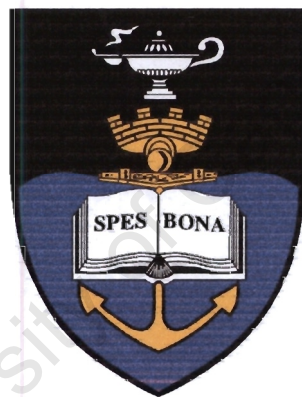


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A Low-Cost Design of Multiservice SDH Networks with Multiple Constraints

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This thesis is submitted in partial fulfillment of the academic requirements

for the degree of

Master of Science in Electrical Engineering

in the Faculty of Engineering and The Built Environment

University of Cape Town

August 2006

As the candidate's supervisor I have approved this dissertation for submission.

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Date: Sept 14 2006

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Declaration

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Dedicated to

Mr. Godwin Idiovo, Ughelli, Delta State, Nigeria.

At times our own light goes out and is rekindled by a spark from another person. Each of us has a cause to think with deep gratitude of those who have lighted the flame within us.

... "Albet Schweitzer"

Thank you so much for everything..... Tope Kareem

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Abstract

Multiservice SDH/SONET (Synchronous Digital Hierarchy / Synchronous Optical Network) Optical networks design using ring-based architecture is preferred in practice because of its simplicity, and fast rerouting and restoration capability. The cost of such networks is dominated by the equipment (known as multiservice switches) cost rather than the cost of fiber rings. A number of multiservice switches are deployed on the access rings for native service delivery and few others on the federal rings for interconnecting access rings. In a typical real network scenario, usually there would be more than one option of interconnecting the access rings, depending on the number of Optical and equipment interface constraints. Because low-cost designs of optical networks are of immense benefits to all the stake holders in telecommunications, a network configuration with the minimum number of interconnected rings, which does not violate the set of given constraints requirements, is considered an optimum solution.

This study investigates the problem of ring-node assignment in a Multiservice SDH/SONET Optical network design with constraints in capacity and differential delay.

The problem is characterized as a graph-partitioning problem, and a heuristic algorithm based on constraints programming satisfaction technology is proposed. The algorithm is tested in OPNET simulation environment using different network models derived from a hypothetical case study of an optical network design for Bellville area in Cape Town. Data are collected for analysis from the simulation, and the number and the capacity of nodes and rings, together with traffic delay values are the control variables under investigation.

Simulation results for the different network model under uniform and non-uniform traffic demands are reported. The algorithm is able to return a solution with a performance measure that is close to optimal.

The strength of this technique lies in its ability to handle optical constraints more efficiently, and for this reason, it is considered a suitable alternative for applications that require computationally less intensive search algorithm.

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Table of Contents

Declaration	iii
<i>Dedicated to</i>	iv
Abstract	v
Acknowledgements	vii
Table of Contents	ix
List of Figures	xi
List of Tables	xiii
Glossary	xiv
1.2 Network Planning Problem Scenario	4
1.2.1 Problem Statement.....	5
1.2.2 Requirements	5
1.3 Problem Decomposition	5
1.3.1 Capacity Planning Problem	5
1.3.2 Diversely Routed Traffic Problem	6
1.4 Hypotheses	6
1.4.1 Hypothesis 1: Network Capacity Planning.....	6
1.4.2 Hypothesis 2: Circuit Delay Estimation	7
1.5 Thesis Outline	7
1.6 Contributions	8
2 Existing Proposition	9
2.1 Capacity Planning in NG SDH Ring Design & Associated Problems	9
2.1.1 SONET/SDH Node Assignment Problem (SNAP).....	11
2.1.2 SONET/SDH Ring Assignment Problem (SRAP).....	13
2.1.3 SONET/SDH Ring Loading Problem (SRLP)	14
2.1.4 SONET/SDH Ring Routing Problem (SRRP).....	15
2.2 Delay of Diversely Routed Traffic in NG SONET/SDH Networks	15
2.2.1 Differential Delay Problem.....	17
2.2.2 Management of Differential Delay in NG Systems & Networks.....	17
3 Design & Planning	19

3.1	Capacity Planning	19
3.2	Logical Topology Design	24
3.2.1	<i>Traffic Demand</i>	24
3.2.2	<i>Link Design</i>	26
3.2.3	<i>Bi-Directional Line Switched Ring (BLSR) Design</i>	29
3.3	Fiber Routing & Dimensioning	30
4	<u>Ring-node Assignment Algorithm</u>	32
4.1	Constraint Satisfaction Technology	32
4.2	Minimisation Function	34
4.2.1	<i>Federal Ring versus Number of Access Rings</i>	35
4.2.2	<i>Formal Modeling of the Problem</i>	37
4.2.3	<i>Constraints Propagation</i>	38
4.2.4	<i>Handling Special Constraints</i>	39
4.3	Node Cost Function	40
4.4	Proposed Algorithm	41
5	<u>Simulation results & Analysis</u>	47
5.1	Simulation Testbed	47
5.1.1	<i>Setup of simulation</i>	48
5.2	Result & Analysis	51
5.2.1	<i>Capacity instance</i>	51
5.2.2	<i>Network cost</i>	55
5.2.3	<i>Differential delay</i>	56
6	<u>Conclusion and future work</u>	61

List of Figures

Figure 2.1: BLSR STM-1 traffic is carried on a given timeslot between any two nodes pair 10

Figure 2.2: Using the concept of nested polygon to reduce the number of nodes 12

Figure 2.3: Sample network illustrating diverse delay routing 16

Figure 3.1: Bellville Fiber Routing Plan..... 20

Figure 3.2: STM-1 Frame Structure..... 21

Figure 3.3: Traffic flow between node pair 24

Figure 3.4: Screenshot of Link design result showing fiber length and equipment..... 28

Figure 3.5: A multi-ring SDH topology with several inter ring traffic and fixed number of nodes 29

Figure 4.1: Modeling SDH CSP problem 36

Figure 4.1: The original network of 12 nodes and 7 rings before merging..... 44

Figure 4.3: Scenario 1: A network of 12 nodes and 5 rings..... 45

Figure 4.4: Scenario 2: A network of 12 nodes and 4 rings..... 45

Figure 4.5: Scenario 3: A network of 12 nodes and 3 rings..... 46

Figure 4.6: Scenario 4: A network of 12 nodes and 3 rings..... 46

Figure 5.1: Illustration of traffic demand distributions between access and federal rings 52

Figure 5.2: Illustrates the use of DDR algorithm to solve ring assignment problem..... 53

Figure 5.3: Testing DDR algorithm for all-uniform traffic in different networks 54

Figure 5.4: Comparing model network solution to original network in terms of network cost 55

Figure 5.5: Modeling differential delay problem [Adapted from [25]] 57

Figure 5.6: Testing the performance of the proposed algorithm using differential delay. 59

University of Cape Town

List of Tables

Table 3.1: Estimation of total traffic network capacity for pilot deployment.....	22
Table 3.2: Estimation of total network capacity	23
Table 3.3: Traffic matrix for uniform traffic demand.....	27
Table 5.1: Traffic matrix for Non uniform traffic demand.....	50
Table 5.2: Estimation of end-to-end delay.....	59

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Glossary

A-D

Access ring: This is a portion of communication networks of ring topology that interconnect users to the core network and receives multiple types of services (such as IPTV, IP Telephony, and multimedia and Internet web access).

ADM: This is a device installed at an intermediate point on a transmission line that enables new signal to come in and existing signal to go out.

BLSR: Bidirectional line switched ring is a method of SDH transport in which half of the working network is sent counterclockwise over one fiber and the other half is sent clockwise over another fiber.

CIR: Committed Information Rate is a minimum Frame-relay network bandwidth guaranteed between two sets of terminal equipment connected via PVC (Private Virtual Circuit).

CO: Central Office is a local switching facility of Telephone Company to which telephones are connected.

DXC: Digital Cross Connect is an electronic cross-connect system that has access to lower-rate channels in higher-rate multiplexed signals as well as the capability to electronically rearrange (cross-connect) those channels.

E-H

GFP: Generic Framing Procedure is an ITU-T G 7041 standard that allows mapping of variable length, higher layer client signals over a transport SONET/SDH network and their likes.

Grooming: The method of consolidating or segregating traffic for efficiency

I-L

IP: Internet Protocol provides for the transmission of datagrams from a source to a destination. The source and destination are hosts identified by fixed-length IP addresses.

ITU-T: (The International Telecommunications Union-Telecommunications). An international body associated with telecommunications standardization

M-P

MTU: Multi-Tenant Unit is a building with multiple offices or apartment. MTU are more economical to target for installing DSL and other media Message Service, a method of transmitting graphics, video clips, and sound from broadband link than single-occupancy offices or houses.

OXC: Optical Cross Connect is a device that can move optical signals between different optical fibers, without the need for conversion to electrical signal.

Q-T

QoS: Quality of Service is the idea that transmission rates, error rates, and other characteristics of a network can be measured, improved, and, to some extent, guaranteed in advance. Classes of services used by carriers to service providers to guarantee delivery of traffic as per a service level agreement.

SLA: Service Level Agreement is a contractual agreement between a service provider and a subscriber specifying the QoS parameters that the subscriber can expect to receive.

SDH: (Synchronous Digital Hierarchy). The ITU-T defined world standard of transmission whose base transmission level is 52 Mbps (STM-0) and is equivalent to SONET's STS-1 or OC-1 transmission rate.

SONET: (Synchronous Optical Network). This is a standard for optical transport that defines optical carrier levels and their electrically equivalent Synchronous Transport Signals (STS).

STM: (Synchronous Transport Module). An element of the SDH transmission hierarchy; STM-1 is SDH's base-level transmission rate equal to 155 Mbps; higher rates of STM-4, stm-16, and STM-48 are also defined.

TDM: (Time Division Multiplexing). A method for transmitting multiple calls over a single line; each call is assigned a recurring time slot on the line, and a small portion of that call gets transmitted over the line each time its assigned time slot available.

U-Z

UPSR: (Unidirectional path-switched ring). This is a method of providing redundancy for fiber-optic lines on a SDH ring. The SDH ring consists of two fiber-optic lines, each carrying the same

traffic, but transmitting it in opposite directions around the ring. If one line fails, the backup line is already carrying the same traffic.

VCAT: This is an inverse multiplexing technique used to split SDH bandwidth into logical groups, which may be transported or routed independently.

VoIP: Voice over IP is the two-way transmission of voice information over a packet-switched TCP/IP network. (This is also known as "IP telephony".)

VPN: A virtual private network is a private data network that makes use of the public telecommunication infrastructure; maintain privacy through the use of tunneling protocol and security procedures.

WDM: (Wavelength- Division Multiplexing). (1) A technique of fiber-optic transmission for using multiple light wavelengths (colour) to send data over the same medium. (2) Two or more colours of light on one fiber. (3) Simultaneous transmission of several signals in an optical waveguide at differing wavelengths.

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Introduction

Multiservice provisioning platform (MSPP) is a leading-edge technology that re-engineered the legacy Synchronous Digital Hierarchy (SDH) optical networks to address the demand for the transmission of numerous new services; mostly IP-based, such as voice over IP, VPN, video conferencing, IP television, and online gaming, and many more. With the new capability and functionality, the old Time Division Multiplexing (TDM) based SDH networks, now referred to as next generation SDH is a promising transmission technology.

In network designs using this technology, ring architecture is more favoured for its offer of very fast restoration capabilities in the event of a single network node failure. The building block for ring architecture is the MSPP. Multiple MSPP located at sparsely distributed customer sites can be daisy-chained to form access ring for either bi-directional or unidirectional traffic flow. MSPP of greater switching capacity otherwise known as MSSP (Multiservice Switching Platform), interconnect a number of access rings to the backbone ring. Moreover, the design of backbone ring requires that the number of connected access rings must be minimised in order to reduce the overall network cost.

Within each node (MSSP and MSPP) are a group of hardware called Digital Cross Connect (DXC) and Add and Drop Multiplexer (ADM), whose cost determines the node cost. In a similar manner, a network design should also optimize the placement and the number of this hardware in the node (MSPP) to minimize the cost of the design.

The objective function is to minimize both the number of access rings and the number of nodes installed on each ring to reduce the overall cost of the network design.

A solution to such design and planning problems is complex and difficult to solve due to the number of constraints involved. It is often decomposed into a sequence of small, easier to manage sub-problems in order to solve it. Most times, it may be necessary to divide each sub-problem into smaller sub-problems, and every problem unit modelled using Integer Linear Programming (ILP). This action will certainly generate a list of inequality equations, each defining one or more constraints. It is necessary to solve each of these equations in order to obtain an optimum design solution.

Over the past few years, many research activities have made considerable efforts to solve this problem ([6] and [7]) by developing many ILP-based heuristic algorithms. The intractable nature of this approach led to introduce a workaround solution method whereby the variables defining the constraints are loosely assumed to be 0-1 rather than using arbitrary integer. Paradoxically, the problem of solving 0-1 ILP is still non-trivial, and therefore classified as *NP-hard* in literature. Moreover, some of these studies also include optical constraints, and node interface capacity constraints issue into their design considerations. This is because there is an increasing concern on the impacts of differential delay restriction on the new set of network services.

The growing number of constraints gives an indication that ILP may not be very suitable design approach, most especially for the design of the backbone ring of next generation optical networks. Based on this, we therefore propose a new design technique that will better handle all the sets of constraints to be satisfied, and as well, provide a solution that utilizes minimum number of access rings.

This thesis proposes a new approach for solving ring and node assignment problem with capacity and differential delay constraints in optical network design. The key objective is to reduce the total cost of Multiservice SDH optical network by a way of searching for a solution that is not only cost effective in terms of the number of access rings assigned to the backbone, but also satisfy a number of given constraints.

This chapter presents a general overview of this thesis. A classical approach is adopted whereby we work through the design procedure from the technical specifications extracted from customer service requirements. The role of service operator, otherwise known as carrier is assumed by the author; and collates customer demographical and population data of the area of coverage to classify the service profile. The results obtained in this preliminary design process are used at the later stage.

As a basis, a case study of a typical scenario of a service provider involved in the analysis, design, and implementation of a large optical network that provides service to an excess of 22,000 users is considered. The objective is to provide a cost effective solution by treating the problem as ring-node assignment problem. Rather than use one of the mathematical programming based ring-node assignment heuristic algorithms to deal with this problem, a constraint programming based heuristic that is less cumbersome and computationally less intensive is developed.

1.1 Optical Network Planning Case Study

Suppose a service provider in Cape Town, South Africa involves in the analysis and design of a large optical network that provides services to an excess of 22,000 users. It is the intent of this provider to offer multiservice ranging from voice, data, streaming video, virtual private network service, Internet access and storage services. Available to this provider is the right of use of 60km two-strand of fiber in Bellville¹ and it's environ. One of the first tasks is for the service provider to conduct an initial site survey in order to choose where to locate the nodes of the backbone network. Placement of these nodes in a strategic location will assist in determining the fiber routing options of traffic from

¹ Bellville is a city in the Western Cape province of South Africa

many buildings unevenly distributed. The Service Provider would be wise enough to place these nodes where larger communication demands originate (major towns) in order that traffic bandwidth capacity is effectively utilized.

In order that the service provider meets the various design and customer service requirements, certain optical network constraints must be resolved first. It is the intent of this research to provide a low cost optical network design end-to-end solution by solving ring and node assignment problems towards reducing the network cost within the limitation of optical constraints.

1.2 Network Planning Problem Scenario

Given a budget BG in South Africa Rand, and customer capacity base U of 22,200 differentiated into 14,200 business customers B and 8,000 residential customers R . If 12,000 of B are classified as small and each with an average of 1 employee, and 2,200 are classified as medium sized with an average of 10 employees and the remaining 200 is classified as large customers having up to 100 employees on average. All residential customers are also small office/home office customers that need voice and broadband Internet access, while business customer needs include voice, virtual private network (VPN), and Internet access. In all, 250 buildings must be lit in order to provide connectivity to all the potential customers. The service level agreements must not be less than 99.999% uptime (i.e. network availability) and 25ms end-to-end differential delay.

It is required that a cost effective optical solution be provided, given diverse fiber routing, network and node capacity, delay differential restriction, and logical topology design as possible constraints.

1.2.1 Problem Statement

The purpose of this study is to analyse and design a multiservice next generation SDH optical network subject to ring-node capacity and traffic delay constraints, in order to provide a cost effective optical solution under different traffic types and conditions, without violating the specified service level agreements (SLAs).

1.2.2 Requirements

- * Total number of building to be lit: 250
- * Network Availability: 99.999%
- * End to-end latency: 25 ms
- * Quality of Service: six classes
- * Services: Voice, Internet access
- * Customer equipment Interfaces: Ethernet -E1/Digital signal-DS1

1.3 Problem Decomposition

1.3.1 Capacity Planning Problem

1.3.1.1 Impact of Uniform Traffic Matrix on Capacity Planning Problem

The first sub-problem is to determine whether the network traffic capacity using bi-directional uniform traffic matrix will meet the estimated bandwidth request, such that a low-cost solution that satisfies all the given constraints is feasible and a suitable model can be developed for future forecast. The objective being to maximise throughputs while minimising network cost.

1.3.1.2 Impact of Non-Uniform Traffic Matrix on Capacity Planning Problem

This is to determine whether the network traffic capacity using bi-directional non-uniform traffic matrix will meet the estimated bandwidth request, such that a low-cost solution that satisfies all the given constraints is feasible and suitable model can be developed for future forecast. The objective being to maximize throughputs while minimising network cost.

1.3.2 Diversely Routed Traffic Problem

This sub-problem analyses the performance of SDH network design for diversely routed traffic paths such that a minimum end-to-end differential delay is sustained by the components signals in accordance with service level agreements, thereby reducing the size of buffer memory. The key objective is to reduce the cost of equipments.

1.4 Hypotheses

1.4.1 Hypothesis 1: Network Capacity Planning

The total request of bandwidth of network nodes assigned to the same SONET/SDH ring is equal to the sum of bandwidth request between every pair of nodes in the ring plus the total bandwidth request between nodes and the nodes assigned to other SONET/SDH ring for bi-directional traffic matrix. This traffic demand, and the demand on the federal ring must be less than or equal to the common capacity " B " bandwidth. This point will be discussed in details in subsection 2.1.2.

1.4.2 Hypothesis 2: Circuit Delay Estimation

In a SONET/SDH network where only the terminal nodes are virtually concatenation enabled, the end-to-end delay increases as the number of intermediate network elements for a specified SLAs are increased

1.5 Contributions

An alternative method of solving ring assignment problem in optical network design with multiple constraints has been proposed. This involves the development of heuristic algorithm based on constraints satisfaction technology (CSP). The implementation of algorithm is attempted using a state-of-art optical network simulation tool (OPNET WDMGuru).

The following summarises the essence of this approach as compared to the commonly used Integer linear programming (ILP).

This proposed solution if properly implemented would be less computationally intensive, and the amount of energy dissipated by the system processor will be reduced to about 40%.

It is simple and robust, and capable of finding solution more quickly than Integer linear programming.

It will have a better handling and treatment of general and special optical constraints as compared to the available algorithm developed based on $0-1$ Integer linear programming to solve similar problem.

The proposed algorithm model solution will be supported by a number of existing constraints toolkits such as ILOG Solver, and Eclipse; with this, applications can be developed to solve various types of planning and scheduling problems in telecommunications, transportation, and manufacturing process.

Although the proposed method is applied specifically to Synchronous digital hierarchy/Synchronous optical network (SDH/SONET) technology, it could equally be used for a low-cost design of Wavelength Division Multiplexing (WDM) optical network.

1.6 Thesis Outline

In **Chapter 2**, the author will review common SDH ring-related problems. Most especially the ring assignment problem, and treat it as a graph partitioning problem.

Chapter 3 discusses the design process. Here, related issues such as network traffic capacity planning, Delay analysis and logical topology designs are examined

Chapter 4 discusses ring-node assignment algorithm. The author presents a simulation-based heuristic approach built on constraint satisfaction technology.

Simulation results and detailed analysis of design process are considered in **Chapter 5**.

Finally, in **Chapter 6** the author draws some conclusions and discusses future directions

2 Existing Proposition

The next generation Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) answers the demand for a communications network with improved data QoS, higher data rates, exceptional flexibility, efficiency and scalability, superb protection, and a data-friendly standard; by integrating the simplicity and cost-efficiency of the data network with bandwidth capacity and QoS of the synchronous optical network [1]. The versatility of the technology introduces some design challenges based on both optical and equipment interface constraints. In order that the fundamental design objective is achieved, two metrics play significant roles viz: the network cost, and the quality of service (QoS). The network cost minimization depends on the optimization of the number of rings and nodes in the design, and the QoS issue is addressed by traffic delay analysis. The impact of delay depends on the type of service delivered through the network [24]; however, among network delays, propagation delay that is predominantly dominated by differential delay.

This chapter is sub-divided into two parts. The first part comprises two sections; therein the challenges in rings and node design are discussed, while second part examines the issues related to the estimation of traffic delay. A thorough review of current research activities as related to these issues is done in order to have better understanding of the proposed solution method.

2.1 Capacity Planning in NG SDH Ring Design & Associated Problems

The most popular Next Generation (NG) SONET/SDH architecture for metro and Wide Area Network (WAN) is the ring model. It provides high reliability, survivability and provides 50ms restoration times. The building block for ring architecture is the Add and Drop Multiplexer (ADM), and more recently Multiservice Provisioning Platform (MSPP). MSPP is an integrated optical solution that combines the functionality of ADM and Digital Cross Connect (DXC).

Multiple MSPP can be daisy chained in a ring configuration for either BLSR (Bidirectional Line switched Ring) or UPSR (Unidirectional Path Switched Ring). SDH BLSR is the most efficient standard ring architecture and is widely deployed.

In the configuration of Fig. 2.1, the same set of MSPPs and links use both directions of transmission. It utilises the network capacity ONLY between the MSPPs where the traffic is added and dropped unlike UPSR, whose network capacity is factored on the entire rings thereby leading to inefficient capacity utilization.

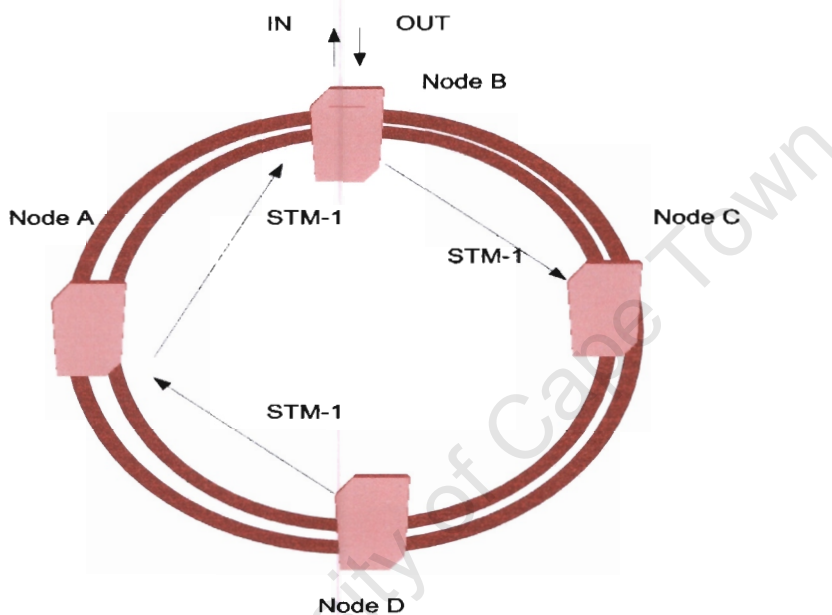


Figure 2.1: BLSR STM-1 traffic is carried on a given timeslot between any two nodes pair

Due to the complex nature of optical design as reported in Chapter 1, and since there is no single optimal solution to any complex design problem [2], the design will consider the trade-off between high capacity ring design and minimum number of nodes such that the overall network cost can be put to the lowest.

The following sub-sections review research work on various components of the SONET/SDH ring architectural planning problems among which are ring selection, ring routing,

node assignment, load balancing, and physical ring design. An overview of work related to models and solution algorithms for various aspects of ring planning problems are examined.

2.1.1 SONET/SDH Node Assignment Problem (SNAP)

SDH node assignment problem (SNAP) entails looking for a solution which makes a full use of the network bandwidth using the minimum number of MSPP. The number of MSPPs is given as constraint, which invariably affects the network service cost.

The initial research work on optical network cost minimization focused on the routing and wavelength assignment (RWA) [3] - [4], which have been extensively studied. However, more recently emphasis has shifted to a more realistic network cost measure called the node cost.

Amongst others, is the work of Mordechai Shalom et al. [5] where an architecture based on successive nested polygon is developed to minimise the nodal cost. Even though, generally the problem of minimising the number of network nodes and assigning virtual concatenated paths (VCAT path) are related but have different objective function. In this work, the author attempted to bring out the trade-off between the two. A follow-up on the argument advanced in [5] would possibly lead to a situation whereby an optimum solution is required for a case when number of paths in VCAT is two; i.e. $VCAT_{path} = 2$ (for example). The algorithm developed returns a solution using $O(VCAT_{path} \log VCAT_{path} + N)$ MSPPs, where N is the size of the ring. We could also infer based on the result he presented that this solution will perform better than the basic architecture which is $NVCAT_{path}$ MSPPs.

Figure 2.2 below is a nested polygon used to show how the number of nodes assigned to a ring could be minimised. In the illustration, it is assumed that no Wave Division Multiplexing (NO-WDM) is deployed, and that only one wavelength per fiber ring is available. In order to analyse the Figure, it is easier to start from the outermost circumscribing circle and move inward to the innermost circle. However, it is much convenient to proceed in the opposite direction, assuming that the inner most circle is the initial SONET ring.

It is assumed that the number of nodes assigned to the inner most ring is maximum and the ring capacity is completely utilised. The task at hand is to search for a solution that would minimise the number of nodes, and maximized the ring capacity.

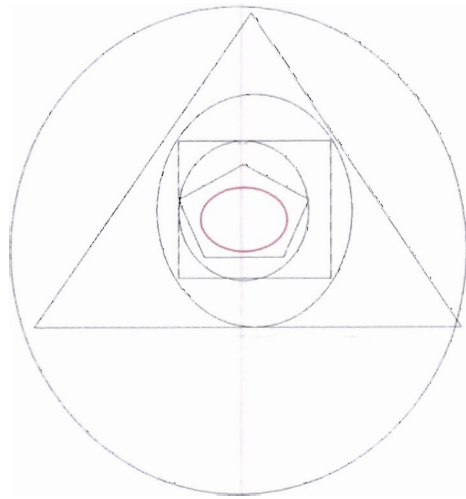


Figure 2.2: Using the concept of nested polygon to reduce the number of nodes

The first thing is to circumscribe the innermost circle with a polygon on N sides; each vertex of the polygon corresponds to the location of assigned nodes. Then a circle of radius r_{n-1} is circumscribed on the polygon with N sides. Next, a polygon with $N-1$ is drawn again, and a circumscribing circle of radius r_{n-2} is drawn. This process continues until the minimum number of polygon (reference polygon) with the capacity equals to the capacity of the original (initial or innermost ring) is obtained. A circumscribed circle corresponding to this polygon is a solution, and its radius is defined as R . If the radius of the initial (inner most) circle is designated as r , then, $r = R \cos(\pi / N)$, and π can be replaced by 180 .

The details of this concept are beyond the scope of this thesis.

2.1.2 SONET/SDH Ring Assignment Problem (SRAP)

SDH ring assignment problem primarily deals with ways of minimising the number of local rings that are interconnected by the backbone ring, generically referred to as federal ring. The local rings are the rings that interconnect the customers sites located on the same rings, while the backbone interconnect two or more sites located on different local rings. It is assumed that the total amount of traffic on all the local rings must be less than or equal to the capacity of the backbone network. Each site on the local rings interconnected by federal rings must be connected by another special device back-to-back, and is known as MultiService Switching Platform (MSSP²). The number of local rings determines the number of MSSP required, and if this is added to the number of MSPP, then overall network cost will increase. It is therefore possible to argue for the strong need of node and ring optimisations in order to reduce network cost.

The work of [6] that was further investigated by [7] adopted Integer linear programming and heuristic algorithm approaches in order to minimise the network cost. The problem is analysed and treated as a graph partitioning problem using an undirected graph $G = (V, E)$, with integers B and K , and a non negative edge weight d_{uv} associated with each edge (u, v) . This problem is considered NP complete. The question raised is that: Is there a partition of V into K disjoint sets V_1, V_2, \dots, V_k such that:

$$\sum_{u \in V_i, v \in V_i, i=1, \dots, k} d_{uv} + \sum_{u \in V_i, v \in V_j} d_{uv} \leq B \quad (2.1)$$

$$\sum_{i=1}^{k-1} \sum_{j=i+1}^k \sum_{u \in V_i} \sum_{v \in V_j} d_{uv} \leq B \quad (2.2)$$

² This is similar to MSPP but of greater switching capability in the minimum range of 300 Gbps

for $i=1,2,\dots,k$, and

In equation 2.1, the first term computes the traffic between any two sites in the ring and the second term computes the traffic between the sites outside the ring and the sites in the ring. Similarly, equation 2.2 computes total traffic on the federal ring and it is less than or equal to the common bandwidth capacity B .

In their results, the proposed algorithm finds the optimal solution that minimises the upper bound of number of local rings interconnected by the federal rings for reduced network cost.

Nevertheless, a recently conducted industrial research [15] shows that the minimum number of OC-48 (OC-92 equivalent) rings in the CO (Central Office) is between 8 and 12 to justify the use of MSSP. With this it makes economic sense to deploy single MSSP that can aggregate multiple rings than single ADM for each of the rings. This implies that any serious attempt to reduce the network cost, node cost must also be considered.

2.1.3 SONET/SDH Ring Loading Problem (SRLP)

This problem also arises in the planning phase of SONET/SDH network with BLSR configuration. In this case, traffic demand must be routed in one of the two possible routes around the ring as discussed in [9] in the manner that no fiber link may be loaded more than the other.

Following the discussion in [8], it is realised that traffic demand on the fibre links between any two nodes in BLSR ring is no longer limited by transmission bandwidth of the link, but rather by the processing capability of electronic switches-MSP. Traffic may be split and routed diversely in any number of independently defined paths. Every link on the same ring has the same capacity, but the ring capacity may be different from one ring to the other. Then the challenging task of any planning software would be to identify the nodes that can be grouped together to form a network of rings of equal capacity constraints.

2.1.4 SONET/SDH Ring Routing Problem (SRRP)

SDH ring routing problem is a problem of determining the best paths to route each traffic demand in SONET/SDH network. It is done so as to right-size the ring, and it is equally one of the important processes in network planning and design. Algorithms for traffic demand routing are numerous and not new, but many of them are for general purposes. However, the works of [11] and improved upon by [10] that runs in $O(n^4)$ and $O(n^2)$ running time respectively are the currently known specialised algorithm for solving ring routing problem in the literature.

In this design, and using the available simulation tool, a cost-based diverse routing algorithm with nodes and link maximally disjoint shall be selected. Using this routing method, the link is assumed to have a non-negative cost, and the network traffic is routed hop-to-hop with minimum cost.

2.2 Delay of Diversely Routed Traffic in NG SONET/SDH Networks

There are several types of delays that affect next generation SONET/SDH systems and networks, and the impact of these delays depend on the types of services delivered. While some services are sensitive to delay variations and less sensitive to transfer delay, others may be sensitive to both. It is then necessary that one needs to consider the delay requirements of each service type, and ensure that it conforms to the service level agreements (SLAs) as specified in the initial specifications. The focus of this work is on the design for multiple service types, and at the end, the delay measurement shall be estimated from the source to the destination end as was clearly stated in the introductory chapter 1.

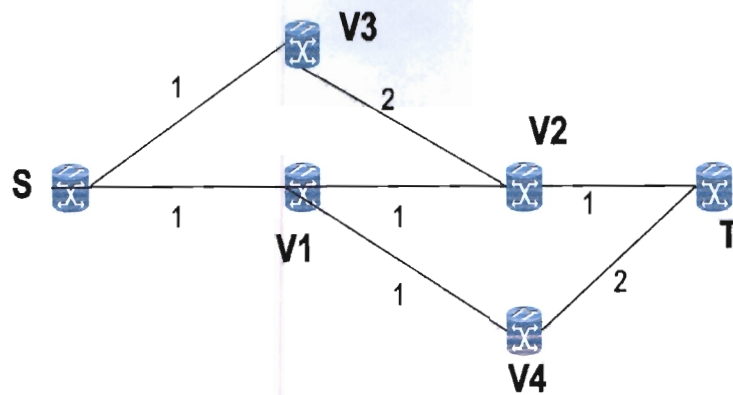


Figure 2.3: Sample network illustrating diverse delay routing

For completeness, any serious analysis of end-to-end delay in next generation SONET systems and network must consider the propagation delay, serialisation and processing delay. Both serialisation and network element processing delay come from the data nature of the Generic Framing Procedure (GFP). Also, the propagation delay is the principal cause of differential delay.

Throughout, only the differential delay is considered; and any discussion on generic framing procedure is beyond the scope of this work. However, all interested readers are therefore advised to review [20] for a comprehensive discussion of GFP and its associated challenges in optical network design. Figure 2.3 illustrates an instance of differential delay problem where the source node S is VCAT enabled. There are two diverse routes for concatenated signals to transverse (S-V3 and S-V1). Signal at V1 can also transverse two paths (V1-V4 and V1-V2), and all the signals from different diverse paths, converge at the destination node T.

Destination node T must be equipped with sufficient memory to buffer all arriving signals before being mapped to the high-speed network.

2.2.1 Differential Delay Problem

Differential delay is the relative arrival time measurement between the members of Virtual Concatenated Group (VCG). Any customer premise equipment supporting VCAT must be equipped with high-speed buffer memory for storage of arriving component signals at the destination node [17]. These signals are assigned sequential number SQ, and they transverse from the source to the destination node in any of the diverse path available in the transport signal. The more the number of diverse paths the greater the size of buffer memory reserved at the destination node, and invariably, this will affect the cost of the equipment.

Research and industrial communities have come up with algorithms (both online and offline) to address issues relating to minimisation of differential delay ([12], [13]) in SDH systems and networks; many of which are heuristic, and are based on modified popular k-shortest path algorithm (SPF) and its variation. The performance of these algorithms is however, hindered by the fact that path routing in optical network unlike in IP is a multiple-constrained problem (MCP), and as such a constrained-based shortest path first algorithm (CSPF) is more appropriate.

After thorough reviews of [14], it shows that CSPF is an intrinsically harder problem. According to [14], several proposed algorithms for CSPF can be categorised into two: those that are based on the extension of the best known Djikstra algorithms, and those based on the prior knowledge of traffic profile of the network and uses a flow-based algorithm. The network simulator is configured to use the first category of routing algorithm.

2.2.2 Management of Differential Delay in NG Systems & Networks

Delay differential in virtually concatenated network system is managed by ensuring that two key things are considered:

* The receiving equipment needs some method of re-aligning the containers arriving on the different paths.

* In order that the network may compensate for the differential delay between different paths transversed by members of the virtual concatenated group, some buffer memory must be reserved in the equipment.

Re-alignment process involves buffering of incoming data and using a sequence indicator (SQ) in the H4 -byte in the path overhead of all members of the higher order virtual concatenated group (VCG) to put containers into the correct order. In order word, each members of the VCG is assigned a sequence number as data are "demultiplexed" onto them. H4-byte defines the structure of multiframe indicator for payload and contains a 12-bit multiframe indicator (MFI) and 8-bit SQ. The multiframe format is defined by H4-byte has two set of MFIs - MFI1 and MFI2. Together they form a 12-bit field that rolls over every 512ms (4096*125 microseconds). This allows for a maximum differential delay path of less than 256ms as allowed by the standard. The network, delay is expected around 60-100ms in real world though.

The main issue with differential delay is the amount of memory buffer space required. The best practice is to calculate the amount of buffer space required using the number of members supported. For example, if 84 members or (number of paths) are supported and VT-1.5/VC-11 (the lowest of the lower order signal) signal is to be transmitted, the size of buffer memory is 33 Mbit. The memory options that support these rates are not many, and very expensive.

The solution to the management of differential delay problem therefore relies on the development of path optimisation algorithms (subsection 2.2.1), which will be able to reduce the paths transversed by members of the virtual concatenated group. In this aspect, there is currently an on-going research as earlier mentioned.

3 Design & Planning

This chapter discusses the design procedure. Capacity planning was conducted for different categories of business and residential users in Bellville in order to determine the capacity of the access and federal rings. The outcome of this capacity plan computation will drive technology and equipment specifications in terms of bandwidth requirements. Next, the link and ring design were completed to pave the way for logical topology design. As a prelude to the analysis of the overall design, traffic routing and dimensioning on diverse paths are also examined. The results of the design serve as inputs to Chapter 4.

3.1 Capacity Planning

In order to estimate the total bandwidth requirements of users differentiated into small, medium and large scaled businesses as stated in section 1.2, it is important to carry out a fiber routing plan as shown in Fig 3.1 to determine the location of sites where services need be provided. For simplicity, analysis of only the first-twelve sites was carried out, and these sites were lighted up in a pilot run.

It is assumed that there are up to 250 sites in Bellville industrial area, and each one is considered a Multi Tenant Unit (MTU) housing 50 small businesses, 21 medium businesses and 5 large businesses. Each of the 50 small businesses has 1 user; each of the medium businesses has 10 users and each of the large businesses has 100 users. Also, a 64 kbps non-normalised voice grade bandwidth and 144 kbps non-normalised data bandwidth is allocated per user. As shown in Table. 3.1, nodes 0-12 each of which represents clients' sites located at selected point within Bellville area. The site naming convention is done such that each node corresponds to the site location and they are distinctively located at designated point. For example, because node "4" is an MTU

located in Blomvlei, it is therefore named Blomvlei. Also, a number of acronyms³ were used to represent users and service classification in terms of bandwidth request.

Using the stated diversity factor (this is the same as the number of users in each business category houses by the MTU), the bandwidth requirements for each MTU were computed, and the contributed bandwidth for the 12 sites add to a total of 2,721.6 Mbps. After normalisation to compensate for oversubscription, the total becomes 272.16 Mbps. Nodes at Hohelsen, Oakdale, Blomvlei and Boston are chosen as data centres and together, they constitute the core ring in the original physical network topology while every other ring interconnected to any of these nodes are designated as access rings. The ring interconnection points are assigned with high capacity switch-MSSP as discussed in subsection 2.1.2.

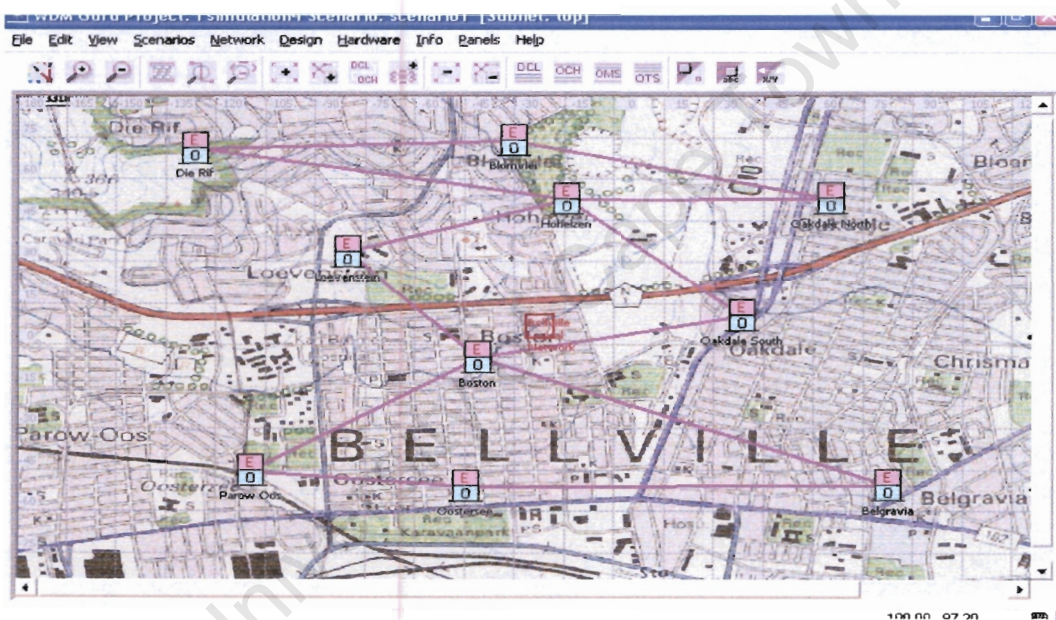


Figure 3.1: Bellville Fiber Routing Plan

After the initial calculation, and using table 3.1 below, it is easily deducible that for a bidirectional traffic matrix, the fiber span between Boston and Blomvlei (See Fig. 3.1) will consume 68.0 Mbps (22.68×3).

³ SB: small business, MB: medium business, LB: Large business, BR: bandwidth requirements

Assuming that the network traffic originated from Boston, and then 22.68 Mbps would be dropped off at Blomvlei, this leaves 45.36 Mbps of traffic on the span between Blomvlei and Hohelzen of which 22.68 Mbps would be dropped off at Hohelzen. Finally, there would be 22.68 Mbps of traffic on the span between Hohelzen and Oakdale South.

The above traffic distribution is also applicable to every pair of nodes in the network, and it is therefore possible to conclude that an STM-1 should suffice for the pilot deployment.

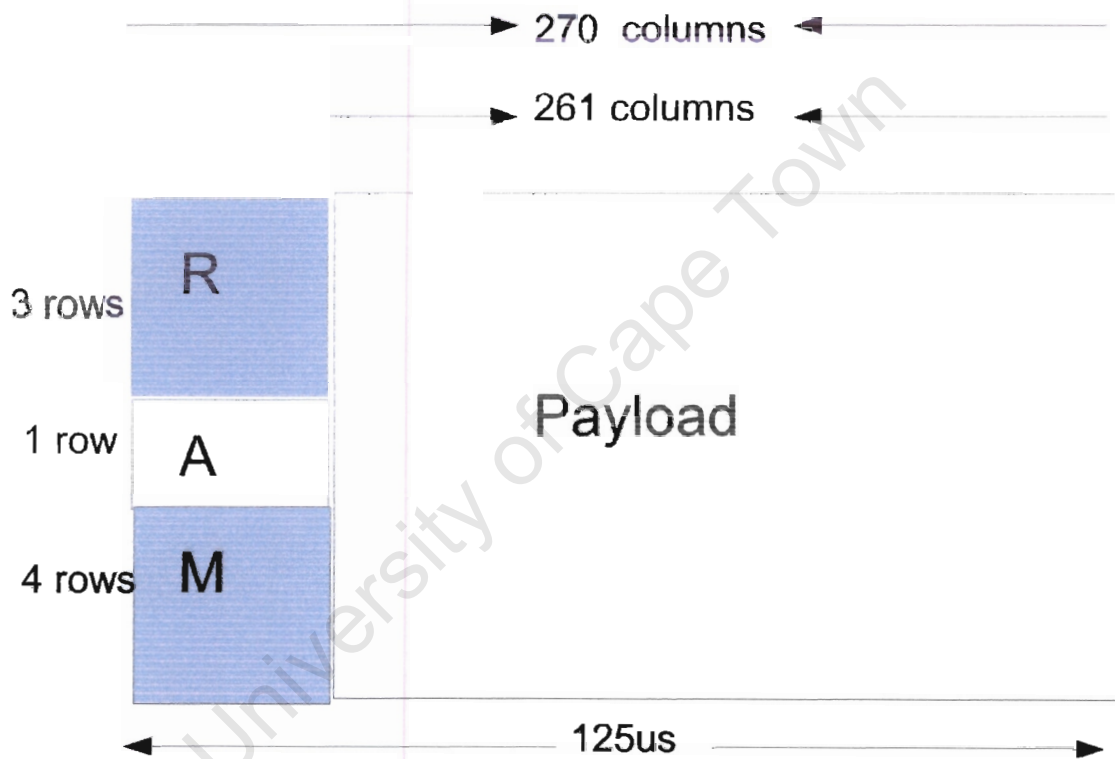


Figure 3.2: STM-1 Frame Structure

Notation: “R” is the regeneration section overhead (RSOH)

“A” is the AU pointer

“M” is Multiplex section overhead (MSOH)

Table 3.1: Estimation of total traffic network capacity for pilot deployment

Sites	Number of users			Contributed bandwidth (Mbps)						Total per site
	SB	MB	LB	SB voice	SB data	MB voice	MB data	LB voice	LB data	BR
Node0	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node1	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node2	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node3	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node4	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node5	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node6	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node7	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node8	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node9	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node10	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Node11	50	210	800	3.2	7.2	13.4	30.2	57.6	115.2	226.8
Sum from all nodes										2721.6
Normalised bandwidth (1:10) oversubscription										272.16

Using the result obtained in section 3.1 and the specifications as outlined in section 1.2, a normalised total bandwidth for voice and data traffic in the entire Bellville network is calculated as shown in Table 3.2.

In the Table, the column "user count" is calculated by multiplying the total number of sites (or call it customers' sites) by the number of employee (or users) at each site. Recall that the business customers are differentiated into 12 000, 2 200, 2 000 and are factor into 1:10:100 respectively. The column "normalized bandwidth" represents the normalized bandwidth with a 1:10 oversubscription. It is assume that in almost all the time, 12 nodes may not utilize the

network simultaneously such that each user could enjoy the maximum committed information rate (CIR).

Table 3.2: Estimation of total network capacity

UNITS	USER COUNT	VOICE TRAFFIC			DATA TRAFFIC		
		Bandwidth per user (Kbps)	Total Bandwidth (Gbps)	Normalized bandwidth (Gbps)	Bandwidth per user (Kbps)	Total Bandwidth (Gbps)	Normalized bandwidth (Gbps)
Residential	8000	64	0.512	0.0512	144	1.15	0.12
Small	12000	64	0.768	0.0768	144	1.73	0.17
Medium	22000	64	1.408	0.140	144	3.17	0.32
Large	20000	64	1.280	0.013	144	2.88	0.29
Total				0.400			0.89
Normalized total network traffic capacity (1:10) : 1.29 Gbps							

A normalized total bandwidth of 1.29 Gbps indicates that STM-13 (OC-36) core should be sufficient to provide enough bandwidth to cover the entire 250 sites in Bellville as per the estimated traffic demand.

3.2 Logical Topology Design

In this section, the result of SDH ring design is presented. Logical topology is the network topology as seen by the higher layer Digital Channel Layer (DCL). The nodes at the lower layer (ADM and DXC) constitute those at the higher layer, and the logical links are the signal or light paths established between any two nodes in the network. The logical design depicts how traffic is routed from one node to the other in the network. It shows the logical interconnectivity of nodes as seen by the higher layer- DCL. From the design point of view, logical design can be divided into two stages:

- The traffic demand estimate
- The link design

3.2.1 Traffic Demand

The two types of user's traffic considered for a logical (or virtual) topology design are uniform and non-uniform. A 12 by 12 traffic matrix was generated between each node pair and the total traffic (demand) capacity for all the 12 nodes. The demand between each pair is 4 units, and the total network traffic capacity is then add to 264 units as shown both in the Table 3.3 and calculation below.



Figure 3.3: Traffic flow between node pair

Let ρ_{ij} represents traffic from node i to node j , and ρ_{ji} represents traffic in the opposite direction.

Let ρ_v represents the offered load, i.e. the traffic demand per node pair. Because, a bidirectional traffic matrix is considered in this design, it is reasonable to assume that:

$$\rho_{ij} = \rho_{ji} \quad (3.1)$$

provided the traffic is uniformly distributed and a balance load system is considered. In this case, the traffic flow from each node is equal to half of the total offered load between the node pair.

Also,
$$0 \leq \rho_v \leq 4 \quad (3.2)$$

But for this particular case, ρ_v is chosen as 4 units, and N is given as the number of nodes in the network, the total traffic capacity is thus given as:

$$N(N-1)\rho_v \quad (3.3)$$

Given that there are 12 nodes in the hypothetical network used as case study, the network traffic capacity is

$$12(12-1)4 = 528 \text{ units.}$$

In Bidirectional Line Switched Ring (BLSR⁴) configuration, the working path carries only one half of the total traffic capacity. This implies that the traffic capacity in this network is only 264 units.

It is interesting to know that irrespective of whether the traffic distribution is uniform or non-uniform, the total traffic capacity remained the same.

⁴ see subsection 3.2.3

3.2.2 Link Design

The result obtained from traffic demand estimation is used to design the ring. However, prior to the ring design, it is important to do optical transport system (OTS) link design. By this, it would be possible to calculate the number of amplifiers and regenerators required on each link that would be used by subsequent design action. Long fiber link are susceptible to signal degradation and as such signal must be amplified and regenerated at regular intervals. All fibers are equipped LH-40 line system with only one active wavelength, and span length set to 100.0 meters with maximum of '6' OA per (optical amplifiers) per link. LH-40 indicates that the line is a Long Haul with a total of 40 channels per fiber strand. The outcome of the design with a list of sites added on each link as shown in Figure 3.2.

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Table 3.3: Traffic matrix for uniform traffic demand

Nodes	Node0	Node1	Node2	Node3	Node4	Node5	Node6	Node7	Node8	Node9	Node10	Node11
Node0	-	4	4	4	4	4	4	4	4	4	4	4
Node1	4	-	4	4	4	4	4	4	4	4	4	4
Node2	4	4	-	4	4	4	4	4	4	4	4	4
Node3	4	4	4	-	4	4	4	4	4	4	4	4
Node4	4	4	4	4	-	4	4	4	4	4	4	4
Node5	4	4	4	4	4	-	4	4	4	4	4	4
Node6	4	4	4	4	4	4	-	4	4	4	4	4
Node7	4	4	4	4	4	4	4	-	4	4	4	4
Node8	4	4	4	4	4	4	4	4	-	4	4	4
Node9	4	4	4	4	4	4	4	4	4	-	4	4
Node10	4	4	4	4	4	4	4	4	4	4	-	4
Node11	4	4	4	4	4	4	4	4	4	4	4	-

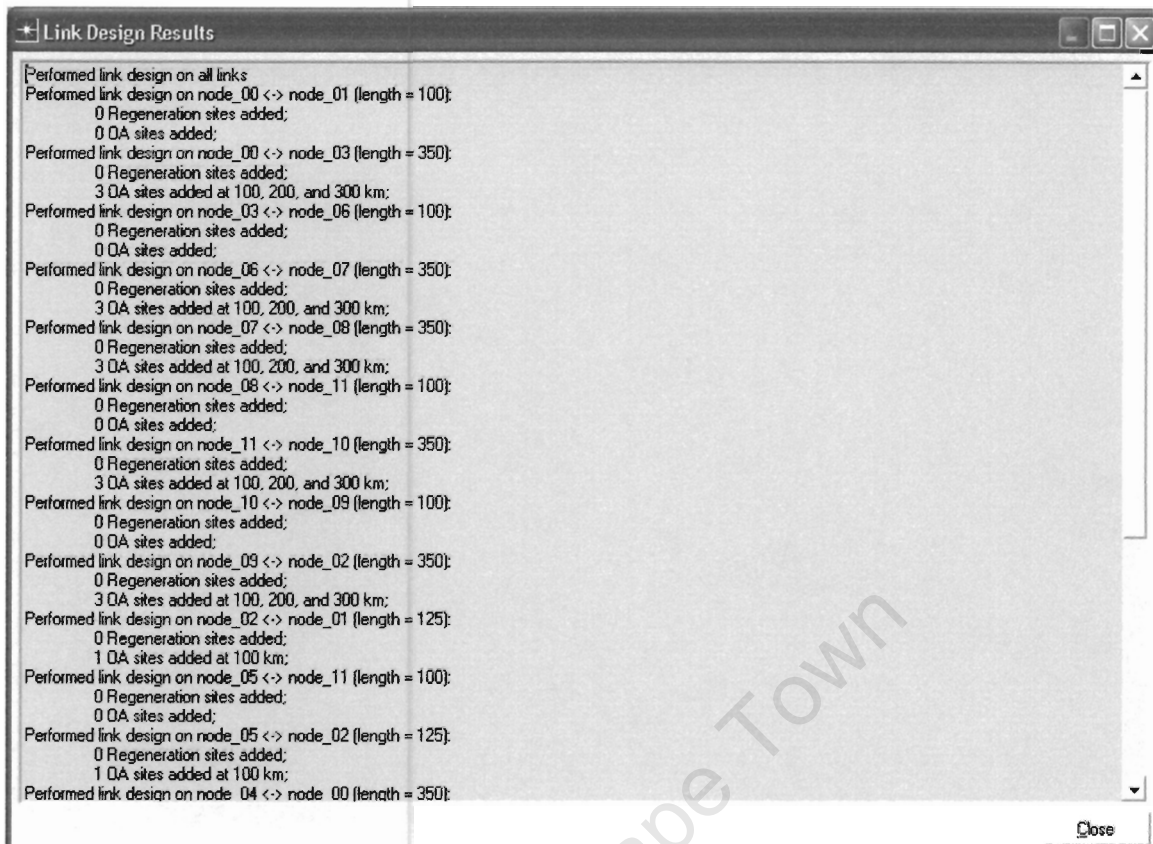


Figure 3.4: Screenshot of Link design result showing fiber length and equipment

The above is a screenshot of the result of the OTS link design. It shows that, for example the link between Blomvlei and Hohelzen has a fiber length of 125 km with no regenerator (R) and 1 optical amplifier (OA) at 100km.

The link is configured as follows: The total number of fiber links in the network is 17, and this divided into three parts thus: 7 links have a span of 350km node-to-node, 6 with a span of 100km from one node to the next and the last 4 fiber links also have a span of 125km between a pair of node. The distances are subject to the appropriate location of each of the nodes, and in this case, all distances are randomly chosen without any on-site measurement.

3.2.3 Bi-Directional Line Switched Ring (BLSR) Design

Using the fiber routing as shown in Figure. 3.1, the network lends itself into a 7-ring topology. For the original network configuration, the ring that spans across nodes "Blomvlei-Oakdale South-Boston-Hohelzen" has maximum of four distinct nodes, each node is a matching node that interfaces with four other rings with an even bandwidth distribution. For the sake of clarity, the ring with four distinct nodes was used to represent the core ring. It is also possible to have nodes on the designated core ring that do not connect to the other rings, otherwise known as access or tributary rings. Such nodes are often reserved as spare for future growth network traffic. Likewise, it is also possible to have (access) collector rings of varying bandwidths that may not be directly connected to the core ring. This situation is often described as ring merging.

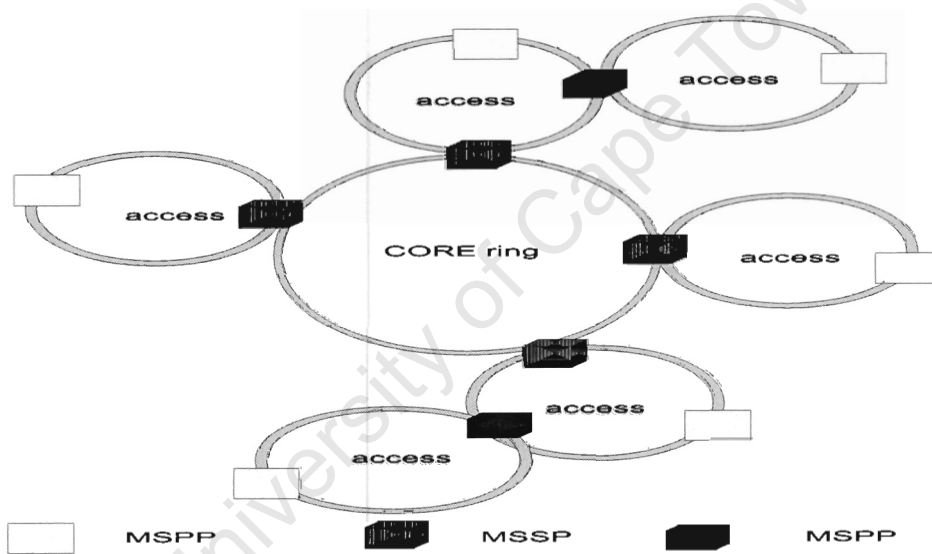


Figure 3.5: A multi-ring SDH topology with several inter ring traffic and fixed number of nodes

It is believed that inter-ring traffic will be "huge", and as such may require metropolitan core aggregation. To cater for that, MSSP is deployed in back-to-back configuration as explained in subsection 2.1.2.

Before designing BLSR (Bidirectional Line switched Ring) ring, it is important to first identify the properties of the proposed ring, and then set the number of sites (nodes) as variable against the number of rings as non-empty domain of possible values and a set of constraints. Details of this is available in [16] for any interested reader.

Next, the ring path was identified and defined by logically assigning nodes to a specific ring. For example, nodes at Hohelsen-Oakdale South-Blomvlei-Boston were mapped as the first ring. Topological location of six other rings in same manner were defined and named access rings. Following this, the specifications of our proposed rings in terms ring type and bit rate was defined, and 2-Fiber Multiplex section-Shared Protection Ring (2F-MSSPRing) - a type of SDH BLSR ring was selected and its capacity is STM-4 (622.080 Mbps).

3.3 Fiber Routing & Dimensioning

In order to set up a platform to test the performance of the design, an alternative traffic of concatenated bit rates- STM-1-21c was chosen. The choice of concatenated bit rates is to enable the network capacity to be used more efficiently.

Using the same baseline topology, nodes located at Die Rif and Belgravia were set as source and destination nodes respectively. A fiber connection is then established between the two nodes to observe the effect of varying the following constraints on network capacity.

* Maximum fiber length

- Shortest path length diversion factor⁵

* Maximum hop count⁶

⁵ The maximum fiber length is calculated by multiplying the factor with the shortest length of the connection

⁶ The maximum hop count is calculated by multiplying this factor with the hop count of the shortest path of the connection

- Shortest path hop count diversion factor⁷
- * Maximum link delay
- Shortest path link delay diversion factor

After this, traffic was routed on the link over 21 unique independent virtual candidate traffic routes (virtual concatenated paths), and two simulations were run to observe the effect. The first case is when there is a single physical fiber connection between the nodes, and second case is when two fiber are physically connected. By implementing two fibers connectivity, the limitation of virtual concatenation under diversely routed traffic condition can be tested.

Traffic information about each route with respect to hop count, fiber length, delay, cost, link capacity, and the number of different equipment installed in each node/site were also collected. Numerical data are collected to validate the performance of the proposed model as discussed in chapter 4.

⁷ The maximum link-delay path is calculated by multiplying this factor with the delay on the lowest-latency path of the connection

4 Ring-node Assignment Algorithm

This chapter commences with an introduction to constraints satisfaction technology. Thereafter, it discusses network cost minimization function with the cost split into node and link cost. Since our emphasis from the beginning of this work is on the node cost and not necessarily the cost of the link, it is important that the node cost is further divided into ADM cost and DXC cost component for a better analysis of the result.

Next, a review of the concept of constraint propagation and method of handling special constraints as it related to ring assignment problem is done. The chapter is concluded with a discussion of the proposed algorithm for solving ring assignment problem with capacity constraints.

4.1 Constraint Satisfaction Technology

This technique has been used in many academic and research parlance to tackle a wide range of search problems including resource allocation, transportation, planning and scheduling. It is defined by a finite set of variables, constraints and domain. The domain is a set of values for each variable, and each constraint involves some subsets of variables and specifies the allowable combinations of values of that subset. Usually, the problem is stated by assignment of values to some or all of the variables. Any complete assignment that satisfies all the constraints is a solution to a pre-defined problem. Generically, there are two techniques for solving constraint satisfaction problem, viz: consistency and search techniques. Search technique is more favoured due to its completeness in searching for a possible solution, although it can be very slow. It can be divided into two broad classes, those that transverse the space of partial solutions (or partial value assignment), and those that explore the space of complete value assignments (to all variables) stochastically. A third possible scheme is to embed consistency algorithm inside a search algorithm for improved efficiency and performance.

Conceptually, problem solving using constraint satisfaction technology involves the following steps:

- * Modeling of the problem

- Definition of problem specifications (Abstract) in terms of constraints on acceptable solution
- Identification and definition of variables and domain.

- * Solve the model

- Search space and choose algorithm for candidate solution is defined
- Often times anomalies in the models are observed when symmetrical solutions are noticed. In order to avoid exploring redundant parts of the search for solution, constraints that eliminate symmetrical solutions are introduced and added; constraints that are implied by other constraints in order to define the domain of minimum value of variables that satisfy the given problem are also added. Finally, redundant constraints are removed and replaced with logical equivalents such that the amount of overhead is reduced. The process of accomplishing this is generally referred to as transformation, and as at the time of writing this thesis, there is no known method of automating this rather complex process.

- * Analyses and verification of possible solutions for consistency

- After modeling and transformation, the models generated may not be suitable enough for input to a commercially available constraints toolkit such as ILOG, ECLIPSe, SICStus Prolog, CHIP, Mozart and others. We therefore, at this stage refine our model to generate a set of alternative models. The process of doing this is called refinement.

According to [18], the reason for choosing to represent and solve a problem as a CSP rather than, say as a Mathematical programming problem as discussed by authors of [6] and [7] are two fold.

- Firstly, the representation as a CSP is often much closer to the original problem. The variables in CSP directly correspond to problem entities, and the constraints can be expressed without having to be translated into linear inequalities.
- Secondly, although CSP algorithms are essentially very simple, they can sometimes find solution more quickly than if Integer Linear programming is used.

4.2 Minimisation Function

The objective function is to obtain a solution for SDH ring assignment problem with minimum number of rings, and traffic capacity less than or equal to B as stated in equation 2.1 and equation 2.2. In order to do this, an instance of 12 nodes and 7 rings was considered. It is important to mention that choosing any arbitrary value of k , where k is the total number of rings including the federal ring, i.e. $2 \leq k \leq 7$, is not necessarily equivalent to solving the problem. This is because a ring assignment solution that minimises the number of rings, does not necessarily minimise the traffic on the capacity on the federal ring as shown in Chapter 5. In other words, there would be another feasible solution that uses more rings, yet puts less traffic on the federal ring.

This simply translates to the fact that solving ring assignment problem by choosing an arbitrary value of k may give only an optimum solution but not the one that satisfy all constraints.

The approach used is to develop an algorithm based on the constraints satisfaction technology as explained in section 4.1. With this, a network was modeled and implemented in OPNET WDMGuru simulation tools environment given a number of constraints as input and other added constraints as described in subsection 4.2.4.

4.2.1 Federal Ring versus Number of Access Rings

Now that a network of 12 nodes and 7 rings has been set up using the defined ring configuration with rings traffic bit rate of STM-1 as calculated in table 3.1. The bandwidth utilization of both the federal ring and access rings are ensured that they nearly conform to that obtained in table 3.1. The common capacity B was also fixed at 240.0 Mbps with reference to equations 2.1 and 2.2. The tasks at hand is to calculate after dimensioning the network to accommodate as much traffic as possible, the bandwidth of both the federal and access rings having allowed network operation on the ring. Any network configuration having the traffic capacity on the federal ring less than or equal to bandwidth B is a feasible solution with a complete assignment of all nodes, provided all the constraints (both given and added implied) are satisfied. For this purpose, the capacity of each ring was dimensioned to STM-4 before performing routing operation.

STM-4 (622.080 Mbps) line rate is sufficient enough to accommodate all expected traffic demand. In succession, simulations were run for cases when the number of rings $R=6, 5, 4, 3,$ and 2. Each of these cases is considered as network model. The model configuration is done such that a node that is common to 3 or 4 ring is denoted as MSSP; those that are shared by two rings are configured as ADM plus DXC and others as ADM. The numerical and simulation results obtained are given and discussed in Chapter 5.

Theory:

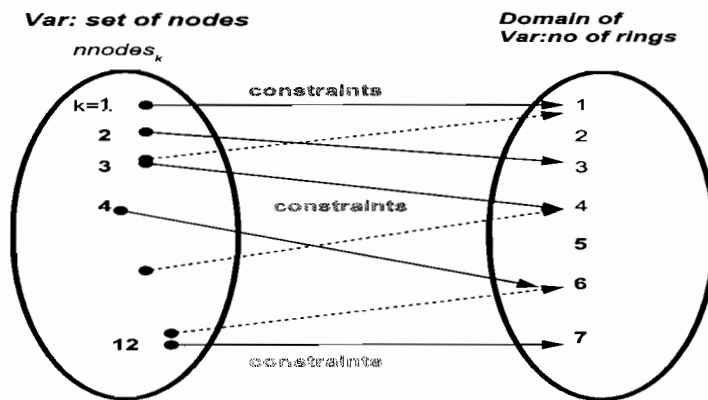


Figure 4.1: Modeling SDH CSP problem

Illustration in Figure 4.1 above represents the generic concept of constraints satisfaction programming. Both the set of nodes and rings are defined and implicitly declared but not typed (unlike other languages) as variables (var). Each of the nodes has a domain of the set of rings. For example node 3 = { 1, 4} implies that node 3 can either be assigned to ring 1 or 4, given that a node can not be assigned to two or more rings. Similarly, node 12 = {6, 7} indicates that node12 can be assigned to ring 6 or 7, and not to both rings.

It is syntactically correct to represent the above example thus: $R_1(\chi, \varphi) \leftarrow N_1$

Whereby χ , and φ are the constraints used to define the problem instance. Usually, it is a considerable task to construct an effective model to provide a solution to such a problem that satisfies the given set of constraints. The technique often adopted is to introduce other constraints in order to transform the problem to a solvable format as discussed in the following subsection.

4.2.2 Formal Modeling of the Problem

Let $nnode_i$ represents nodes assigned to access rings and is defined as X_{1i}

Let $nnode_j$ represents nodes assigned to federal ring and is defined as X_{2j}

Let $nring_k$ represents the access rings, and let $nring_f$ represents the federal ring

At least 4 nodes are assigned to the federal ring:

$$\sum_j X_{2j} \geq 4 \quad (4.1)$$

Note that: $2J \neq 2 * J$

At most 1 $nnode_i$ (X_{1i}) must be assigned to every access rings.

$$\sum_i X_{1i} \leq 1 \quad (4.2)$$

Alternatively, it can be said that $X_{1i} = 1$ if $nnode_i$ is assigned to access ring k

Recall that $nring_k$ represents the access rings, and at instance $t=0$, and the total number of access rings in the given network is 6

$$\sum_{k=1}^6 nring_k \quad (4.3)$$

as $t \geq 1$, the number of access rings $nring_k \rightarrow 1$

In a similar manner, recall that $nring_f$ represents the federal ring, and at instance $t=0$,

$$\sum_f nring_f = 1 \quad (4.4)$$

as $t \geq 1$, the size of federal ring increases. This phenomenon is described as ring merging and is further explained in subsection 4.2.4.

The traffic demand between any two nodes (p to j) on the access rings is given as 4 units, and this is stated formally thus:

$$\sum_{j,p} X_{1p}X_{1j} = 4 \quad (4.5) \quad \text{for}$$

uniform traffic demand, and

$$\sum_{j,p} X_{1p}X_{1j} = M \quad (4.6)$$

where $2 \leq M \leq 6$ for non-uniform traffic demand.

The expressions 4.1 to 4.6 and those that would be added in subsection 4.2.4 constitute the formal definitions of the important constraints considered in the design.

Then, the objective function is therefore given as:

$$\text{Minimise } \sum_k nring_k \quad (4.7)$$

4.2.3 Constraints Propagation

Since it was required that multiple constraints be considered in this design as stated in chapter 1; therefore, for simplicity it was suggested that n-ary constraints should be translated to binary constraints. In order to do this, the author chose the number of nodes, “nnodes” as variable and the number of rings, “nrings” as domain of variables (domain of values) with their respective values as indicated in the technical specifications to define the proposed algorithm.

The strength of algorithm lies in its ability to prune the solution search space to a minimum using the constraints propagation technique. Pruning the solution space involves elimination of symmetry and careful handling of special constraints, and it would make the

problem easier to manage and solve. This is a general process of handling constraints, and the process of handling special constraints is further discussed in subsection 4.2.4.

Pruning is implemented in the proposed algorithm using a combination of the best of both backtracking and consistency algorithms. Backtracking attempts to try all combinations in order to obtain a solution. Its strength is that it avoids trying many partial combinations, thus speeding up the running-time. In consistency technique, unlike backtracking it does not try all possible combinations but only those that are consistent. Specifically, with consistency algorithm, it uses a combination of arc and node consistency with forward checking for finding an optimum solution. Arc consistency is implemented by firstly defining the constraints between the two variables of interest (n_{nodes_k} , n_{ring}). Secondly, the algorithm would then find a value of any one of the variables in its domain and match it with that of the other variable in such a way that all the constraints are satisfied.

4.2.4 Handling Special Constraints

Special constraints are those that are not explicitly defined in the specification but are derived from those clearly stated. The techniques of handling these constraints differ from the general purpose methods discussed in subsection 4.2.3.

The two major constraints considered in this design are stated as follows:

- * For any feasible solution, the total number of rings must be less than 7. i.e. $n_{rings} \leq 7$, this implies that the number of ring-node mapping be minimised.

$$\text{Minimise } |rings - nodes| \quad (4.8)$$

- * For any solution to be feasible, the capacity of any rings including the federal ring must be less than the common ring capacity

$$\forall r \in R : |ring - node| \leq B \quad (4.9)$$

The derived, otherwise known as implied constraints are stated thus:

* Every nodes 'u' is placed on exactly one ring, except nodes on federal ring that interconnect one or more access rings. In this case, we placed a lower limit restriction on the number of "open ring" i.e. ring with only one node installed.

$$\sum_{i=1}^n X_{ui} = 1, \quad \forall u$$

* A ring is considered active if and only if a site is placed on it.

* Ring merging is done only when any two rings have up to or more than 5 nodes.

At the initial configuration, the network is set up by taking into consideration all the major constraints. After each simulation run, we re-configure the network model as discussed in subsection 4.2.1 by ensuring that the three implied constraints stated above are complied with prior to the next simulation run.

4.3 Node Cost Function

Each node has associated nodal cost which is the total cost of the underlying equipment that constitutes the node. In this case we primarily talk of add and drop multiplexer (ADM) and digital cross connect (DXC) system. Obviously, the cost of a ring shall be the total cost of all nodes assigned to that ring and the fiber link cost.

The node cost comprises the fixed and the per-port costs of ADM, DXC, Patch panel and short-reached transponders. A transponder is technically equivalent to an optical channel regenerator.

The link cost comprises cable cost, fiber cost and channel cost. Also included is the cost of terminal multiplexer in each MSPP node, optical amplifiers and regenerator cost.

The capacity of access rings were made to be different but collectively equal in all the five different networks as explained in subsection 3.2.2. However, the total request on any ring is the total bandwidth of all nodes assigned to that ring and the bandwidth between interconnecting node and the nodes on other rings to which are linked.

4.4 Proposed Algorithm

This section presents the logical design of optical ring SDH network using our proposed heuristic algorithm. The heuristic is then applied to five different network topologies whereby the number of rings are $R=6, 5, 4, 3,$ and 2 . For each topology, the network was populated with both uniform and non-uniform traffic demands. The resulting network topologies after reconfiguration for different number of rings with the same number of nodes and traffic demand are given as illustrated in Figure 4.2 to Figure 4.6 below.

It is important to note that at the digital channel layer, all nodes appear as digital cross-connects while at the optical channel layer as optical cross connect. Any network configuration done at the optical channel layer is logically implemented in the digital channel.

An instant of the problem shows the inability of the original network to accommodate a substantial amount of network traffic; and the challenge is either to stack the ring with rings of equal capacity or merge any two rings in the network in accordance to the implied constraint conditions. The process of merging means that nodes are assigned to rings such that the total numbers of rings used in the network are reduced. During this process, all the inter-nodes distances were maintained and all the nodes were retained; and the following variables: i.e. the number of rings, n_{ring} , and the capacity of the rings, c_r^8 are used. The input data to the algorithm are the network topology as mentioned and the traffic demand to be served (see the traffic matrix in table 3.1). The network topology is defined by the set of nodes and link as shown below.

⁸ capacity of the federal ring

For a solution to be feasible, the algorithm must return within the domain of ring assignment problem a solution that corresponds to a complete dimensioning, routing and ring assignment combination for the set of nodes/sites interconnection that represent the traffic demand to be satisfied over a specified network model.

The routing is implemented by ensuring that the total traffic over all rings are optimised, dimensioning is done without equipping any new fiber channel and using a stack ring of the same capacity and bit rates as the original ring.

Procedure: DRR ($nnodes$, $nrings$, C_r)

begin:

 given: $Nnodes \in \{nnodes_i, nnodes_j\} : \text{nat}$,
 $Nrings \in \{nrings_f, nrings_k\} : \text{nat}$ B : real

 initialise:

$Nnodes \leftarrow y_{\max}$: start with max no of nodes
 $Nrings \leftarrow y_{\max}$: start with max no of rings

 for each $nnode \in Nnodes$
 and for each $nring \in Nrings$; **do**
 Ringdesign($Nnodes, Nrings$) $\leftarrow C_r$

while
 (| ring-nodes | : > B) ; {
 Ringmerging($Nnodes, Nrings$)
 }
 if ($Nrings_k = 1$) {
 $nnodes \leftarrow ADM$;
 } else if ($Nrings_k = 2$) {
 $nnodes_i \leftarrow ADM$ plus DXC
 } **else if** ($Nrings_k > 3$) {
 $nnodes_f \leftarrow MSSP$
 else
 Dimensioning (STM-N)
 Routing (optimised over all routes)
 Ringassignment (stacked, merge)

end

Above is the proposed DRR algorithm for solving the ring-node assignment problem. DRR is the name of the procedure that calls Dimensioning, Routing and Ring assignment processes. n_{nodes} , n_{ring} and c_r are the arguments; together they form arity of DRR/3. The total number of nodes N_{nodes} in the network is differentiated into two: n_{nodes}_i , and n_{nodes}_j and both are declared as natural number. Similarly, the total number of rings N_{rings} in the network is also differentiated into two: the federal ring - $ring_f$ and the access ring - $rings_k$ are both declared as natural number. The common bandwidth capacity is also declared as natural number and set to the value B Mbps

The author initialised both N_{nodes} and N_{rings} to maximum and commences the Ring design procedure. This subroutine (procedure) completes the ring design process with ring capacity c_r set as STM-4 2F-MSSPRing. Following this, is the test that verifies if the ring-nodes capacity is less than or equal to B . For all values of ring-nodes capacity greater than B , another subroutine Ringmerging is called. This process involves testing and assigning different nodes for each ring depending on the ring-node assignment. For any node connected to ONLY one ring, it must be configured as ADM back-to-back. Those that are connected between two distinct rings are also configured as ADM plus DXC, otherwise known as MSPP; while any nodes connecting three or more rings are configured as MSSP. All the nodes configured as MSSP are collectively form the backbone or federal ring. The details of network configurations for individual network are further discussed in Chapter 5.

Afterwards the algorithm proceeds by calling the Procedure DRR again and return.

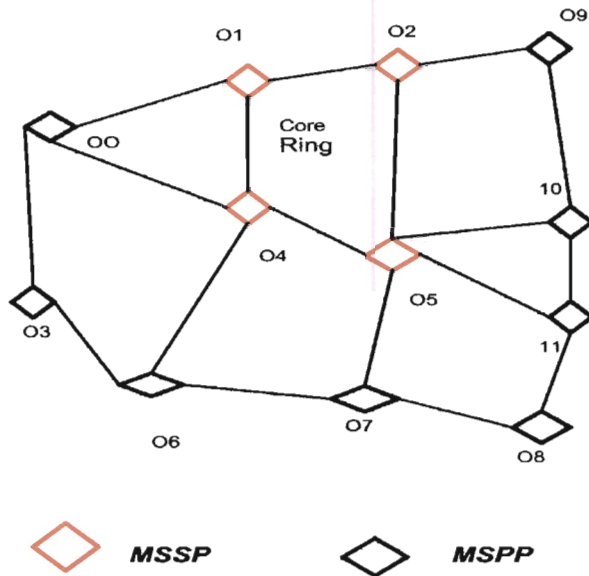


Figure 4.1: The original network of 12 nodes and 7 rings before merging

Fig. 4.2 above shows the original network model. Initially, the capacity of the network could not accommodate all traffic in the rings due to capacity shortage and has been off-loaded to a mesh network traffic matrix; only less than 25% of the total traffic was accommodated even though the ring utilization was as high as 90%. Since the objective is to ensure that all traffic was accommodated ONLY in the ring network, the author stacked the rings with a set of STM-4 rings until all the traffic is completely accommodated in the network. The simulation, computational and analytical results are as shown below whereas this configuration is set as the worst case scenario.

The figure above illustrates a scenario when two access rings are merged. The total ring capacity is less than the common bandwidth capacity as previously stated. The traffic was routed under the same constraints as above and the numerical data were collected as before. The goal is to compare the result in subsequent scenarios to the worst case scenario such that the validity of hypothesis 1 as stated in subsection 1.4.1 may be tested.

In a similar manner, simulations were run on the network shown in scenario 3-5 and the result is also shown and discussed in chapter 5.

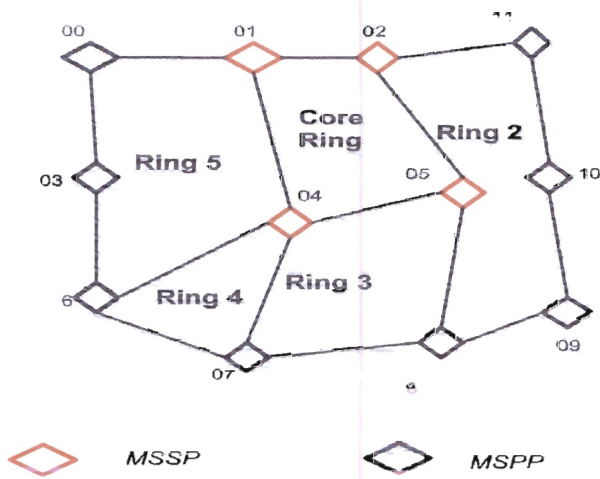


Figure 4.3: Scenario 1: A network of 12 nodes and 5 rings

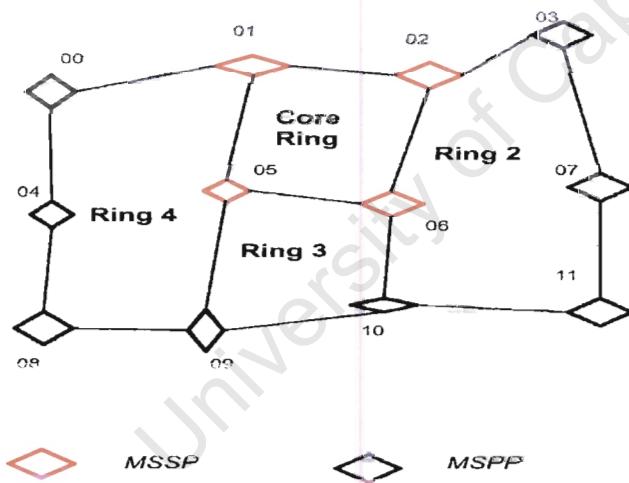


Figure 4.4: Scenario 2: A network of 12 nodes and 4 rings

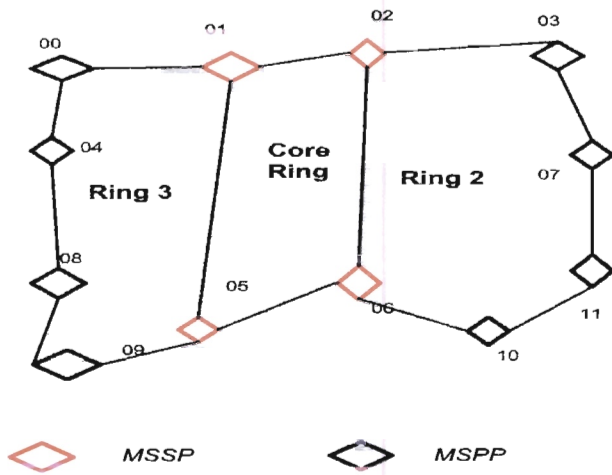


Figure 4.5: Scenario 3: A network of 12 nodes and 3 rings

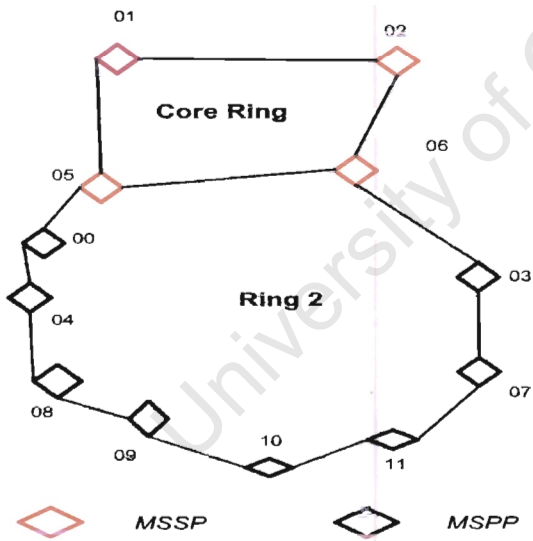


Figure 4.6: Scenario 4: A network of 12 nodes and 3 rings

5 Simulation results & Analysis

This chapter discusses the relevance of the proposed DRR algorithm to solving the ring assignment problem as described in chapter 4 in terms of network cost and capacity. In order to further assess the performance of the design, the result of the differential delays among the members of the virtually concatenated group is included. In this case, only the bit rates of the traffic matrix was changed to equivalent concatenated bit rates, while every other parameters and network operation remained the same as before.

The chapter is ended with an erudite analysis of the results.

5.1 Simulation Testbed

A functional algorithm simulation technique was used to develop functional algorithm simulation testbed (FAST) in OPNET WDMguru tool for predicting the computation and communication characteristics of the DRR heuristic algorithm.

The information derived with FAST was used to evaluate the performance of the algorithm. It is important that we point out that the testbed does not simulate every single instruction, but only procedure (i.e. Dimensioning, Routing and Ringassignment; DRR) calls that would be performed in a real life execution. It relies on knowledge of algorithm under investigation and data-structures it constructs when provided with some specific set of input data. Interested readers could check [21], [22] and [23] for more information on the application of this technique.

5.1.1 Setup of simulation

The author employed two different input traffic types for these simulations. One corresponds to an approximately uniform traffic distribution as in Table 3.1, and the other corresponds to non-uniform traffic distributions as shown in Table 5.1. (typically real-life traffic).

In both cases, the traffic demand was set and the rings are created in the network. During the ring creation process, the ring parameters comprising the type, bit rates, protection type and disjointedness are set. It was ensured that all nodes are disjointed and the links are only disjointed at the OTS layer.

In addition to the traffic types, three algorithmic parameters were specified at the input of the simulation testbed: one is the number of rings a solution is sought, the network configuration; and the third is the capacity of each of the rings- here, the size of the rings was set to STM-4. By setting up the capacity as STM-4, it guarantees that 100% of the ring capacity will be used in both the uniform and non-uniform traffic distributions before performing any network operations; and at the same time, ensures that the common bandwidth capacity is greater than those of the access and federal rings as hypothesised. Please see a detailed computational data in appendix A.1.

The network configuration is done such that the routing method selected controls how the algorithm will calculate the paths transverse by the traffic over the rings. In this particular case, the algorithm was set to optimise the network traffic over all rings. The consequent of this is that the bandwidth request between the nodes on the same ring plus the total bandwidth request between these nodes and the nodes assigned to other rings will be equivalent to the total traffic over all rings⁹.

⁹ see section 5.2.1

For a network of seven rings under uniform load traffic, all the network nodes are configured. Firstly, nodes 04 and 05 are configured as MSSP because these nodes are each associated with 3 or 4 distinct rings. While node 00, 01, 02, 06, 07, 10, and 11 are configured as ADM plus DXC because they are also associated with ONLY 2 rings, and nodes 03, 08 and 09 are associated with only 1 ring and are therefore configured as ADM back-to-back. In a similar manner, networks of six, five, four, three and two rings are configured in the same way as discussed below.

For a network of six rings under uniform load traffic, nodes 04 and 05 are configured as MSSP, nodes 00, 01, 02, 06, 07 and 11 are configured as ADM plus DXC, and finally nodes 03, 08, 09, 10 are also configured as ADM back-to-back.

In a network of five rings under uniform load traffic, the nodes configuration is also done as follows: Nodes 04 and 05 are configured as MSSP, nodes 01, 02, 06, 07, 11 are ADM plus DXC, while nodes 00, 03, 08, 09, 10 are ADM back-to-back.

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Table 5.1: Traffic matrix for Non uniform traffic demand

Nodes	Node0	Node1	Node2	Node3	Node4	Node5	Node6	Node7	Node8	Node9	Node10	Node11
Node0	-	4	6	2	6	6	5	5	4	6	2	2
Node1	4	-	3	4	3	3	2	4	4	3	3	6
Node2	6	3	-	4	5	4	4	3	3	5	2	4
Node3	2	4	4	-	3	3	5	6	4	4	6	2
Node4	6	3	5	3	-	6	5	3	4	5	5	6
Node5	6	3	4	3	6	-	3	3	5	5	4	6
Node6	5	2	4	5	5	3	-	4	4	4	6	5
Node7	5	4	3	6	3	3	4	-	3	6	5	3
Node8	4	4	3	4	4	5	4	3	-	2	2	4
Node9	6	3	5	4	5	5	4	6	2	-	5	3
Node10	2	3	2	6	5	4	6	5	2	5	-	2
Node11	2	6	4	2	6	6	5	3	4	3	2	-

The same procedure is used to configure all the nodes for the different network under non-uniform traffic as discussed below:

When the number of rings is seven, nodes 04 and 05 are configured as MSSP, while nodes 00, 01, 02, 06, 07, 10 and 11 are configured as ADM plus DXC, and nodes 03, 08, 09 and 10 are configured as ADM back-to-back

Also for a network of six rings, nodes 4 and 5 are configured as MSSP, and nodes 00, 01, 02, 06, 07, 11 are configured as ADM plus DXC, while nodes 03, 08, 09, and 10 are configured as ADM back-to-back

In a similar manner, for a network of five rings, nodes 04 and 05 are configured as MSSP, nodes 00, 01, 02, 06 and 11 are configured as ADM plus DXC, and nodes 03, 07, 08, 09 and 10 are configured as ADM back-to-back.

A complete table of network configuration is available in appendix B.1.

5.2 Result & Analysis

In this section the author discusses the results obtained when the DRR heuristic algorithm was run on both uniform and non-uniform traffic using OPNET simulation tool. The goal of this simulation was to investigate performance of the algorithm in finding a solution under different traffic scenario.

5.2.1 Capacity instance

From the figure above, it is assumed that the traffic originated from node "a", and flows clockwise to a destination node "e". If d_{bc} is associated with edges "b" and "c", d_{cd} is associated with edges "c" and "d" and if d_{de} is as well associated with edges "d" and "e", then the total demand in ring a-b-c-d when node "b" sends traffic to an external node "e" is given as:

$$d_{bc} + d_{cd} + d_{de} \quad (5.1)$$

where d_{de} is the demand between nodes in the access ring and those assigned to node in other ring. Strictly, this must be less than the common capacity bandwidth B as stated above.

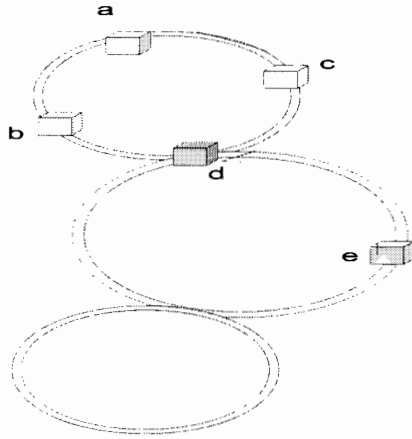


Figure 5.1: Illustration of traffic demand distributions between access and federal rings

The simulation result in Figure 5.2 and Figure 5.3 show the capability of the newly proposed DRR algorithm to return a solution in a ring assignment problem with the ultimate goal of reduced network cost. Figure 5.2 shows an instance where the algorithm is applied on two different network configurations with uniform and non-uniform traffic. In both cases, an optimal solution that satisfies all the defined optical constraints was obtained at a point "Z" = (4, 98.9). Here the number of rings in the network is 4, and the percentage routed traffic is 98.9.

For the uniform traffic instance, the graph could be divided into two distinct parts. The first part is the linear region where the number of ring and total traffic capacity carried therein is directly proportional to the percentage of traffic routed in the network.

The second part is depicted with a region that is almost nearly parallel to the horizontal axis (the "No of Rings" axis). At the point of discontinuity of the two parts are the optimal solution, and any attempt to dimension the network to admit more traffic in the network beyond the critical point will yield little or no effect on the overall percentage of routed traffic in the network.

Non-uniform traffic that constitute the bursty data traffic and are unpredictably erratic in characteristic as shown in the second graph ("Non-uniform traffic"). However, it was still possible for our algorithm to return a solution at almost the same point as in the case of uniform

traffic under the same optical constraints. Regrettably, the algorithm breakdown at any other point outside this critical point, and may be possibly due to non-deterministic nature of the data traffic. Adaptation of the algorithm to such a scenario is left as an open issue to be considered in future work.

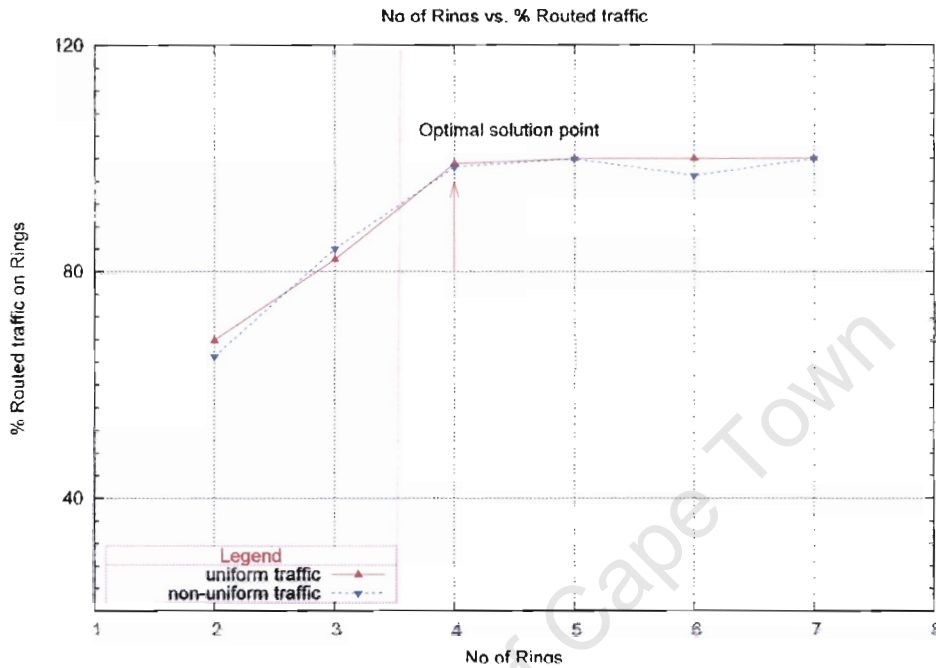


Figure 5.2: Illustrates the use of DDR algorithm to solve ring assignment problem

Furthermore, the effectiveness of the algorithm to return a solution was tested on four different networks of the same traffic types (all uniform). The networks were randomly configured from the same parent network using the same sets of rules as specified in the algorithm for only the uniform traffic demand. The simulation was run at succession and the results are collated for analysis.

A similar trend in the result for all the different networks was noticed: therein the algorithm returns an optimal solution at nearly the same point.

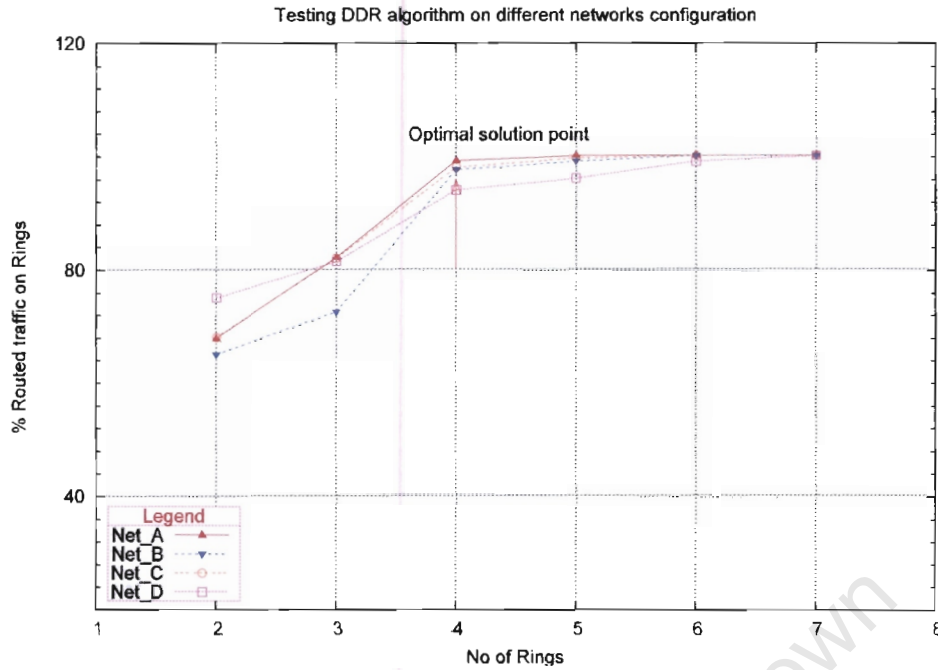


Figure 5.3: Testing DDR algorithm for all-uniform traffic in different networks

Figure 5.3 depicts the percentage routed traffic demand that corresponds to the four investigated networks as a function of number of stacked rings. Each of the rings (2 to 7) as shown compose of a number of stacked rings just sufficient enough to allow all the requested traffic demand to be completely routed in the each network. The % routed traffic increases linearly as the number of rings increases only to the maximum point, and then remained constant. At the point of optimal solution, all the specified optical constraints are satisfied, and any increase in number of rings beyond this optimum value will have little or no effect on the total amount of traffic admitted to the network. This shows that the DDR algorithm is "well-behaved" and therefore suitable for finding a solution to a ring assignment problem under uniform traffic demand.

A solution whereby the number of rings = 4 is a minimum solution that satisfies all the requirements and is therefore chosen as the optimum solution. Clearly, neither 2 nor 3 rings are feasible solution and are therefore rejected as candidate solutions. However, any number of rings greater than 4, though is equally a solution but will as well incur high network cost as shown in subsection 5.2.2.

Further analysis of the optimum solution conducted in order to test the validity of hypothesis 1 as it was stated in subsection 1.4.1 shows that none of the access rings, including the federal ring has its bandwidth greater than the common capacity bandwidth B .

5.2.2 Network cost

It is expected that normalised network cost should increase as the number of interconnected rings increase.

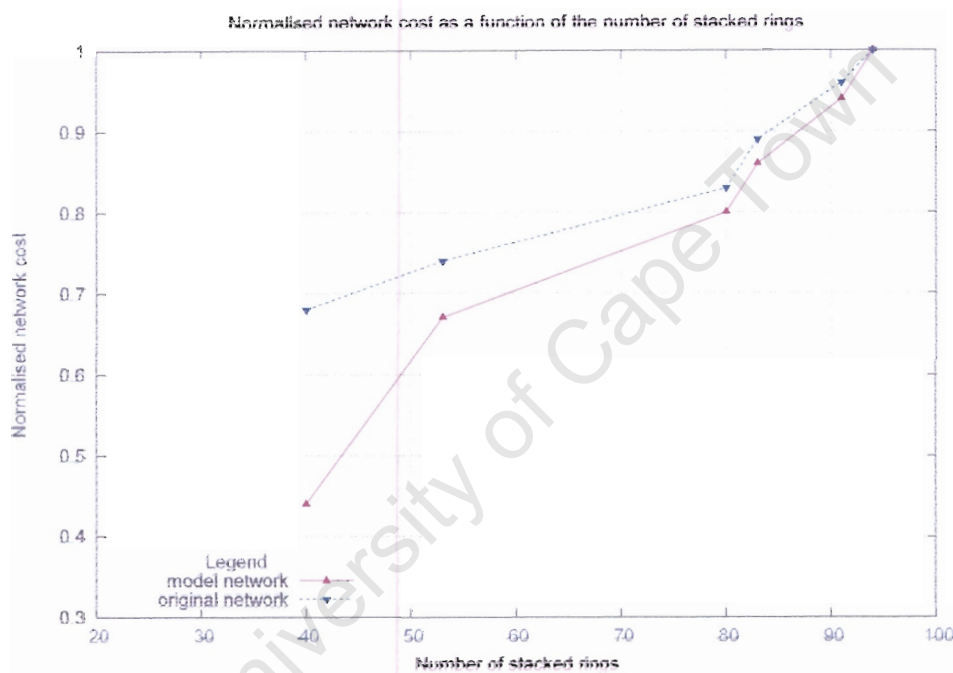


Figure 5.4: Comparing model network solution to original network in terms of network cost

The network cost compares favourably within the domain of feasible solution i.e. when the number of rings is between 7 and 4, and diverges as it moves down the curve until the number of rings is 2. The difference in network cost between the two networks in the region of feasible solutions (4 and 7 rings) is less than 5% when the total number of stacked rings is between 80 and 94 respectively. The difference is well above 50% in the region where our algorithm failed to find a suitable solution that satisfy all the given constraints i.e. between 40 and 79 stacked rings corresponding to 2 and 4 rings respectively before stacking.

5.2.3 Differential delay

The aim of this test is to determine the end-to-end differential delay in our model network and verify that it lies within the service level agreement. The approach used is to setup a diverse path in such a way the value of the differential delay can be estimated from the link delay. Link delay is typically composed of two components: the fiber propagation delay and the equipment processing delay. The simulator was configured for various values of these two parameters in order to have a good approximation of the link delay and consequently calculate the differential delay. The values are carefully chosen in such a way as to stay within the limit of the service level agreement as indicated in the design requirements. The task of the algorithm is to search for an optimum solution by setting the original network as the input while it iterates until a solution is sought. If the algorithm is able to return a solution that corresponds to that obtained in Figures 5.2 and 5.3 above with the value of the differential delay equal to the service level agreement as specified; then the solution is considered absolute.

5.2.3.1 Setting up the Simulation Testbed for Differential Delay Estimation

For simplicity, only a pair of ingress-egress node was shown. In the real implementation one would randomly select any node pair within our network of 12 nodes to measure the fiber link delay. At every instance, only the source and destination node pair shall be virtual concatenation enabled. In order to create differential delay routing problem, the network traffic demands bandwidth is chosen to be greater than link capacities such that the traffic from the source node will be forced to transverse multiple paths.

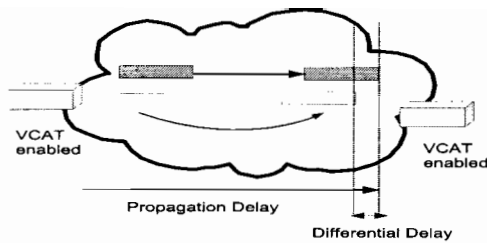


Figure 5.5: Modeling differential delay problem [Adapted from [25]]

It is important to note that the intricacy of any differential delay algorithm lies in its ability to find the maximum number of diverse paths to route the traffic while also keeping the delay value to a minimum. The greater the value of differential delay the bigger the size of the buffer memory reserved in the node. These two parameters are contrasting; the more the number of diverse paths, the lesser the time taken for the traffic to be completely routed; and the greater the differential delay among the virtual concatenated group.

5.2.3.2 Delay settings and Analysis

Recall that in section 2.2, it was mentioned that analytically, delay in optical network can be classified into three: serialisation, network element processing and propagation delay. Setting the delay figure in our simulator in such that both serialisation delay and network element are grouped together and named DCL processing delay was done first. According to the ITU-TG.series specifications, signal must ingress and egress an optical network elements within 0.45 ms and depending on the number of elements on its way to its destination, the total network elements processing delay is given as: NE processing delay = Total number of NEs on the paths * 0.45 ms. Also, note that in the users' requirements in section 1.2.2 that the user would be required

to use an Ethernet services on E1 equipment interface. With this in mind, the serialisation delay is also calculated thus:

$$\text{Ethernet_frame_size} / \text{Interface_bits_rates} = \text{serialisation_delay}$$

$$(1500 * 8 \text{ bits/byte}) / (1.544 \text{ Mbps}) = 7.8 \text{ ms}$$

The next tasks is to set the DCL processing delay to $(7.8 + \beta * 0.45)$ ms, where β represents the number of network elements in the path of the signal.

In a similar manner, the propagation delay value was also set to 0.005 ms/km. Details of how this was calculated is described in appendix C.1. Intuitively, nodes "00" and "11" were selected as our source and destination nodes respectively, and both are virtually concatenated enabled while all other nodes are not; they are configured as ADM only.

In order that traffic may be routed independently, three different routes from the source to the destination nodes as shown were selected as shown below:

Route "A" 00-04-08-09-10

Route "B" 00-04-08-09--05--06-10-11

Route "C" 00-04-08--09-10-06-02-03-07-11

Each of these routes has a hop counts β as 5, 7 and 9 respectively, and the average cost of proposed algorithm finding an optimum solution on each of these routes are given as shown in Table 5.2.

Table 5.2: Estimation of end-to-end delay

No of hops (Counts)	5	7	9
Delay (ms)	9.50	12.42	16.48
Average cost of solution	5.05	7.05	9.05

In Table 5.2 above, total estimate of end-end-delay in model network (a network that has optimum solution) is 16.48 ms, and this satisfies the initial SLA agreement of 25 ms that must not be exceeded. In fact, the table shows that model network has spare capacity and is therefore capable of accommodating extra 2-4 intermediate nodes without any breach of service level agreement.

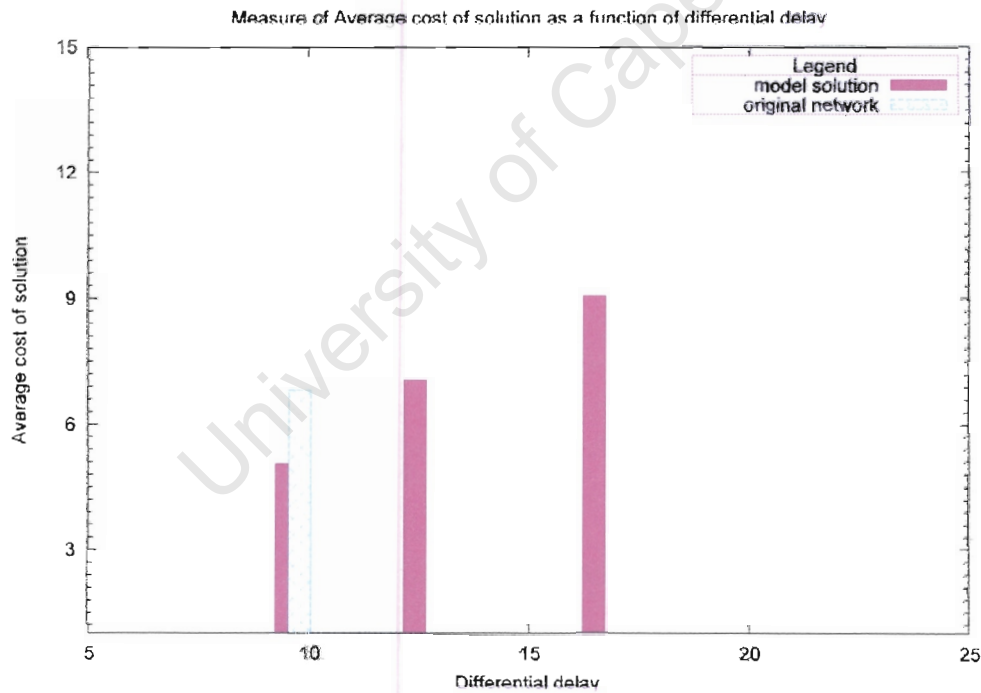


Figure 5.6: Testing the performance of the proposed algorithm using differential delay

Figure 5.6 above further asserts that our algorithm is not just able to find a solution but the one that satisfies a service level agreement of 25 ms as given in the user requirements. The

average cost of solution at the maximum differential delay is 9.05 units when the number of diverse paths is only 5. This implies that the network solution can still support more diversely routed traffic without violating the end-to-end delay requirements of users' applications.

Conversely, the average cost of solution in our original network is higher for almost the same value of differential delay as in our model network, and no feasible solution that satisfies the delay requirements outside the range was identified. This is the motivation for this experimental analysis.

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6 Conclusion and future work

An alternative approach based on Constraints Satisfaction Programming (CSP) technology to solve ring assignment problem in multiservice, multiple constraints SDH optical networks design has been discussed. In this work, a heuristic algorithm was developed using the CSP technology to search for a network topology that provides an optimum solution in a wide area network (WAN). The solution does not only provide a low-cost design but also satisfies all constraints defined as users' and network requirements. In the past, almost all the algorithm used to solve such problem was based on the relatively complex, and computationally intensive Integer linear programming (ILP). This new proposed algorithm is mathematically less-cumbersome, has faster running time, and can handle multiple constraints in parallel as compared to ILP. This algorithm was tested by considering a hypothetical optical design case study of Bellville area in Cape Town. The goal of this design exercise is to generate network capacity and delay constraints value to be used as data inputs to the algorithm.

The study commences by extracting the generic constraints from the given users' and network requirements. Implied constraints were also generated, and together they form a set of inputs data to the proposed algorithm. The algorithm treated the network design process as graph partitioning problem and therefore attempts to find an optimal solution through searching method. In this process, procedure calls like ring assignment, network dimensioning and traffic routing were initiated. The call that returns a solution with minimum network cost, and that also satisfy the underlying constraints is chosen and considered optimum. The implementation of this algorithm was done in OPNET network simulator, returns a solution with a network of lower number of rings for both uniform and non-uniform traffic conditions. It also satisfies almost all the constraints without violating the end-to end service level agreement (SLA).

The well considered opinion of the author is that, special nodes assigned to federal ring that interconnects the access rings play a major role in the estimation of the cost of optical network design, and are relatively more expensive. Minimising the number of such nodes installed on the ring is a major issue addressed by the ring assignment problem that was geared towards improving the capacity of the network. The available options are whether to stack the ring with rings of the same size to accommodate more traffic or to increase the bit rates of the existing rings. After testing our algorithm under both conditions, it was deduce that the percentage routed traffic is higher in the latter than the former, and a lower network cost is incurred. Also, optical network system design with such concept often performs better in terms of support for greater value of differential delay among members of diversely routed traffic.

Even though, it is clear that the scheme is sufficient for finding solution(s) with minimal network cost, its efficiency is yet to determine in terms of CPU time. The major problem lies in the difficulty of automating the process of transforming the constraints specifications to the format that could be easily represented in the supported programming language (CSP). There is currently an ongoing research in this area.

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Appendix A

Simulation Data

A.1 Capacity and Network cost

Network topology is often dimensioned according to the specific traffic matrix. The process of dimensioning increases the capacity of the network, and it is done at the network layer. Using the simulation tool, the required node and link equipment to support at the given traffic matrix can be installed directly. Throughout the simulation process, all dimensioning operation is done ONLY at the Digital Channel Layer (DCL layer) of the network layer. The following algorithm options are available:

- Shortest path. This algorithm dimensions the network using lowest-cost routes for each connection.
- Heuristic algorithm. This algorithm dimensions the network using shortest-path algorithm, and includes an additional optimization steps.
- Diverse-route dimensioning. This option is available when unprotected dimensioning is selected. The diverse route ensures that if there is a failure, each node is remains as reachable as possible.

Network cost is obtained from link cost and node cost (hardware cost). The cost of the link is determined based on the proportional relationship to the physical distance between any two locations. While node cost may be fixed or variable. In this design; however, a fixed node cost is considered throughout in this design. The objective function is to dimension a network with a minimum network throughput.

The output data may be one or more of the following: (1) a set of connections in each network layer, (2) a list of switch facilities, (3) overall performance analyses, and (4) a total of network cost. In this case output data (4) is the data under investigation.

Experimental Analysis							
No of Rings: 7				No of Rings: 4			
Before stacking		After stacking		Before stacking		After stacking	
Data	Value	Data	Value	Data	Value	Data	Value
nRings	7	nRings	94	nRings	4	nRings	80
TotCapRings	14	TotCapRings	188	TotCapRings	8	TotCapRings	160
% ringCapUsed	100	% ringCapUsed	86.26	% ringCapUsed	100	% ringCapUsed	80
% RoutedTraffic	13	% RoutedTraffic	100	% RoutedTraffic	9.4	% RoutedTraffic	98.6
Network cost	39064	Network cost	129160	Network cost	48523	Network cost	103667
Node cost	32292	Node cost	106035	Node cost	42648	Node cost	78192
Link cost	6775	Link cost	23125	Link cost	6475	Link cost	25475
No of ADM	17	No of ADM	22	No of ADM	14	No of ADM	280
No of DXC	12	No of DXC	12	No of DXC	12	No of DXC	12
No of Rings: 6				No of Rings: 3			
Before stacking		After stacking		Before stacking		After stacking	
Data	Value	Data	Value	Data	Value	Data	Value
nRings	6	nRings	91	nRings	3	nRings	53
TotCapRings	12	TotCapRings	182	TotCapRings	6	TotCapRings	106
% ringCapUsed	100	% ringCapUsed	81.76	% ringCapUsed	100	% ringCapUsed	90.77
% RoutedTraffic	13.5	% RoutedTraffic	97	% RoutedTraffic	6.6	% RoutedTraffic	84
Network cost	58899	Network cost	120700	Network cost	28351	Network cost	87004
Node cost	52224	Node cost	96725	Node cost	21976	Node cost	65279
Link cost	6675	Link cost	23975	Link cost	6375	Link cost	21725
No of ADM	16	No of ADM	241	No of ADM	15	No of ADM	272
No of DXC	12	No of DXC	12	No of DXC	12	No of DXC	12
No of Rings: 5				No of Rings: 2			
Before stacking		After stacking		Before stacking		After stacking	
Data	Value	Data	Value	Data	Value	Data	Value
nRings	5	nRings	83	nRings	2	nRings	40
TotCapRings	10	TotCapRings	166	TotCapRings	4	TotCapRings	80
% ringCapUsed	100	% ringCapUsed	80.69	% ringCapUsed	100	% ringCapUsed	77.19
% RoutedTraffic	12.1	% RoutedTraffic	93.8	% RoutedTraffic	3	% RoutedTraffic	65
Network cost	58715	Network cost	111494	Network cost	8179	Network cost	56887
Node cost	52140	Node cost	87119	Node cost	1904	Node cost	35412
Link cost	6575	Link cost	24375	Link cost	6275	Link cost	21475
No of ADM	15	No of ADM	257	No of ADM	16	No of ADM	320
No of DXC	12	No of DXC	12	No of DXC	12	No of DXC	12

Fig A.1: Measurement value

A.2 Overview of utilization links per layer in model solution

Layer	Number of Links	Link utilization		used capacity	Total Capacity	Utilization (%)	Unit
		Between 100 and 90%	Between 75 and 0%				
OTS	15	15	0	0	750	100	Fiber pairs
OMS	15	0	0	15	750	2.27	Fiber pairs
OCH	15	3	0	12	680	72.06	Wwavelengths
DCL	15	8	4	3	948	79.11	STM-1 Units

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Appendix B

Network configuration

Because we are designing at the network layer, our focus is on network design rather than hardware design. The difference between the two is that hardware configuration design simply is a “post-design” design step in network design flow. In our case, hardware design is only done after routing and dimensioning operations. In this case, all the traffic must have been routed and sufficient network capacity has been added.

The following are decisions made prior to network configuration: (1) which node type is required. (2) How to route existing traffic. (3) How much traffic is required to support the traffic? (What line rates and bit rates to use)

B.1 Node configuration

Two sets of nodes are chosen for network configuration, and there are three ring interconnection types. (1) MSSP, (2) ADM plus DXC (MSPP) (3) ADM

The two node types are

- MSSP
- DXC

Each of them is configured with a specified number of tributary and trunk ports depending on the ring interconnection types chosen.

Nodes configuration for uniform traffic

No of rings=7			Routing algorithm:Optimised over all rings			No of rings=6			Routing algorithm:Optimised over all rings		
Node ID	Node type	Inteconnection type				Node ID	Node type	Inteconnection type			
0	MSPP	MSPP				0	MSPP	MSPP			
1	MSPP	MSPP				1	MSPP	MSPP			
2	MSPP	MSPP				2	MSPP	MSPP			
3	MSPP	ADM				3	MSPP	ADM			
4	DXC	MSSP				4	DXC	MSSP			
5	DXC	MSSP				5	DXC	MSSP			
6	MSPP	MSPP				6	MSPP	MSPP			
7	MSPP	MSPP				7	MSPP	MSPP			
8	MSPP	ADM				8	MSPP	ADM			
9	MSPP	ADM				9	MSPP	ADM			
10	MSPP	MSPP				10	MSPP	MSPP			
11	DXC	MSSP				11	MSPP	MSPP			
No of rings=5			Routing algorithm:Optimised over all rings			No of rings=4			Routing algorithm:Optimised over all rings		
Node ID	Node type	Inteconnection type				Node ID	Node type	Inteconnection type			
0	MSPP	ADM				0	MSPP	ADM			
1	MSPP	MSPP				1	MSPP	MSPP			
2	MSPP	MSPP				2	DXC	MSPP			
3	MSPP	ADM				3	MSPP	ADM			
4	DXC	MSSP				4	DXC	MSSP			
5	DXC	MSSP				5	DXC	MSSP			
6	MSPP	MSPP				6	MSPP	MSPP			
7	MSPP	MSPP				7	MSPP	ADM			
8	MSPP	ADM				8	MSPP	ADM			
9	MSPP	ADM				9	MSPP	ADM			
10	MSPP	MSPP				10	MSPP	ADM			
11	MSPP	MSPP				11	MSPP	MSPP			
No of rings=3			Routing algorithm:Optimised over all rings			No of rings=2			Routing algorithm:Optimised over all rings		
Node ID	Node type	Inteconnection type				Node ID	Node type	Inteconnection type			
0	MSPP	MSPP				0	MSPP	MSPP			
1	MSPP	ADM				1	MSPP	ADM			
2	DXC	MSPP				2	DXC	ADM			
3	MSPP	ADM				3	MSPP	ADM			
4	DXC	MSSP				4	DXC	MSSP			
5	DXC	MSSP				5	DXC	MSSP			
6	MSPP	ADM				6	MSPP	ADM			
7	MSPP	ADM				7	MSPP	ADM			
8	MSPP	ADM				8	MSPP	ADM			
9	MSPP	ADM				9	MSPP	ADM			
10	MSPP	ADM				10	MSPP	ADM			
11	MSPP	ADM				11	MSPP	ADM			

B.2 Link configuration

Within WDMGuru simulation tool, a network may be designed for a specific WDM line system type (LS type) or a combination of different LS types. WDM Guru has an internal set of LS models and design algorithm that can select the lowest-cost LS type according to the cost factors and traffic requirements on a link.

At the Digital Channel Layer DCL level, the link is divided into timeslots, which can either be configured for working path or protection path or both. All links are specified in terms of Bit Rate, capacity of the link, supporting Line System, the rings on which is deployed and ring type. In the case of the model network solution (network of four rings), the bit rate is STM-4, link capacity is 2, supporting Line system is LH 40-WDM, and the Ring type is 2F-MSSPRing.

Appendix C

Formulae & Calculations

C.1 calculating propagation delay

Propagation delay is introduced due to the finite speed of light and the laws of physics. Propagation delay introduces asymmetrical delay in large BLSR/SNCP rings and must be taken into consideration during optical network design. The nominal velocity of propagation (NVP) is defined as the ratio of the speed of light in a vacuum to the refractive index of the material. The value of c is a constant fixed at 300,000 km/seconds. The refractive index for single is 1.5.

$$\text{NVP} = c / \text{refractive index of fiber}$$

The NVP for SMF can be calculated as follows:

$$\text{NVP} = (300,000 \text{ km/seconds}) / (1.5) = 200,000 \text{ km/sec}$$

The inverse of this equation results in the propagation delay of SMF at 0.005 ms/km. This means the propagation delay of Single Mode Fiber SMF in milliseconds can be calculated as follows:

$$\text{Propagation delay} = \text{Fiber length (km)} * 0.005 \text{ ms/km}$$