the dependence of service unit prices on optimal demand generation for various traffic streams and the required provisioning of network capacity. From a time scale point of view the application of elasticity in the management of optical network capacity is positioned between capacity planning and dynamic load balancing. Elasticity motivated and induced alterations to the network can be performed at any time given that it is recognised that such actions have a response time that is in the order of several days to several weeks. It is therefore advisable that immediate results should not be expected when the delicate relationship between traffic volume and traffic unit cost is disturbed.

The price elasticity of demand is presented in equation 4.2 [56] based on the fundamental assumption that demand is a function of price, where D denotes demand, P is price and ϵ is the elasticity parameter.

$$\epsilon = -\frac{P}{D}\frac{dD}{dP} \tag{4.2}$$

Revenue R is simply the product of price and demand as expressed in equation 4.3 [56]. Exactly how price influences demand is not known, since it is in itself a complex function influenced by factors such as the network under investigation, the type of users, the state of the international economy *etc.*

$$R = P \times D \tag{4.3}$$

Elasticity values of $\epsilon > 1$ correspond to the favourable situation where a decrease in unit traffic price results in an increase in the total revenue R of the network. An elasticity value of $\epsilon = 1$ describes a situation where a decrease in unit traffic price does not result in any change in total revenue, and an elasticity of $\epsilon < 1$ means that a decrease in unit traffic price would result in a reduction in the total revenue, clearly not a favourable situation. When it is assumed that a constant price elasticity model accurately describes communication bandwidth the influence of price on demand is described by the following equation [56]

$$D = \frac{A}{P^{\epsilon}}, \tag{4.4}$$

where A is the so-called demand potential found when $P = 1$.

When it comes to how revenue is affected by increases in the unit traffic price, the inverse effect typically applies. It is intuitive that no network scenario can exist where both a decrease and an increase in the unit traffic price can result in an increase in the total revenue. This would lead to a network operator's nirvana where customers will be willing to pay anything for a service or product. By the same argument it would be impossible for a network scenario to exist where both a decrease and an increase in the unit traffic price can result in a decrease in the total revenue. *By the very nature of the price elasticity of demand, conditions of revenue stability are unachievable, especially when it is realised that factors outside the control of a network operator also influence the demand and subsequent revenue generated by a communication network.*

Elasticity is estimated [56] at around 1.05 for voice traffic and at around 1.3-1.7 for data traffic, which is encouraging for network operators. With the convergence of voice and data traffic and the gradual maturation of VoIP technology these values for elasticity are bound to change, most probably settling around 1.1-1.2 before slowly approaching the unity plus epsilon level. This epsilon level will be non-zero just like that of motorcar fuel, which have been on the market for around a century and still exhibit price elastic demand behaviour. This is but one example of the similarities between the information transportation industry, otherwise known as the communication networking industry, and the physical transportation industry through characteristics such as traffic, routes, capacity, QoS, connectivity *etc.*