MULTI-RING SDH NETWORK DESIGN OVER OPTICAL MESH NETWORKS

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By

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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The evolution of networks in telecommunications has brought on the importance of design techniques to obtain survivable and cost-effective transportation networks. In this thesis, we study *Synchronous Digital Hierarchy* (SDH) ring design problem with an interconnected multi-ring architecture overlaid over an optical mesh network. We decouple the problem into two sub-problems: the first problem is the SDH ring selection, and the second problem is the mapping of these rings onto the physical mesh topology. In this structure, the logical topology consists of SDH *Add/Drop Multiplexers* (ADMs) and *Digital Cross-Connects* (DXCs), and the physical topology consists of *Optical Cross-Connects* (OXCs).

The ring selection problem is to choose the rings that give minimum inter-ring traffic in the network. Since inter-ring traffic increases the network cost and complexity, we aim to minimize the inter-ring traffic. We propose a greedy heuristic algorithm for this problem that finds a solution subject to the constraint that the number of nodes on each ring is limited. Numerical results on the ring design problem are presented for different topologies.

Once the logical topology is obtained, resilient mapping of SDH rings onto the mesh physical topology is formulated as a *Mixed Integer Linear Programming* (MILP) problem. In order to guarantee proper operation of SDH ring protection against all single failures, each link on an SDH ring must be mapped onto a lightpath which is link and node disjoint from all other lightpaths comprising the same ring. The objective of this mapping is to minimize the total fiber cost in the network. We also apply a post-processing algorithm to eliminate redundant rings. The post-processing algorithm is very useful to reduce the cost. We evaluate the performance of our design algorithm for different networks.

Keywords: SDH over optical networks, multi-ring SDH networks, ring selection, resilient ring mapping over mesh networks

ÖZET

OPTİK AĞ ŞEBEKELER ÜZERİNE ÇOKLU HALKA SDH ŞEBEKE TASARIMI

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Telekomünikasyonda şebeke evrimi, uzun ömürlü ve uygun maliyetli ulaşım ağları elde etmek için tasarım tekniklerinin gelişmesine neden olmuştur. Bu tezde, optik ağ şebekesi üzerinde birbirine bağlı çoklu halka yapısındaki eşzamanlı sayısal hiyerarşi halka tasarımı üzerinde çalışılmıştır. Problem iki alt probleme ayrılmıştır: ilk problem eşzamanlı sayısal hiyerarşi halka seçimi, ikinci problem ise bu halkaların fiziksel ağ topolojisi üzerine haritalanmasıdır. Bu yapıda, mantıksal topoloji eşzamanlı sayısal hiyerarşi ekle/çıkar çoklayıcılarından ve sayısal çapraz bağlantılardan oluşur, fiziksel topoloji ise optik çapraz bağlantılardan oluşur.

Halka seçim problemi, şebekedeki en düşük halkalar arası trafiği verecek halkaları seçmektir. Halkalar arası trafik, şebekenin maliyetini ve karmaşıklığını artırdığı için, halkalar arası trafiği en aza indirmeyi hedefledik. Bu problem için her halkadaki düğüm sayısı sınırlamasına sahip bir çözüm bulan buluşsal bir algoritma öngörüldü. Farklı topolojiler için halka tasarım probleminin sayısal sonuçları sunulmuştur.

Mantıksal topoloji elde edildikten sonra, eşzamanlı sayısal hiyerarşi halkalarının fiziksel ağ topolojisi üzerine esnek haritalanması karma tamsayılı doğrusal programlama ile formüle edildi. Bütün tek hatalara karşı eşzamanlı sayısal

hiyerarşi halka korumasının uygun çalışmasını garanti altına almak için, bir eşzamanlı sayısal hiyerarşi halkasının her bağlantısı aynı halkayı kapsayan diğer tüm ışıkyollarından, bağlantı ve düğüm ayrık olacak şekilde bir ışıkyoluna haritalandı. Bu haritalamanın hedefi şebekedeki toplam fiber maliyetini en aza indirgemektir. Ayrıca, gereksiz halkaları ortadan kaldırmak için bir işlem sonrası algoritma uyguladık. Bu işlem sonrası algoritma maliyeti düşürmek için çok kullanışlıdır. Tasarım algoritmamızın performansını farklı şebekeler için değerlendirdik.

Anahtar Kelimeler: optik şebekeler üzerinde eş zamanlı sayısal hiyerarşi, çoklu halka eşzamanlı sayısal hiyerarşi şebekeleri, halka seçimi, ağ şebekeleri üzerine esnek halka haritalama

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To My Father...

Chapter 1

INTRODUCTION

Today's transport networks must cope with ever increasing traffic inflation by the high-capacity and reliable systems. The demand is increased by many different factors. The rapid growth of the Internet, voice, data, videoconferencing, and private networking services consumes large amounts of bandwidth. Especially Internet connections load the telephone network enormously. There are also increasing technological revolutions on the industry, finance, education, medicine, government and especially business intranet applications. All these factors increase the need for bandwidth in networks. Optical fiber transmission has played an important role in carrying high bit rates traffic. Traditionally, before optical fibers were available, coaxial cables were used in long distance transport networks. The cost of coaxial cables is dependent of the bandwidth of the cable. With the introduction of optical technology in transmission network, the transmission cost was reduced drastically over the past years as seen in Figure 1.1.

Optical fibers can carry much higher bit rates than copper cables. Thus, it is preferred medium for transmission data in long distance transmission networks. The cost of the optical fiber is independent of the bit rate carried by it. The widespread use of optical fibers and technological improvements in fiber technology reduced the cost in today's networks.

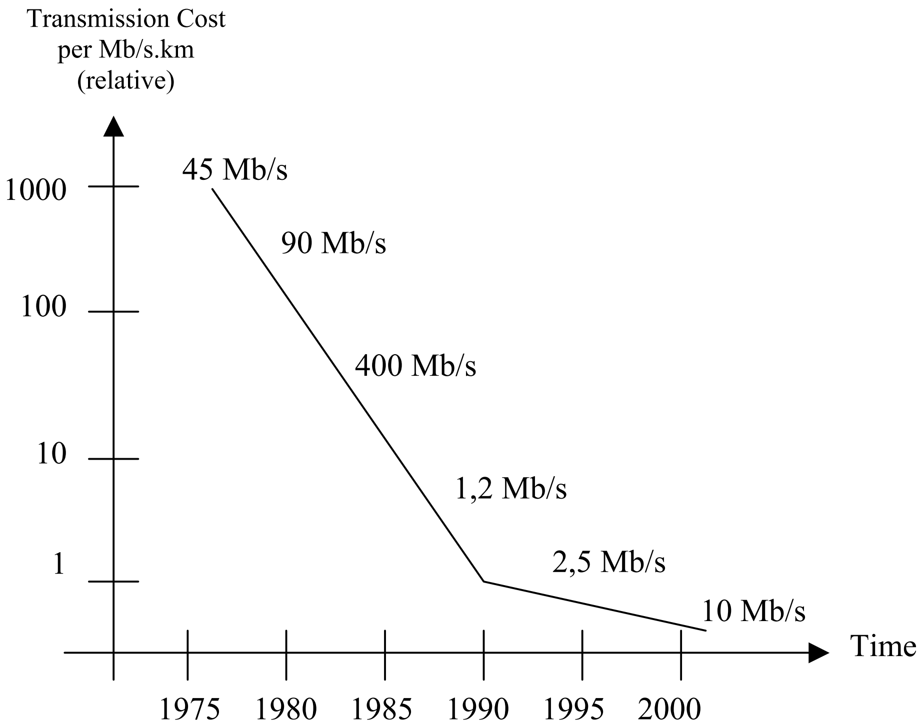


Figure 1.1 Evolution of optical transmission fiber cost

Until the mid 1980s, *Plesiochronous Digital Hierarchy* (PDH) systems were used in transmission networks. In the mid 1980s, telecom operators needed a high capacity, flexible transmission system, so researchers started to define a new, high capacity worldwide system. In the 1990s, *Synchronous Digital Hierarchy* (SDH) transmission system compatible with existing PDH systems were started to be used by telecom operators. In SDH transmission systems, *Time Division Multiplexing* (TDM) technology is used to multiplex lower order bit rates into higher order bit rates. Today, the highest transmission rate commercially used in SDH telecommunication networks is 10 Gb/s, and 40 Gb/s is being developed. Another technology has been deployed commercially since 1996 is called *Wavelength Division Multiplexing* (WDM). WDM transmission systems allow multiplexing multiple optical channels on a single fiber at different wavelengths. It has become the preferred transmission technology in long distance transport networks at the end of 1990s. Today's *Dense Wavelength Division Multiplex* (DWDM) systems can multiplex 16, 32, 64, 80, and 96 channels each carrying 10 Gb/s onto a single fiber and

160 channels DWDM systems are being developed. Currently, WDM is widely used in point-to-point configurations to offer fiber cost savings in long distance backbone architectures.

The network design process is influenced by the resulting network architectures. The network can be consisting of many layers interoperating with each other. In the design strategies different layering structures are used. The most important point is to offer reliable uninterrupted services to the customer by telecommunications operators. Typically, the failure of a single optical fiber link may cause loss of hundred thousand or more calls or data connections in progress. Therefore, *network survivability* is a major factor that affects the design of the networks to handle all types of failures. In order to provide high quality services, the traffic should be restored within a small period. Different layers have their own protection mechanisms. SDH and WDM layers can be designed to work with other layers or they can operate directly over fiber independent on the other layers to handle protection and restoration.

In this thesis, we work with the SDH over WDM topology. In SDH networks, point-to-point connections are widely replaced by ring structures. A ring network is a 2-connected structure and there are two separate paths between any pairs of nodes. This provides resilience to any single failure. When a failure occurs on a link, the traffic is rerouted over the paths on the reserved capacity of the ring. This protection is called as ring protection. The most popular protection architecture of SDH is self-healing rings in network protection and we will discuss these structures in more detail in the next chapter. Since ring networks have several advantages such as fast restoration time, simple operationally and cost affectivity, the usage of ring networks are now very common for survivability design. In this thesis we only consider single link failures, and the protection is provided by only the SDH layer.

SDH networks consist of several functional equipments: *Terminal Multiplexers* (TMs) in point-to-point connections, *Add/Drop Multiplexers* (ADMs) in individual nodes to terminate a part of traffic and add some traffic to pass through, and *Digital Cross-Connects* (DXCs) to interconnect multiple rings. Digital cross-connects are used to cross-connect inter-ring traffic between multiple rings where inter-ring traffic is defined as the set of demands such that source node belongs to one ring and the destination node belongs to another ring.

In this thesis we discuss and formulate two interrelated problems in the transport network design. First part is the logical ring design, and second part is the mapping of these rings onto the physical topology. In the first step, we connect ADM nodes with each other using a multi-ring architecture. We select the rings to be deployed such that the resulting interconnected multi-ring structure can be used to route all demands between their source and destination ADMs and each ring satisfies node size constraints. The objective of this first part of the design process is to obtain a multi-ring architecture that results in the minimum inter-ring traffic. By minimizing the inter-ring traffic, we aim to reduce the cost of the DXC equipments and decrease the complexity of the network. After all SDH rings are determined, we try to map these rings onto the physical topology. This mapping has to be done in such a way that each link on a ring is mapped onto an optical path, called a lightpath, which is physically diverse, i.e., node and link disjoint, from all other lightpaths corresponding to other SDH links on the same ring. This is required since SDH rings have to cope up with all possible single link or node failures. The objective of this mapping is the minimization of the cost of fibers used by each ring.

We discuss the evolution of transport network architectures and new technologies in Chapter 2. We also present the protection architectures of SDH over DWDM networks and provide the advantages of ring protection. Then, we describe the ring design problem. Finally we make a summary and comparison of different network design techniques in the literature.

In Chapter 3, we propose a greedy heuristic algorithm for solving the ring design problem. The first step in the design process is to generate the logical graph, which has the ADMs as its nodes and possible connections between ADMs as its links. This graph is constructed such that it has a planar embedding. The faces, i.e., simple rings, of this topology are used as the starting solution for the heuristic ring design algorithm. There are two main constraints in the logical ring design process. First, each ring can have a maximum number of nodes. The second constraint is that the rings must ensure the 2-connectivity. In the logical ring design, the objective is to minimize inter-ring traffic in the network. In this chapter we also provide some numerical examples for the application of this algorithm.

Once the logical ring design problem is solved, we represent the mapping of logical rings onto the physical topology in Chapter 4. We formulate the mapping of logical rings onto the physical topology as a *Mixed Integer Linear Programming* (MILP) problem. We map each logical ring onto disjoint physical links and nodes. The objective of the mapping is to minimize the total fiber costs in the network. We compare our solution on different topologies. Finally, we conclude our thesis with some improvements for future work in Chapter 5.

Chapter 2

EVOLUTION TOWARDS SDH

In this chapter, the evolution towards the transmission system based on SDH will be discussed. We present the transmission hierarchy from PDH to DWDM. We also discuss the survivability issue and SDH network protection architectures; especially, ring protection. SDH ring design problem is also considered extensively. Finally, we present a literature survey.

2.1 Transmission Hierarchy

Telecom operators must cope with explosion of data traffic. In the 1970's, first order multiplexing is used, where only 30 speech channels are multiplexed. When the need for high capacity systems increased, higher order digital transmission rates, multiplexing even more speech channels were designed.

The transmission medium of the networks can be coaxial cables, copper, radio links, satellites, or fiber optic medium that has been widely used in recent years. Before optical fibers were available, coaxial cables were widely used in traditional long distance transmission networks. In coaxial cables, as bandwidth increases, the quality and resultant cost of cables also increase. Therefore it was so important to design the network carefully for the capacity need. In contrast, the optical fibers, consisting of a glass cylinder surrounded by a cladding glass tube, can carry information at very high bit rates, e.g.; exceeding 1 Tb/s (Figure 2.1).

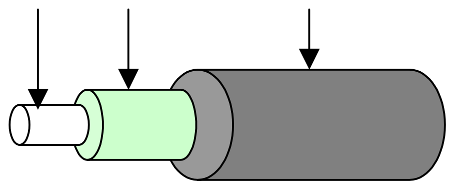


Figure 2.1 An Optical Fiber

2.1.1 The Problem in PDH

The set of standards that explains the higher order transmission rates is referred as the PDH. As fast developments occur in the transmission systems, PDH systems become expensive and complex solutions due to some weak points.

The first problem is different PDHs defined in North America, Europe, Japan and Trans Atlantic as shown in Table 2.1. These different hierarchies were an unwanted situation and a new common worldwide hierarchy of higher order signals, SDH, was defined.

Hierarchical Level	***North America (Kb/s)***	***Europe (Kb/s)***	***Japan (Kb/s)***	***Trans Atlantic (Kb/s)***
0	64	64	64	64
1	1544	2048	1544	2048
2	6312	8448	6312	6312
3	44736	34368	32064	44736
4	139264	139264	97728	139264

Table 2.1 Four different Plesiochronous digital hierarchies

The second problem of PDH is back-to-back multiplexing. If we insert a tributary signal into the higher order signal, the inverse procedure should be done. Therefore, lots of processing is needed and it increases the number of equipment in the network, such as multiplexers and demultiplexers. Thus, the networks become expensive and complex solution.

In PDH transmission systems, it is impossible to remove a 2 Mb/s signal from a 140 Mb/s directly. Three multiplexing steps are required to obtain a 2 Mb/s lower order signal from a 140 Mb/s higher order signal. The procedure is shown in the Figure 2.2.

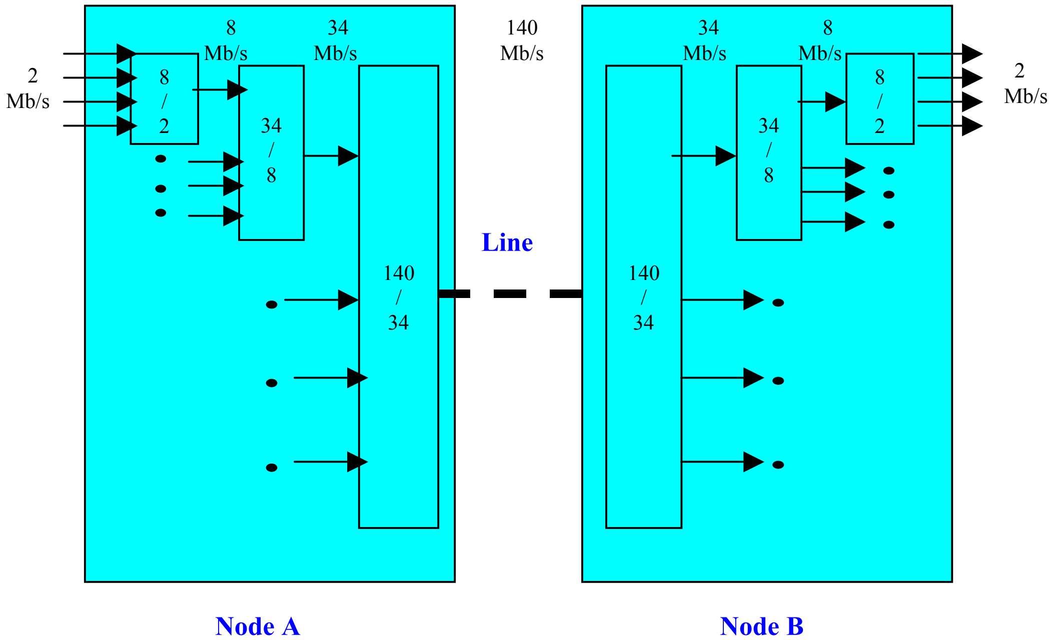


Figure 2.2 PDH multiplexing

2.1.2 The Solution in SDH

The SDH (Synchronous Digital Hierarchy), which results from SONET (Synchronous Optical NETwork) is an international standard for high-speed telecommunication over optical/electrical networks, which can transport digital signals in variable capacities.

Since Telecommunication Operators first introduced digital transmission into the telephone network in the 1970's, the demand for transmission capacity and higher order transmission rates has rapidly increased in the telephone network. As a result, the existing transmission systems based on PDH became a weak transmission system and a new, high capacity, flexible transmission system was needed to overcome the limitations presented by PDH networks.

To cope with the disadvantages of PDH, the new, high capacity and flexible transmission system was developed in 1980's. It became a standard in ANSI (American National Standards Institute) referred to as the SONET in 1984. In 1988, CCITT (International Consultative Committee on Telephony & Telegraphy) agreed a standard on this transmission system as the SDH with certain changes to define a worldwide system. The first SDH standards were approved by the ITU-T in November 1988 and recommendations G707, G708 and G709 were published in the CCITT Blue Book in 1989. They define the rate, frame and multiplexing processes and the SDH became an international, high-rate telecommunication network standard.

SDH uses one worldwide hierarchy and is based on optical fiber transmission links in order to take advantage of the high bandwidth and reliability of the fiber optic medium. It is also compatible with the existing PDHs. Unlike PDH systems, SDH can directly add lower order signals to higher order signals or drop them from higher order rates, without having to multiplex/demultiplex.

A network element can be configured as Terminal Multiplexer (TM), Add and Drop Multiplexer (ADM) or as a hub. Also, Digital Cross-Connect (DXC) network elements are used in a traditional network.

The Add/Drop multiplexing reduces the number of elements, so it results in less system cost. An ADM used to add/drop lower order rate traffic can be seen in the Figure 2.3.

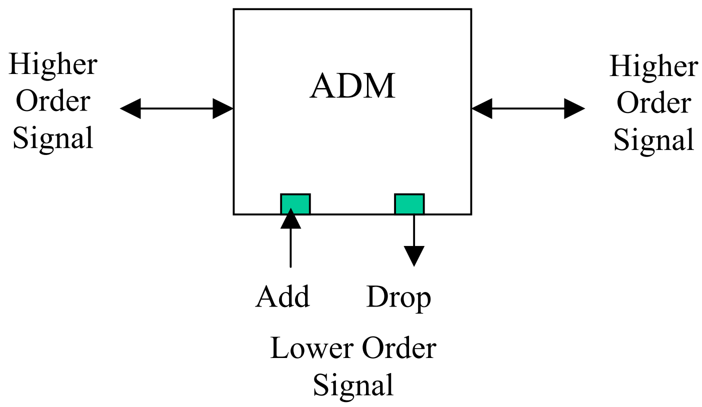


Figure 2.3 ADM Structure

Digital Cross-Connects, which are bigger and having more capacity systems than an ADM, are usually used in the backbone network or at the gateway nodes between two regional and backbone networks. This equipment has internal cross connection capabilities and very similar functionality to ADMs, but they are very expensive with respect to ADMs. In the DXCs, signals can be switched between two lines, or between tributaries, or line to tributaries by switching functionality of the equipment (Figure 2.4).

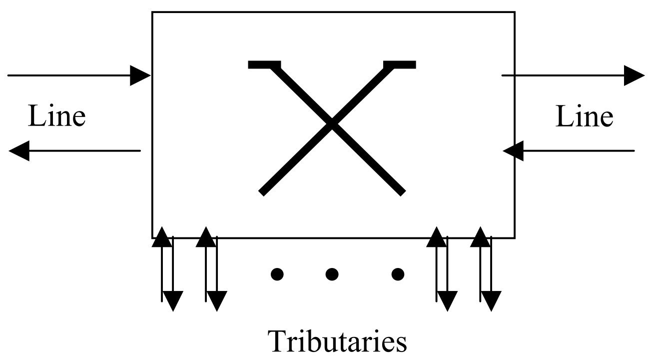


Figure 2.4 DXC Structure

The standardized SDH transmission frames, called Synchronous Transport Modules of Nth hierarchical level (STM-N) which correspond to Synchronous Transport Signals of SONET are shown in Table 2.2.

Frame Rates (Mb/sec)	*SDH*	*SONET*
155,520	STM-1	STS-3
622,080	STM-4	STS-12
2488,320	STM-16	STS-48
9953,280	STM-64	STS-192

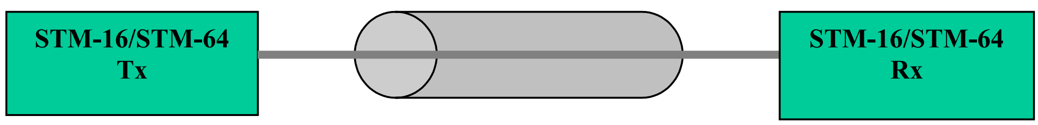
Table 2.2 Standardized Frame Rates

SDH systems are practical and produce powerful management architecture; this easy management results in high reliability and flexibility. This Time Division Multiplexing (TDM) based transport systems are widely used to provide high capacity transmission for voice, data and leased-line applications.

2.1.3 Introduction to WDM

For high-speed networks, to satisfy the increasing demands and to use the optical switching and routing, the new technology, WDM has become the preferred transmission technology for point-to-point connections.

WDM allows combining many channels onto a single fiber in contrast to classic transport protocol of SDH, which uses one traffic channel per fiber as seen in Figure 2.5. In Figure 2.5 (b), each channel is transmitted on a different "color".



(a) One Traffic Channel per Fiber

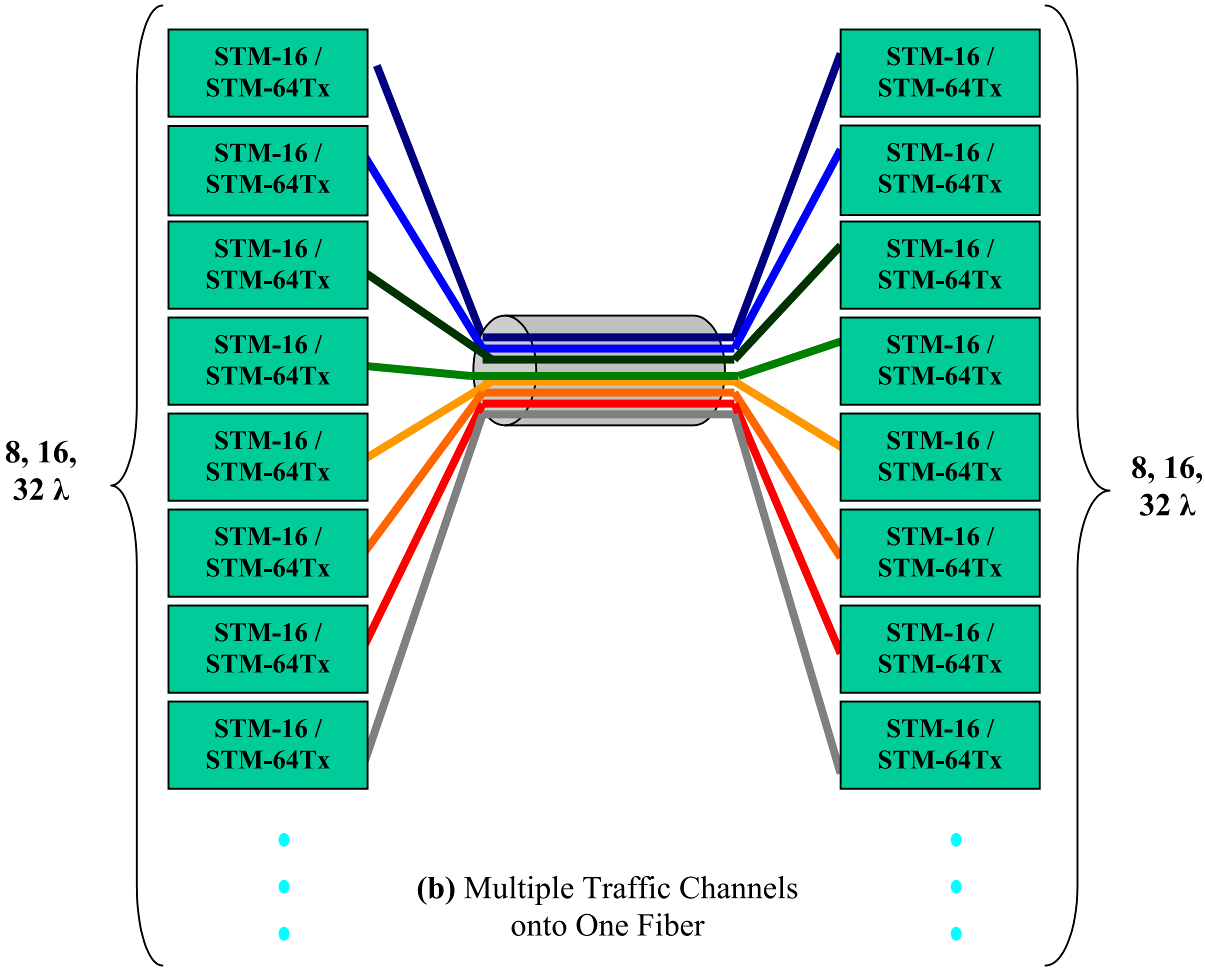


Figure 2.5 (a) Classic Transport Protocol

(b) Dense Wavelength Division Multiplexing

While two traffic channels are transmitted per fiber in WDM, 8,16,32 or more traffic channels can be transmitted in Dense Wavelength Division Multiplex (DWDM). DWDM implies closely spaced wavelengths such as 0.8 nm spacing. It solves the fiber shortage problems.

A DWDM backbone network may consist of routers interconnected through an optical mesh, built from optical cross-connects (OXCs). OXCs are used for routing wavelengths or optical pass-though for optical channels that carry traffic destined to another node. There are two main types of OXCs: Wavelength Selective Cross Connects (WSXC) or Wavelength Interchanging Cross-Connects (WIXC). In WSXCs, an incoming wavelength channel continues with the same wavelength to the outgoing fiber, it means there is no wavelength conversion. In WIXCs, the incoming wavelength is converted to another wavelength. More details about optical cross-connects can be found in [1-3].

2.2 Survivability

Survivability is the ability of a network to reroute the interrupted traffic affected by the failure of some of the network elements via the spare capacity that is reserved for that purpose. Possible failure scenarios such as physical fiber optic link cut, transmission system or node breakdown can occur as the result of natural disasters or as the result of human action or even by unexpected failures in software or control systems.

In recent years, the survivability issue has become a major factor since the telecommunication industry deploys very high capacity fiber networks in order to respond to the explosion of demand. Since the node or link failures cannot be avoided in real world and they result in loss of revenue, the networks have to be designed to handle failures. The design of survivable networks is discussed in [4-6].

The survivability is supplied by installing spare capacity over the network, so in case of a failure, the interrupted traffic can be diverted to the reserve capacity. Designing such survivable networks has also an objective of minimizing the spare capacity costs and becomes a difficult problem.

There are two main approaches to achieve survivability: *protection*, which uses dedicated capacity in the ring and mesh networks to restore the traffic when a failure occurs, and *restoration*, a dynamic re-routing algorithm for handling the interrupted traffic using paths available in the mesh networks.

Different telecommunications services may use different survivable architectures due to economics and demand distribution and network planners have a great concern of reducing network protection cost while supplying an acceptable level of survivability.

The architectures to supply survivable networks are protection and restoration. Protection is pre-assigned capacities between any two nodes in a network in order to recover a failure, used in both ring and mesh networks. Restoration may or may not use any pre-assigned capacity. If no pre-assigned capacity is used, dynamic re-routing algorithms are used to find a transport path to recover an interrupted capacity. This technique is used generally in mesh networks.

There are different protection/restoration possibilities having different recovery time, granularity and fault coverage specifications that result in different survivability performance.

We now introduce the term of layered architecture for the discussion of survivability in different network protocols. The functions of the network may be broken up into different layers. Each layer performs different functions and provides a set of services to the higher layer.

Today's network layering structures may be complex, and employ with several sub-layers and multiple protocol stacks. An example can be seen in Figure 2.6. In this example, an IP over ATM over SDH network is represented. The SDH layer is treated as the data link layer of ATM layer and ATM layer is treated as the data link layer of above IP layer.

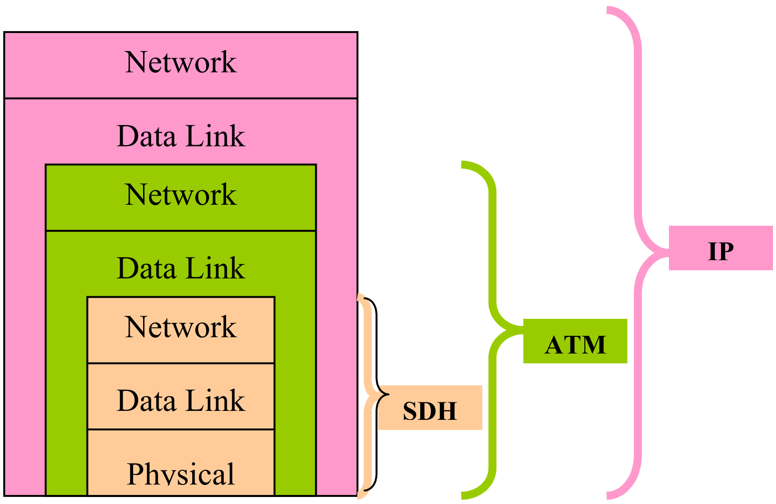


Figure 2.6 An IP over ATM over SDH network

These layers are called the first-generation networks [7]. The second-generation networks introduces optical layer in the protocol hierarchy. The optical layer has been defined by the ITU. This definition is appropriate to describe DWDM networks. This second-generation optical layer provides lightpaths to the first-generation network layers. A lightpath is an end-to-end connection across the optical network, and on each link, a wavelength is used to establish the connection.

In public and private telecommunications networks, first-generation optical networks, especially SDH networks have been widely deployed. With the advances in DWDM technology, carriers are widely using the SDH over DWDM architecture shown in Figure 2.7.

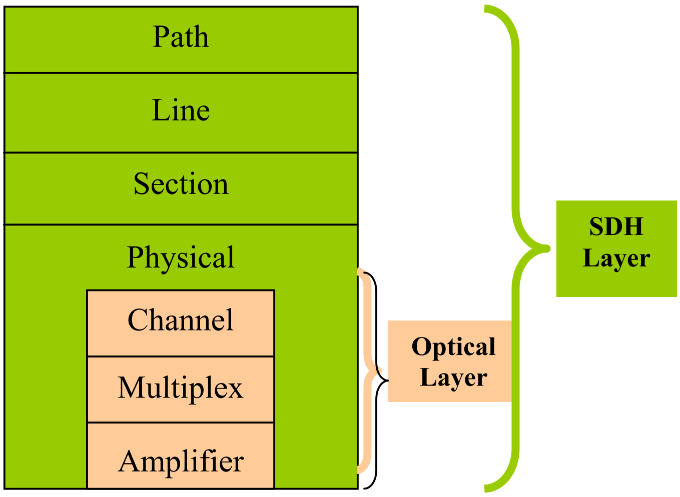


Figure 2.7 A SDH layer over optical layer

The SDH layer consists of four sub-layers. The highest layer is the path layer and responsible for end-to-end connections between nodes. The path layer corresponds to the network layer in classical layered hierarchy. The line layer is responsible for multiplexing a set of path-layer connections onto the link between two nodes and for performing the protection switching in case of a line failure. The section layer above the physical layer is present at each regenerator and terminal in the network. The line layer and section layer correspond to the data link layer in classical layered hierarchy. The lowest physical layer is responsible for actual transmission of traffic across the fiber. The physical layer of SDH is replaced by the optical layer. The optical layer also consists of the channel, multiplex and amplifier sections. In this thesis, we work with the SDH over DWDM architecture.

A network consists of many layers and the multi-layer model is a complicated structure as a result of different networks working with each other. Each layer in the hierarchy has their own protection mechanisms, independent of other layers. Having different protection mechanisms in different layers have some advantages and also some disadvantages.

The advantages of having separate protection mechanisms in different layers are as follows. If one of the layers does not have any protection mechanisms, other layers can provide the protection in case of a failure. Also, different layers can handle different types of failures, so best utilization can be obtained by giving the different protection responsibilities to the different layers.

There are also some disadvantages of having different layers' own protection mechanisms. In case of a single failure, multiple protection mechanisms may try to restore the traffic simultaneously. This multi-layer protection results in a complexity in management. To handle this problem, a priority mechanism can be added to the system. First, one layer restore the service, then the second layer try to restore. Another possibility is giving the protection responsibility to only one layer.

In the SDH over DWDM architecture, there are two possibilities for survivability. First, the protection can be provided completely by the SDH layer in case of optical fiber link and node failures. The SDH protection mechanisms will be discussed in Section 2.3 in more detail. Second, the optical layer can handle the optical fiber cuts. In this case, the optical layer cannot handle SDH equipment failures. Thus, the fiber cuts are handled by the optical layer and SDH node failures are handled by the SDH layer. In dealing with link and node failures, SDH protection is faster than DWDM-based protection.

In this thesis, we assume that the whole survivability function is fulfilled by the SDH layer, and leave the multi-layer resilience outside the scope of this thesis. In the next section, we discuss how protection function is realized in the SDH layer.

2.3 SDH Ring Protection

To provide survivability, there are several possible transport network architectures. Mesh and multi-ring structures are available for protecting optical transmission networks using SDH layer.

2.3.1 SDH Network Architectures

SDH networks can be configured as point-to-point links, linear configurations, mesh topologies or rings and multi-ring topologies.

There exist only two terminal multiplexer network elements at both end of link in point-to-point links as shown in Figure 2.8. This network structure can either be protected or unprotected. In protected links, two extra fibers are needed to be reserved for protection in case of a failure.

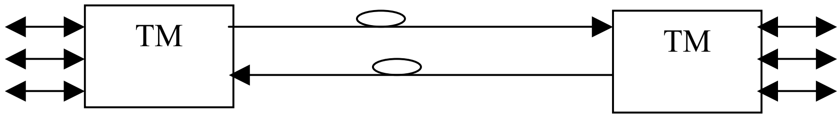


Figure 2.8 A point-to-point SDH link

In linear networks, SDH ADM nodes are connected in a linear fashion where two terminal multiplexers exist at both ends as shown in Figure 2.9. This topology provides drop and insert capability to all network elements. There may be unprotected linear networks, establishing two fiber connections between two ADMs or protected with four fiber connections where two of them are working and other two serving as a backup or protection pair.

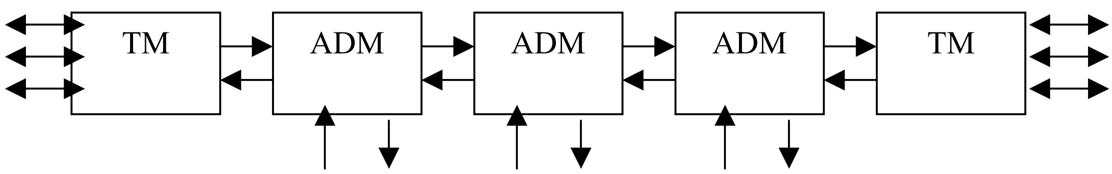


Figure 2.9 A linear drop and insert SDH network

In linear networks, even if two fibers are used for protection between two ADMs, it is possible for all four fibers to be cut at the same time. Thus, rings are the most commonly used topology because they provide an alternate path to communicate between any two nodes, as shown in the Figure 2.10.

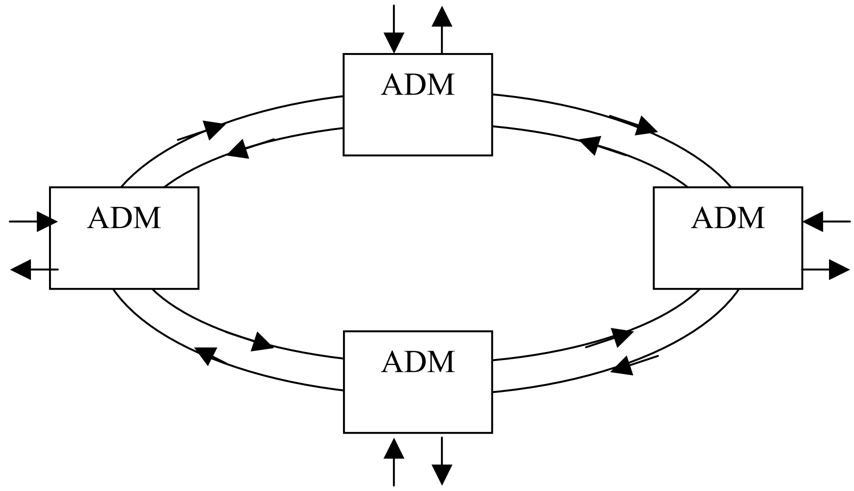


Figure 2.10 A SDH Ring Network

A two-fiber ring can be operated either as a unidirectional ring, or as a bi-directional ring. In ring architecture, either two fiber or four fiber protection can be selected. In unidirectional rings, traffic is limited to one fiber and flows the same way around the ring. The second fiber works as the protection fiber and is used to provide restoration. In a bi-directional ring, traffic is sent on both fibers, so both are working fibers. In order to provide the restoration in case of a failure, half of the capacity on both fibers is reserved for backup, or two more fibers are deployed exclusively for protection. Ring protection types will be discussed in Section 2.3.2. Two or more rings can be connected configuring a multi-ring topology as seen in Figure 2.11. In this topology, the expensive digital cross-connect equipment is required at hub-nodes. Each ring has their ring protection mechanisms. It is better to have two hub nodes between two rings in case of a node failure. A DXC in a central office interconnects multiple rings and cross-connects inter-ring traffics between these rings. Thus, each DXC has an important role in a multi-ring topology. If only one central office exists in this topology, a node failure at this central office results in disconnectivity between two rings. If there are two hub nodes, in case of one node failure, other hub node transmit the traffic between two rings.

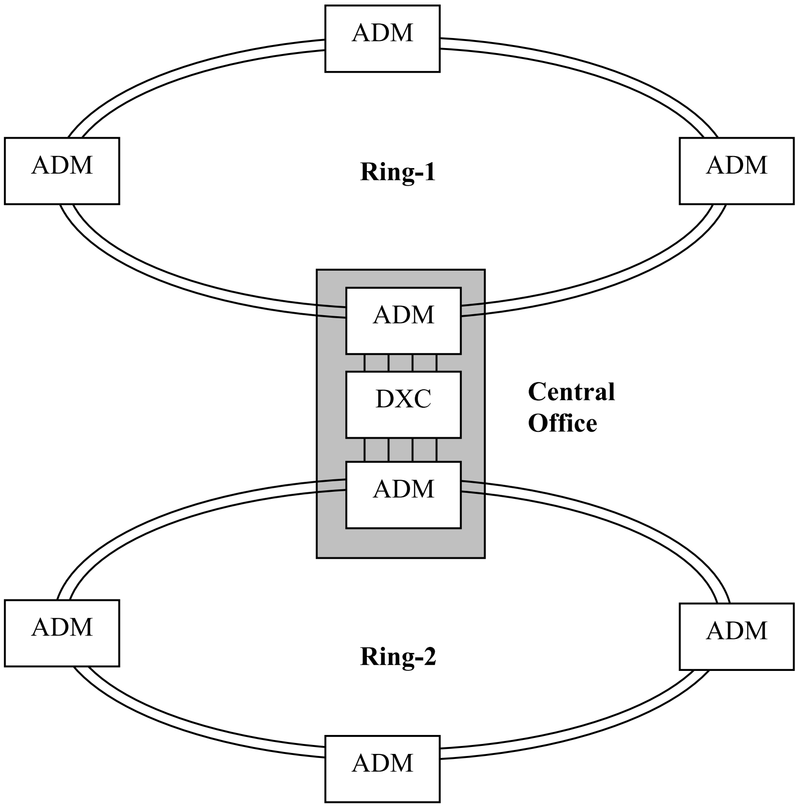


Figure 2.11 Multi-Ring SDH Topology

Another general type of SDH network is the mesh architecture as shown in Figure 2.12. Ring architectures are often preferred in practice because of their simpler and faster switching mechanism. Despite their greater capacity requirements, rings can also be more economical than mesh networks, particularly in metropolitan area networks where nodal costs, especially DXC costs usually dominate over distance-dependent costs for fiber and regenerators. For these reasons, SDH rings have already been widely deployed.

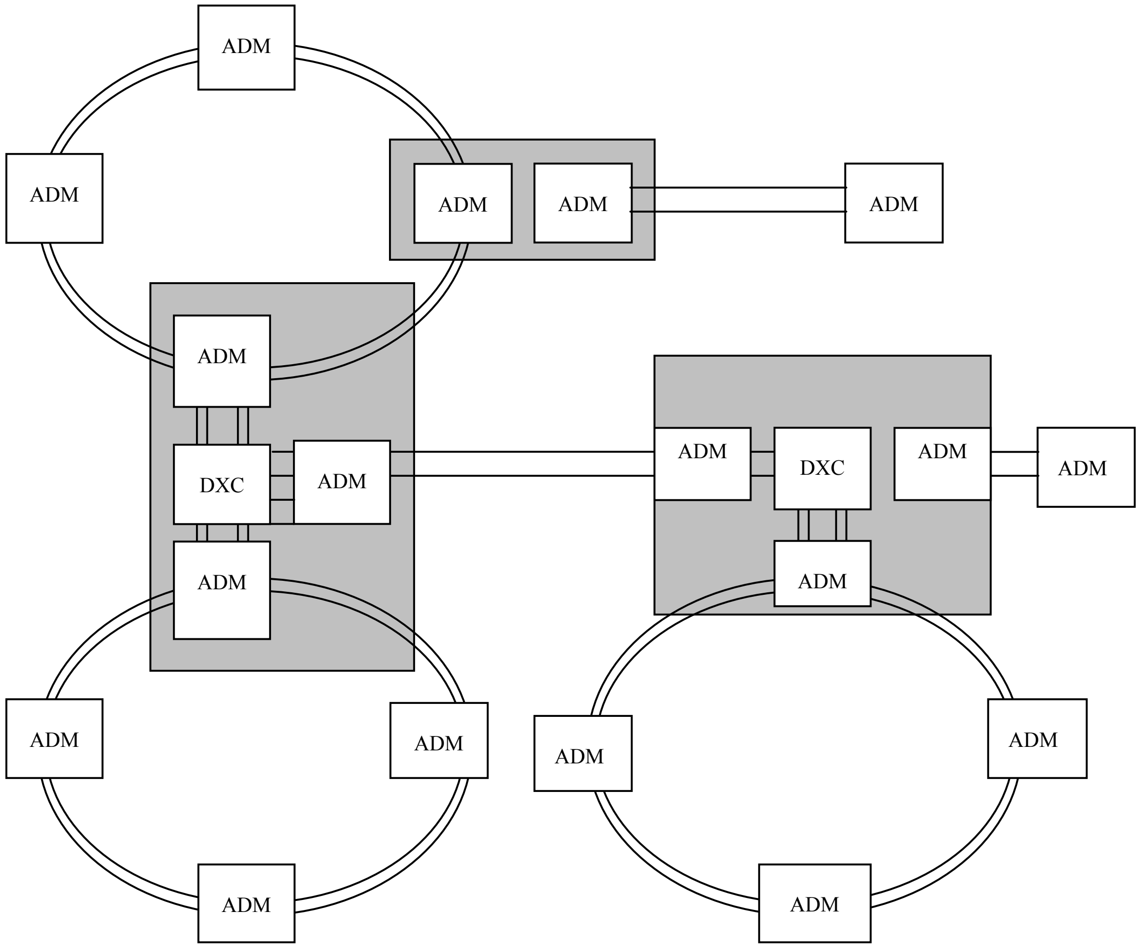


Figure 2.12 A mesh topology of SDH network

2.3.2 SDH Ring Protection Mechanisms

The ring protection types are as follows;

1. In Europe, 2f-MS-SPRing, 4f-MS-SPRing or 2f-SNCP
2. In USA, 2f-BLSR, 4f-BLSR or 2f-UPSR

Where, BLSR is Bi-Directional Line-Switched Rings, UPSR is Uni-Directional Path-Switched Rings and MS-SPRing is the Multiplex Section-Shared Protected Rings, SNCP is Sub-Network Connection Protection. Table 2.3 illustrates this logical equivalence of terminology.

SONET in USA	**SDH in Europe**
2 fiber Uni-directional Path-Switched Ring (2f UPSR)	2 fiber Sub-Network Connection Protection Ring (2f SNCP Ring)
2 fiber Bi-directional Line-Switched Ring (2f BLSR)	2 fiber Multiplex Section Shared Protected Rings (2f MS-SPRing)
4 fiber Bi-directional Line-Switched Ring (4f BLSR)	4 fiber Multiplex Section Shared Protected Rings (4f MS-SPRing)

Table 2.3 The Ring Protection Architectures

SDH rings are also called self-healing rings since they incorporate protection mechanisms that detect failures and reroute traffic onto reserved channels rapidly.

In a dedicated protection ring, every normal path has a corresponding protection path and in a shared protection ring, several normal paths may use a single protection path.

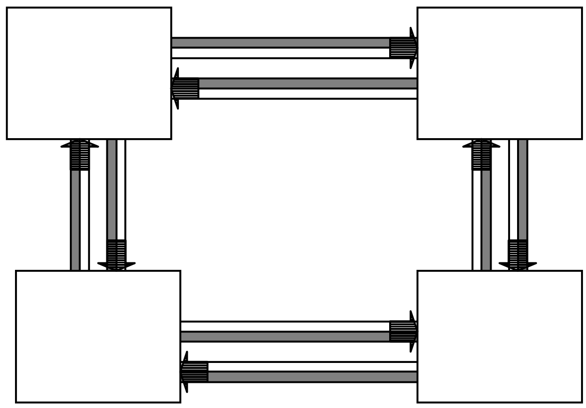
Although SDH meshed architectures offer more advanced functionalities and ring networks require high capacity and have limited flexibility, ring networks have dominant advantages as fast restoration, being economical, practical and easy management.

The main advantage of ring protection schemes is fast restoration time since the network switching time is a major factor for the transmission networks. The switch completion time in a SDH ring for a failure on a single span is defined as less than 50 msec by *ITU Telecommunication Standardization Sector* (ITU-T) Recommendation G-841. Ring networks are also preferred due to economical reasons since their lower nodal costs in Metropolitan Area Networks [8].

MS-SPRing architecture implements traffic routing function electrically in the SDH equipment of nodes. The nodes adjacent to a section or node failure are responsible for the protection switching action. Protection is shared at the Multiplex Section level by dividing the capacity of the SDH frames in half for service and protection channels [9].

The communication protocol restricts the number of nodes to 16 in a ring in the MS-SPRing mechanisms.

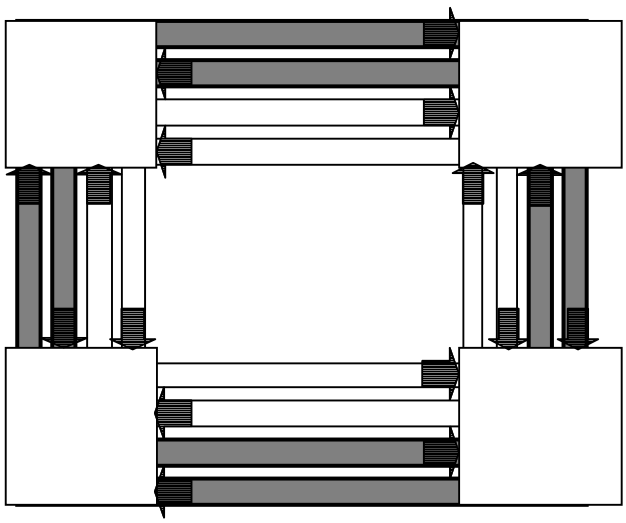
There are two types of MS-SPRing; 2-fiber and 4-fiber rings that are shown in Fig. 2.13, Fig. 2.14 respectively.



: Working Channels

: Protection Channels

Figure 2.13 Two-fiber MS-SPRing



: Working Channels

: Protection Channels

Figure 2.14 Four-fiber MS-SPRing

2-fiber MS-SPRing protection architecture uses half of the capacity of the ring for working traffic, and reserves the other half of the ring capacity for protection. This protection mechanism uses both of the fibers to carry working traffic, but half of the capacity on each fiber is reserved for protection purpose. 2-fiber rings with shared protection use ring switching for protection purposes.

4-fiber MS-SPRing uses two fibers for working traffic and reserves the other two fibers for hot stand-by in case of a failure. A 4-fiber MS-SPRing has two types of protection mechanisms, span switching and ring switching. 4-fiber rings enable the protection mechanisms of either ring or span switching, but not both of them simultaneously.

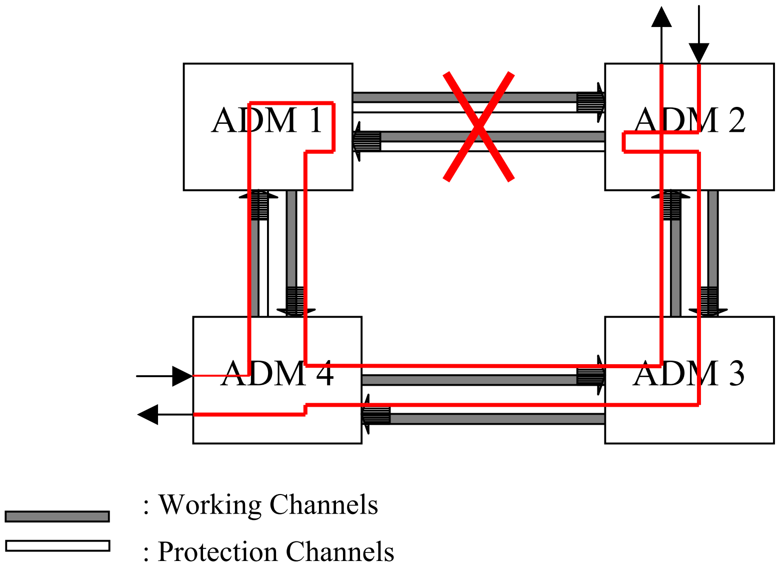


Figure 2.15 Two-fiber MS-SPRing Protection under link failure condition

An example of MS-SPRing protection with two fibers against a single link failure is given in Figure 2.15. In normal conditions, both channels of the demand 2-4 travel through 2-1-4. When a failure occurs on the fiber between node 1 and node 2, the adjacent ADMs to the failure node 1 and node 2 are responsible for protection switching. In the case of the failure condition, the traffic is looped back to the channels dedicated for protection as illustrated in the Fig.2.15. Since MS-SPRing Protection architecture is used, the half of the capacity is reserved to handle failures.

In span switching, if an optical fiber cut occurs on a working fiber, the responsible nodes adjacent to the failed link try to send the traffic to the dedicated protection channels in the same direction around the ring. Thus, the traffic is routed onto the protection fiber between the two end nodes of the failed link**.** If both working and protection channels breakdown at the same time, the ADM nodes loop the traffic to the reverse direction around the ring on the reserved protection fibers. Thus, ring switching is the mechanisms that reroute the traffic along the other part of the ring using the protection fibers available in the other direction of the ring in case of a link or node failure.

Although most of the deployed networks use 2-fiber MS-SPRing protection mechanism, some carriers have deployed 4-fiber rings. 4-fiber MS-SPRing can handle more than one failure in the network. However, management of 4-fiber ring is more complicated than 2-fiber MS-SPRing because multiple protection mechanisms must be coordinated.

In SNCP ring protection architecture, every demand is duplicated at the origin node and routed to both ways around the ring, in which a main path along one side of the ring and a dedicated backup path along the other side of the ring as seen in Fig. 2.16. In the case of a failure, the receiving node selects the protection path through switching establishing 1:1 selection.

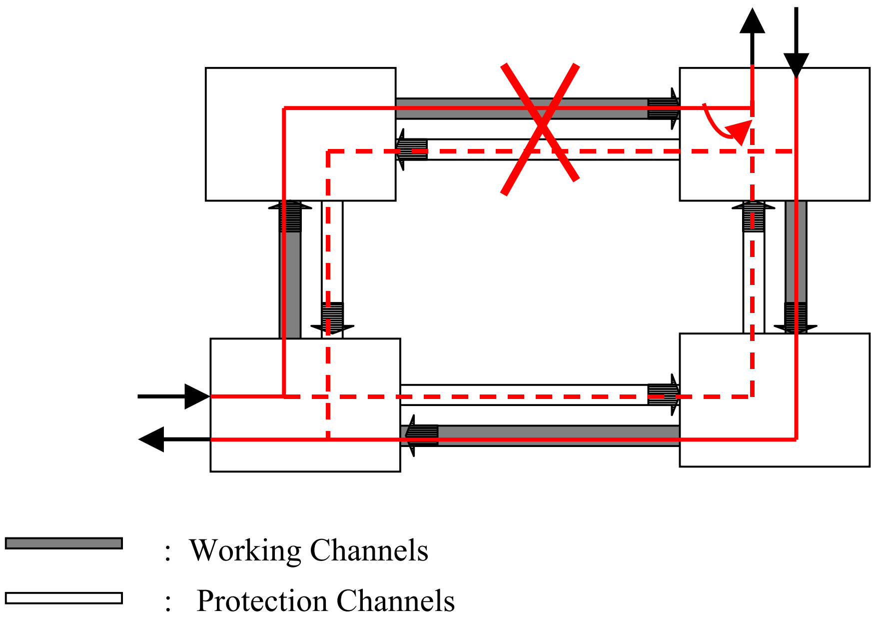


Figure 2.16 SNCP Protection under link failure condition

In MS-SPRing, the bandwidth is bounded with the largest sum of traffic routed over any span, also reserving 100% extra capacity for protection; whereas in SNCP, the ring bandwidth must be at least the sum of all traffic demands in the ring.

If the traffic is more evenly distributed around the ring, MS-SPRing is more capacity efficient than SNCP rings. Furthermore, it is possible to transmit extra low-priority traffic on the protection capacity, whereas this is not supported in SNCP rings since the protection capacity is used for the protection switching operation. The extra traffic transmission possibility is only available on protection channels under normal conditions, in case of a failure the low-priority traffic is not considered and will be preempted. There is no limit on the number of nodes in a SNCP ring, and SNCP rings are easy to implement because of their simple protection mechanisms.

2 or 4-fibre MS-SPRing has some advantages over SNCP rings whenever traffic sources and destinations are more evenly distributed around the ring. Furthermore, although it is possible to support extra low-priority traffic on the protection capacity of MS-Spring architecture, it is not possible in a SNCP ring network since the protection capacity is always used for the protection switching operation.

2.4 SDH Ring Design Problem

In the previous sections, we have presented several network architectures and protection types. The importance of survivability and the layered structures also have been discussed. In this section we present the problem of SDH ring design and of embedding the logical rings onto the physical topology.

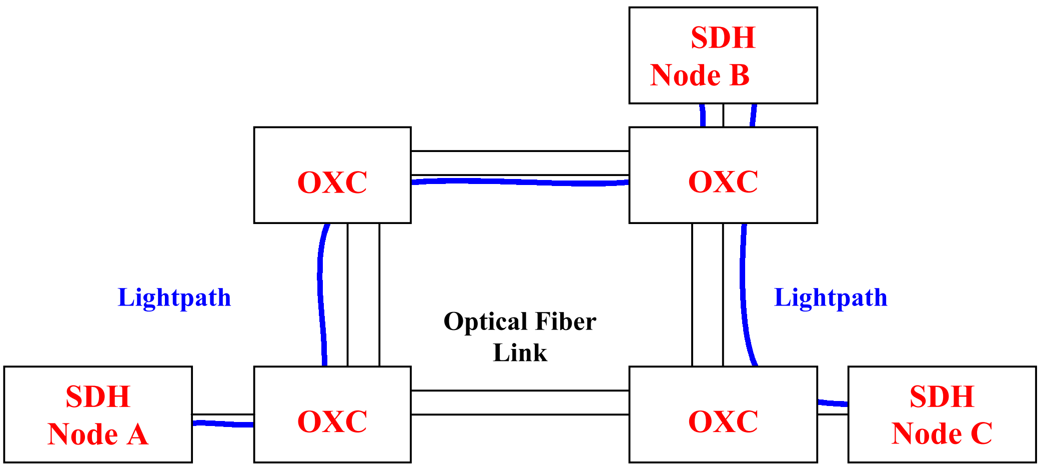
As we have discussed the layered architecture, there are several layered network structures. Survivability may be implemented in different layers. In our work, we have the mesh physical topology with some ADM nodes over this physical topology. The demand between ADM pairs are also given. SDH ring design problem solves the following sub-problems:

- Selection of SDH rings to be deployed in the multi-ring architecture, which is overlaid over the mesh physical topology.
- Routing of demand over the multi-ring network.
- Embedding of SDH rings over the mesh physical topology.

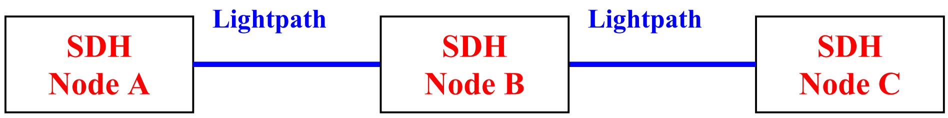
We use SDH ring protection for resilience. We have discussed the advantages of ring networks for protection. A ring provides two diverse paths between any two nodes and the protection mechanisms work well for any single failure. The survivability in other layers and multi-layer survivability is not included in this thesis.

The problem we deal with is connecting the given ADM nodes with rings satisfying the given traffic demands. We decouple the problem into two sub-problems. The first one is the logical (SDH) ring design. The problem is how to select the SDH rings to be deployed. The second problem is mapping of these selected rings onto the physical topology.

In section 2.2, the layered structure was discussed. In our problem, we can divide our network into two: *logical* and *physical* topologies. The physical topology is the network topology seen by the optical layer. The nodes in this topology correspond to the optical cross-connects (WSXCs or WIXCs), and two nodes are connected by a link if the OXCs are connected by an optical fiber link. The logical or virtual topology is the network topology seen by the higher SDH layer. The nodes in this topology are the nodes of the higher layer, ADMs or DXCs, and a link corresponds to a lightpath established between two SDH nodes. The SDH layer is responsible for routing and multiplexing the connections over the links in the logical topology. This structure can be seen in Figure 2.17.



(a)



(b)

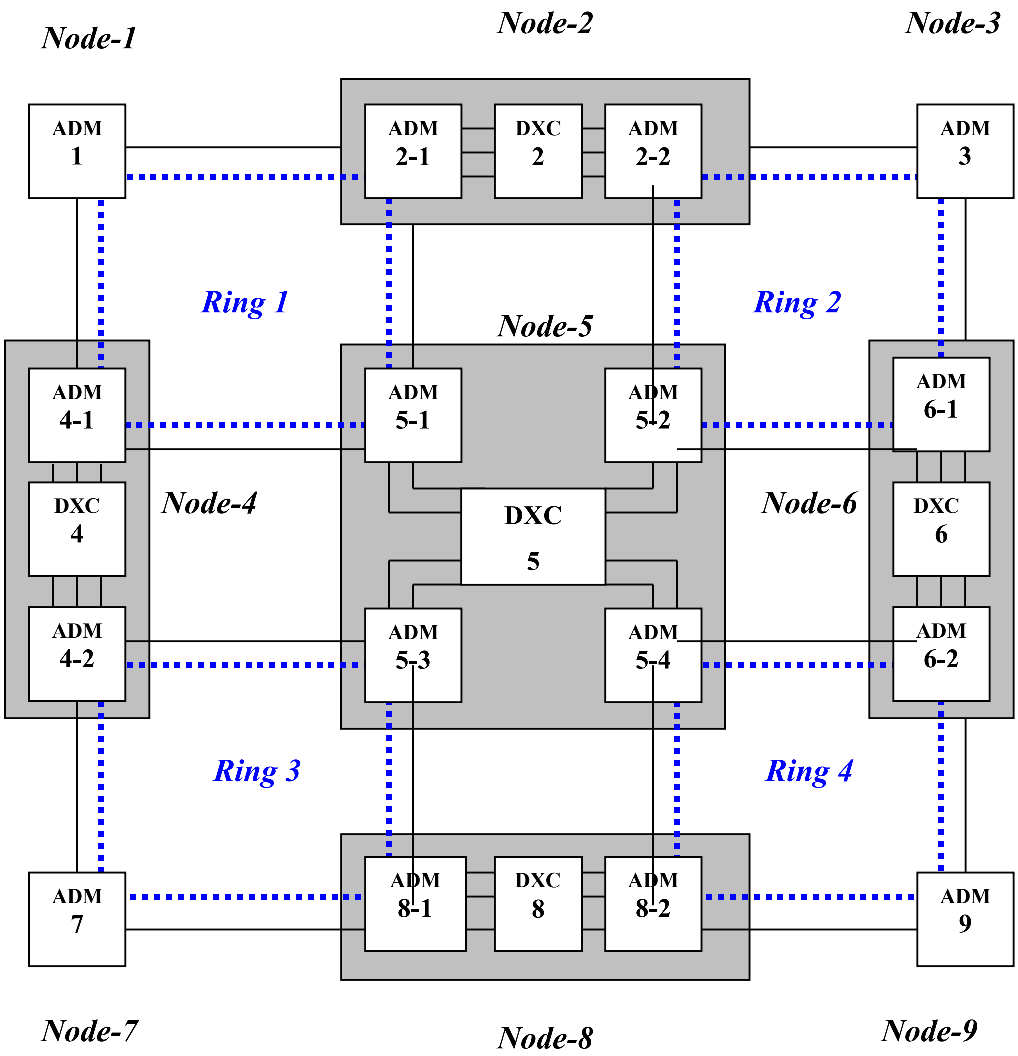
Figure 2.17 Physical and logical topologies for a SDH network over the DWDM layer
(a) The physical topology (b) The logical topology

We are given the nodes in the logical network and the traffic between different SDH node pairs. The physical topology, which has a mesh structure, is also given. Given these inputs, we determine the topology of the logical network, routing of the traffic over this topology and mapping of this logical topology onto the physical layer. This problem is known to be a hard problem and there are several heuristic design algorithms in the literature about designing the logical network and embedding into the physical topology. A survey of previous works on the design will be discussed in Section 2.5.

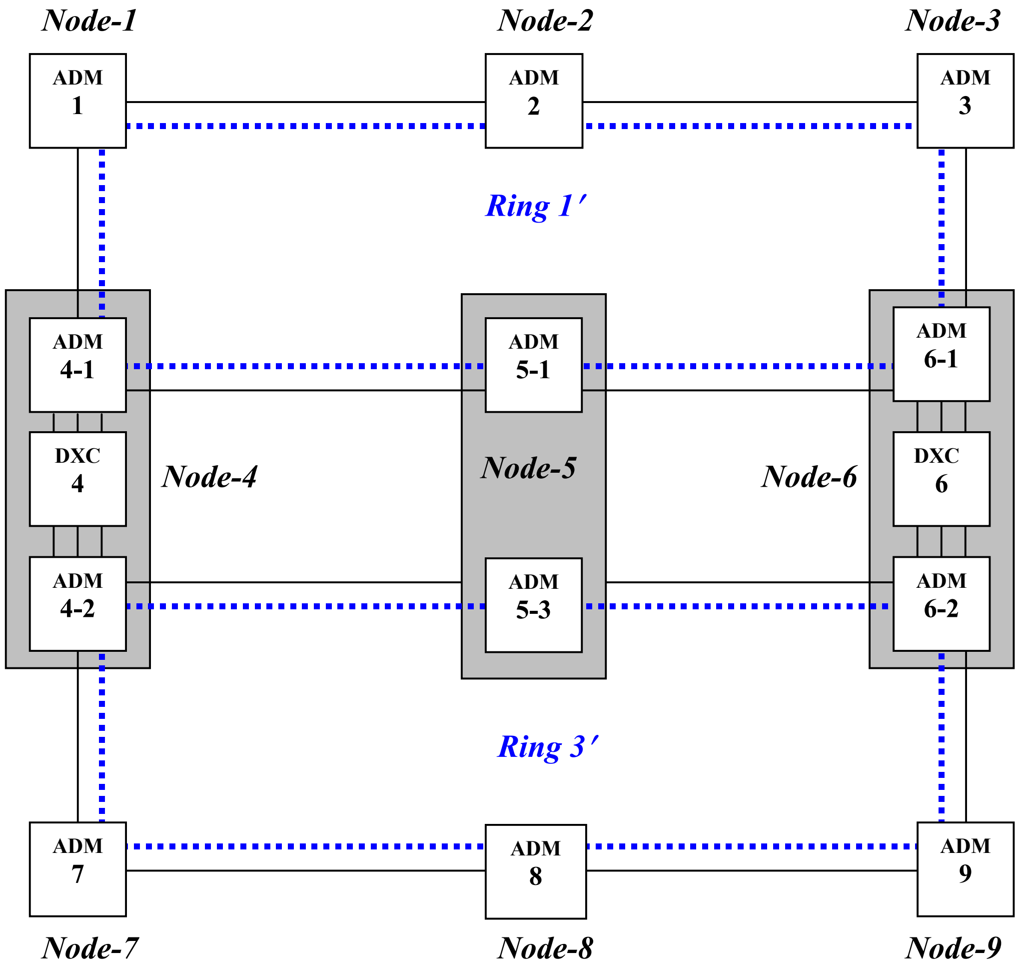
In general, the logical topology design problem is the problem of satisfying the traffic demand requirements and minimizing the cost while ensuring the protection level against single link or node failures. We assume that there is enough capacity in the physical network for carrying given demand pairs.

When selecting the SDH rings, we try to minimize the inter-ring traffic. Inter-ring traffic is the amount of the traffic between two demand nodes belonging to different rings. Inter-ring traffic requires high cost cross-connect equipments and increase the overall cost and also the complexity of the network. Digital Cross-Connects are the major components in the SDH infrastructure and they are used to manage all the transmission facilities in the central office. DXCs are used to interconnect the SDH rings, and they may also incorporate ADM functions. To provide the connectivity between rings, DXCs are connected to ADMs. DXCs automatically cross-connect the traffic ports between different ADMs belonging different rings. They can handle a large number of ports. The bigger DXCs with more cross-connect port capabilities result in higher costs. If DXCs do not exist, the inter-ring traffic has to be cross-connected by manual patching in a patch panel.

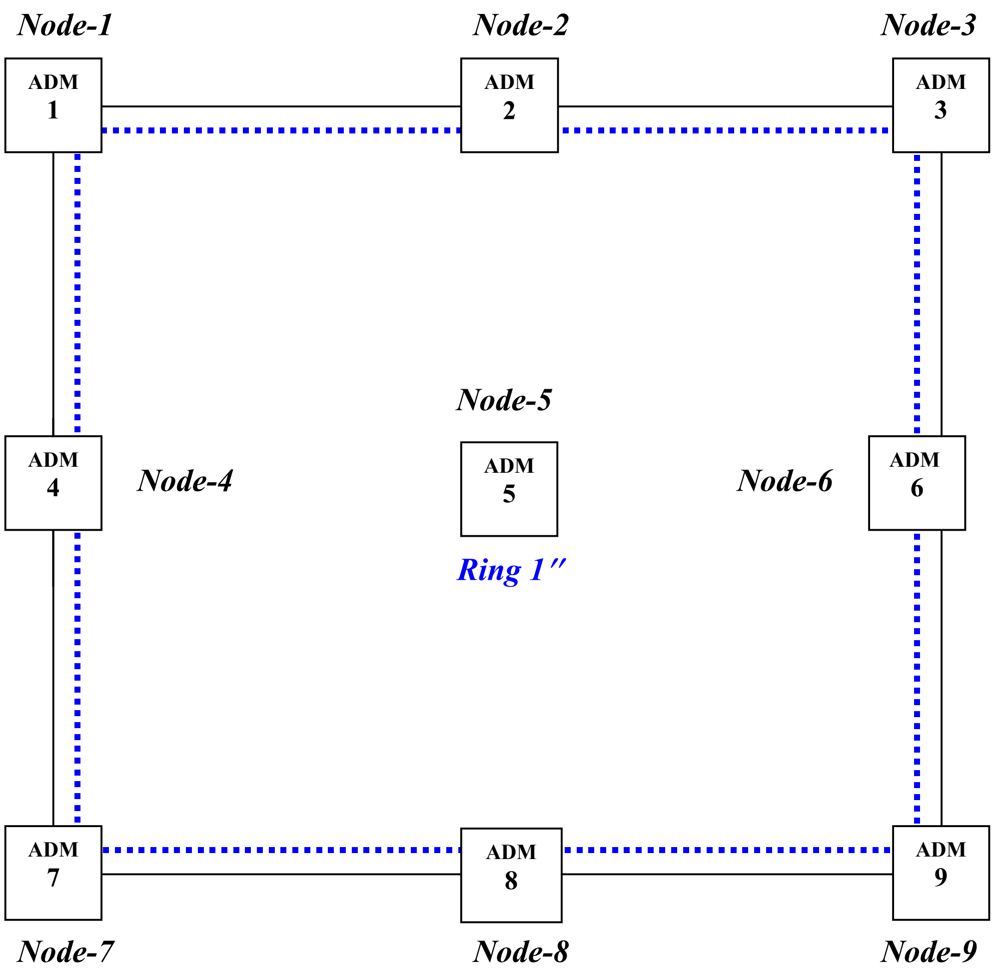
When determining the SDH rings, the networks must satisfy two constraints. First, each ring should satisfy 2-connectivity, i.e. there should exist two physically diverse paths between any two nodes on the ring. Second, the number of nodes on each ring should not exceed a maximum node number. Examples of ring selection are illustrated in Figure 2.18.



(a) SDH network with 4 rings



(b) SDH network with 2 rings

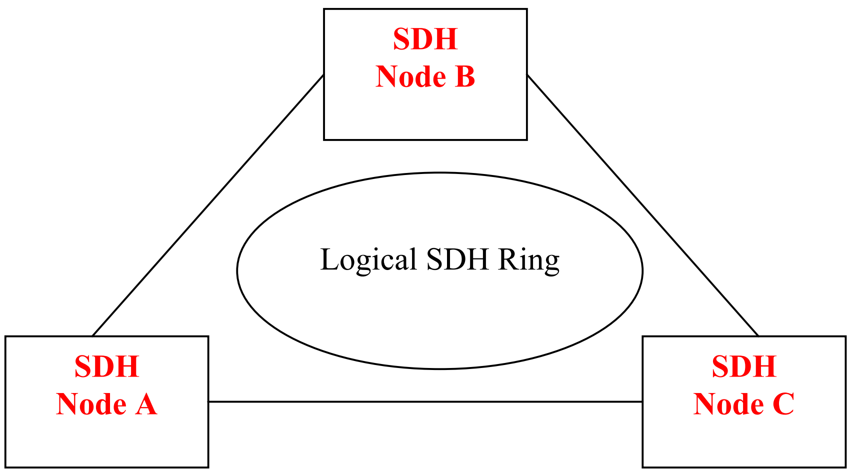


(c) Unwanted situation, Node-5 is disconnected

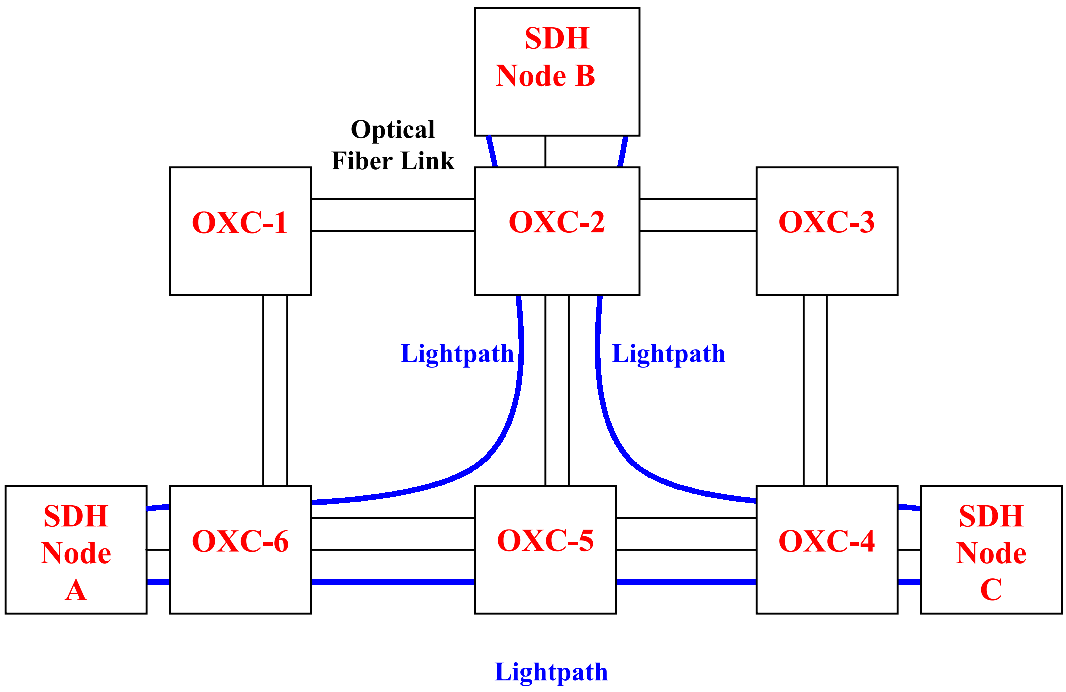
Figure 2.18 The SDH ring structures and face merges.

This example summarizes the ring design steps. Figure 2.18 (a) illustrates the network with four SDH rings. The inter-ring traffic is large and at each hub node DXCs are used to interconnect SDH rings. To provide the connectivity between rings, DXCs with different sizes are connected to ADMs according to the amount of inter-ring traffic. While a smaller DXC is deployed at nodes 1,2,3 and 4 that interconnect two SDH rings each, a DXC with greater cross-connect capability is deployed at node 5, which interconnects rings 1, 2, 3 and 4. In order to reduce the network cost, we try to decrease the inter-ring traffic, so the cost of DXCs. In Figure 2.18 (b), ring 1 and ring 2 as well as ring 3 and ring 4 are merged. Thus, there are two new rings, ring 1′ and ring 3′. In this architecture, node 1 and node 4 have no longer any digital cross-connect equipment because these nodes belong to only one ring. Also, in node 5, smaller DXC is needed since the inter-ring traffic is smaller. If two new rings in Figure 2.18 (b) are tried to be merged, node 5 will no longer be connected to other nodes in the network and the traffic demands of this node cannot be routed. Thus, this merging step is not allowed and ring 1″ is not feasible. The 2-connectivity condition guarantees 100% restoration against any single failure within the network. The second constraint is the node constraint. The total number of nodes on a ring is upper bounded. This constraint is mainly due to technological limitations in optical transmission.

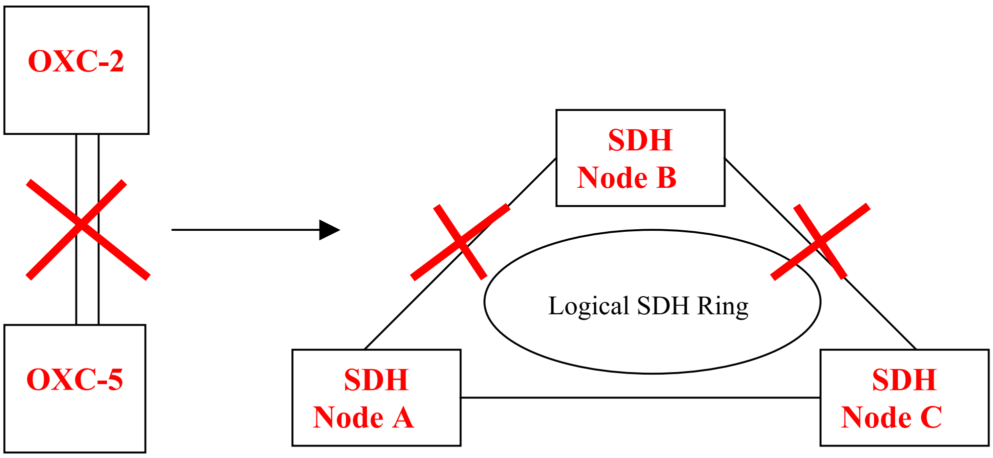
Once SDH rings are determined, the second problem is the deployment of selected rings onto the physical topology. For this mapping, we need to ensure the survivability while minimizing the network. As we have discussed before, different layers have their own protection mechanisms, however in our work we assume that only SDH layer protection is used. An SDH ring provides the survivability in case of one node or link failure, but one physical link or node failure may result multiple simultaneous failures in logical layer if there are multiple logical links sharing this physical link. To solve this problem, all SDH links belonging to one ring have to be mapped onto link and node disjoint lightpaths in the physical topology.



(a)



(b)



(c)

Figure 2.19 An example of mapping a logical ring onto physical topology
(The logical links of ring are mapped onto <u>not</u> physical link disjoint paths)

An example of embedding a logical SDH ring onto a physical topology is illustrated in Figure 2.19. Figure 2.19 (a) shows a logical SDH ring with three nodes. In Figure 2.19 (b), this ring is mapped onto the physical topology. The two logical links between A-B and B-C belonging to the same SDH ring are mapped onto the same physical link between OXC-2 and OXC-5. In this case, the failure of the link between OXC-2 and OXC-5 results in two simultaneous failures on the ring. As illustrated in Figure 2.19 (c), two logical links are broken at the same time, and the ring protection mechanism does not work in this case. Therefore, each ring should be mapped onto physically disjoint links. The same is true for node sharing; the logical links should not pass through the same node more than once for any ring. Otherwise, multiple failures in logical layer may occur due a single node failure, and ring protection cannot restore the failed traffic.

2.5 Survey of Previous Work on SDH Ring Design

Since fiber optic cable has a great potential to carry large quantities of data over large distances, telecommunications networks utilize a SDH/SONET based infrastructure.

Optimality or cost effectivity is the crucial design parameter in telecommunications networks. There are a large number of network designs for this complex, multi-faced problem.

The other important criterion for the design problem is network survivability. Thus, the design algorithm must be capable of generating survivable and cost effective networks. Ring or multi-ring architectures are generally preferred since they offer high network survivability in case of a failure and considered as cost effective.

Although the functional operation of a single ring for restoration is simple, the design of fully restorable networks employing multiple rings is an extremely complex optimization problem.

Also, the network ring design problem is a complex problem since it consists of several parts to achieve an optimum solution. The main parts of network ring design are link capacity assignment, routing and ring determination. The problem consists of sub-problems such as determining the number of rings, the number of nodes in each ring and the interconnection among rings. These problems are generally solved with heuristic methods leading to locally optimal design solutions.

There exist several criteria to determine the objective of the ring design problem. In this section some of the studies on this problem will be discussed.

In the traditional mesh transport networks, determining which of the possible SONET/SDH rings will be built is the main problem. The objectives can be minimizing the cost, minimizing the number of rings, minimizing the inter-ring traffic or other approaches.

There are several approaches on ring design, some of them are SDH/SONET ring design, and others are optical ring design. In the design algorithms, there exist several network types: single SDH-layered networks, single WDM-layered networks, and SDH over WDM transport networks. We summarize the ring design approaches as follows:

An approach of a Genetic Algorithm to the cost-effective network ring design problem is presented in [10], that the Genetic Algorithm representation encapsulates all aspects of the problem and solves them simultaneously. Genetic Algorithms work with a population of solutions and have shown themselves to be efficient at searching large problem spaces and have been successfully used in a number of engineering problem areas, including telecommunications network design. Optimal network ring design is divided into three main parts: routing of all traffic in the network, link capacity assignment and determination of multi-ring topology of the network. In the ring design, the traffic is routed using Dijkstra shortest path algorithm and link loadings are computed to determine link bandwidths and costs. The objective of [10] is to minimize the overall cost of the network while determining the routes used by all traffic in the network, the link capacities and the multi-ring topology of the network. The cost term includes the link lengths, link bandwidths and also a term dependent upon the multi-ring topology of the network.

The ring design problem is described as the SONET Ring Assignment Problem (SRAP) in [11]. In mathematical formulation, the objective is to minimize the number of rings such that the constraints limit the total demand on a ring and force that every site is placed on exactly one ring and connect the rings with a federal ring. There is also another alternative as k-SRAP that minimizes the traffic on the federal ring which is an effective approach but more time-consuming. Same as in [10], it is chosen to single out the objective of minimizing the number of rings to minimize the Digital Cross Connects costs.

The self-healing ring network design problem is also studied and described several planning problems of survivability [12]. A formulation of the design of a network composed of multiple interconnected unidirectional Self-Healing Rings is given. The objective is again to minimize the sum of ADM and inter-ring traffic costs.

SONET ring design, called the Minimum Coverage Connected Rings (MCCR) problem is represented in [13]. The objective is to select the least expensive set of self-healing rings such that given traffic demands are all covered. This problem is formulated and solved using Integer Programming (IP) techniques.

Since the network ring design problem is known to be NP-hard, a lot of heuristic approaches have been developed to obtain an approximate solution. In recent years, many metaheuristics such as genetic algorithms, simulated annealing, tabu search have been used for solving a wide range of combinatorial optimization problems in network design. A survey of these algorithms can be found in [14].

A tabu search algorithm for self-healing ring network design has been proposed in [15]. The tabu search algorithm is based upon a general iterative search method. The tabu search method generally uses neighborhood search strategies to search for better solutions using memory list of history of the recently searched processes for avoiding cycling.

A design of hybrid ring-mesh network in survivable communication network is discussed in [16]. The problem is to assign each given traffic demand to rings and mesh network. In this assignment problem, the objective is to minimize the cost of ADM and DCS equipments using a tabu search solution. But, the algorithm does not generate a node-disjoint topology, which prohibits its usage against node failures.

Designing ring networks for metropolitan area networks are discussed in [17]. This work focuses on designing a feasible ring with an objective of maximizing the sum of all revenues excluding the construction costs for metropolitan area networks. Various heuristics are applied and a metaheuristic is determined as giving the best results concerning solution quality.

The ring identification and routing in the logical network are investigated in [18]. To provide the necessary transport capacity for a given traffic pattern, an optimized algorithm is presented to embed a mesh of rings network onto an arbitrary network topology. The objective is minimizing the network cost while also minimizing the inter-ring distance cost. Three-layer graph model and simulated annealing is used to optimize the ring configuration in the design process. The general aim is to minimize the ring configuration and the routing on the virtual network with respect to the given objective function so that all traffic demands are fulfilled under the constraints, e.g. the capacity per link. The first and lower layer, called the ring configuration layer, consists of the real fiber links and real node topology. The second layer, called virtual network layer, defines the connection allocation resulted from the lower layer rings. At this layer, the nodes belonging to more than one ring are represented with multiple virtual copies, and an efficient logical topology routing is realized. The ring connection layer is the third layer defining the connections among the actual rings. In this representation, every ring is drawn as a node and the edges are constructed between rings if there is a network node belonging to both rings. The routing between rings is computed using this architecture.

The summaries of ring design approaches above are all about SDH ring network design. SDH over WDM network design and optical ring design approaches are summarized as follows:

The cost of laying a new fiber is very high, and DWDM has an advantage because it offers customers a less expensive way to expand capacity. The usage of DWDM in metropolitan area networks is discussed in [19]. Metro optical networking is introduced using optical ADMs (OADMs). Higher transport efficiencies are achieved by eliminating high-speed TDMs, and reducing the cost of fiber in the network. Optical protection architectures, especially self-healing optical rings and 1+1 protections are introduced.

The multi-ring optical network design problem is discussed in [8]. The problem is described as designing minimum-cost transport networks using path-protection and shared-protection optical rings. Three integer-programming formulations are proposed, and their features for the multi-ring network design are discussed. They indicated that these approaches could provide useful solutions to a difficult optimization problem.

SDH-over-WDM network design involving survivability requirement, ring selection, traffic routing, and overlay ring optimization in order to recover from network failures are described in [20]. Two key issues are represented for designing. One of them is the appropriate choice of survivability strategy; the other is the dimensioning of the network. Three types of survivability architecture are discussed: inter-connected protection rings, end-to-end path protection and restoration. Since restoration has slower restoration time, it is not considered. Two types of ring protection strategies are considered: MS-SPRings and SNCP rings. The MS-SPRings are shown to be less cost-effective than using SNCP rings in an interconnected ring network. Therefore, in GTS's transport network, SNCP rings are selected. Some design concepts for IP-over-WDM networks are provided as well.

In transport networks, there are two main problems for different transmission architectures with an objective of minimizing the total network cost. In the first one, the architecture of the transport network is known and the problem is integrating the new technology, such as DWDM, into the existing SDH infrastructure. The second problem is designing and dimensioning of SDH rings and mapping these logical rings onto the existing physical DWDM topology. In both problems, the aim is to obtain a cost effective network. We focus on the second problem in this thesis.

In the first problem, the integration of WDM technologies into the existing SDH/SONET transport network, there are several approaches. A heuristic technique based on simulated annealing was used to optimally design the physical layer in [21]. SDH design, WDM optical layer design, physical layer design, and global optimization problems are discussed. The main objective is again minimizing the network equipment and infrastructure requirements based on the requested protection level. In this design process, two sub-problems exist. First one is to create an ideal topology for designing the SDH/SONET layer, based on the network infrastructure cost and offered traffic. In the second problem, sets of nodes are grouped to form rings with respect to traffic demands. After the rings are identified, the demands are routed over the rings.

We work on another problem in this thesis: mapping the logical SDH rings onto the existing physical DWDM topology. There are also some design approaches in the literature dealing with this problem.

With lower layer network usage, like WDM, the failure of a single link or node may cause the simultaneous failure of several traffic channels, making impossible to reroute the failed traffic in higher layers, such as SDH. The “design protection” is represented in [22] of which aims at making such failure propagations impossible. Protection inside WDM networks, performed at physical and design levels is discussed. The Disjoint Alternate Path (DAP) algorithm is presented to maximize the protection.

2.6 Summary of Proposed SDH Ring Design Algorithm

In the previous section, previous work on SDH ring design and related design approaches are described. The complexity of network design is considered with several parts of the design process in order to achieve an optimum solution.

In this thesis we assume that the transport network architecture is composed of two layers. The lower order physical layer contains the fiber topology and WDM nodes. The higher order logical layer comprises multiple SDH rings. In this layer a path exists between all demand pairs, and these rings are mapped onto the physical topology.

Our work consists of two parts: first one is to determine the SDH rings to satisfy the given traffic demands ensuring the survivability, and the second part is to map these rings onto physical topology with an objective of minimizing the network cost.

The first sub-problem aims to minimize the inter-ring traffic since the inter-ring traffic can be routed by digital cross-connects, which increases the cost substantially. There are two constraints, one limiting the ring size and second ensuring the connectivity.

The second sub-problem is to map the logical rings onto the physical topology. In this approach, the logical links of one ring must be mapped onto disjoint paths over the physical topology. Otherwise, the protection mechanism of SDH rings does not work properly in case of a single failure.

To address these two problems, we have divided the solution into two parts. First part is the logical ring design. In the design algorithm, first we obtain a logical topology interconnecting the closest SDH nodes such that the logical graph is planar. Once the logical graph is obtained, we construct rings using the *faces* of the planar graph. To minimize the inter-ring traffic, each route passes through minimum number of rings. After all traffic demands are routed, faces are started to be merged such that in the resulting topology inter-ring traffic is decreased. Faces are merged until there exists no feasible ring merging that satisfies 2-connectivity and maximum ring size constraints.

The solution for the first sub-problem can be summarized as follows:

1. Obtaining the logical graph: In this part, the problem is to connect geographically close SDH nodes to each other. The logical graph is obtained such that it is planar.
2. Finding the faces: To find the rings we use faces of the planar logical graph as a starting solution. After faces are fixed, traffic is routed using a shortest path algorithm.
3. Face merges: In the process of ring selection, the objective is minimizing the network cost. Minimizing the inter-ring traffic reduces the digital cross-connect costs, which in turn reduces the overall network cost. Thus, we try to merge faces under the connectivity and ring size constraints with an objective of minimizing the number of rings and the resulting inter-ring traffic.

After all feasible face-mergings are completed, the SDH rings are obtained. Next part of the solution is to deploy these rings onto disjoint physical paths. We formulate the problem as an integer linear program (ILP). Our objective is to minimize the total network cost such that the traffic is routed over physically link and node disjoint paths.

In the remaining part of this section we summarize other approaches for SDH ring design in the literature and compare with the design process proposed in this thesis. The self-healing ring design problem is considered to protect the transmission of demands in a network in [15]. A modeling approach taking into account ring interactions is proposed, and a tabu-search-heuristic algorithm is presented. Multiple SHR network design problems dealing with networks in which nodes can be connected to more than one ring are considered and the traffic is routed over SHRs such that the inter-ring traffic is minimized. In the design, each node may be connected to several rings and the resulting SHRs are only logical structures since it is not guaranteed that a feasible cycle connecting the nodes of the ring exists.

A tabu search algorithm is proposed for this problem, which based on simple moves such as adding or removing a single node from a ring. They start with a ring and fill the residual capacity of that ring without inter-ring traffic. However, to provide some free capacity in anticipation of the inter-ring traffic, the flow on a ring is limited to a proportion of its nominal capacity. After the rings are determined and demand nodes are assigned to the rings, the second sub-problem performs the routing of the resulting inter-ring traffic verifying the maximum ring capacity constraint. Indeed, once the ADM connections are chosen, the problem reduces to a minimum cost multi-commodity flow problem on the auxiliary graph.

This design process does not have a step merging rings in order to minimize the inter-ring traffic. Instead the rings are pre-determined. Furthermore, mapping of these rings over the physical layer such that full protection is guaranteed under all single failures is not considered.

In the SONET Ring Assignment Problem (SRAP) approach presented in [11], an ILP formulation, which has an objective of minimizing the number of rings, is given. The constraints limit the total demand on a ring to a bandwidth and limit the capacity of a federal ring, which connects all rings together. This special ring carries all the traffic between sites on different rings. There is also an alternative solution: instead of minimizing the number of rings the traffic on the federal ring is minimized.

In our design algorithm, there is no assumption of a federal ring, and we minimize the inter-ring traffic. To minimize the number of rings can result in a similar solution since there is smaller amount of inter-ring traffic in a network with larger rings.

After logical ring design is completed, the second important issue is the mapping of these rings onto the physical topology. The failure of a single optical link or node in a WDM network may cause multiple simultaneous failures in the higher level. These multiple failures may prevent restoring of services in the higher level if the layers are not properly designed. This phenomenon is called “failure propagation” in [23]. There are two solutions for avoiding failure propagation. First one is to make failures invisible to higher-layer links. This assumes that the lower layer has its own protection mechanism. In the case of SDH over WDM, lower level network, based on WDM has to duplicate resources. This method effectively keeps layers independent and has the advantage of simplifying design and operation. Alternatively, higher-layer links can be mapped onto several disjoint paths. Methods of the second type are joint network design or routing at both the higher and lower layer networks. In this case, the topology of the lower layer is taken into account by the design of higher-layer end-to-end paths. These methods are impractical since they require SDH management software to use all details of the WDM layer.

In our approach, the designs of two layers are decoupled from each other in order to reduce network design and management complexity. We assume that all protection functionality is fulfilled in the SDH layer, and SDH links are routed over physically diverse lightpaths in the WDM layer.

Chapter 3

SDH RING DESIGN PROBLEM

In this chapter we present the problem of selecting the SDH rings to be deployed over the physical topology. We are given the physical topology, locations of SDH ADM nodes and traffic demands between these nodes. The problem is to map this traffic onto physical topology in order to obtain a logical topology comprising multiple rings interconnecting SDH nodes.

The logical topology is the network topology seen by the higher SDH layer. The higher layer SDH network is also called the logical or virtual topology. The nodes in the logical topology are the nodes of the higher layer, ADMs or DXCs, and a logical link corresponds to a lightpath established between two SDH nodes. The SDH layer is responsible for routing and multiplexing the connections over the links in the logical topology.

An example of SDH over DWDM topology consisting of OXCs at the lower layer, ADMs and DXCs at the higher layer is seen in Figure 3.1. The logical topology is indicated by dashed lines and physical topology is indicated by straight lines.

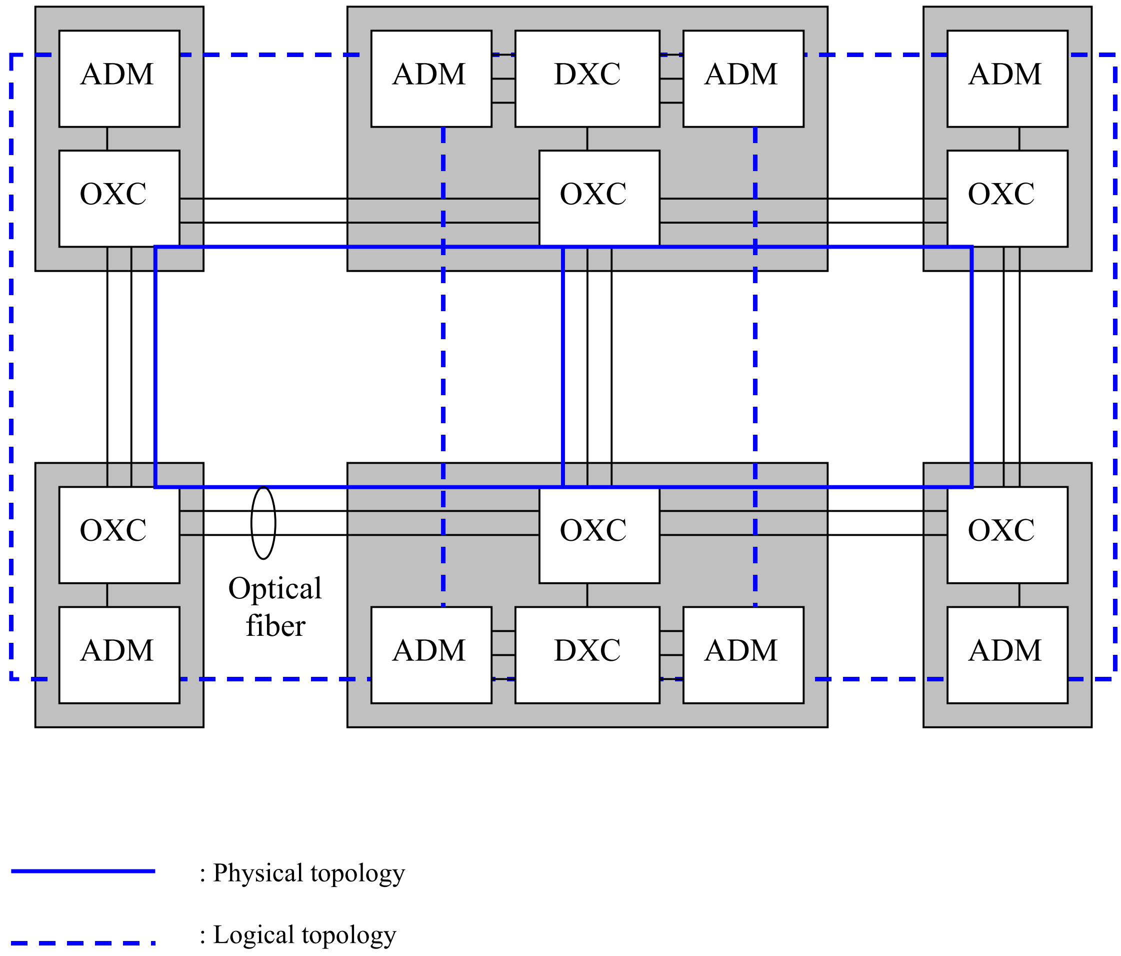


Figure 3.1 A SDH network over the optical (DWDM) layer

Our main objective is to minimize the inter-ring traffic, which is the set of demands between two SDH nodes belonging to different rings. Inter-ring traffic requires high cost cross-connect equipments and increase the overall cost and also the complexity of the network as shown by the example in Figure 3.2. In this example, there are five seperate SDH rings in the network. This situation requires DXC equipments at the interconnection nodes of network for carrying the inter-ring traffic between nodes belonging to different rings. Network management becomes more complex when there are several DXCs at the intermediate nodes between rings.

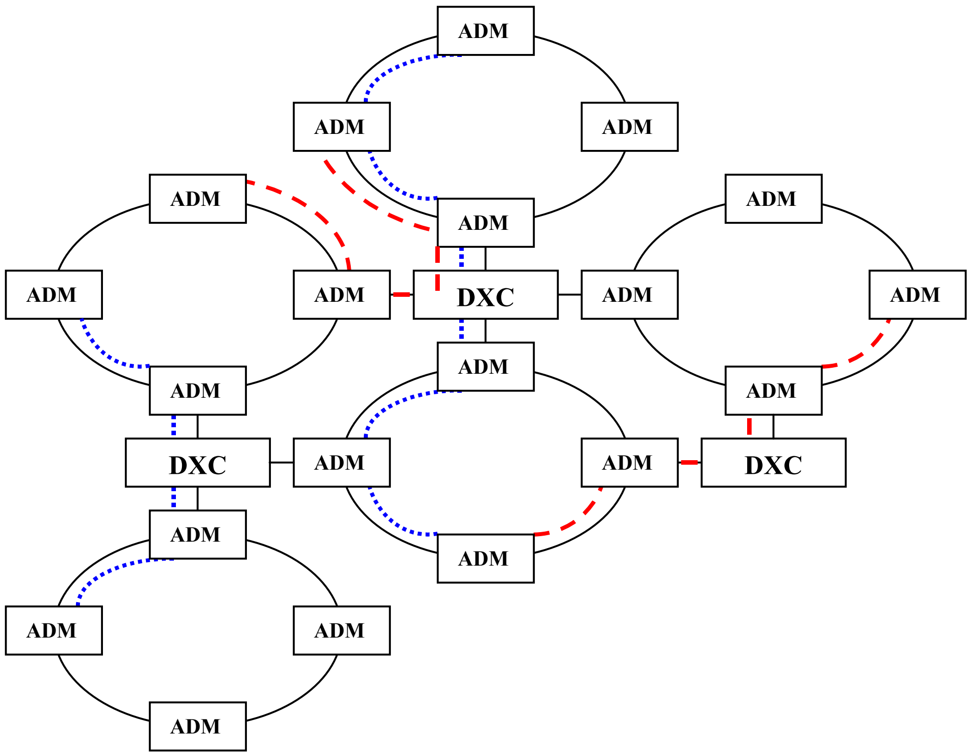


Figure 3.2 A multi-ring SDH topology with several inter-ring traffic

3.1 Logical Topology

As we have discussed in previous sections, the network can be represented by two layers. Higher layer is the SDH logical layer with multi-ring SDH topology and the lower layer is the physical layer composed of physical links with fiber optic cables and nodes with DWDM optical cross-connects. The physical topology is represented by a mesh network. ADMs are located at some of these nodes and traffic demands between these ADM nodes are also given.

First, we want to determine which SDH nodes can be connected to each other using lightpaths. The idea we use is to connect the ADM nodes with others starting from the closest ADMs. The first step is to find the constrained shortest paths between all ADMs in the physical topology such that there are no other ADMs between two SDH nodes. If there exists such a path, these two ADMs are connected in the logical topology with a link. The weight of the link is equal to the number of hops on the path connecting the two ADMs in the physical topology. If there is no such path, a link is not placed between these ADMs in the logical topology.

Once the logical topology is obtained, we find a maximal sub-graph of the logical graph such that this graph is planar and no other edge in the logical topology can be added. A planar graph is a graph that its edges do not intersect except their common end vertices [24]. It means that there exists an ADM node at the junction point of two links. The reason that we require a planar logical graph is that we use *faces* of a planar graph in order to construct rings.

In order to obtain the planar logical graph, we first sort all links in the logical topology in an ascending order. Starting from the shortest link in the list, we try to include each link in the logical topology such that the graph is planar. We continue this procedure until all links are considered. The reason that shorter links are considered first is that closer SDH nodes are better candidates for placing on the same ring.

The planar logical graph corresponding to the physical topology in Figure 3.3 is shown in Figure 3.4. The link weights denote the number of hops on the path connecting two nodes in the physical topology. The links that hinder planarity are not included in the logical graph.

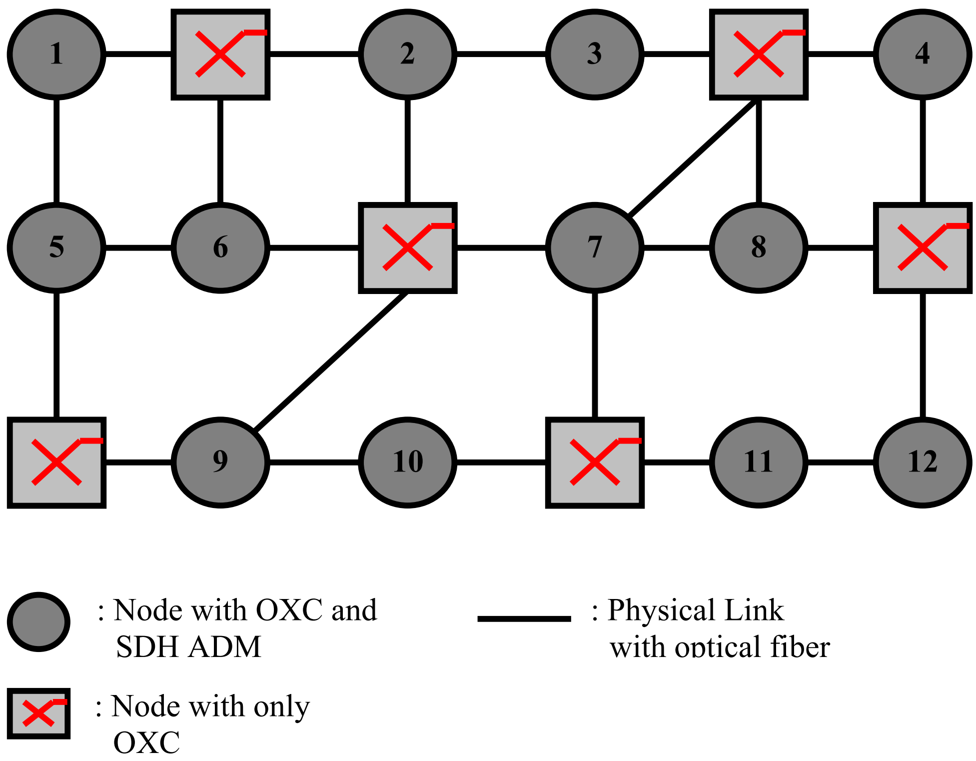


Figure 3.3 A physical topology with OXC and ADM nodes

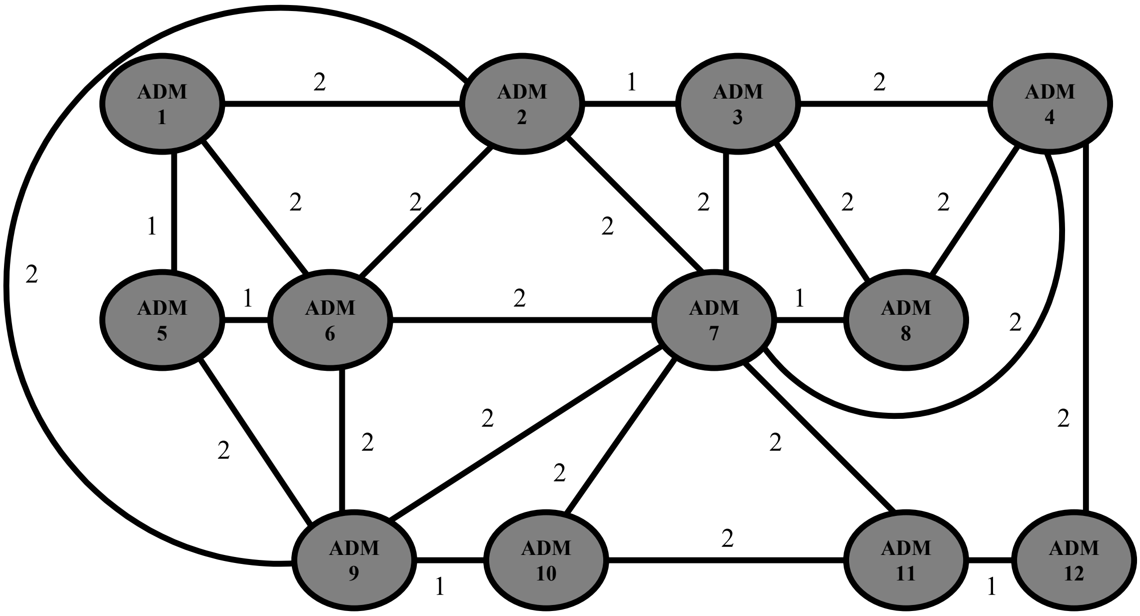


Figure 3.4 Planar logical graph with link weights

Next, we find the *faces* of the planar logical graph. A *face* is the cycle bounded by the edges of a planar graph that forms a ring. Every connected planar graph can be decomposed into faces. These faces are used as the basis for rings in the network. The greedy heuristic algorithm proposed in this thesis uses the faces of the logical graph as the starting solution. In Figure 3.5, the faces of a planar mesh network are shown.

In graph theory, there exist several algorithms for finding the faces of a planar graph [25]. To determine a face, starting from one node, the edges have to be followed by the clockwise or counter-clockwise direction. The procedure is followed until the first node is reached [18].

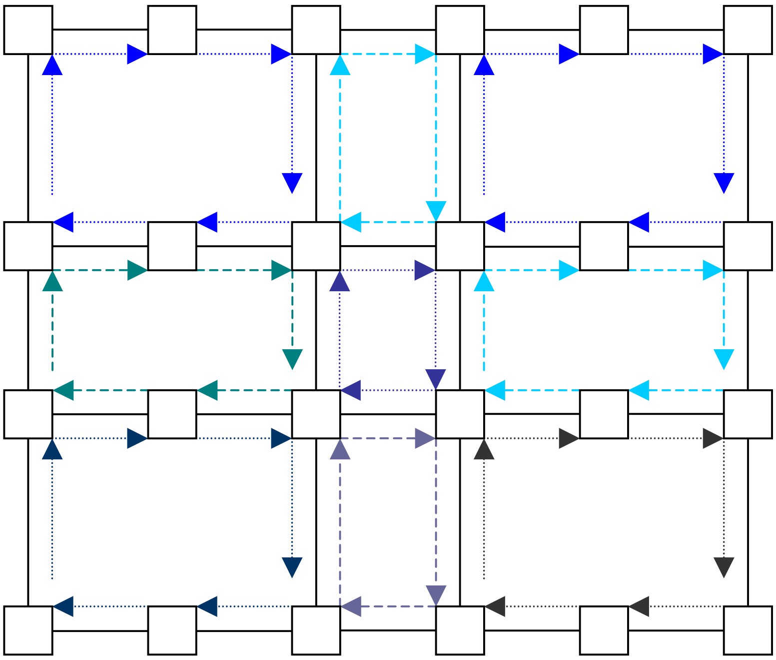


Figure 3.5 The constructed faces of a planar mesh network

The links belonging to a face should be 2-connected. The number of faces of a planar graph G=(V, E) is given by the Euler Formula [26],

$$|F|=|E|-|V|+2$$

where $|F|$ is the number of faces, $|E|$ is the number of edges and $|V|$ is the number of nodes in G.

3.2 Greedy Heuristic Algorithm for Ring Selection

The problem of multi-ring network design is a complex optimization problem to be solved. Heuristic span elimination strategies for reducing the topology were discussed for the ring coverage problem [27]. An important point is not selecting the wrong link to be eliminated. If this is done, inter-ring routing costs increase due to excessive increase in routing with respect to the shortest path. Our algorithm for ring merging is based on simple moves such as removing a single link from the multi-ring topology.

Inter-ring traffic includes all demands between nodes that belong to different rings. Since the cost of a ring depends heavily on the cost of digital cross-connects and the inter-ring traffic defines the size of DXCs, the objective in minimizing the inter-ring traffic is to reduce the cost of DXCs. To minimize the inter-ring traffic we merge adjacent rings using a face-merging algorithm. By removing the link shared by two adjacent faces, we combine two rings. Since there is a larger ring containing both rings, the inter-ring traffic between these two rings is eliminated.

3.2.1 Face Merging

Given the faces of the planar logical topology and the demands between SDH nodes, the first step in ring design algorithm is to fix the routing such that each route passes through minimum number of rings. The routing algorithm for achieving minimum inter-ring traffic can be described as follows:

For each s-d demand pair,

1. Calculate k-shortest paths between s and d.
2. For each path, find the path traversing minimum number of rings among the k-shortest path.

An example of starting point at route selection is shown in Figure 3.6.

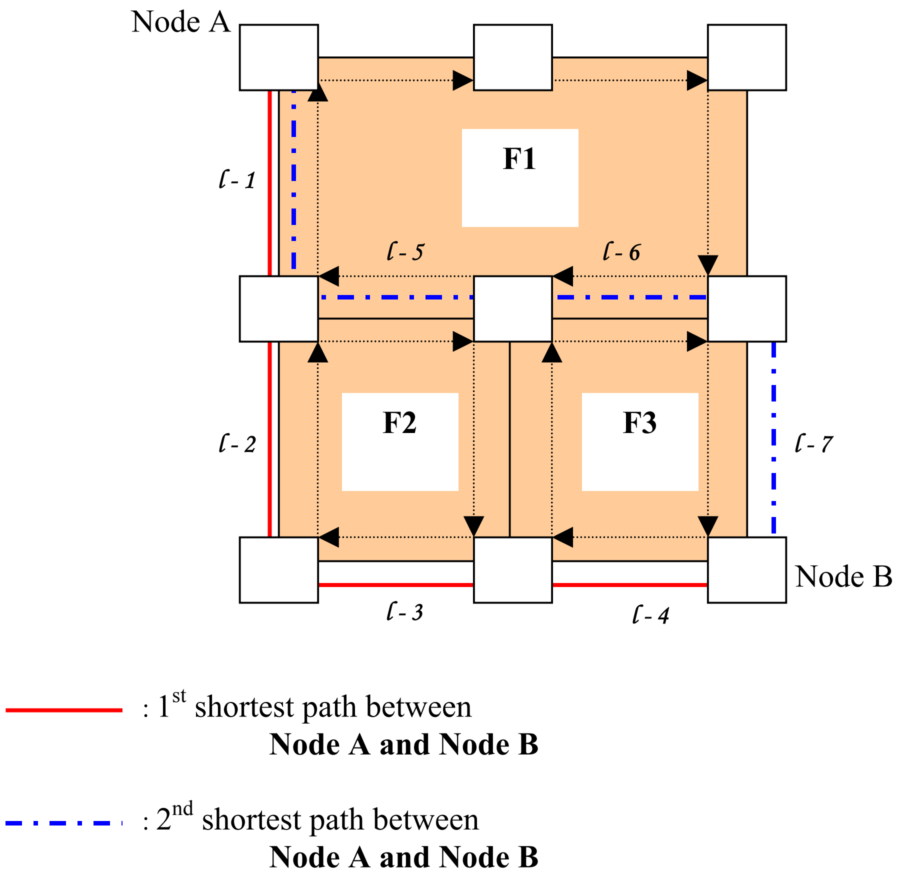


Figure 3.6 An example of routing in a multi-face topology

In the example, there is a network with three faces: F1, F2 and F3. Using k-shortest path algorithm, the 1st shortest path between Node A and Node B is found as $\ell - 1$, $\ell - 2$, $\ell - 3$, and $\ell - 4$. The 2nd shortest path is given by $\ell - 1$, $\ell - 5$, $\ell - 6$, and $\ell - 7$. Since the path traversing minimum number of rings is required between nodes A and B, we construct a trellis graph for finding the path with the minimum number of rings for both paths as shown in Figure 3.7 and Figure 3.8.

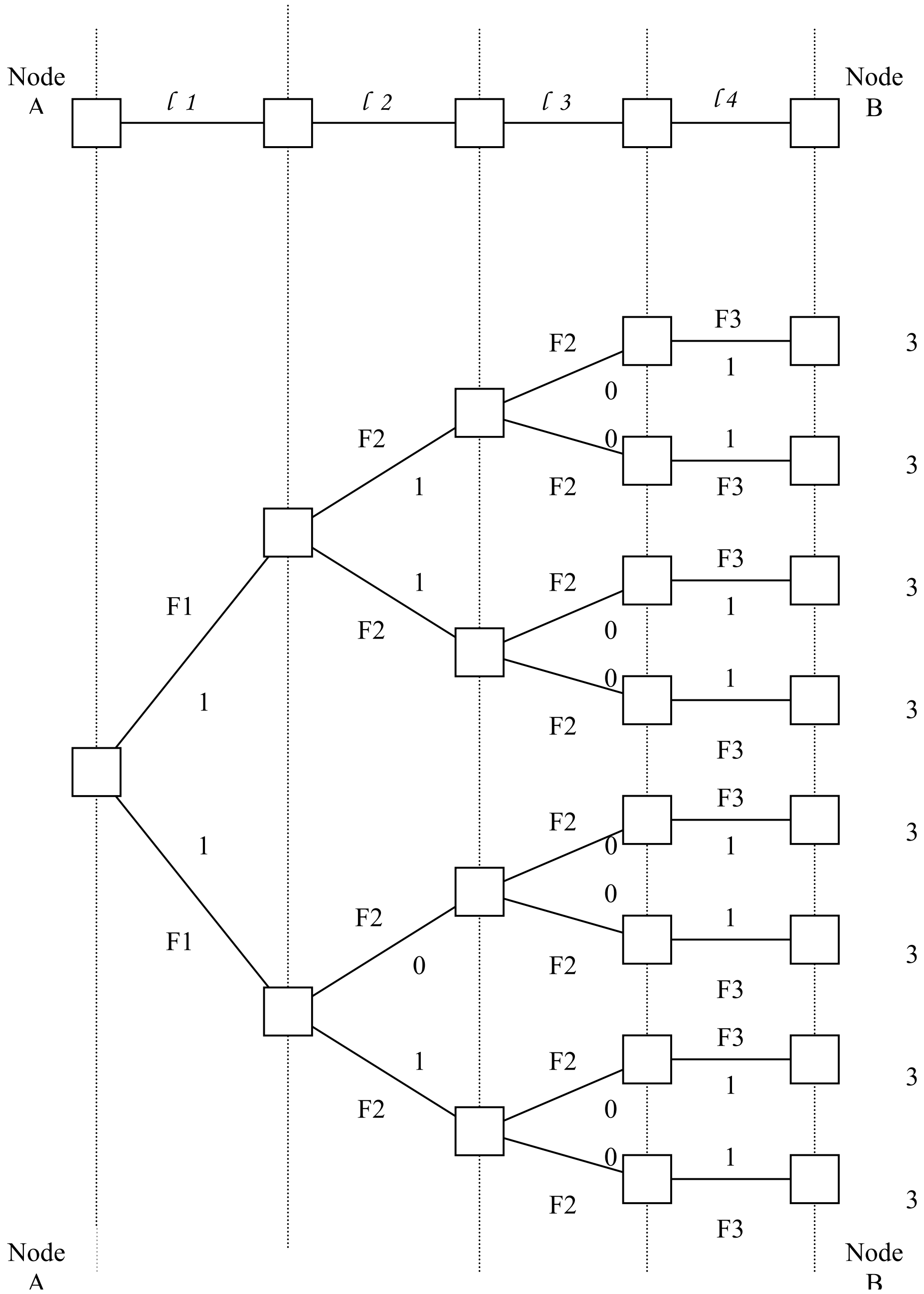


Figure 3.7 Minimum number of rings path for 1st shortest path

Since some links may belong to more than one face, we determine the routing which achieves minimum number of ring crossings.

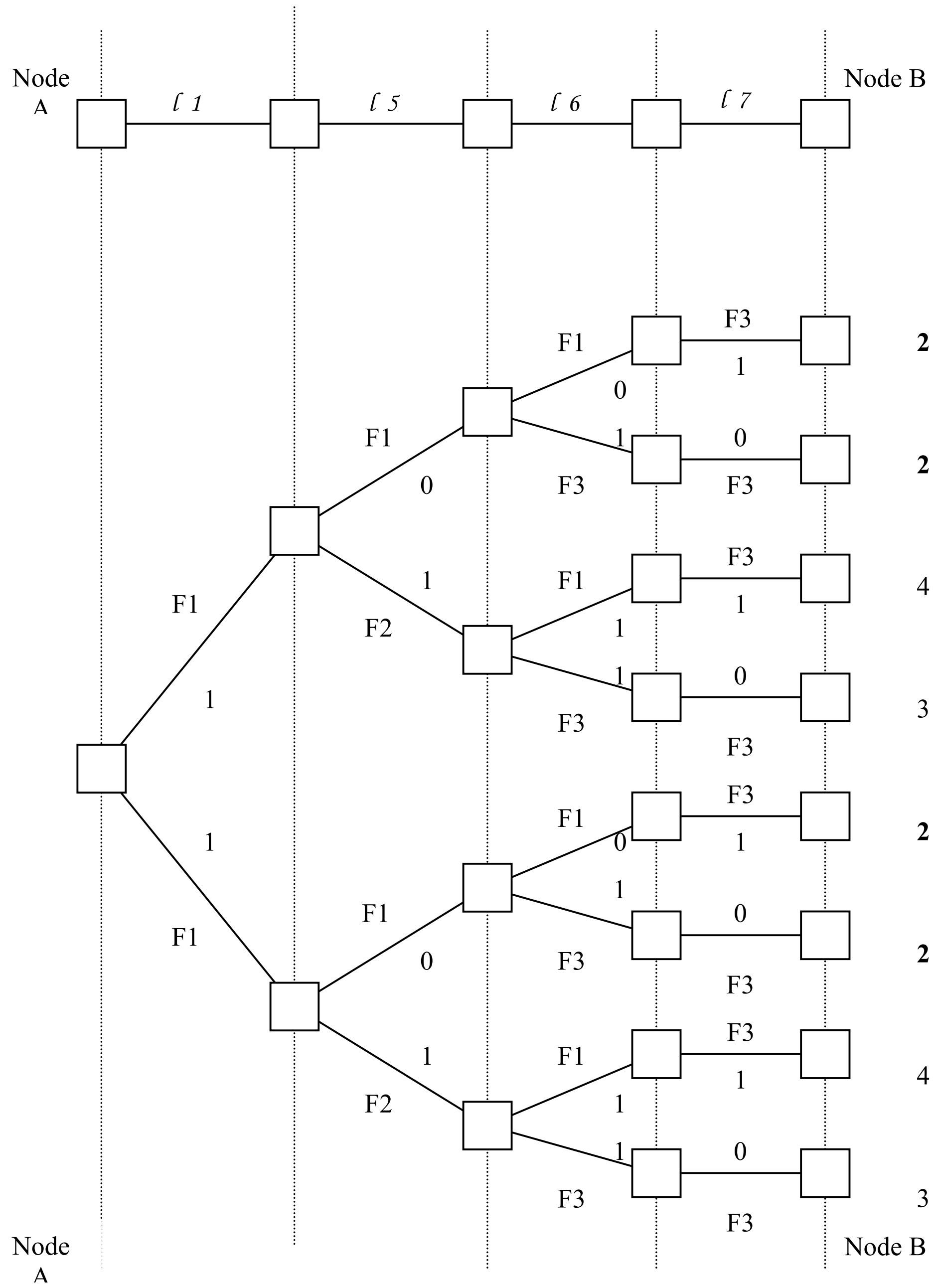
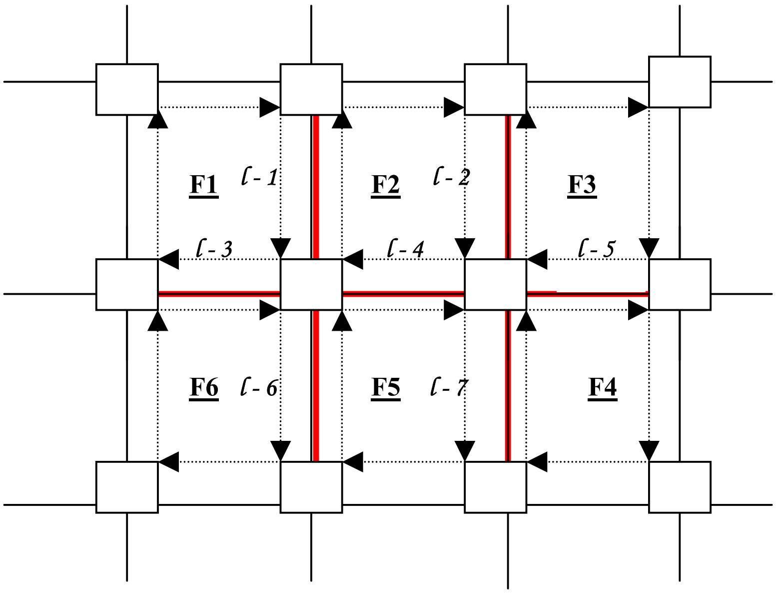


Figure 3.8 Minimum number of rings path for 2nd shortest path

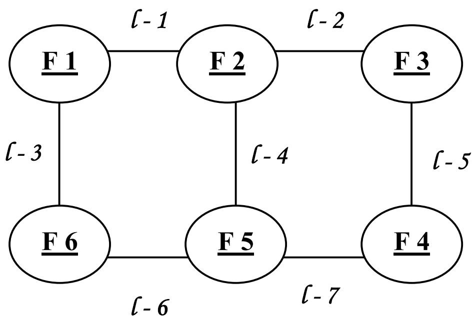
In this example, 2nd shortest path can be routed over two rings whereas routing of the 1st shortest path requires at least three rings. Thus, 2nd shortest path is selected as the path with the minimum the inter-ring traffic.

After the route for each demand is fixed for a given set of rings, we start to merge the rings in order to minimize the inter-ring traffic.

The face adjacency graph is obtained by assigning a node corresponding to each face and by connecting the faces that share a link in the logical topology with a link in the face adjacency graph. An example of a planar logical topology and the corresponding face adjacency graph is given in Figure 3.9.



(a)



(b)

Figure 3.9 An example of a network topology (a) A planar logical graph with faces (b) Face adjacency graph

After the all traffic demands are routed and the face adjacency graph is constructed, we start to merge adjacent faces. Face merging is combining two adjacent faces by eliminating the shared link.

In our greedy heuristic algorithm, we look all feasible face mergings, and choose two faces that give minimum inter-ring traffic as the rings to be merged. In the face-merging algorithm, there are two constraints that determine feasibility of each possible face merging. The first one is the node constraint. The number of nodes belonging to the new face after merging must be smaller than Nmax. If the network becomes too large, there may be inefficient routing in this network. The node size constraint is dictated by the limitations in the SDH technology. The second constraint is the 2-connectivity. Two faces can only be merged if the resulting graph satisfies 2-connectivity. Faces can be merged if they share at least and at most one link. If they share two links, they cannot be merged because the resulting graph may not be 2-connected as shown in the example given in Figure 3.10.

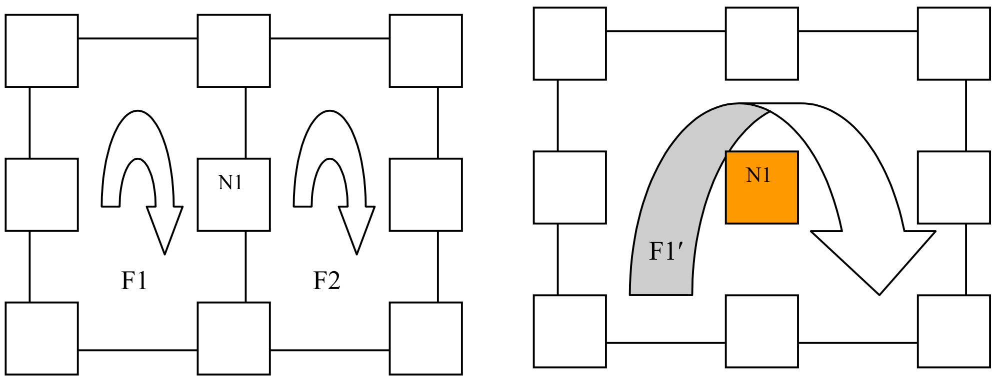


Figure 3.10 An example of disconnected graph after face merging

In this example, face 1 and face 2 are adjacent faces and shares two links. If we merge these two faces, the node N1 will be disconnected. In this case, it is not possible to transmit any traffic to or from N1. 2-connectivity is also a crucial constraint for protection purpose. If a network is 2-connected, there are at least two disjoint paths between any two nodes, and the network is resilient to any single failure.

We continue enlarging the faces until there exists no feasible face merging. After each face-merging step, the routing algorithm is used to fix the new paths and the face adjacency graph is updated accordingly.

3.3 Numerical Results

In this section, we present the design of logical (SDH) rings of a given network topology using the proposed heuristic algorithm. Our greedy heuristic algorithm is applied to three different network topologies. The topologies are given in Figures 3.11 - 3.13 respectively. The 32-node mesh topology is composed of optical cross-connects at all nodes and SDH ADMs and DXCs at 13-nodes for all three examples. The weights of the links in the network are the real distances between nodes. For the 13-node SDH logical network, 3 different node size constraints were used in the merging process. The heuristic algorithm is implemented on Microsoft Visual C++ 6.0.
The logical topologies obtained by the algorithm are shown in Figures 3.14 - 3.16.

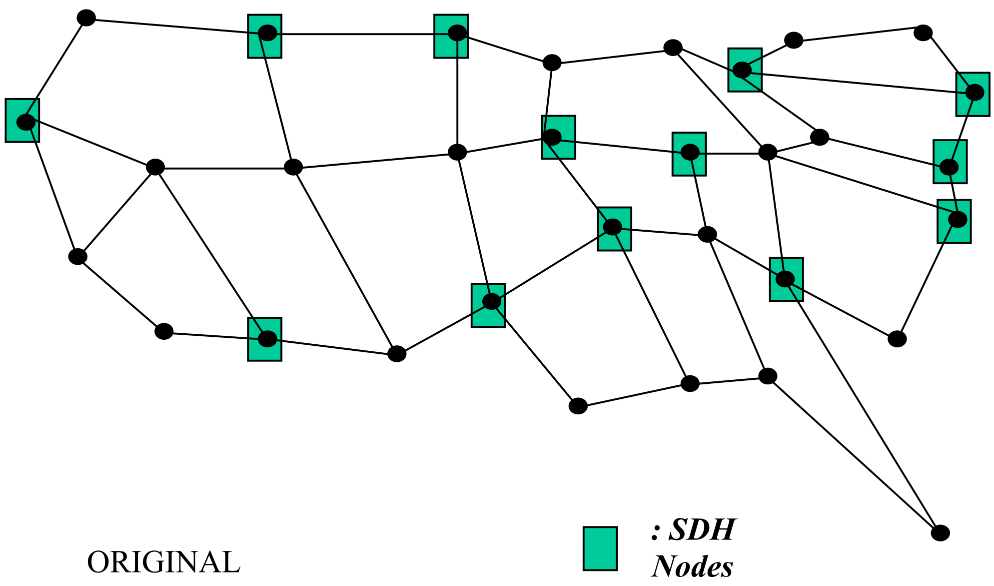


Figure 3.11 The first example: physical topology with 32-nodes

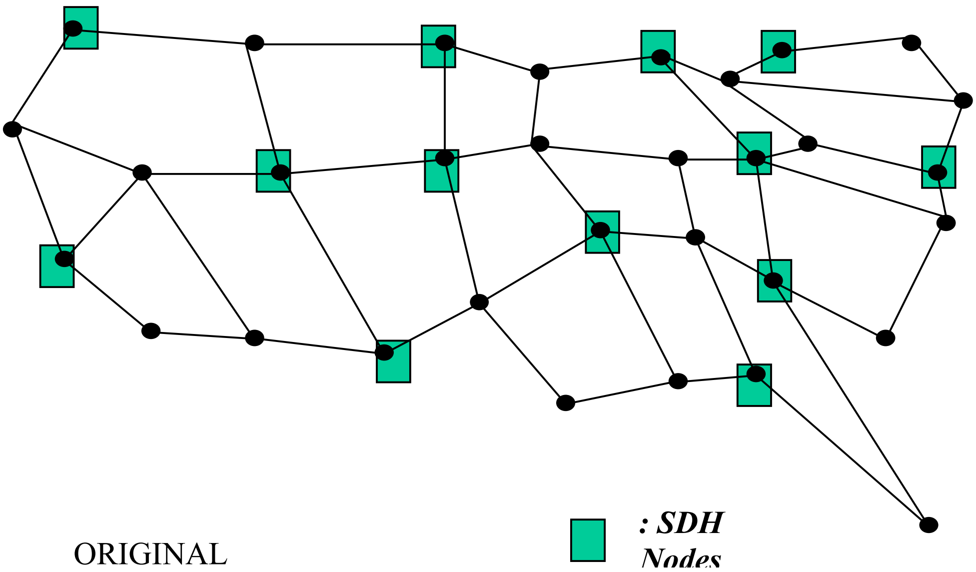


Figure 3.12 The second example: physical topology with 32-nodes

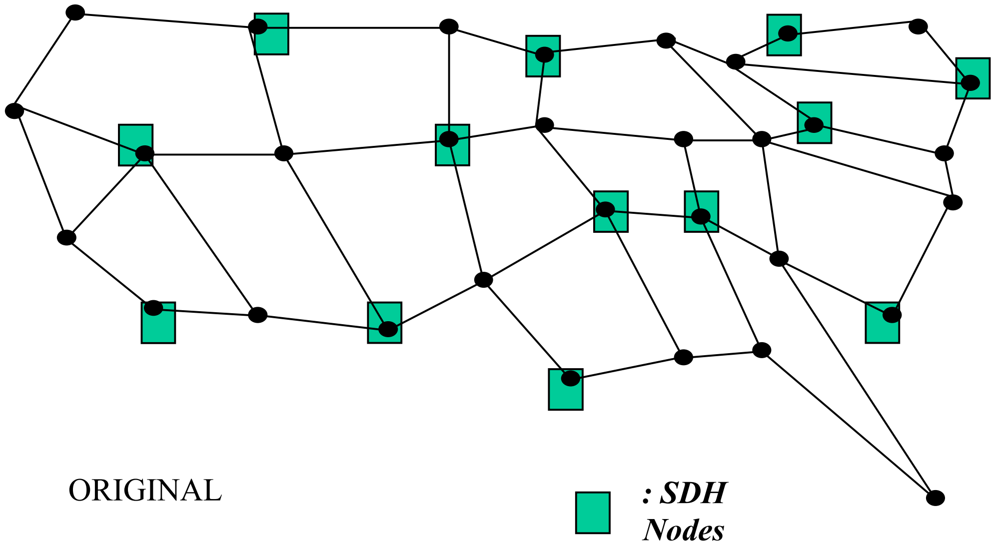
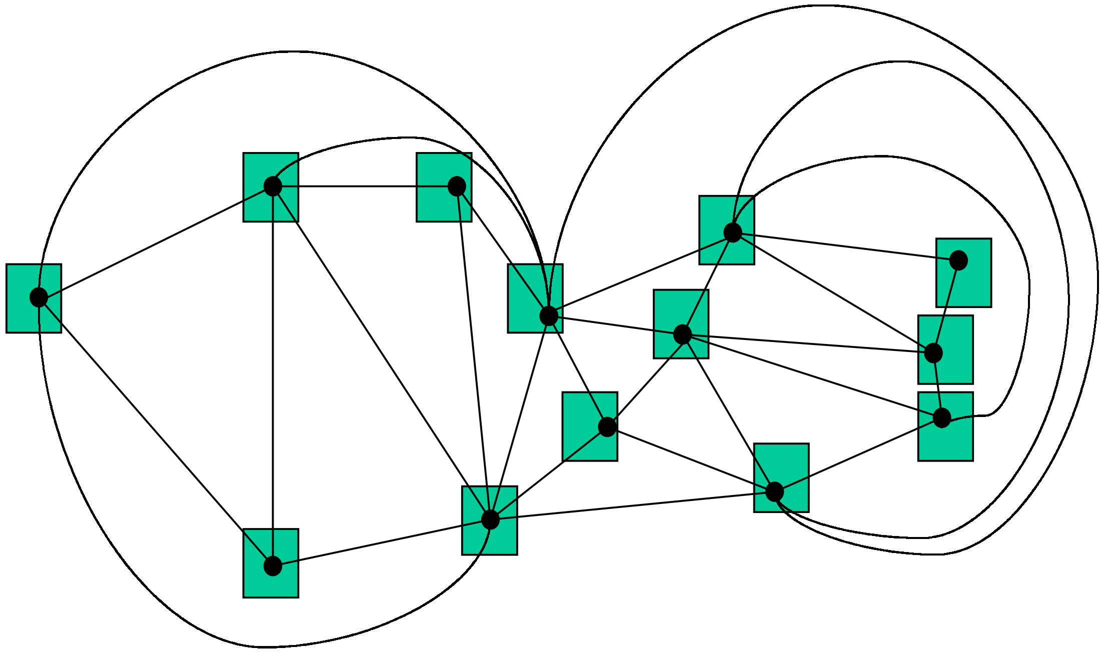
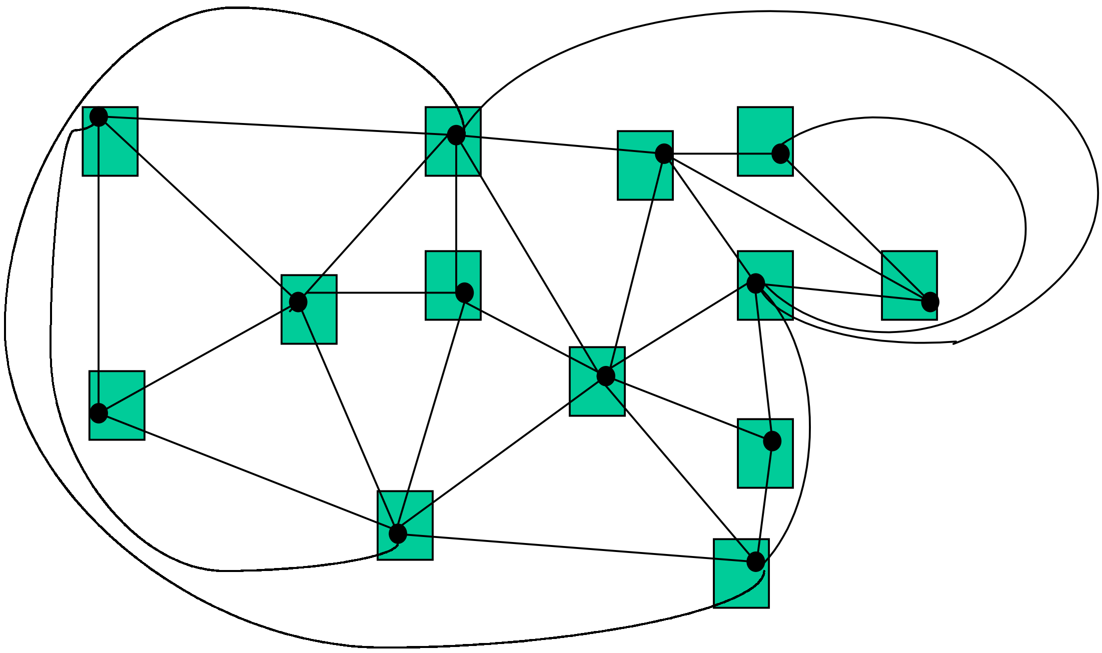


Figure 3.13 The third example: physical topology with 32-nodes



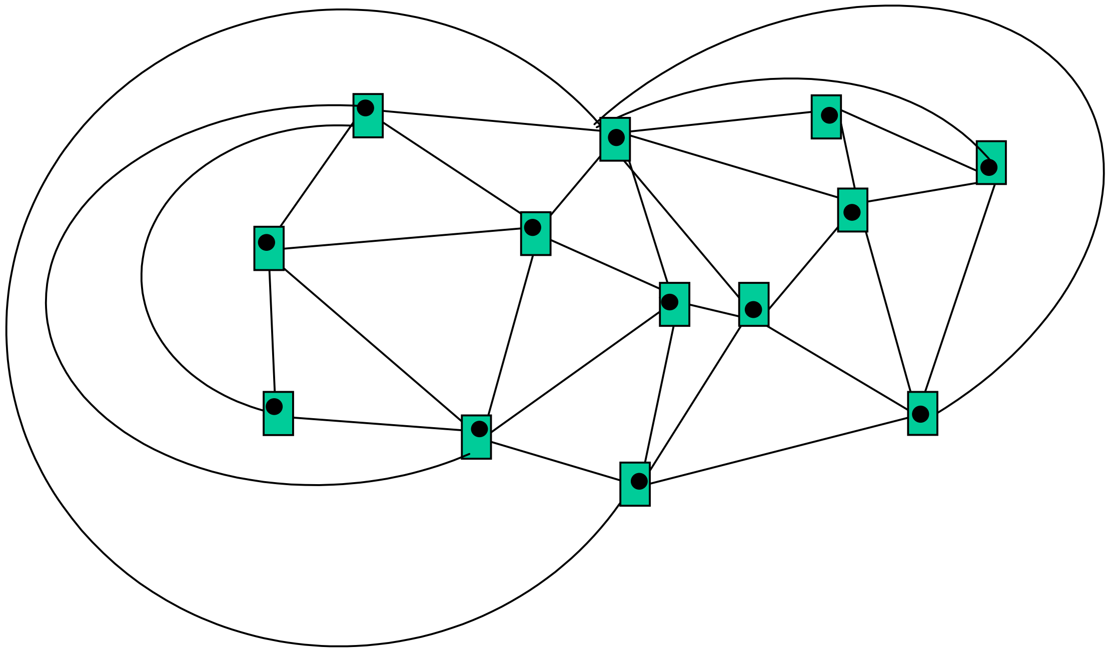
BEFORE MERGING

Figure 3.14 Logical Topology obtained for 13-nodes SDH network of the <u>first example</u>



BEFORE MERGING

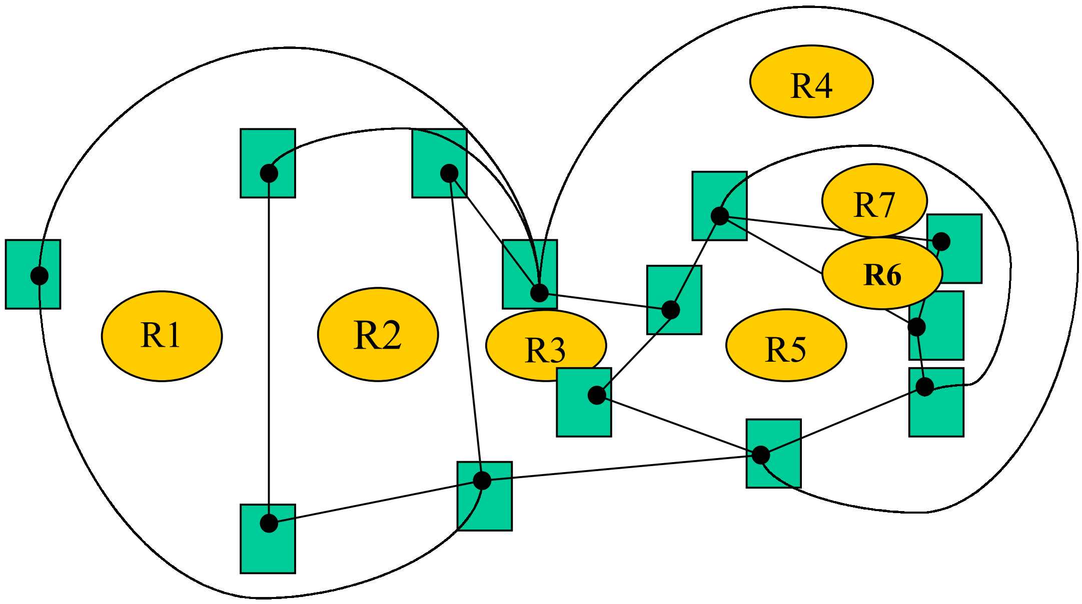
Figure 3.15 Logical Topology obtained for 13-nodes SDH network of the <u>second example</u>



BEFORE MERGING

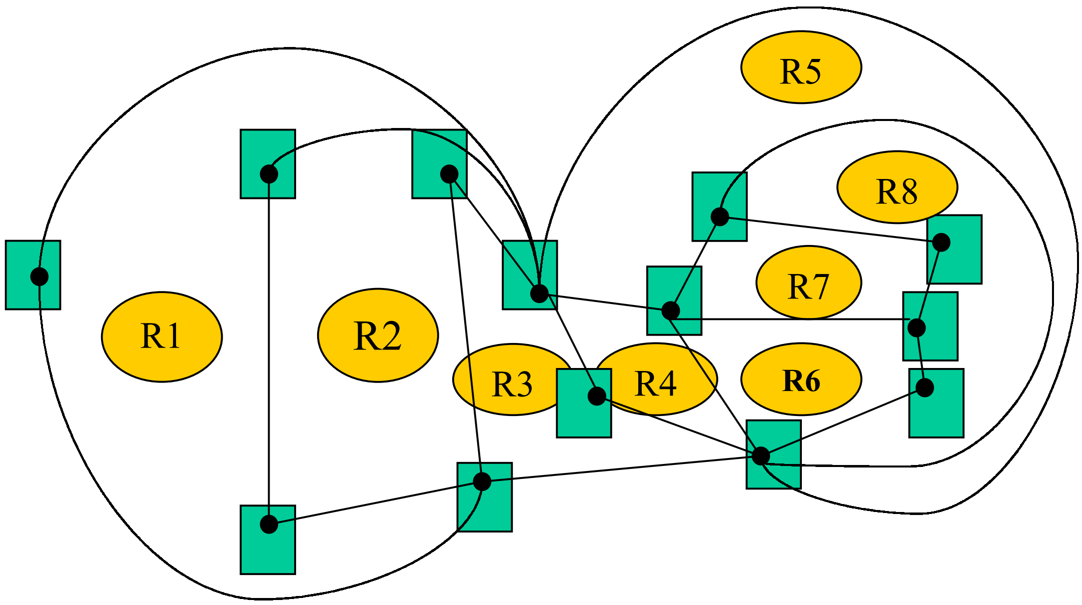
Figure 3.16 Logical Topology obtained for 13-nodes SDH network of the third example

After the logical topology is obtained, rings are merged to minimize the inter-ring traffic as shown in Figures 3.17 - 3.19. In this process, the maximum node number constraint is used for the heuristic merging algorithm.



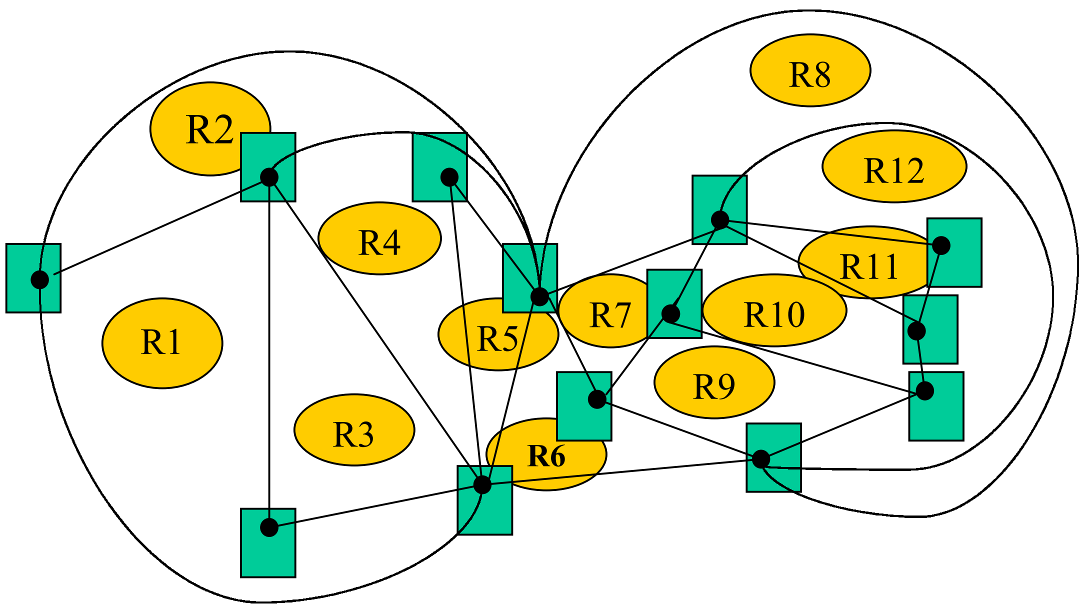
AFTER MERGING
Nmax=6

(a)



AFTER MERGING
Nmax=5

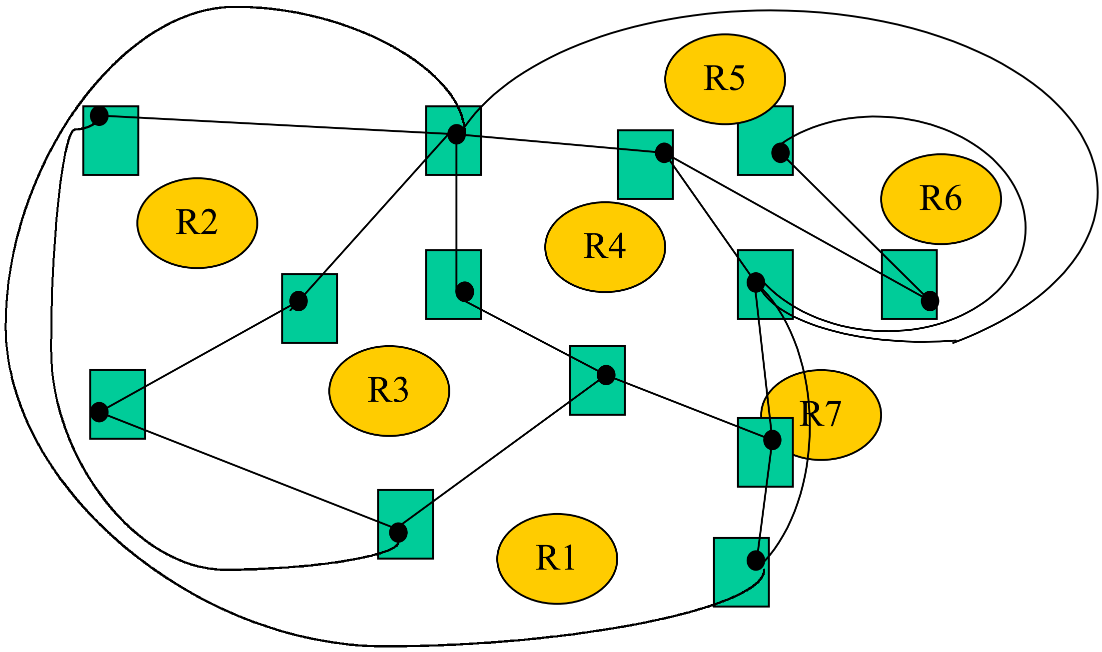
(b)



AFTER MERGING
Nmax=4

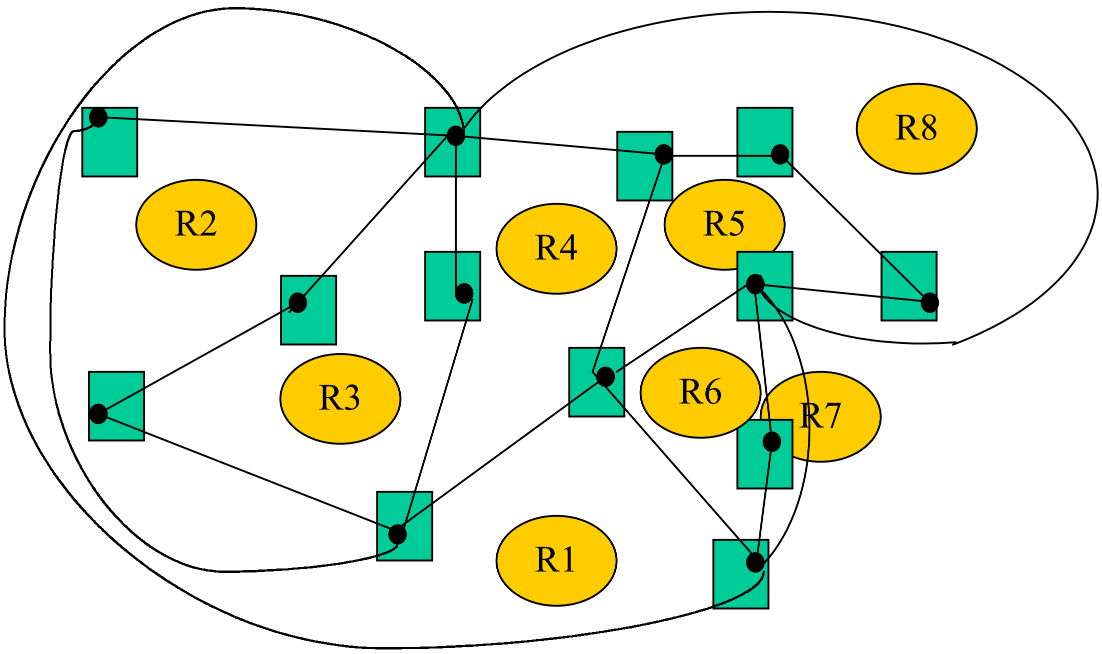
(c)

Figure 3.17 Ring Merges for the first example (a) Nmax=6, (b) Nmax=5, (c) Nmax=4



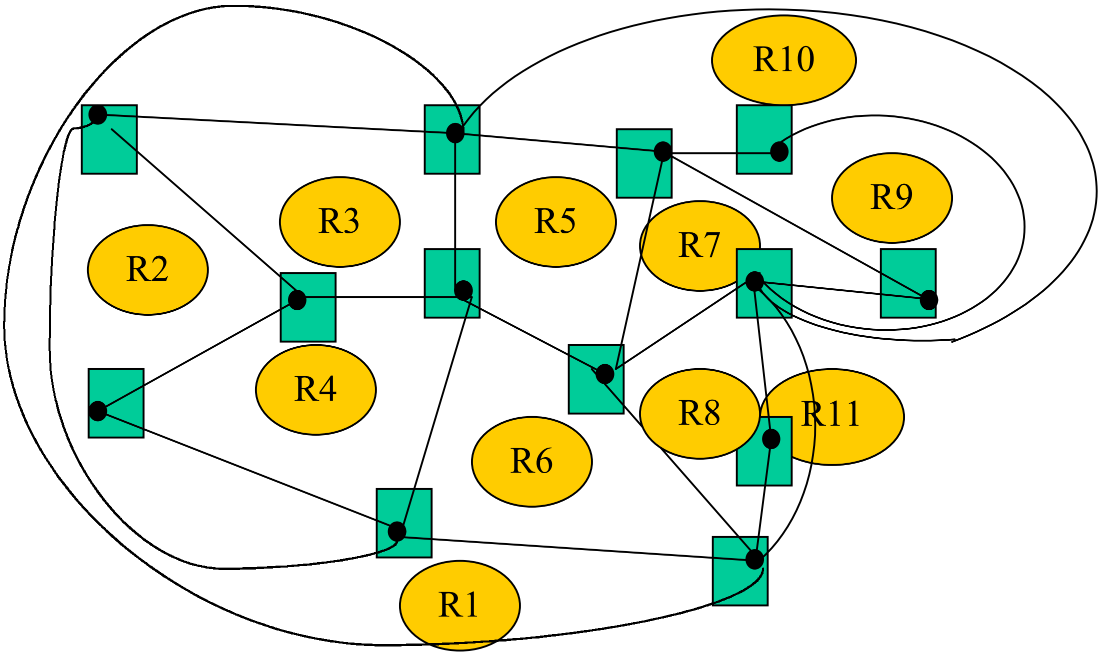
AFTER MERGING
Nmax=6

(a)



AFTER MERGING
Nmax=5

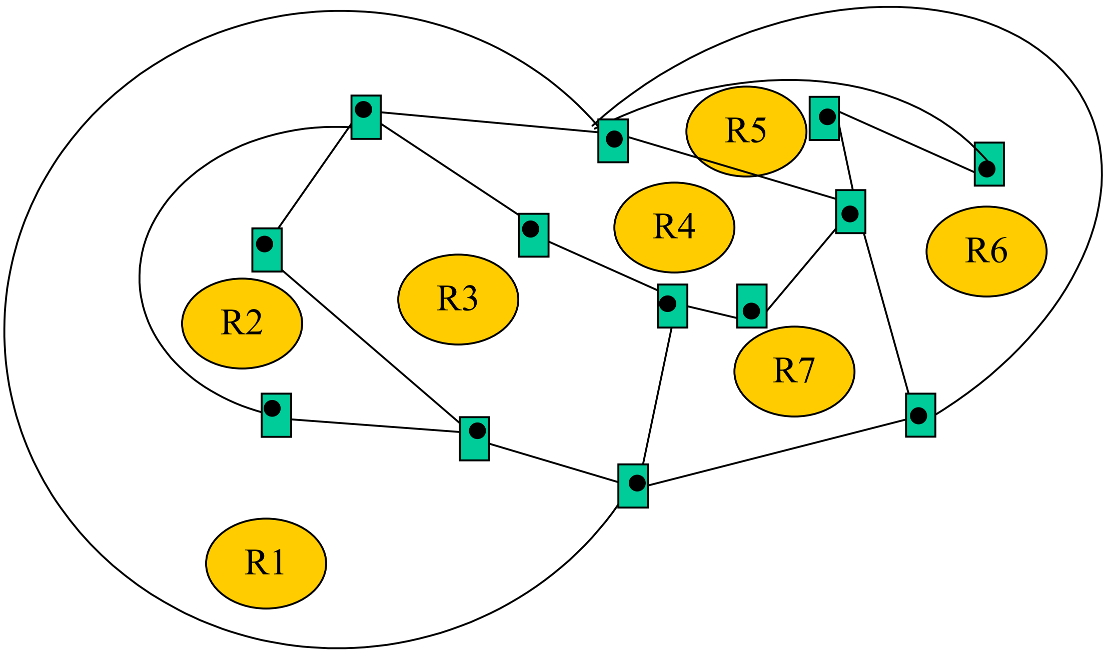
(b)



AFTER MERGING
Nmax=4

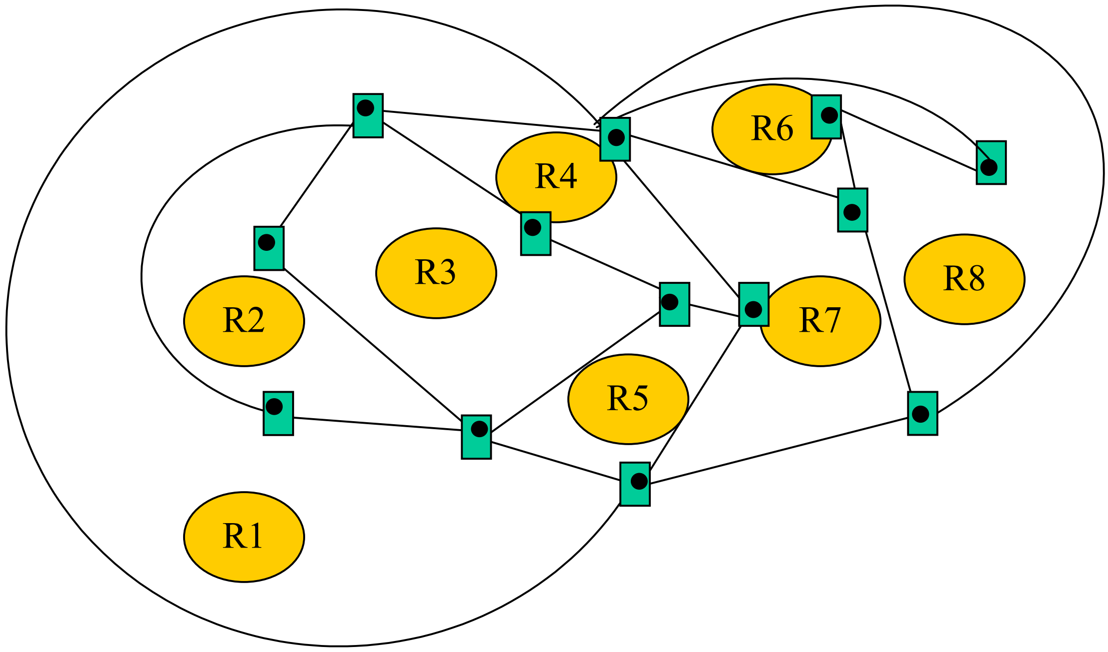
(c)

Figure 3.18 Ring Merges for the second example (a) Nmax=6, (b) Nmax=5, (c) Nmax=4



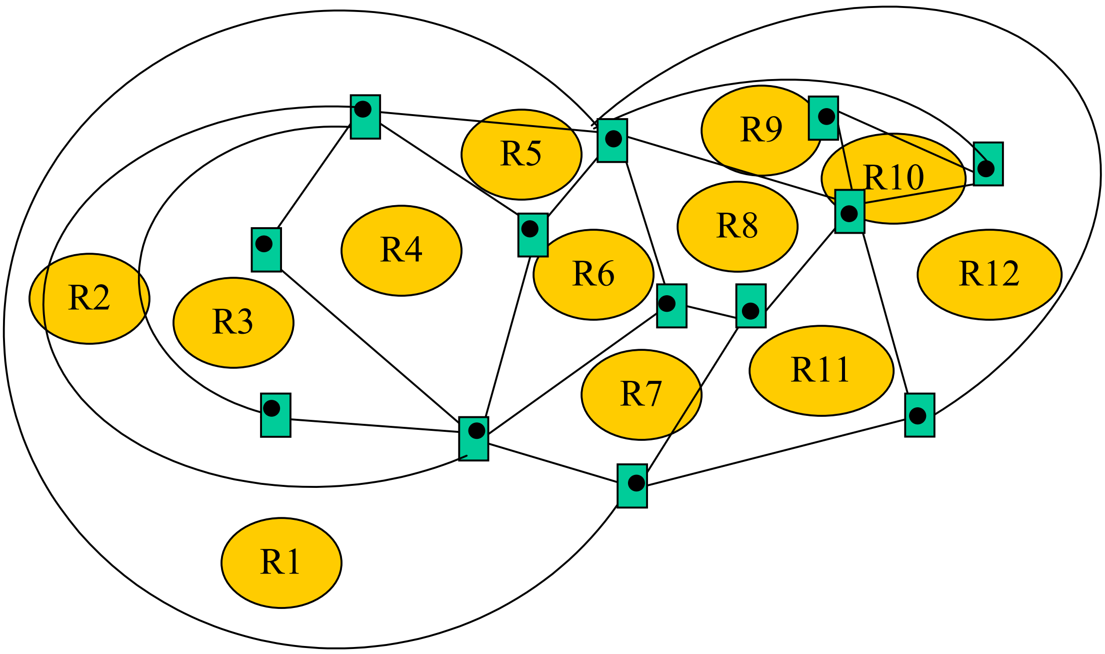
AFTER MERGING
Nmax=6

(a)



AFTER MERGING
Nmax=5

(b)



AFTER MERGING
Nmax=4

(c)

Figure 3.19 Ring Merges for the third example (a) Nmax=6, (b) Nmax=5, (c) Nmax=4

As maximum node size constraint decreases, total number of rings increases. The inter-ring traffic before and after ring mergings for each node size is given in Table 3.1.

	NODE NUMBER	***INTER-RING TRAFFIC BEFORE MERGING***	***INTER-RING TRAFFIC AFTER MERGING***	***INTER-RING MINIMIZATION RATES***
FIRST EXAMPLE	6	30	24	20%
	5	30	25	16,67%
	4	30	28	6,67%
SECOND EXAMPLE	6	31	20	35,48%
	5	31	23	25,8%
	4	31	27	12,9%
THIRD EXAMPLE	6	26	15	42,31%
	5	26	20	23,08%
	4	26	24	7,69%
AVERAGE				***21,18%***

Table 3.1 Inter-ring traffic changes for a demand set for different size constraints

As shown in Table 3.1, inter-ring traffic is decreased by about 7-42% after the ring mergings. The average reduction in the inter-ring traffic is about 21,18%, taken over all examples.

After logical topology is obtained, the next step is to map these logical rings onto given physical topology. In the next chapter we discuss how SDH rings can be mapped onto the optical mesh topology.

Chapter 4

EMBEDDING IN A PHYSICAL TOPOLOGY PROBLEM

Since today's telecommunications industry requires high-speed and high-capacity transport networks, optical fibers are very popular for the large bandwidth supplement. DWDM allows multiplexing of many wavelengths onto a single fiber, so it is the simplest way to expand the capacity of the network. The optical layer with DWDM nodes provides the lightpaths to the higher SDH layer. These lightpaths can currently carry bit-rates as high as 10 Gb/s, and 40 Gb/s systems are under development.

Different layers have their own protection mechanisms. In our design model, the higher-layer protection is selected for the advantages of SDH ring protection. The design process for a network to survive all single link and node failures is a realistic scenario, because the multiple link or node failures are not often the case in practice. Thus, the ring protection topology is designed to handle only one failure at any time and reserves the capacity for rerouting all interrupted traffic.

Even if optical layer protection and restoration is not used in our design, an important point is taken into account. In the networks with DWDM equipments, if different logical links use the same physical resources, the failure of a node or physical link may cause more than one failure in the higher layer, making it impossible to restore the affected traffic in the SDH layer. To address this problem, we aim to map each logical ring onto physical links and nodes such that no two logical links share the same resources in the physical layer. This is accomplished by routing each logical link on an SDH ring over a lightpath, which is link and node disjoint from all other lightpaths forming the SDH ring.

In this chapter, we present an algorithm of embedding the logical rings onto the physical topology under the link disjoint and node disjoint paths constraints. The objective of the algorithm is to minimize the overall fiber cost in the physical layer.

4.1 MILP Formulation

A Mixed Integer Linear Programming (MILP) formulation is developed for the ring-embedding problem. The complete problem can be divided into two sub-problems. The first problem is to determine the order in which SDH nodes belonging to the same ring are connected to each other. Once the logical links on the ring are fixed, these links are mapped onto the physical topology in the second part. Link and node disjoint paths are used in this part in order to guarantee correct operation of the SDH ring protection. The objective of the MILP formulation is to minimize the fiber cost of the physical topology. This cost is calculated by the total length of all links used by the link disjoint flows.

To formulate the problem in mathematical terms, we introduce a number of definitions. Suppose the logical network topology is represented by a directed graph $G=(V, E)$, where V is the set of SDH nodes in the logical topology and E is the set of edges. The decision variables are defined as follows:

$$y_{pq} = \begin{cases} 1 & \text{if there exists a logical link from SDH node } p \text{ to q i.e., } (p, q) \in E \\ 0 & \text{otherwise} \end{cases}$$

$$z_{pq}^{rs} = \begin{cases} 1 & \text{if there exists flow on logical link } (p, q) \in E \text{ resulting from traffic} \\ & \text{carried between SDH nodes } r \text{ and } s, \\ 0 & \text{otherwise} \end{cases}$$

Suppose the physical network topology is represented by a directed graph $G' = (V', E')$, where V' is the set of OXC nodes in the physical topology and E' is the set of edges. d_{nm} is the length of the physical link, where $(n, m) \in E'$. The decision variable x_{nm}^{pq} is defined as follows:

$$x_{nm}^{pq} = \begin{cases} \mathbf{1} & \text{if there exists flow on physical link } (n, m) \in E' \text{ resulting from the} \\ & \text{flow on logical link } (p, q) \in E, \\ \mathbf{0} & \text{otherwise} \end{cases}$$

Objective:

Minimize $\sum_{(n,m) \in E} \sum_{(p,q)} x_{nm}^{pq} \cdot d_{nm}$

Subject to:

Cycle constraint:

$$y_{pq} + y_{qp} \leq 1 \qquad \forall\ (p, q) \in E \qquad (4.1)$$

Total flow on a logical link:

$$\sum_{q \neq p} y_{pq} = 1 \qquad \forall\ p \in V \qquad (4.2)$$

$$\sum_{q \neq p} y_{qp} = 1 \qquad \forall\ p \in V \qquad (4.3)$$

$$z_{pq}^{rs} \leq y_{pq} \qquad \forall\ (p, q), \forall\ (r, s) \qquad (4.4)$$

Flow conservation at each SDH node:

$$\sum_{q \neq p} z_{pq}^{rs} - \sum_{q \neq p} z_{qp}^{rs} = \begin{cases} \boldsymbol{1} & \text{if } p = r, \\ \boldsymbol{-1} & \text{if } p = s, \\ \boldsymbol{0} & \text{otherwise,} \end{cases} \qquad \forall\, p \in V, \forall\, (r, s) \tag{4.5}$$

Physical Link Disjoint Paths Constraint:

$$\sum_{(p,q)} (x_{nm}^{pq} + x_{mn}^{pq}) \leq \boldsymbol{1} \qquad \forall\, (n, m) \in E' \tag{4.6}$$

Node Disjoint Paths Constraint:

$$\sum_{\substack{m \\ (\mathrm{n,\,m}) \in E'}} \sum_{(p,q)} x_{nm}^{pq} = 1 \qquad \forall\, n \in V' \tag{4.7}$$

Flow conservation at each physical node:

$$\sum_{\substack{m \\ (\mathrm{n,\,m}) \in E'}} x_{nm}^{pq} - \sum_{\substack{m \\ (\mathrm{n,\,m}) \in E'}} x_{mn}^{pq} = \begin{cases} y_{pq} & \text{if } n = p, \\ -y_{pq} & \text{if } n = q, \\ \boldsymbol{0} & \text{otherwise} \end{cases} \qquad \forall\, n \in V', \forall\, (p, q) \tag{4.8}$$

Integer Constraints:

$$y_{pq}, z_{pq}^{rs} \in \{0, 1\} \qquad \forall\, (p, q) \in E$$

$$x_{nm}^{pq} \in \{0, 1\} \qquad \forall\, (n, m) \in E'$$

The objective of the formulation is to minimize the total fiber cost in the network, which is the sum of all physical link lengths used by deployed logical rings. Constraint (4.1) guarantees that two logical links between the same logical nodes do not form a cycle. Constraints (4.2) and (4.3) express that; for any node on a ring, both the in-degree and out-degrees are 1. Constraint (4.4) indicates that if there is no SDH logical link between *p* and *q*, i.e., y_{pq} =0, it is not possible to have flow between *p* and *q* carrying the demand between nodes *r* and *s*. Constraint (4.5) verifies the flow conservation at each SDH node for logical topology such that each demand is routed from its source to its destination. Constraint (4.6) implies that each logical link on a ring maps onto physical link disjoint paths. Constraint (4.7) implies that mapping is done onto node disjoint paths. Constraint (4.8) states the flow conservation at each node for the physical topology. This algorithm is implemented separately for all rings in the network.

4.2 Post Processing

After mapping of each logical ring onto the physical topology is completed, it is possible to have some redundant rings. In these situations, we apply a post-processing step to eliminate these rings. These situations can be summarized as follows:

1. If we have a ring, which is a subset of another ring, this can be eliminated. An example is shown in Figure 4.1. In this example, Ring 2 is a subset of Ring 1 and the nodes of Ring 2 are all included in Ring 1. Thus, Ring 2 is redundant and it can be eliminated.

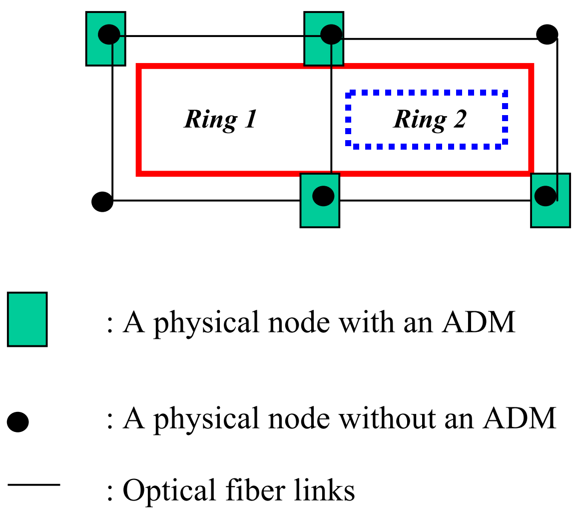


Figure 4.1 First example of post-processing

2. If we have a ring, which is mapped onto the same physical links of another ring, this can also be eliminated. An example is shown in Figure 4.2. In this example, Ring 2 is same as Ring 1 and Ring 2 is redundant and it can be eliminated.

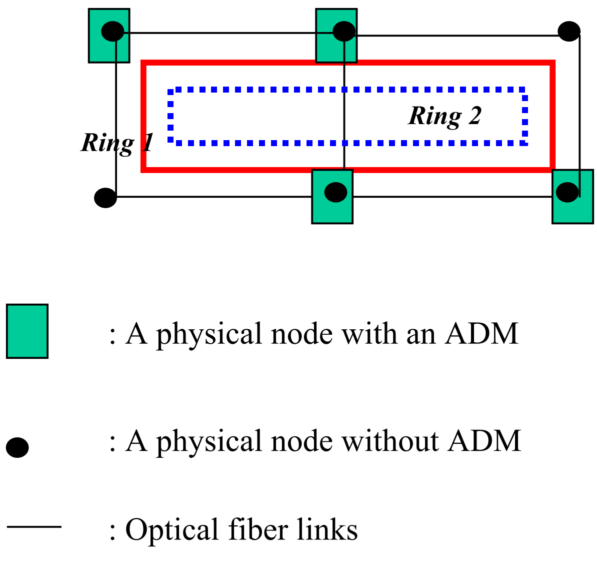


Figure 4.2 Second example of post-processing

3. If two rings are mapped onto the physical topology such that they both span the same SDH nodes, one of them can be eliminated as seen in Figure 4.3.

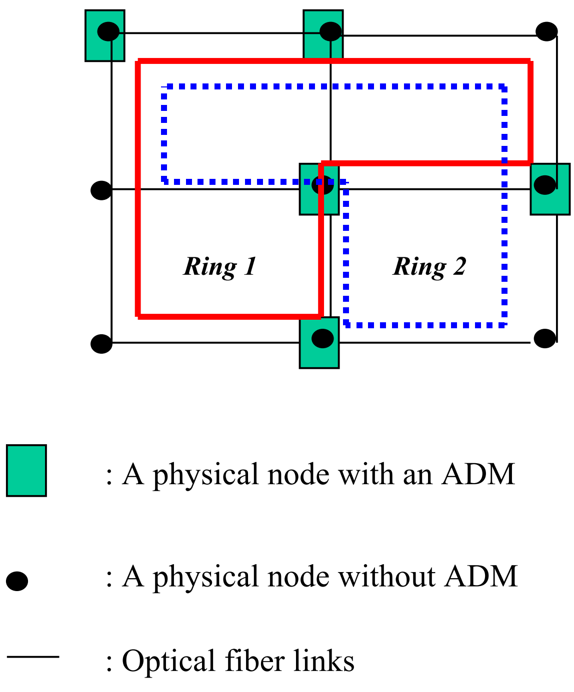
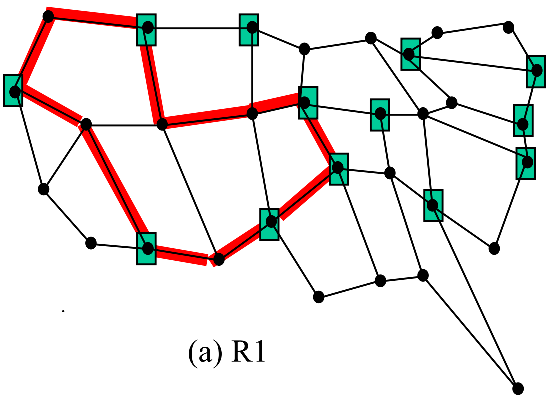


Figure 4.3 Third example of post-processing

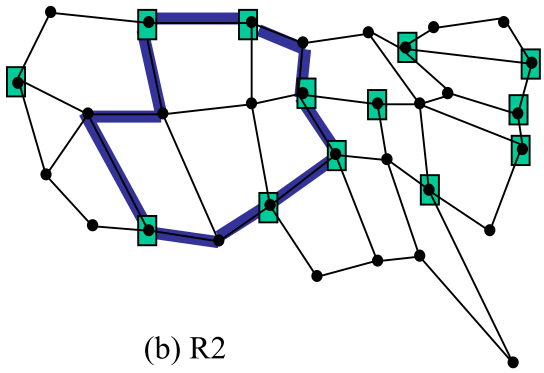
We continue eliminating the rings until there exists no redundant ring. After the post-processing step, we obtain the solution of the SDH ring design problem.

4.3 Numerical Results

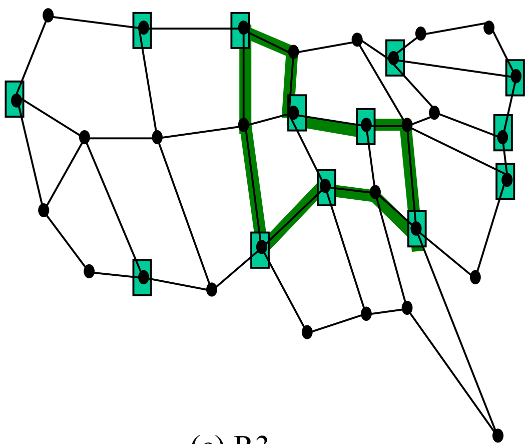
In this section, we represent the mapping of the logical rings obtained in Section 3.3. Using the MILP formulation, each SDH ring is mapped onto link and node disjoint lightpaths. The MILP formulation is implemented on GAMS and CPLEX commercial optimization software packages. The SDH rings shown in Figures 3.17 - 3.19 are mapped onto the 32-node physical topology. The results of three examples are shown in Figures 4.4 - 4.12 for different size constraints.



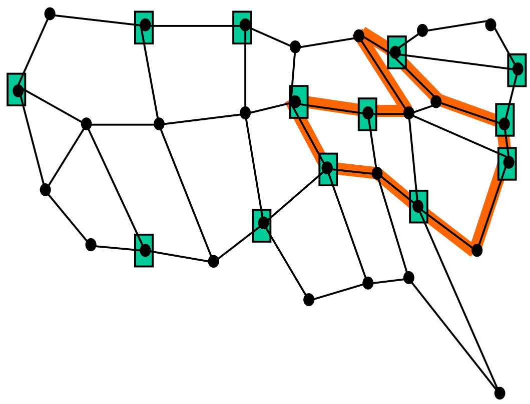
(a) R1



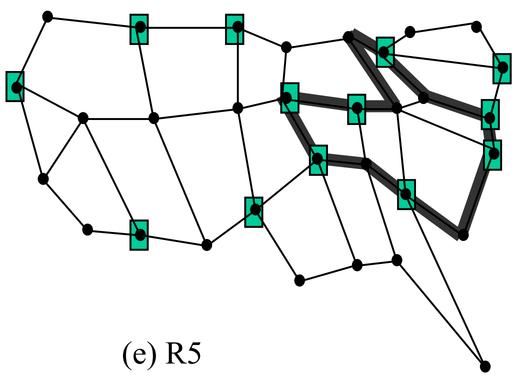
(b) R2



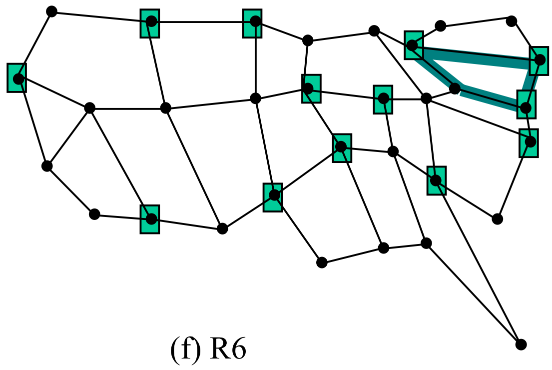
(c) R3



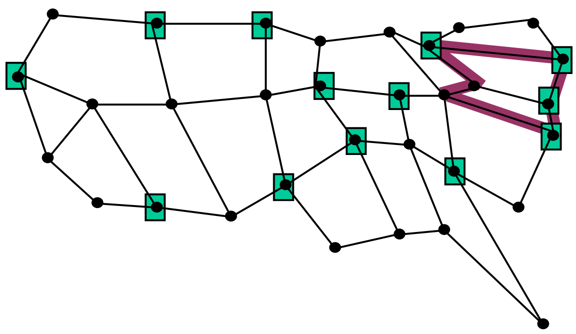
(d) R4



(e) R5

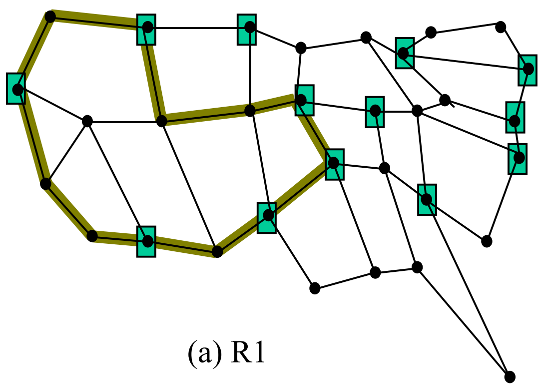


(f) R6

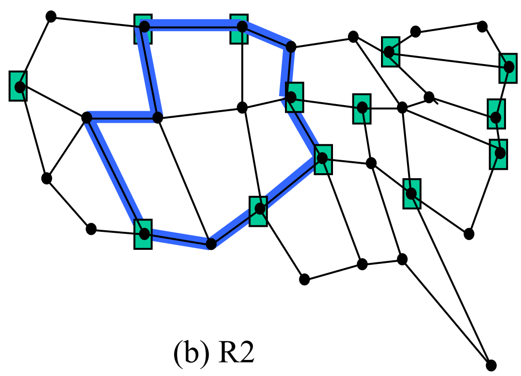


(g) R7

Figure 4.4 Mapping of logical rings of first example (Nmax=6)



(a) R1



(b) R2

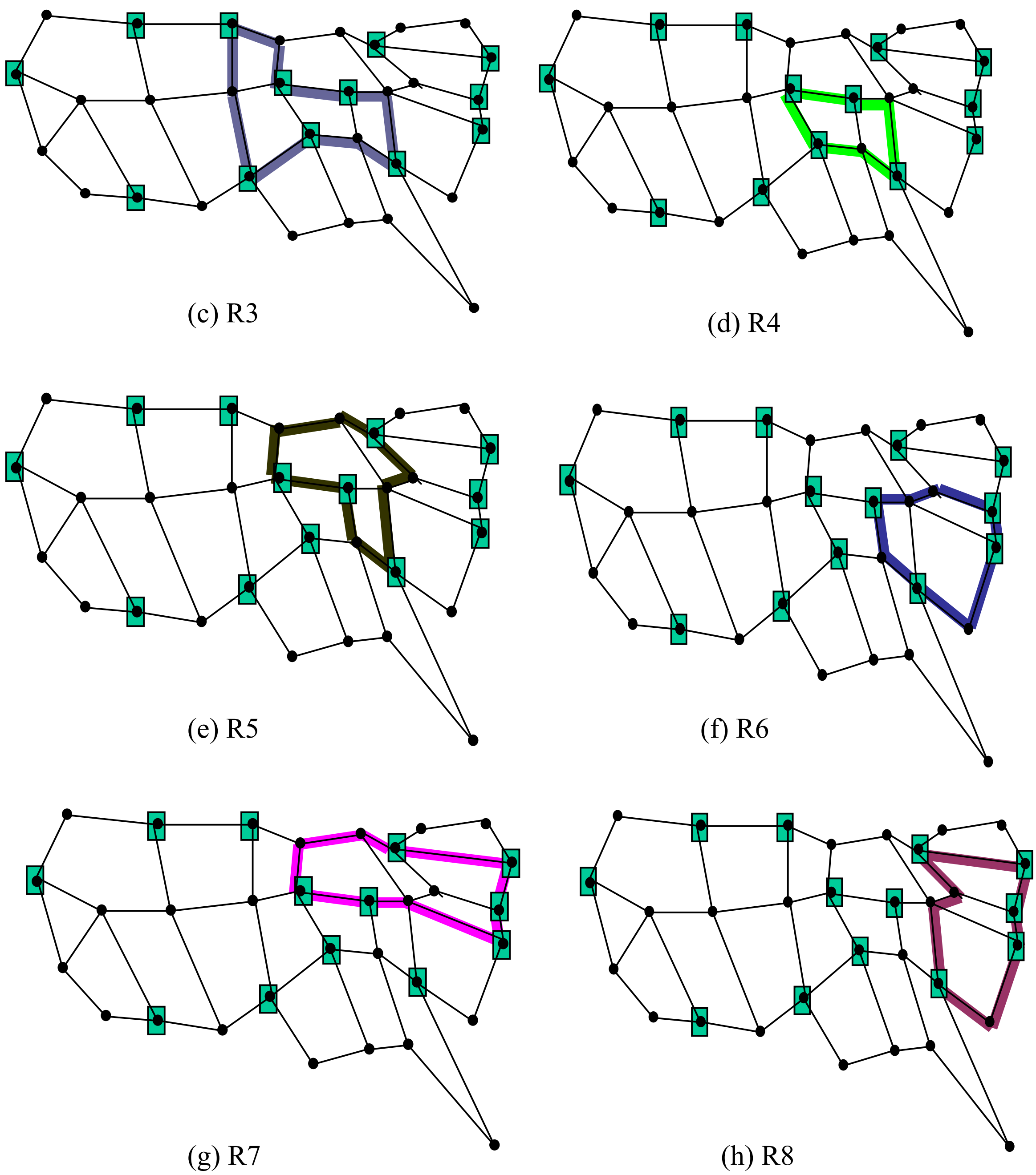
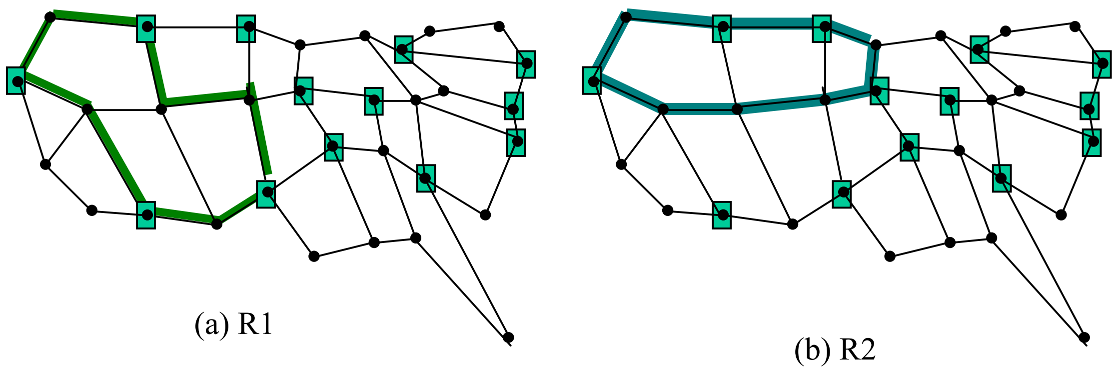
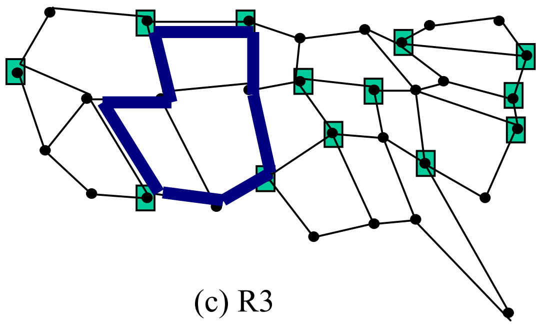
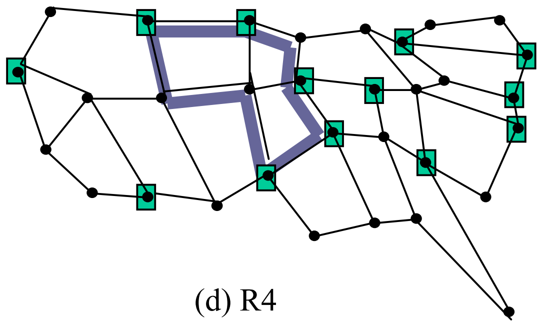


Figure 4.5 Mapping of logical rings of first example (Nmax=5)

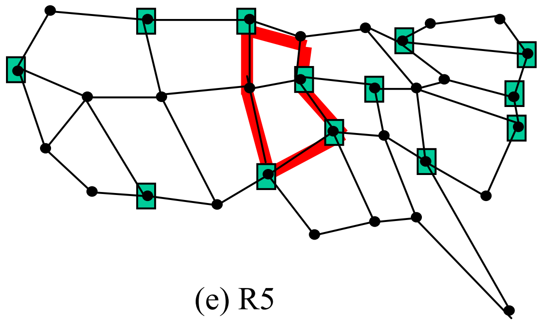




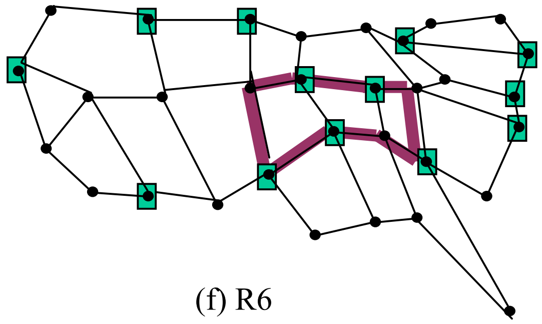
(c) R3



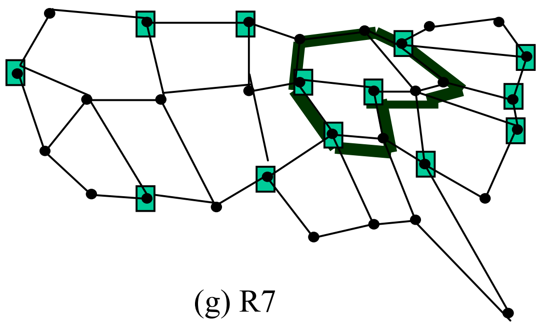
(d) R4



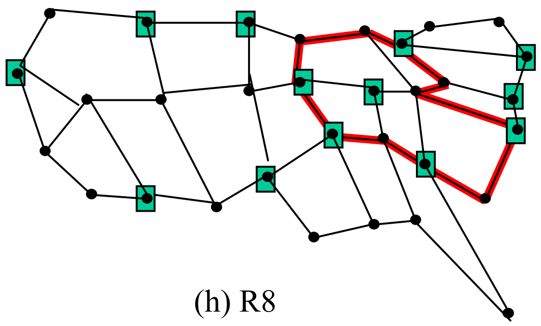
(e) R5



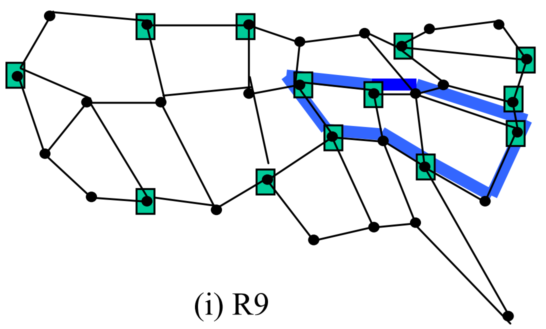
(f) R6



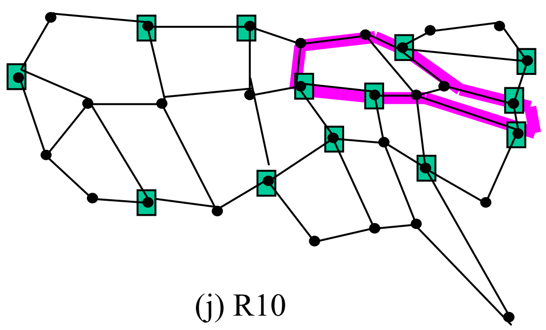
(g) R7



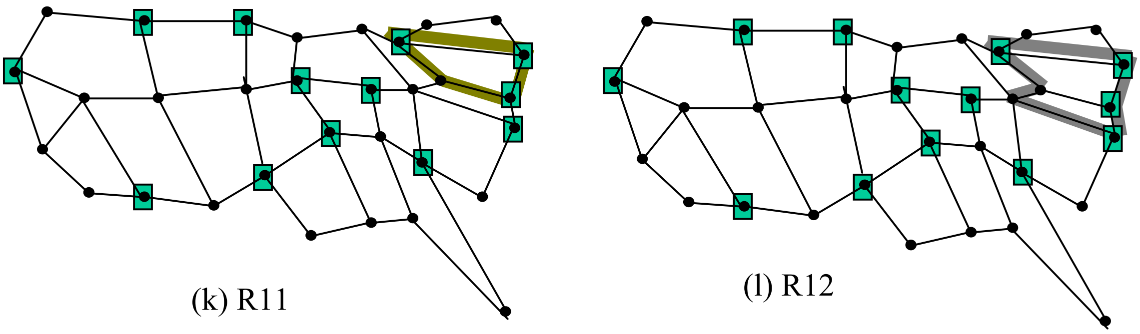
(h) R8



(i) R9

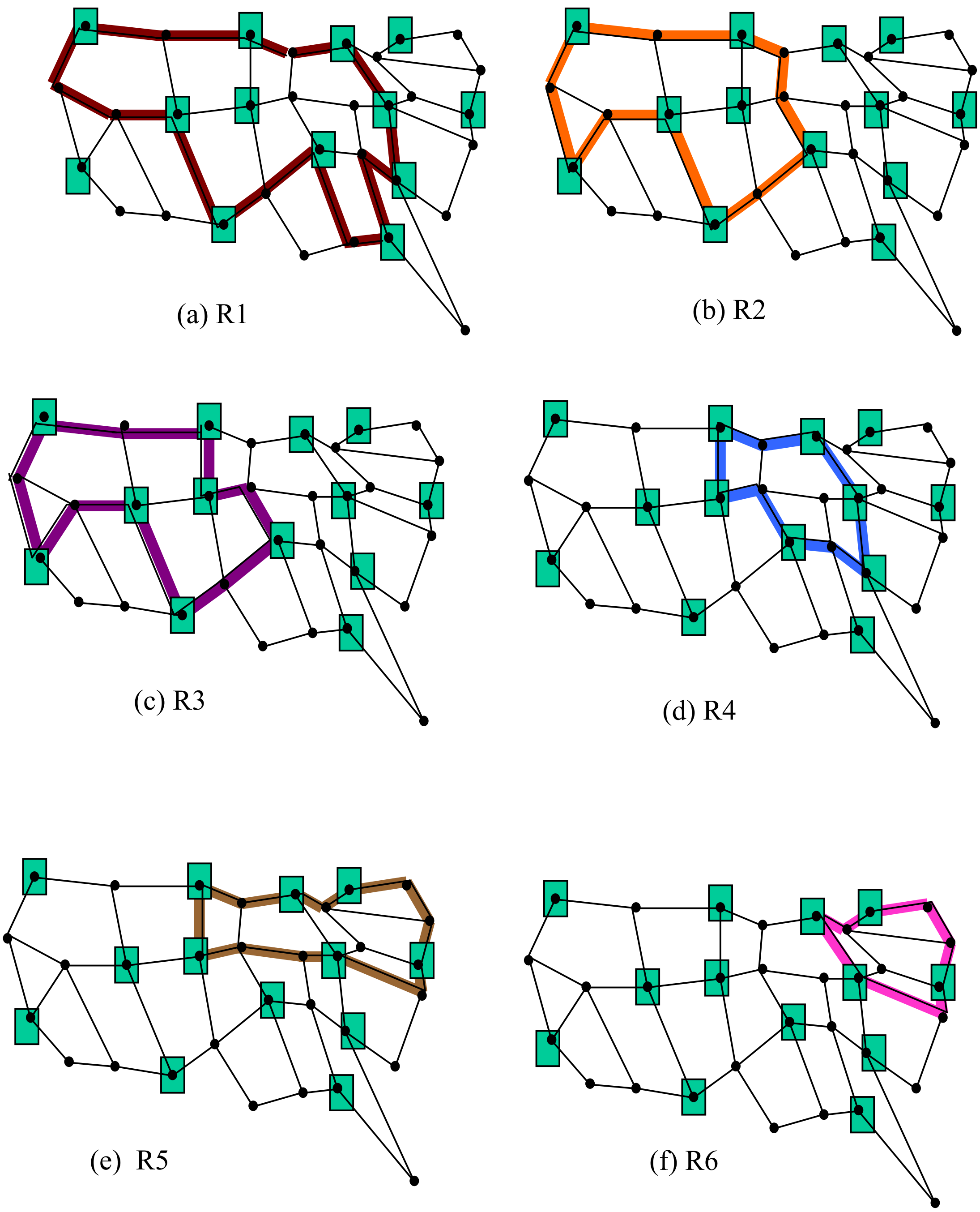


(j) R10



(k) R11 (l) R12

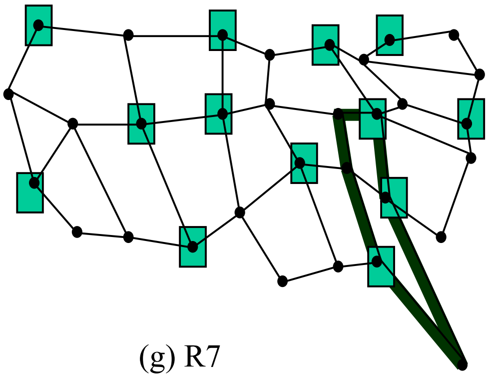
Figure 4.6 Mapping of logical rings of first example (Nmax=4)



(a) R1 (b) R2

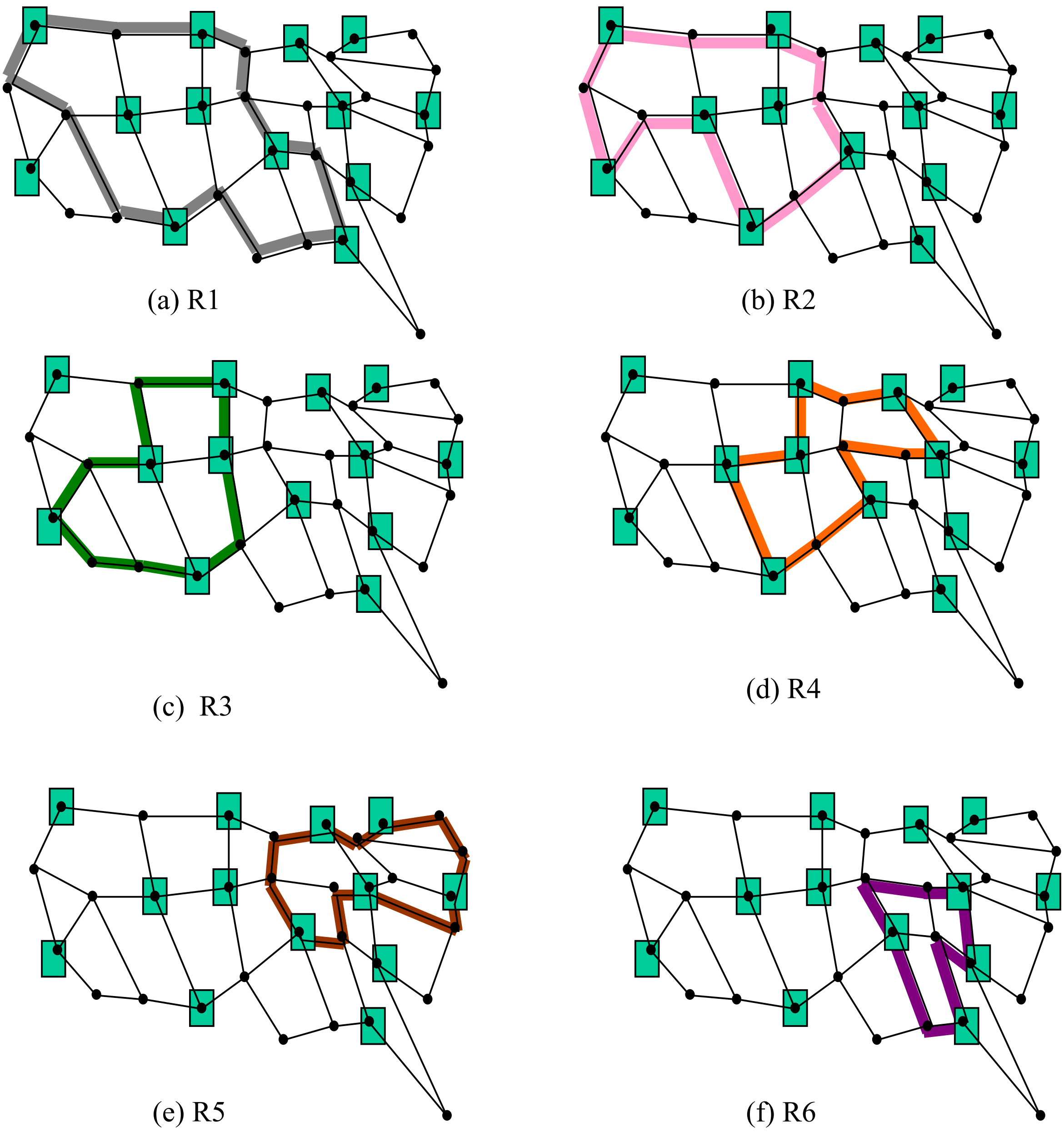
(c) R3 (d) R4

(e) R5 (f) R6



(g) R7

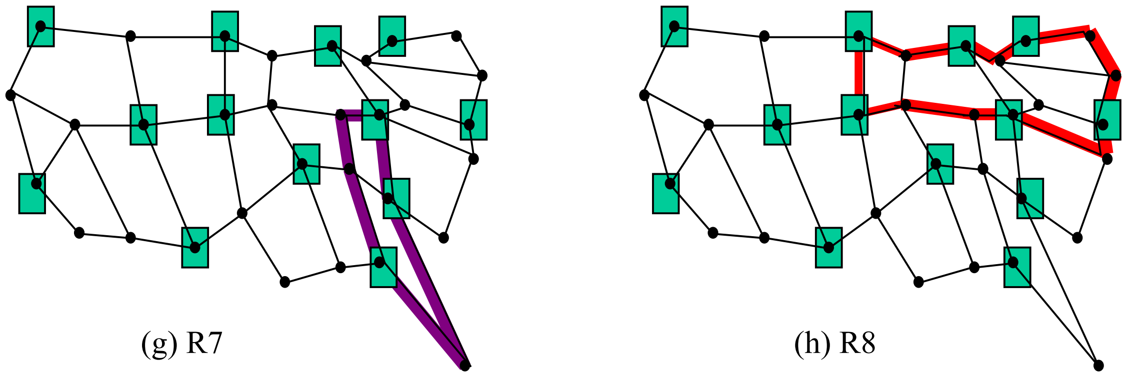
Figure 4.7 Mapping of logical rings of second example (Nmax=6)



(a) R1 (b) R2

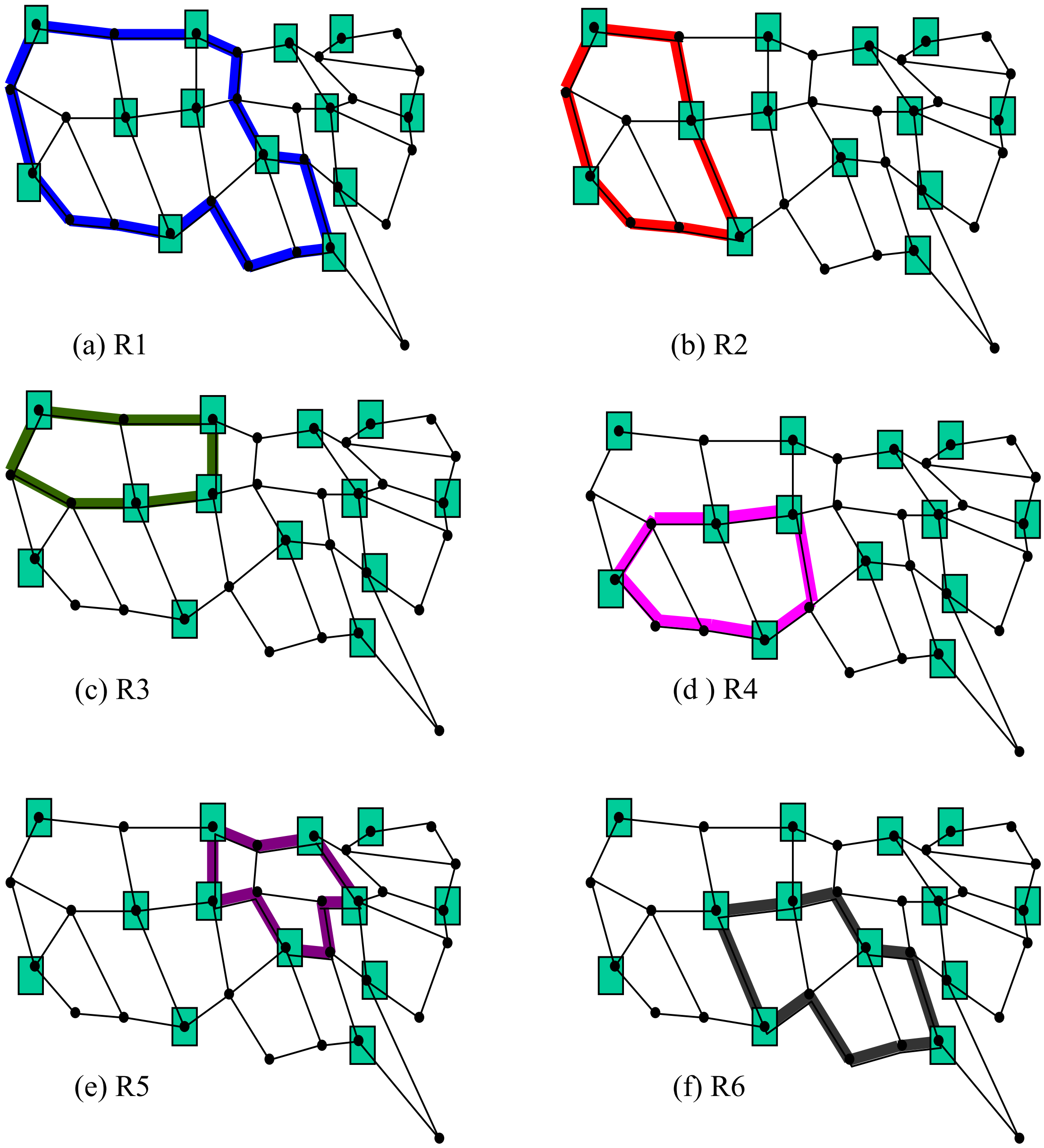
(c) R3 (d) R4

(e) R5 (f) R6



(g) R7 (h) R8

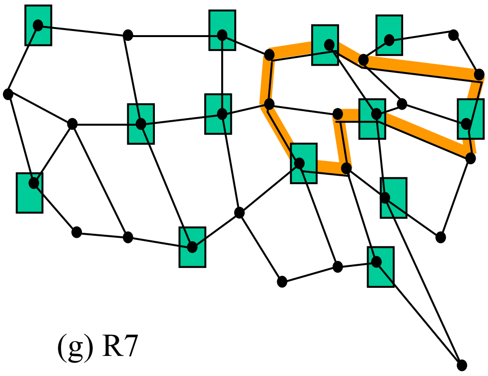
Figure 4.8 Mapping of logical rings of second example (Nmax=5)



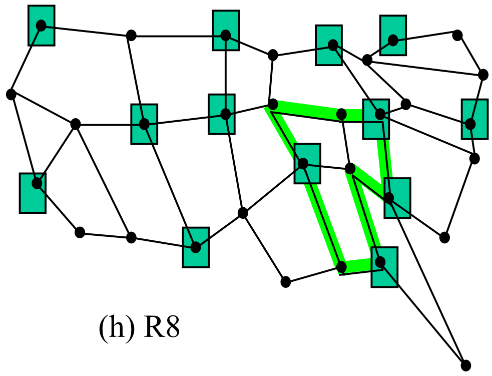
(a) R1 (b) R2

(c) R3 (d) R4

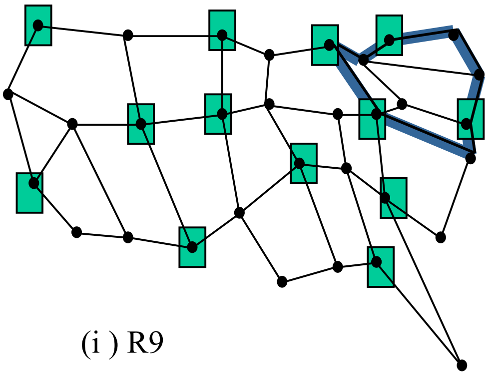
(e) R5 (f) R6



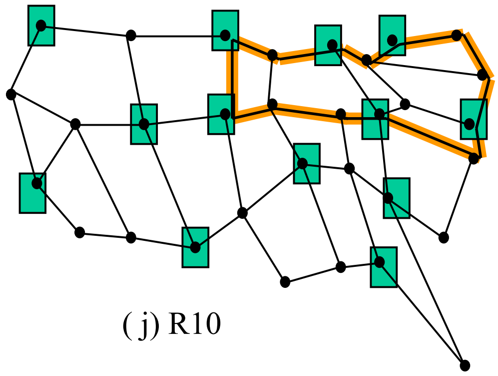
(g) R7



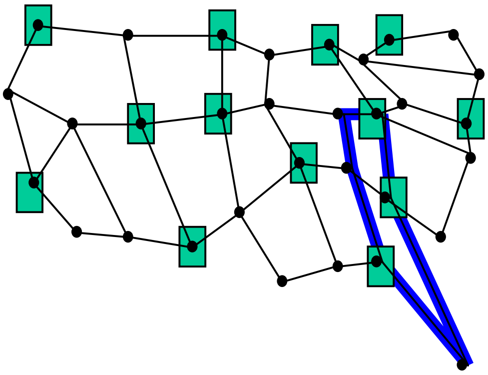
(h) R8



(i) R9

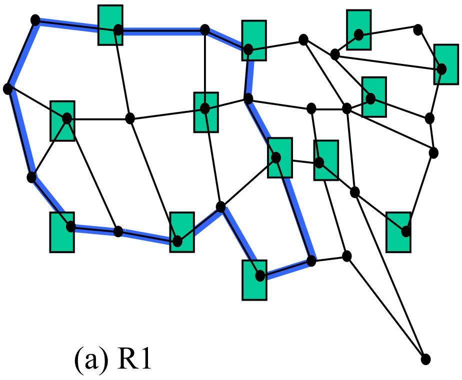


(j) R10

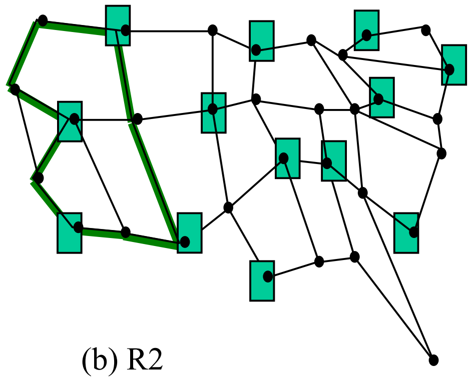


(k) R11

Figure 4.9 Mapping of logical rings of second example (Nmax=4)



(a) R1



(b) R2

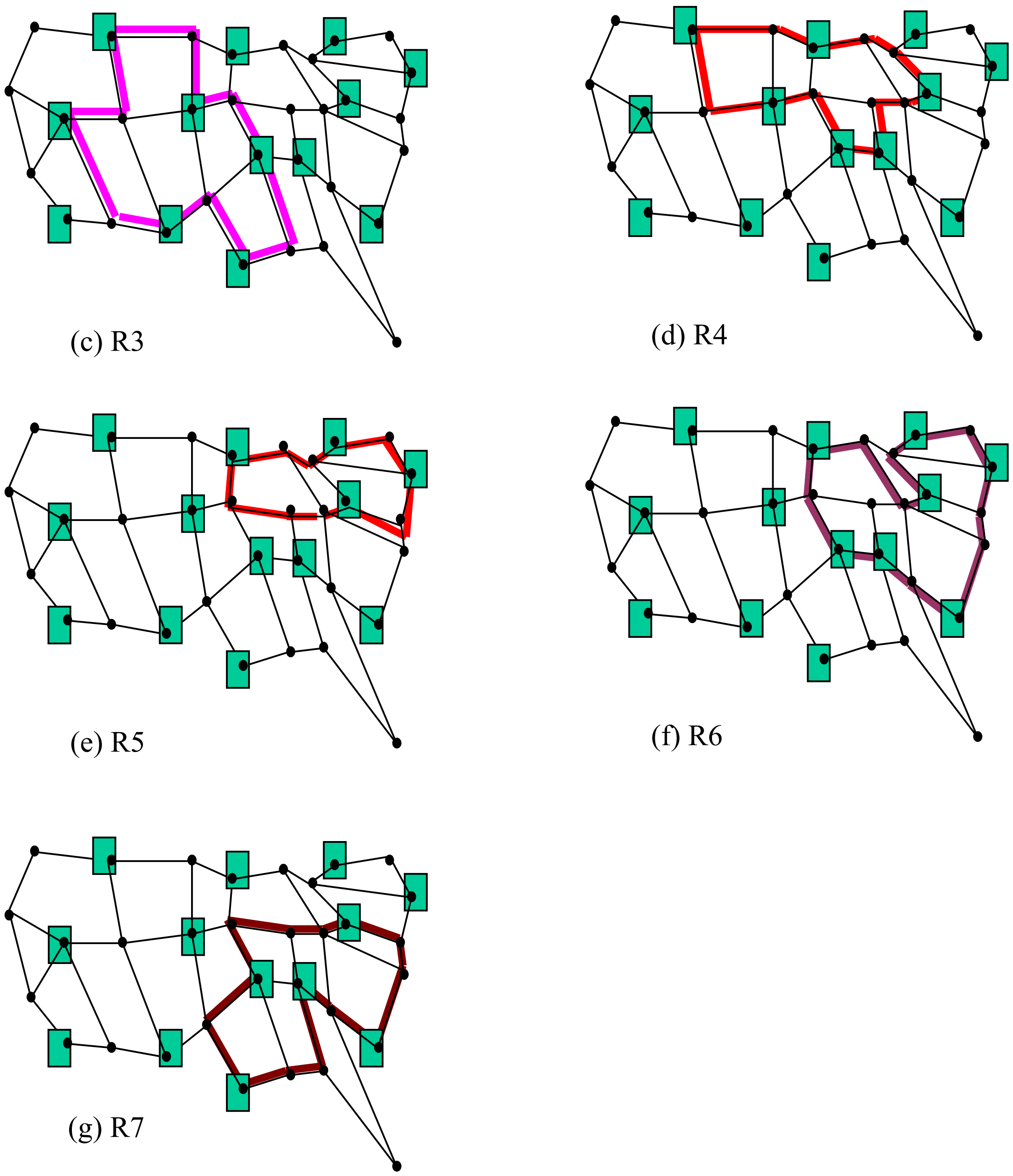
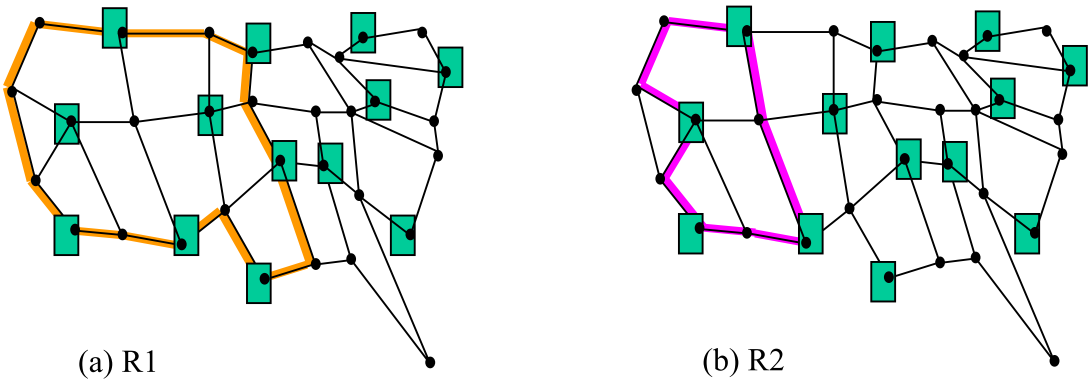
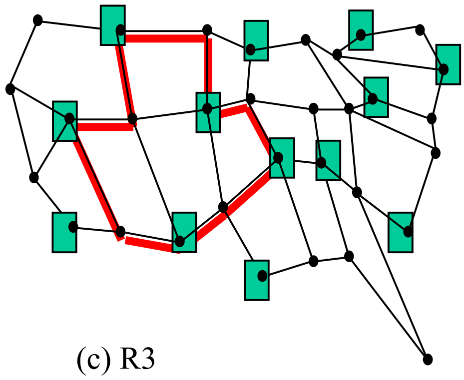
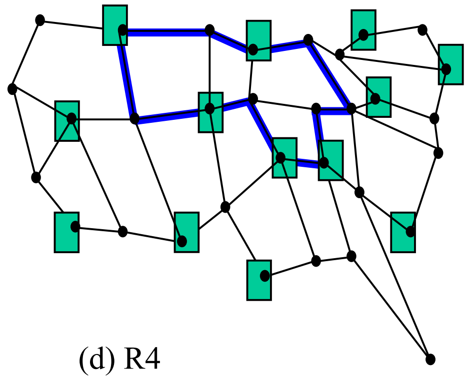


Figure 4.10 Mapping of logical rings of third example (Nmax=6)

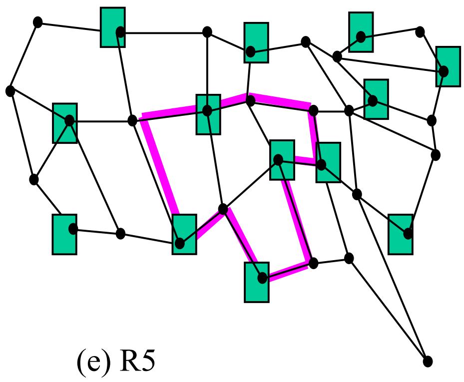




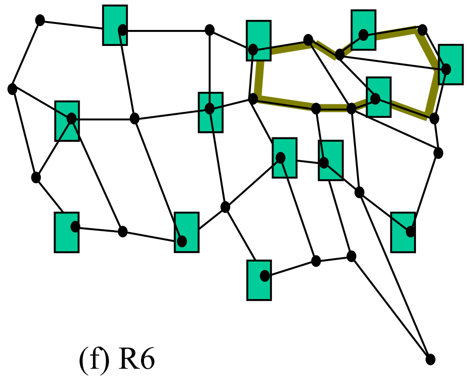
(c) R3



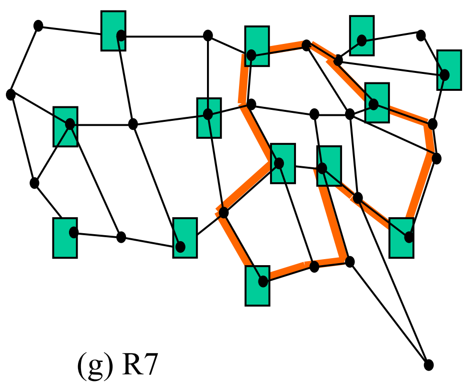
(d) R4



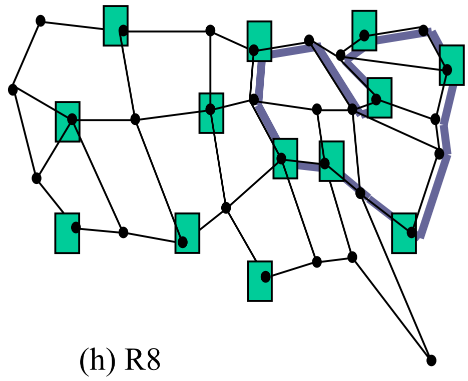
(e) R5



(f) R6

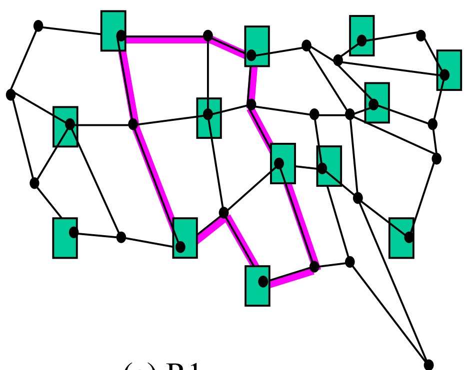


(g) R7

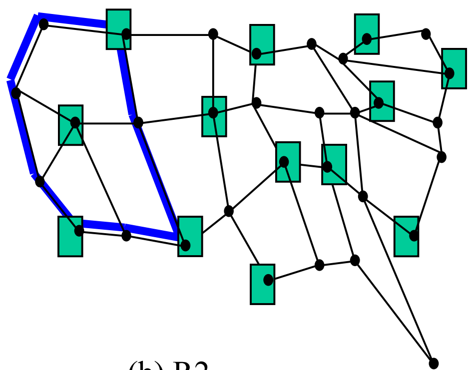


(h) R8

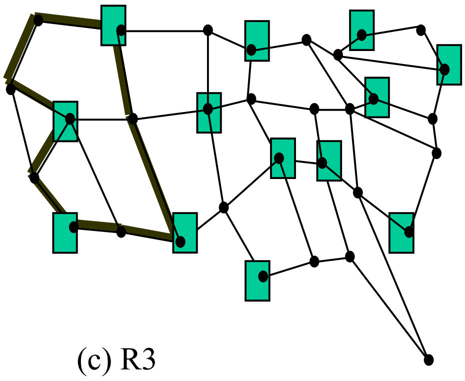
Figure 4.11 Mapping of logical rings of third example (Nmax=5)



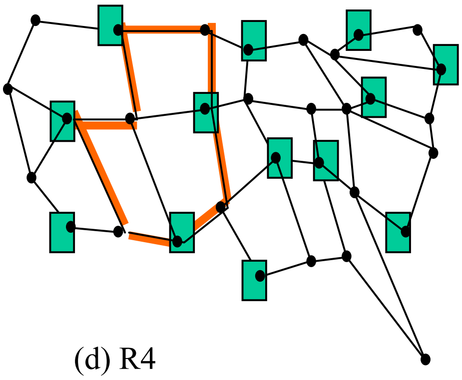
(a) R1



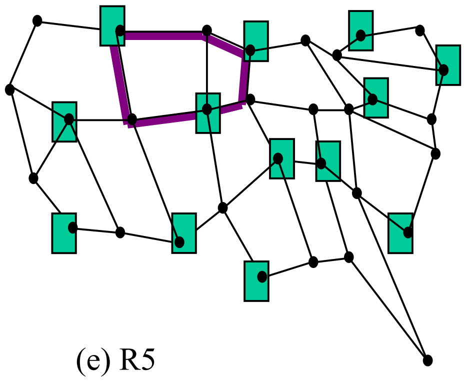
(b) R2



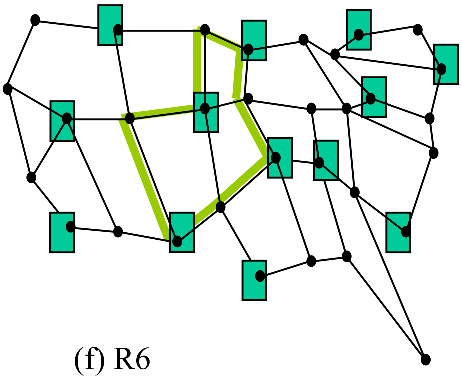
(c) R3



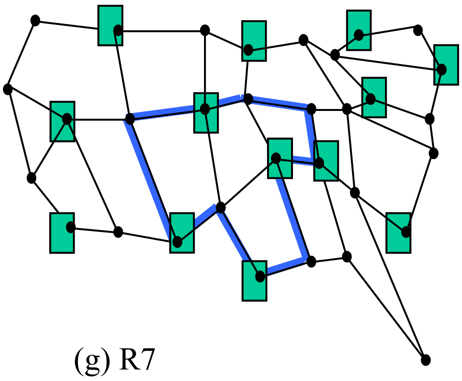
(d) R4



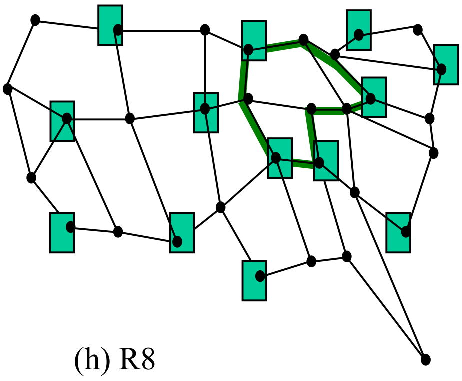
(e) R5



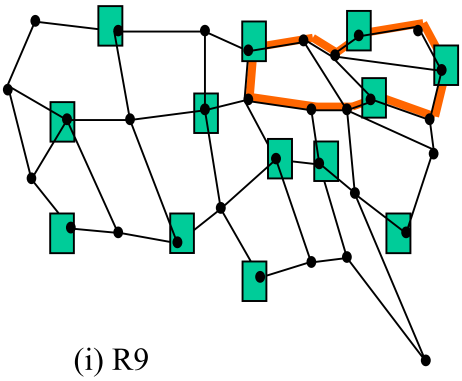
(f) R6



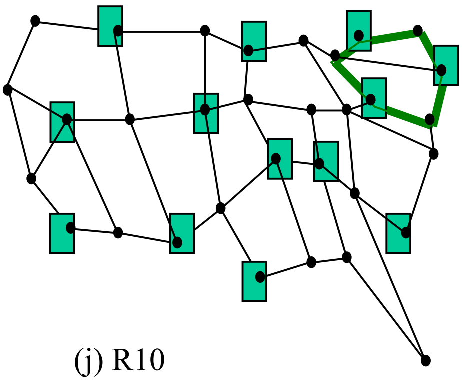
(g) R7



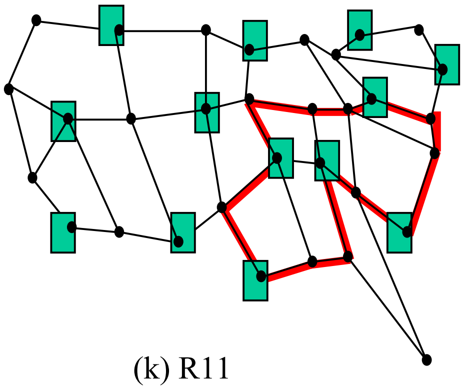
(h) R8



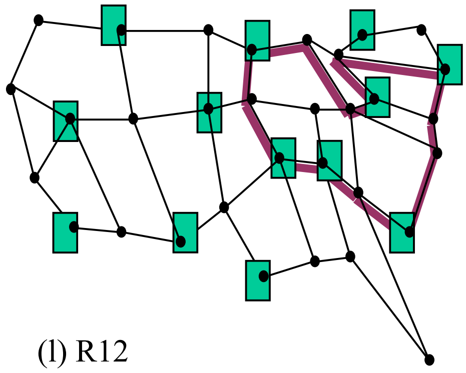
(i) R9



(j) R10



(k) R11



(l) R12

Figure 4.12 Mapping of logical rings of third example (Nmax=4)

After all rings are mapped onto the physical topology, some rings are eliminated by the post-processing algorithms. After all redundant rings are eliminated, the remaining rings and their costs are shown in Table 4.1. In the numerical examples, post-processing decreases the total cost at some rates for different node constraints.

If we compare the total fiber costs of the network after post-processing, as maximum node number of the ring increases, total fiber cost decreases as expected which is shown in Table 4.1. After post-processing is applied to the solutions, the fibers cost is reduced by about 4-33 % for the 32-node network. The average fiber cost reduction after post-processing is about 12,92% over all examples.

1st Example		*2nd Example*		*3rd Example*	
Nmax=6		*Nmax=6*		*Nmax=6*	
R1	2.686	R1	3.672	R1	3.096
R2	2.413	R2	2.695	R2	2.312
R3	1.561	R3	2.737	R3	2.856
R4	1.367	R4	1.496	R4	2.317
R5	1.377	R5	1.653	R5	1.316
R6	441	R6	796	R6	1.717
R7	541	R7	1.206	R7	1.882
TOTAL	**10.386**	**TOTAL**	**14.255**	**TOTAL**	**15.496**
ELIMINATED	441	ELIMINATED	4.697	ELIMINATED	1.316
	4,25%		***32,95%***		***8,50%***
Nmax=5		*Nmax=5*		*Nmax=5*	
R1	2.686	R1	3.444	R1	3.096
R2	2.413	R2	2.695	R2	2.312
R3	1.561	R3	2.537	R3	2.455
R4	826	R4	2.099	R4	2.081
R5	1.185	R5	1.427	R5	2.074
R6	1.021	R6	1.329	R6	1.316
R7	1.001	R7	1.206	R7	1.989
R8	1.010	R8	1.653	R8	1.717
TOTAL	**11.703**	**TOTAL**	**16.390**	**TOTAL**	**17.040**
ELIMINATED	826	ELIMINATED	1.206	ELIMINATED	1.316
	7,06%		***7,36%***		***7,72%***
Nmax=4		*Nmax=4*		*Nmax=4*	
R1	2.637	R1	3.434	R1	2.255
R2	2.408	R2	2.147	R2	2.147
R3	2.306	R3	2.164	R3	2.312
R4	1.854	R4	1.932	R4	2.306
R5	1.022	R5	1.300	R5	1.558
R6	1.110	R6	1.979	R6	1.691
R7	1.063	R7	1.248	R7	2.074
R8	1.376	R8	1.329	R8	1.063
R9	1.017	R9	796	R9	1.316
R10	1.001	R10	1.653	R10	620
R11	441	R11	1.206	R11	1.882
R12	541			R12	1.538
TOTAL	**16.776**	**TOTAL**	**19.188**	**TOTAL**	**20.762**
ELIMINATED	3.769	ELIMINATED	2.002	ELIMINATED	2.767
	22,47%		***10,43%***		***13,33%***

Table 4.1 Fiber costs of mapped SDH Rings before and after post processing

We also compare the average shortest paths for the networks before merging and after post-processing. After post-processing, the average shortest path distance increases by about 1-17 % of the original mesh network as shown in Table 4.2. The average increase of the average shortest path length taken over all examples is about 3,66%.

These numerical results show that additional fiber cost due to routing over a multi-ring architecture mapped over a mesh topology is reasonably small. This additional cost is compensated by the larger reduction in DXC costs due to smaller inter-ring traffic after ring-mergings as shown in Section 3.3. Furthermore, the reduction in the inter-ring traffic also decreases the network management complexity.

	Over the physical mesh topology	*Over the multi-ring topology after ring mappings*		
1st Example		***Nmax=6***	***Nmax=5***	***Nmax=4***
Average Shortest Paths	1456,08	1473,62	1482,35	1506,53
Increase with respect to mesh topology		***1,21%***	***1,80%***	***3,47%***
2nd Example		***Nmax=6***	***Nmax=5***	***Nmax=4***
Average Shortest Paths	1528,50	1604,60	1543,24	1791,69
Increase with respect to mesh topology		***4,98%***	***0,96%***	***17,22%***
3rd Example		***Nmax=6***	***Nmax=5***	***Nmax=4***
Average Shortest Paths	1509,60	1514,87	1529,85	1529,92
Increase with respect to mesh topology		***0,35%***	***1,34%***	***1,35%***

Table 4.2 Average shortest path comparisons for different maximum node number of three examples

Chapter 5

CONCLUSION

The evolution of the telecommunication networks and enormous growth in data traffic increase the importance of the network protection design. Telecom network operators strive to deploy their networks such that it is cost-effective and resilient against failures. Among several technologies, SDH and WDM networks play an important role. Both networks can be used independently or multi-layer solutions can be used for obtaining solutions with better performance.

In this thesis, we consider the two-layered network design problem for the SDH over WDM topology. Since SDH ring networks are widely installed currently and they have several advantages, in this thesis we study the SDH over WDM network architecture such that all resilience functions are fulfilled by SDH ring protection. Design of SDH rings design has been studied extensively in the literature, but the combination of ring design and embedding of rings onto the mesh optical topology has not been addressed before.

We decouple the overall network design process into two design problems: SDH ring selection and mapping of these rings onto the physical topology. Both problems are studied as optimization problems. For the SDH ring selection problem, we present a greedy heuristic algorithm based on minimization of the inter-ring traffic in order to reduce the cost and complexity of digital cross-connects. There are two limitations on the greedy heuristic algorithm: ring size and 2-connectivity. For the embedding of the logical rings onto the physical topology, we introduce a MILP formulation based on link and node disjoint mapping of each ring in order to guarantee proper operation of SDH protection against all single link or node failures.

We have tested the proposed ring selection algorithm with different network topologies and we obtained the cost reductions at different steps on the network. After all ring mergings are completed, the average inter-ring traffic is reduced by about 21,18% compared to the initial solution where the average is taken over all examples. Also, network management complexity is reduced by the minimization of the inter-ring traffic.

Once all rings are selected we mapped these rings onto the mesh optical topology using the proposed MILP formulation, and then we applied the post-processing algorithm in order to eliminate redundant rings. The average fiber cost reduction after post-processing is about 12,92% taken over all examples. The proposed mapping algorithm generates cost-effective and resilient multi-ring SDH networks.

We have also computed the increase in the average path length for the resulting multi-ring topology and compared it with the average path length over the optical mesh network. Our results show that the average path length increase due to longer paths in the multi-ring topology is only 3,66%, where the average is taken over all examples. This quantitative result shows that the multi-ring architecture overlaid over an optical mesh topology increases the average shortest path length at a small amount. Based on these results, we believe that the architecture of SDH rings over a mesh optical network can be used for efficient design of resilient networks.

The network design process proposed in this thesis for SDH over WDM networks can be used to improve the efficiency and cost of the transport networks used by Telecom operators. Future studies can be focused on developing new heuristic algorithms and MILP formulations that result in lower network costs. Developing an algorithm for designing a cost-effective network in which SDH protection and WDM restoration are used jointly against failures is also an important research problem.

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