The design of physical and logical topologies for wide-area WDM optical networks

by

Albert Dirk Gazendam

Submitted in partial fulfilment of the requirements for the degree

Master of Engineering (Electronic)

in the

Faculty of Engineering, Built Environment

and Information Technology

University of Pretoria, Pretoria

December 2003

Die ontwerp van
fisiese en logiese topologieë vir
wye-area WDM optiese netwerke
deur
Albert Gazendam

Promotor:	Prof. F. W. Leuschner
Departement:	Elektriese, Elektroniese and Rekenaar-Ingenieurswese
Graad:	Meester in Ingenieurswese (Elektronies)

Sleutelwoorde

wye-area optiese netwerk; golflengte-verdelingsmultipleksering; ontwerpmetodologie; verkeeropknapping; aangepaste gravitasie-model; nodusweging; ekonomiese aktiwiteit; netwerkbestuur; netwerkbetroubaarheid; loknodus; multi-vlak netwerkmodel; Ward-skakeling; intra/inter-groep verkeersverhouding; groepering

Opsomming

Die doelstelling van hierdie verhandeling is om the faktore te ondersoek wat die ontwerp van wye-area golflengte-verdelingsmultipleksering (“WDM”) optiese netwerke beïnvloed. Wye-area netwerke word aangebied as kommunikasie netwerke wat in staat is om spraak sowel as data kommunikasie oor groot geografiese areas te bewerkstellig. Hierdie netwerke strek gewoonlik oor 'n hele land, streek of selfs kontinent.

Die vinnige ontwikkeling tot volwassenheid van WDM tegnologie oor die laaste dekade het kommersieel suksesvol geblyk en moedig nou die ontwikkeling van vaardighede in die ontwerp van optiese netwerke aan.

Die fundamentele doel van alle kommunikasie-netwerke en tegnologieë is om die verbruiker se behoeftes te bevredig deur die lewering van kapasiteit oor gedeelde en beperkte infrastruktuur. Inagname van die besigheidsaspekte verbonde aan kommunikasieverkeer en die opknapping daarvan is belangrik, indien die gebruiker se behoeftes verstaan wil word ten opsigte van die kwaliteit en beskikbaarheid van dienste en toepassings. Uitgebreide kommunikasie-netwerke benodig komplekse bestuurstegnieke om hoë vlakke van betroubaarheid en winsgewendheid te verseker.

'n Geïntegreerde metodologie word voorgestel vir die ontwerp van wye-area WDM optiese netwerke. Die metodologie maak gebruik van fisiese, logiese, en virtuele topologieë, saam met roetering en kanaalaanwysing ("RCA") en groeperingsprosesse om objektiwiteit aan die ontwerpsproses te verleen. 'n Nuwe benadering, gebaseer op statistiese groepering met die Ward-skakeling as ooreenkomsmate, word voorgestel vir die bepaling van die hoeveelheid en posisies van die loknodusse op die multi-vlak netwerkmodel. Die invloed van die geografiese verspreiding van netwerkverkeer, en die intra/intergroep verkeersverhouding word in ag geneem deur gebruik te maak van aangepaste gravitasie-modelle en die innoverende weging van netwerknodusse.

The design of
physical and logical topologies for
wide-area WDM optical networks
by
Albert Gazendam

Promoter: Prof. F. W. Leuschner
Department: Electrical, Electronic and Computer Engineering
Degree: Master of Engineering (Electronic)

Keywords

wide-area optical network; wavelength division multiplexing; design methodology; traffic grooming; modified gravity model; node weighting; economic activity; network management; network reliability; hub node; multi-level network model; Ward linkage; intra/inter-cluster traffic ratio; clustering

Summary

The objective of this dissertation is to investigate the factors that influence the design of wide-area wavelength division multiplexing (WDM) optical networks. Wide-area networks are presented as communication networks capable of transporting voice and data communication over large geographical areas. These networks typically span a whole country, region or even continent.

The rapid development and maturation of WDM technology over the last decade have been well-received commercially and warrants the development of skills in the field of optical network design.

The fundamental purpose of all communication networks and technologies is to satisfy the demand of end-users through the provisioning of capacity over shared and limited physical infrastructure. Consideration of the business aspects related to communications traffic and the grooming thereof are crucial to developing an understanding of customer requirements in terms of the selection and quality of services and applications. Extensive communication networks require complex management techniques that aim to ensure high levels of reliability and revenue generation.

An integrated methodology is presented for the design of wide-area WDM optical networks. The methodology harnesses physical, logical, and virtual topologies together with routing and channel assignment (RCA) and clustering processes to enhance objectivity of the design process. A novel approach, based on statistical clustering using the Ward linkage as similarity metric, is introduced for solving the problem of determining the number and positions of the backbone nodes of a wide-area network, otherwise defined as the top level hub nodes of the multi-level network model. The influence of the geographic distribution of network traffic, and the intra/inter-cluster traffic ratios are taken into consideration through utilisation of modified gravity models and novel network node weighting.

My sincere gratitude and appreciation to:

My promoter, Prof. Wilhelm Leuschner, for his input and guidance.

Lucent Technologies - Bell Labs Innovations, for the privilege to spend three months at their research facility in Holmdel, NJ.

The CSIR, for the opportunity to further my studies.

My family and friends, for their interest and encouragement.

My wife, Inge, for her sustained support.

List of abbreviations

3R	regeneration with re-timing and re-shaping
ANSI	American National Standards Institute
APS	automatic protection switching
ARPA	Advanced Research Projects Agency (United States)
ATM	asynchronous transfer mode
BER	bit error rate
bps	bits per second
BT	British Telecommunications
CAD	computer aided design
CWDM	coarse wavelength division multiplexing
DARPA	Defense Advanced Research Project Agency (United States)
dB	decibel
DCS	digital cross-connect system
DS	digital system (PDH signal)
DWDM	dense wavelength division multiplexing
EDFA	erbium-doped fiber amplifier
EON	European Optical Network
FDM	frequency division multiplexing
FTIR	Fourier transform infrared
Gbps	gigabits per second
GHz	gigahertz
GUI	graphical user interface
IP	Internet protocol
ISP	Internet service provider
ITU	International Telecommunications Union
LAN	local area network
LED	light emitting diode
MAN	metropolitan area network
MB	megabyte
Mbps	megabits per second
MEMS	micro electro-mechanical systems
MONET	multi-wavelength optical networking
MPLS	multi-protocol label switching

NAS	network access station
NE	network element
NGN	next generation networking
NP	nondeterministic polynomial time
NSF	National Science Foundation (United States)
OADM	optical add-drop multiplexer
OC	optical channel
OEO	optical-electronic-optical
ONN	optical network node
OR	optical receiver
OT	optical transmitter
OXC	optical cross-connect
PD	photo diode
pdf	probability distribution function
PDH	plesiochronous digital hierarchy
PIN	positive-intrinsic-negative
PoP	point-of-presence
PNNI	private network-network interface
PSTN	public switched telephone network
QoS	quality of service
RCA	routing and channel assignment
ROI	return on investment
SADM	SONET/SDH add-drop multiplexer
SDH	synchronous digital hierarchy
SEM	scanning electron microscope
SHR	self-healing ring
SNR	signal-to-noise ratio
SONET	synchronous optical network
STM	synchronous transport module
STS	synchronous transport signal
Tbps	terabits per second
THz	terahertz
vBNS	very-high speed backbone network service
VoD	video-on-demand
VoIP	voice-over-IP
WADM	wavelength add-drop multiplexer
WAN	wide-area network
WDM	wavelength division multiplexing
WIXC	wavelength interchanging cross-connect
WRN	wavelength-routed network
WSXC	wavelength-selective cross-connect
WWW	World Wide Web

Contents

Chapter 1

Introduction

Optical fiber technology has a broad base of applications, including industrial, medical and communications. This investigation focuses exclusively on the application of optical fiber technology in the communications domain. Within the communications domain the use of optical fiber technology is not new, with operational commercial installations dating back to the early 1970's. These installations and the overwhelming majority of installations done today can be loosely classified as optical fiber equipped communication networks, since they are actually conventional communication networks that merely harness the cost and performance benefits of optical fiber links. The routing and consequent intelligence of these optical fiber networks still depend on electronic components with opto-electronic input interfaces and electro-optic output interfaces. True optical networking is however very young, with the testing of experimental next-generation optical networks only commencing in the early 2000's.

True optical networks are communication networks that not only utilise optical fiber on its links for the cost and performance benefits that it offers above conventional copper cables, but also for the new multiplexing and routing dimension that wavelength division multiplexing (WDM) provides. The next step in the evolution of optical communication technologies will be the all-optical network that does away with any and all forms of electronic bottlenecks that currently limit the throughput of increasingly intelligent optical network nodes. The vision is a protocol independent network capable of transmitting anything from anywhere to anywhere else at a fraction of the cost and time of existing technologies. In a heavily monopolised world of competing communication providers and diverse end-user applications, a more realistic aim would however be the establishment of an Internet protocol (IP) network comprising an all-optical core and non-standard proprietary electronic edge.

1.1 Background

A single optical fiber has the bandwidth to carry data at rates of several terabits per second (Tbps). Since the digital electronic circuits that interface with optical fiber are not able to support such high data rates, a technique had to be developed to harness this immense bandwidth. Partitioning the bandwidth offered by an optical fiber into N channels, each having a different carrier wavelength, and utilising N electronic source and detector pairs, each pair tuned to a different wavelength, increases the net data rate by a factor N. This technique of using multiple carrier wavelengths on a single optical fiber, is known as WDM.

The earliest proposals for wavelength-routed networks (WRNs) appeared in independent articles, dated 1988, by Brain and Cochrane [1] and Hill [2]. The term *WRN* refers to an optical network that utilises WDM to reduce the need for routing in the electronic domain. Hill focused on the implications that wavelength routing would have on the network architecture, while Brain and Cochrane considered the influence of wavelength routing on physical aspects such as signal-to-noise ratio (SNR) and bit error rate (BER).

WRNs can be divided into two groups, namely: WRN that do not allow wavelength conversion; and WRN that do allow wavelength conversion. It should be noted that a network operating on F wavelengths with one fiber pair per link and all of its nodes equipped with wavelength converters, is equivalent to the same network with F fiber pairs per link each operating on a single wavelength. Experimental results [3] do however suggest that wavelength conversion at the nodes of an optical network do not remarkably reduce the number of wavelengths required to satisfy the virtual connectivity requirements for a given physical topology. It has been shown by Barry and Humblet [4] that at least $\sqrt{\frac{N}{e}}$ wavelengths and at most $\sqrt{N \log_2 N}$ are required to support full permutation connectivity in an N-node static network. In subsequent research [3, 5], it has been suggested that the normalised connectivity, as opposed to the number of network nodes, determines the lower bound on the required number of wavelengths.

The design of wide-area WDM optical networks is influenced by various factors and is consequently not a very well understood problem. Researchers have not been able to propose methodologies for solving this problem when more than only a few factors are considered. Mukherjee *et al.* [6] presents some principles for designing wide-area WDM optical networks, but focus on issues related to the design of the network's virtual topology. Dividing the problem of optical network design into several seemingly independent sub-problems has been the approach used since Bannister *et al.* [7] first suggested it in 1990. This approach is inherently flawed due to its inability to consider the correlation that exists between the factors that influence the sub-problems.

The sub-problems into which the design of wide-area WDM optical networks is divided are usually that of designing the physical topology [8] and doing the routing and channel assignment (RCA) to create the virtual topology. Some authors [6, 9] use the term *virtual topology* to describe the logical interconnection both before and after the RCA, while others [10] use the term *logical topology* to describe the logical interconnection only prior to the RCA. It is agreed however that the final virtual topology is obtained by integration of the physical topology and demand matrix by means of the RCA. It should be noted that most research in the field of optical network design assumes a given demand matrix without consideration of the factors that determine and influence it. An investigation into the factors that determine and influence the logical topology, and hence the demand matrix, is thus warranted.

As with any kind of communication system, there are physical effects that influence the way in which a wide-area WDM optical network performs. Brain and Cochrane [1] realised this early and emphasised the importance of considering these effects when designing an optical network. It has been shown that, due to effects like crosstalk, the use of multiple wavelengths in a single optical fiber results in higher BERs [11]. SNR requirements have also been shown to play an important role in the cost optimisation of an optical network design [9].

Consideration of issues such as failure restoration and protection are key to the successful design of practically applicable optical networks [2]. Several algorithms exist for designing virtual topologies that support different levels of protection and offer different kinds of failure restoration features. It has been shown [3] that increasing the number of wavelengths by approximately 25% can ensure that full logical connectivity be maintained in the case of single link failures in existing networks. The ability of a network design to absorb changing user requirements with regard to factors such as traffic distribution and protection requirements, without merely worst-case designing the network, is a very sought after design characteristic. The planning of network evolution and deployment phases thus constitutes an important part of a complete optical network design.

The RCA problem for small optical network designs can easily be solved by using a technique known as graph colouring [12], where the vertices of a path interference graph are coloured subject to certain interference constraints. Determining the virtual topology of more complex optical network designs by solving the RCA problem is NP-hard when wavelength-continuity is assumed between all source and destination pairs [7]. NP stands for nondeterministic polynomial time, from a definition involving nondeterministic Turing machines that are allowed to guess a solution and then check it in an amount of time that is a polynomial function of the size of the problem. An NP-hard problem is at least as hard as or harder than any NP problem, which means that an algorithm that computes an exact solution of the problem requires an amount of computation time that is an exponential function of the size of the problem. When the wavelength-continuity constraint is dropped, meaning that wavelength conversion is allowed at all nodes of the network, the RCA problem can be linearised, resulting in a problem that can be easily solved by linear programming techniques [13]. This enables an optimal solution of the RCA problem, which leads to an optimal virtual topology. The concept optimal should however be understood in the context of the problem. Any solution can only be optimal with regard to the optimisation criteria that were selected for it.

Although the potential bandwidth is far greater, the propagation delay of signals in optical networks is comparable to that of signals in conventional electronic networks. Optimisation of the mean packet delay is consequently an important performance metric in the design of virtual topologies for optical networks [9]. The mean packet delay consists of three major components: transmission time, propagation delay and switching time. Another contributor to the mean packet delay is the queuing delay at the network nodes, but it is usually ignored because of its small contribution compared to the propagation delay resulting from the long inter-nodal links [8]. Transmission time is defined as the elapsed time from when data first enters a transmitter to when photonic transmission commences, while switching time is defined as the elapsed time from when a photonic signal first enters a switch to when it leaves the switch. Besides delay minimisation, the maximising of the load that can be offered to the network is another popular optimisation criterion [6]. This optimisation criterion allows for the design of a virtual topology that is able to handle increasing traffic demand for a given physical topology. These examples show why the investigation of existing and new optimisation criteria is paramount in a holistic approach to the design of optical networks.

Economic considerations often play a more important role than technical consideration in the design of optical networks. The number of wavelengths, degree (number of inter-nodal ports) of the network nodes, number of transit nodes, and the length of the fiber, are a few of the network parameters that influence the cost of the network [14]. Design techniques that consider the network's cost model have been proposed [13], but fail to represent all of the influencing factors. Economy-of-scale consideration have been found [5] to encourage topology reduction in mesh restorable network topologies, due to the concentration of network traffic through nodes with larger switching capacities.

The issue of how wavelengths are allocated for multiplexed data streams of various rates is known as grooming, and introduces new challenges to the design of the virtual topology by means of solving the RCA problem [15]. This situation is one that occurs often in practice since very few users require an integer multiple of the bandwidth that a single wavelength channel offers, which necessitates the multiplexing of different users' data streams into the same wavelength channels in order to maximise the utilisation of the wavelengths employed in the network.

Researchers often refer to existing, planned or hypothetical optical networks to demonstrate their theories or apply their findings. Metropolitan area networks (MANs) differ from WANs with respect to factors such as geographical coverage, number of nodes and the statistical nature of the traffic. Examples of research that apply to the MAN context are by Bannister *et al.* [7] and Vetter *et al.* [8]. Researchers of optical networks for the WAN context often refer to NSFNet [6] in the United States and EON [16] in Europe. The simulated application of research findings in a practical context can contribute greatly to the relevance of results obtained through theoretical study.

1.2 Motivation

The design of wide-area WDM optical networks has various aspects and can be influenced by several factors. The aspects of WDM optical network design that are considered include: physical topology, logical topology, optimisation, routing and channel assignment (RCA) and future expansion. These aspects can be influenced by several factors that are determined by the unique requirements and characteristics of the country for which the network is to be designed.

South Africa is a developing country with tremendous economic growth potential. The establishment of communication infrastructure capable of supporting existing and future demand can be an essential catalyst for this growth. The large percentage of the population currently without access to reliable communication infrastructure is another motivator for the careful consideration, planning and design of communication infrastructure that will satisfy the requirements of this developing country.

The trend in international communication technology research and development suggests WDM optical networking to be the most viable technology for satisfying the increasing demand on wide-area networks (WANs) to offer more bandwidth at lower cost. The problem of designing these WDM optical networks is however quite new, since technology to utilise multiple wavelengths simultaneously in a single fiber has only recently been developed. In fact, it took until the late 1990's for the technology to mature enough to enable the commercial implementation of the first WDM optical networks.

1.3 Objectives

A key component to the design of any network is a thorough knowledge and understanding of the factors that influence it. The importance and relative influence of these design factors vary with the context of the network, which is why this investigation has as an objective the identification and investigation of the factors that influence the design of wide-area WDM optical networks in general.

Most research on the design of wide-area optical networks assume hub nodes and demand matrices to be known, and regard these as mere input parameters to the problem of routing and channel assignment. An objective of this investigation is to implement a clustering approach to the design of wide-area optical networks, addressing the establishment of a logical topology as well as identification of the hub nodes, which is the most crucial aspect to the design of a physical topology.

In order to integrate the obtained results and developed models, an objective of this investigation is to formulate a methodology for designing wide-area WDM optical networks in general. The design methodology includes topics such as: designing the physical and logical topologies; finding the RCA; and optimising the network for various parameters.

To demonstrate the practical relevance of the performed research, the hub nodes and logical topology for a wide-area WDM optical network was designed for South Africa. This design is not intended to be used as a reference, but should rather be regarded as a practical demonstration of how the theoretical results can be applied to the context of a real-world design problem. In order to maintain generality, the network design emphasises theoretical optimality in favour of vendor-specific practical applicability.

1.4 Contribution

The factors that influence the design of a wide-area WDM optical network for South Africa differ from that of other countries. Most research and development in this field is conducted in the USA, Europe and the Far East, which inhibits its applicability to South Africa. There are however certain fundamental principles that can be applied to the design process irrespective of the context. This research attempts to integrate these fundamentals in such a way that contributes to the body of knowledge in the field.

A great need exists for public domain knowledge on methods for finding what is traditionally regarded as input parameters to the wide-area WDM optical network design problem. These input parameters include the number and positions of hub nodes as well as the logical topology of a network under design. A paper [17] outlining the application of statistical clustering in finding these input parameters, was presented at the international IEEE AFRICON 2002 conference in George, South Africa. This research contributes to satisfying this need for *input parameter methods* and aims to establish an appreciation for the fact that routing and channel assignment is only one component of the network design problem, and not the only as is often suggested.

It is postulated that the fundamentals of the design methodology formulated in this research would be applicable to other developing countries and adaptable to virtually any context. A paper discussing the results presented in chapter 6 is currently being reviewed for publication in the Transactions of the South African Institute of Electrical Engineers. Although the obtained results are tailored to the South African context, the fundamental principles underlying the design methodology are universal and will therefore contribute to the field of wide-area WDM optical network design in general.

1.5 Overview

Chapter 2 provides an introduction to optical technology and standards. Readers that are new to the field of optical communication are encouraged to start with this chapter in order to familiarise themselves with some of the terminology and relevant technologies, whereas people more familiar with the field might choose to skip over it.

The factors that influence the design of wide-area WDM optical networks have been identified and categorised as follows:

Communication traffic engineering related factors investigated in chapter 3. This category of factors include the geographical distribution of communication traffic (section 3.1.1), traffic models (section 3.1.2), network node weighting (section 3.1.3), traffic symmetry (section 3.2.1), intra-and inter-nodal traffic (section 3.2.2), and traffic grooming (section 3.3).

Communication network engineering related factors investigated in chapter 4. This category of factors include the multi-level network model (section 4.1), physical topologies (section 4.2.1), logical topologies (section 4.2.2), virtual topologies (section 4.2.3), network management (section 4.3), reliability (section 4.4), and business modelling (section 4.5).

Wide-area network design related factors investigated in chapter 5. This category of factors include optimisation parameters (section 5.1.1), and commercial and proprietary design software (section 5.1.2).

An integrated design methodology is presented in section 5.1.3 and a methodology for finding hub nodes from economic statistics is proposed in section 5.2. A simulation experiment of the clustering approach to the design of logical topologies can be found in section 5.3, where specific reference is made to the intra/inter-cluster traffic ratio defined in section 5.3.3.

Chapter 6 concludes the investigation be demonstrating the methodology for finding backbone hub nodes and clusters in a hypothetical South African network design problem where 349 network nodes, representing the magisterial districts of the country, are networked with an aggregate capacity of 1 Tbps.

Chapter 2

Optical technology and standards

2.1 Enabling technologies

The field of optical communication encompasses various disciplines, ranging from physics and photonics to topologies, protocols and even economics. The use of lasers for communication purposes was first proposed in the 1960's. Remarkable advances in technology over recent years have had an incredible impact on the rapid growth of this field and the subsequent popularity of optical communication technology as a whole.

Developments such as low-loss optical fibers, erbium-doped fiber amplifiers (EDFAs), solitons, dense wavelength division multiplexing (DWDM) and micro electro-mechanical systems (MEMS) enable the optical communication networks of today, while the theoretical all-optical networking node boasting multi-protocol label switching (MPLS) and the all-optical processing of header information, will enable the optical communication networks of tomorrow.

Enabling technologies and their development influence the design of wide-area optical communication networks due to the technical context which they define. Aspects such as data rates, number of wavelengths, propagation delay and link span are all functions of the underlying technology as well as critical parameters in the design of optical communication networks. From a purely mathematical point of view, a certain network topology or protocol might be superior to others based on its robustness or load balancing characteristics, but if the technology required for its implementation does not exist, it will be nothing more than a theoretical dream.

The manufacturers of modern network equipment tend to base their design philosophies solely on the technologies that they want to sell. This approach makes sense from a business point of view, but fails when considering that its very nature does not stimulate or encourage novel solutions to old problems, solutions that could enable the consideration of new problems and better ways of solving them. It is for this reason that a network designer should tread lightly through the myriad of design philosophies preached by the vendors of network equipment. Throughout this investigation a neutral approach is taken towards the issue of enabling technologies. The focus is on the theoretical aspects of network design, while considering the influence of enabling technologies and the technical limitation that they impose.

2.1.1 Basic building blocks

A dichotomy of elementary geometric ray theory and advanced electromagnetic wave theory, governed by Maxwell's equations, describe the principles behind the propagation of light in optical fibers. Wavelengths of 1310nm and 1550nm are predominantly used due to their favourable attenuation and dispersion characteristics. As with all communication systems, the basic building blocks of an optical fiber link is a trans-

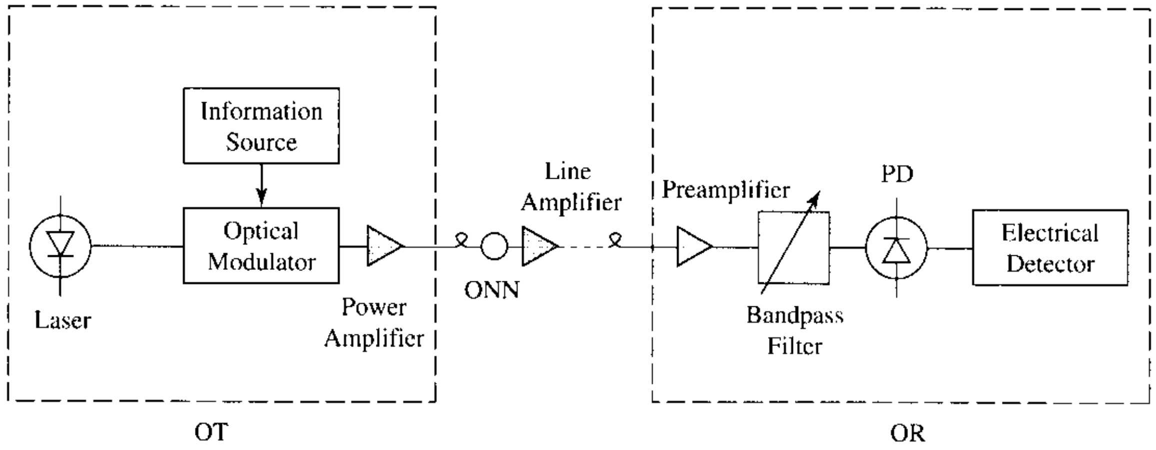


Figure 2.1: A generalised point-to-point optical connection [18].

mitter, a medium (the optical fiber) and a receiver. Figure 2.1 shows a generalised point-to-point optical connection comprising an optical transmitter (OT) and optical receiver (OR), with a transmission medium that could contain optical network nodes (ONNs) and line amplifiers in conjunction with the implicit optical fiber.

In wide-area optical networks narrow-band lasers are the most commonly used transmitters, while light emitting diodes (LEDs) are more prevalent in shorter distance low-cost applications. Positive-intrinsic-negative (PIN) photodiodes and avalanche photodiodes are the most well-known types of optical detectors. An in-depth discussion of these devices and their operation is beyond the scope of this investigation, and the interested reader is referred to the several introductory textbooks on optical fiber communication, of which some are listed in the bibliography section.

2.1.2 Combating transmission impairments

The two main phenomena that impact negatively on BER in digital systems and SNR in analog systems are attenuation and dispersion. The problem of attenuation is addressed by lowering the attenuation of the optical fiber or by amplification of the signal. Lowering of the attenuation in the fiber is not a trivial issue, and it has taken several decades for researchers to reduce the attenuation of optical fibers from several dB/km to well below 0.1 dB/km. Choosing the wavelength of the transmitted light carefully leads to lower attenuation due to the wavelength dependence of attenuation, which is shown in figure 2.2.

There are several techniques for combating dispersion and thereby limiting the occurrence of inter-symbol interference which negatively impacts system performance. The use of dispersion shifted fiber, dispersion compensating fiber and other dispersion management techniques are popular. On long-haul fiber links the use of soliton waves can potentially eliminate the need for the costly process known as regeneration with re-timing and reshaping (3R) that needs to be performed every few hundred kilometres above and beyond the signal amplification which is also required, but at typically more frequent intervals.

EDFA

The erbium-doped fiber amplifier revolutionised optical communication and is widely considered to be the most important enabler for wavelength division multiplexing. The EDFA is the most important amplifier in optical communications due to the fact that it has a relatively wide amplification bandwidth, around 35nm, and even more importantly operates in the very low attenuation window around 1550nm shown in figure 2.2.

The EDFA is a true optical amplifier as opposed to the earlier receive-amplify-retransmit amplifiers that require optical-to-electronic conversion at its input and electronic-

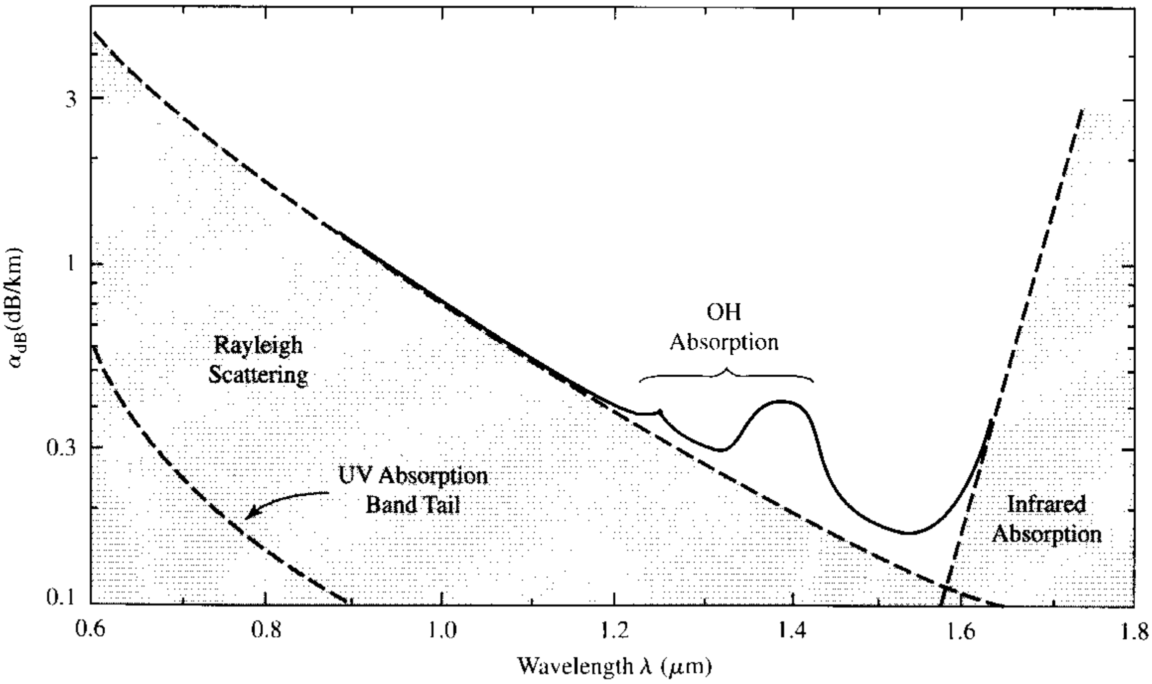


Figure 2.2: Graph showing attenuation as a function of wavelength in a conventional glass optical fiber [18].

to-optical conversion at its output. This enables the EDFA to amplify signals at virtually any data rate and at any wavelength in its amplification window. In WDM systems an EDFA is thus able to amplify several adjacent wavelengths simultaneously, even though it is with gains that vary according to the gain profile shown in figure 2.3.

Solitons

Long before optical fiber communication, it was known that a special wave shape exists that can propagate in certain media without experiencing dispersion. This phenomenon was first recorded by John Scott Russell in 1838 based on observations that he made at a canal in Scotland. This soliton wave is fundamentally stable, meaning that any wave approximating a soliton wave launched into a fiber will tend towards a soliton wave as

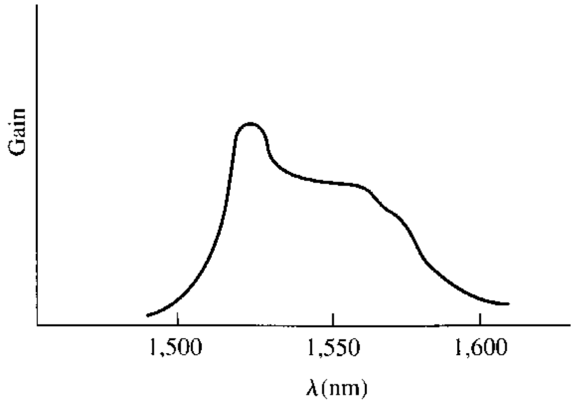


Figure 2.3: The gain profile of an erbium-doped fiber amplifier [18].

it propagates down the fiber, and consequently assume the unique soliton characteristic of dispersion immunity.

Solitons used in optical communication systems are narrow, high powered pulses that do not exhibit pulse broadening normally associated with dispersion. The shape of the soliton can be constant as it propagates through the fiber, this being referred to as a fundamental soliton. A soliton of which the shape periodically changes is referred to as a higher-order soliton. Due to a soliton's dependence on a high pulse energy, optical amplifiers are however required at more regular intervals than would normally be necessary.

2.1.3 DWDM

Dense wavelength division multiplexing is to optical communication what frequency division multiplexing (FDM) is to the conventional communication fraternity, the only exception being that the bandwidth available in the optical frequency domain is orders of magnitude greater, hence translating into orders of magnitude greater potential data rates. In the EDFA window around 1550 nm alone, there is around 4 THz of bandwidth.

This incredible bandwidth translates into volumes of capacity unheard of in conventional communication technology. At an aggregate data rate of 1 Tbps, a single optical fiber with a diameter of less than 250 μm can accommodate around 40 million 28 kbps data connections, 20 million digital voice channels, or half a million compressed digital video channels [19]. Although commercial installations do not yet possess this kind of capacities, the popularity and commercial success of DWDM technology is apparent when it noted that in 1998 already more than 90% of the networks of long-haul carriers in the United States utilised DWDM technology [20].

With the inherent limitations of electronic modulation circuitry, it is impossible to harness this immense bandwidth while operating at a single wavelength, thus the motivation for wavelength division multiplexing. Figure 2.4 shows how several wavelengths are simultaneously used when the spectrum of a single fiber is analysed. The four indicated wavelengths are in the 1550 nm band, with signal powers in the region of 6 dBm and an optical rejection ratio of 38 dB. It is customary to specify optical rejection ratio at a distance of one-half the wavelength spacing from the carrier wavelength.

Initial WDM systems utilised less than nine different wavelengths simultaneously. Technology however improved so rapidly and the popularity of WDM with it, that the term *DWDM* was coined and is used for systems that utilise in excess of 8 wavelengths on single fibers simultaneously. The family of multiplexing techniques that utilise the wavelength domain has three main members:

WDM refers to initial systems utilising 8 or less wavelengths, typically the current implementation of wavelength division multiplexing

DWDM refers to systems utilising more than 8 densely packed wavelengths, typically

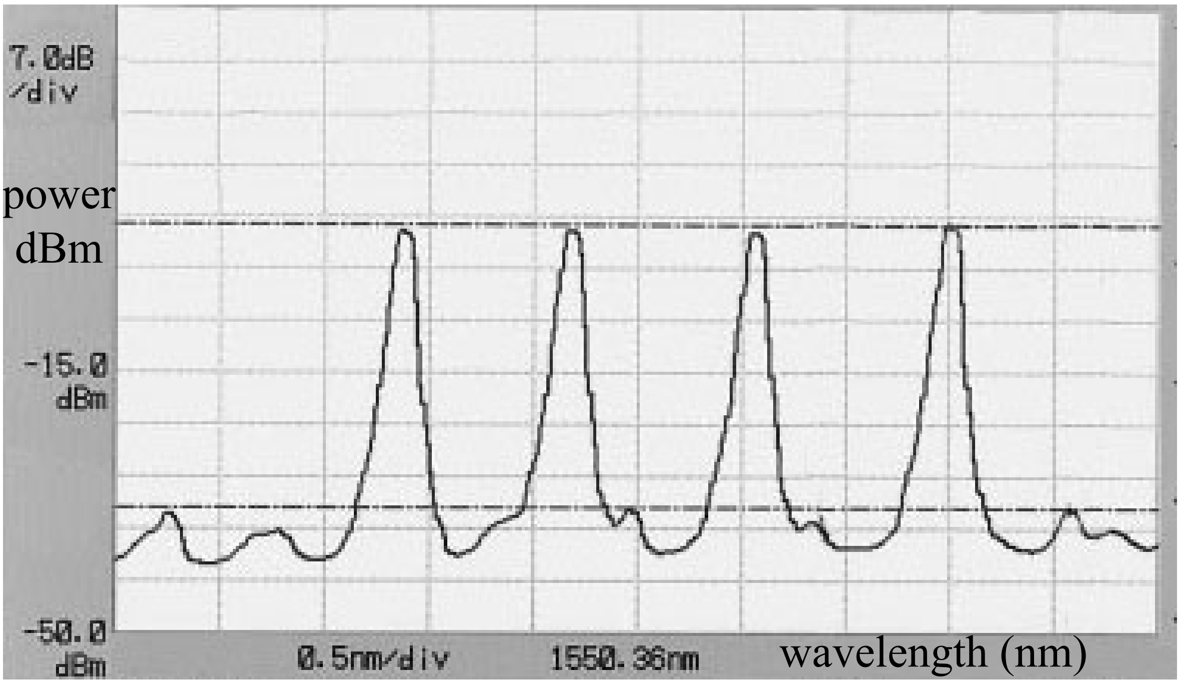


Figure 2.4: An example of an optical fiber's spectral occupancy in a WDM system as displayed on an optical spectrum analyser [21].

used in new wide-area and long-haul networks

CWDM refers to systems utilising more than 8 coarsely packed wavelengths, typically used in new metropolitan area networks

Since there is often not a clear distinction in literature between WDM and DWDM systems, the term *WDM* is used throughout to refer to systems utilising wavelength division multiplexing irrespective of the number of wavelengths. This investigation is however aimed at the application of wavelength division multiplexing in future wide-area optical networks, hence the focus, although not in name, on what has been described as DWDM. Section 2.2.2 provides more information on the standards that govern WDM.

2.1.4 Micro electro-mechanical systems

MEMS is a platform technology that enables the fabrication of microscopic structures by micro-machining. The structures range in size from a few hundred micrometers to several millimetres and are fabricated on silicon substrates using mostly existing semiconductor processing techniques. Use of the same efficient and proven mass-production processes that were developed for the semiconductor industry during the last 30 years, is one of MEMS technology's great motivators. Although MEMS technology utilises similar fabrication processes to that of semiconductor devices, its operation is electromechanical in nature, which makes reliability one of its greatest challenges.

The micro-machines are formed on silicon substrates using epitaxial growth, patterning, and etching processes developed for manufacturing integrated circuits. Where an acid wash etches away layers of oxides, mechanical parts are released and moving pieces are created. Researchers have made three-dimensional micro-machines crafted so that flaps or mirrors spring into place when the parts are released. Figure 2.6 shows a scanning electron microscope (SEM) image of a two-axis electro-statically actuated micro-mirror.

The MEMS anti-reflection switch can be used as a micro-mechanical modulator, and MEMS 2-axis micro-mirrors which can be used in routing applications, shows potential for drastically reducing the cost of future fiber access applications. At an end point such as a customer's home such a device, when used in conjunction with a local modulator, could impose signals on a stream of light generated by a laser somewhere else in the network. In practice, eliminating the need for large numbers of expensive lasers with cheap silicon devices is a very appealing prospect. Similar devices, configured as wavelength-selective attenuators, could be used to flatten amplifier gain across a band of wavelengths, even providing active equalisation in real time. A mode-eclipsing

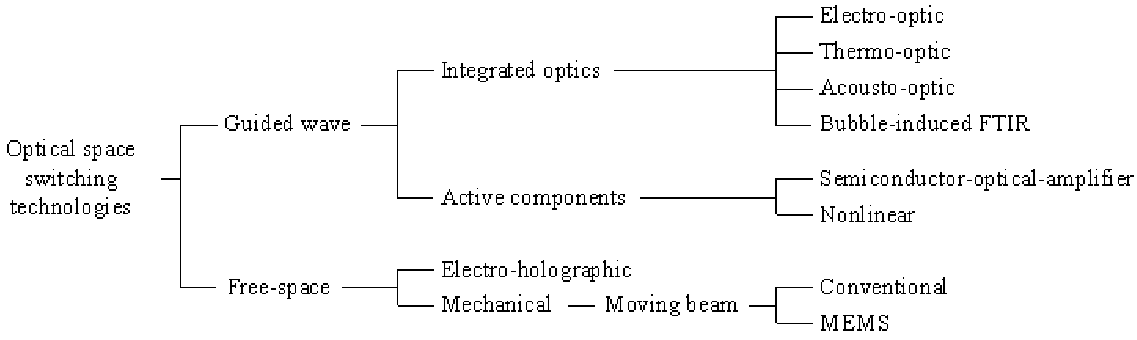


Figure 2.5: Taxonomy of optical switching technologies [22].

optical switch can be used as an on-off switch, a shutter, or an attenuator to control signal power and protect components.

More than a dozen types of MEMS devices have been designed, prototyped, and demonstrated for optical communications, and each of these could serve a number of different purposes. Such potential applications have enabled this technology, though still in exploratory stages, to make the leap from a research curiosity to a serious contender for large-scale deployment in revolutionary network architectures.

Of the various optical switching technologies shown in figure 2.5, MEMS is now pursued by more researchers than any other, as the most viable technology for optical switching in optical networks. The reasons for this are: MEMS's inherent batch fabrication characteristics and the related economic benefits; insensitivity to bit rate or data protocols due to optical transparency; and the high performance that characterises transparent optical networking components.

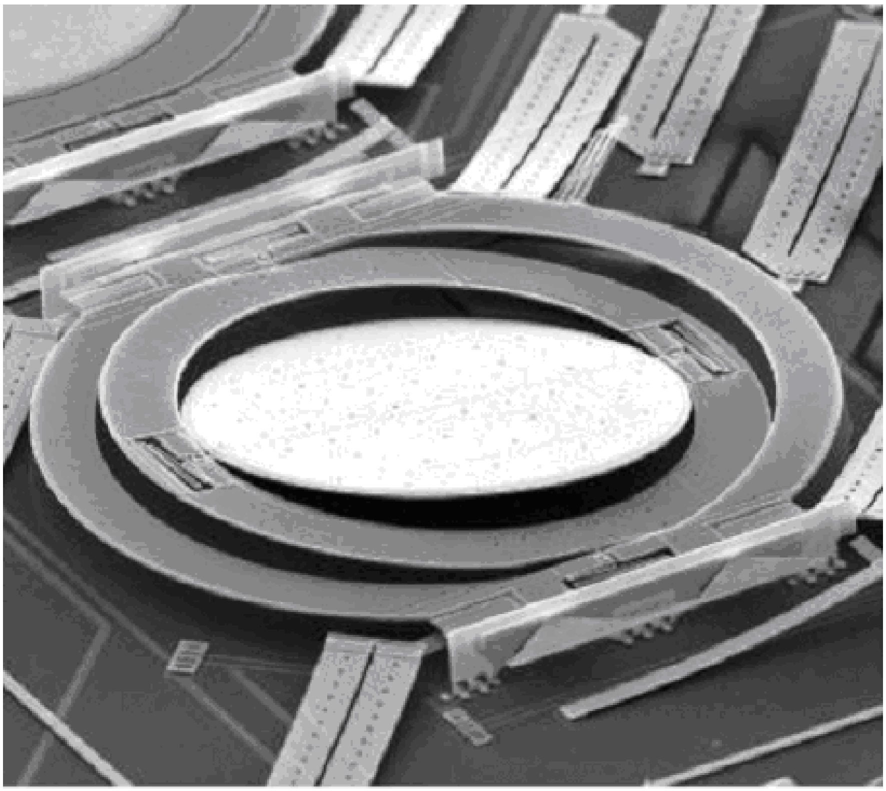


Figure 2.6: A SEM image of one of the 256 free-rotating 2-axis electro-statically actuated micro-mirrors used in Lucent's WaveStar LambdaRouter [23].

2.1.5 All-optical network node

The all-optical network node is a theoretical device similar to the switches, routers and exchanges that we are familiar with in modern communication networks. The network node is a place in a network through which physical connectivity with adjacent nodes in the network is established. Logical connectivity between any combination of nodes in a network is achieved through the wavelength dimension that WDM and optical networking exploit. This enables logical connectivity to be obtained through an infrastructure on which various protocols can be implemented, as opposed to through the protocols themselves as in conventional communication networks. Figure 2.7 shows a theoretical ONN, with an emphasis on the wavelength selectivity and spatial switching characteristics thereof.

Network nodes are the basic building blocks of a network and are defined as being responsible for all traffic on the network. The all-optical network node is one of the basic building blocks of the wide-area WDM optical network. It should not be confused with the network access station (NAS), which serves as interface between the electronic and optical parts of the network. In the context of a multi-level network where local, metropolitan and wide-area networks co-exist on different levels of the network, it is important to be aware of the different distribution, access and transport functions that network nodes perform.

The concepts of a network edge and a network core should be handled with care, since they do not explicitly define the function of a network node. These edge and core concepts have a place when the communication infrastructure is considered as a whole, with a user's mobile communication device being close to the network's edge and far from the network's core. As a matter of fact there would be various networks that interconnect to provide this seemingly singular connectivity solution.

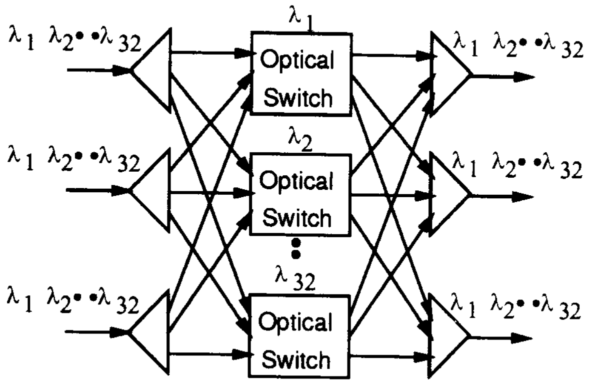


Figure 2.7: The theoretical optical network node showing wavelength selectivity and spatial switching [24].

2.2 Standards

The establishment of standards by organisations that govern and regulate the telecommunications industry has advantages as well a disadvantages. Advantages of standards include the resultant compatibility of conforming vendors' equipment and focused efforts of researchers and developers. Disadvantages of standards on the other hand include the cumbersome support required for legacy equipment and unfashionable or impractical parts of these standards. The existence of several seemingly uncoordinated regulatory bodies negates the potential advantages of inter-vendor compatibility to such an extent that one of the main selling points of new networking equipment is its promised compatibility with other vendors' offerings. In a marketplace fearing monopolies and proprietary bindings, standards have become nearly as important if not more important than the technologies that they describe.

2.2.1 SONET/SDH

Synchronous optical network (SONET) is the well-known standard for high data rate digital transmission in North America, published by the American National Standards Institute (ANSI). Its sibling, used in most other countries including South Africa, is published by the International Telecommunications Union (ITU) and is known as synchronous digital hierarchy (SDH). These similar standards are jointly referred to as SONET/SDH and supersede an earlier standard called plesiochronous digital hierarchy (PDH). SONET/SDH is capable of transporting a myriad of digital traffic types including PDH and asynchronous transfer mode (ATM), but has as one of its most important features a very organised protection method known as automatic protection switching (APS) whereby traffic is efficiently rerouted, i.e. self-healing rings (SHR), to avoid damaged or malfunctioning links and nodes.

PDH is still predominant in conventional telephony networks with the basic building block known as digital system - level 1 (DS1), which is the framing format and interface specification with its transmission medium known as T1. This nomenclature is used throughout the four levels of PDH with data rates for each level differing slightly based on the region of implementation, with ANSI and ITU being the references for PDH standards as shown in table 2.1.

The first level of the SONET hierarchy is known as the synchronous transport signal - level 1 (STS-1), with the synchronous transport module - level 1 (STM-1) being the first level of the SDH hierarchy. The data rates at which these level 1 building blocks of SONET and SDH operate are however different. Table 2.2 shows the difference between the levels of SONET and SDH as well as where they fit into the OC-x classification system with an optical channel (OC) as its basic building block.

ANSI			ITU		
Signal	Bit rate (Mbps)	Channels	Signal	Bit rate (Mbps)	Channels
DS-0	0.064	1 DS-0	64 kbps	0.064	1 64 kbps
DS-1	1.554	24 DS-0	E1	2.048	30 64 kbps
DS-2	6.312	96 DS-0	E2	8.448	4 E1
DS-3	44.736	28 DS-1	E3	34.368	16 E1
N/A	N/A	N/A	E4	139.264	64 E1

Table 2.1: PDH levels and data rates defined by ANSI and ITU.

The STS-x and STM-x nomenclature applies to signals while still in their electrical state. The OC-x classification system applies to optical signals used at equipment and network interfaces, with OC-1 being the lowest level of the hierarchy, obtained from a scrambled STS-1 bit stream being converted from electrical to optical. Although it is commonly used, SDH does not officially make use of the OC-x classification, but rather extend the STM-x naming convention to signals in the optical domain, with STM-1, in its capacity as optical domain descriptor, being the equivalent to the optical OC-3. Higher data rate optical signals are created through multiplexing by the interleaving of lower level STS or STM bytes.

2.2.2 WDM

The ITU standardised the nominal centre frequencies for use in multi-wavelength systems with the G.692 recommendation. Table 2.3 shows the ITU frequencies and wavelengths for use in the 1550nm band of wavelength-division multiplexing optical communication networks for spacings of 50GHz and 100GHz anchored around the 193.10 THz reference. It is important to note that wavelength values are indicated relative to fre-

Data rates (Mbps)			SONET		SDH	
Line	Payload	Overhead	Electrical	Optical	Electrical	Optical
51.840	50.112	1.728	STS-1	OC-1	STM-0	STM-0
155.520	150.336	5.184	STS-3	OC-3	STM-1	STM-1
622.080	601.344	20.736	STS-12	OC-12	STM-4	STM-4
1244.160	1202.688	41.472	STS-24	OC-24	N/A	N/A
2488.320	2405.376	82.944	STS-48	OC-48	STM-16	STM-16
9953.280	9621.504	331.776	STS-192	OC-192	STM-64	STM-64
39813.120	38486.016	1327.104	STS-768	OC-768	STM-256	STM-256

Table 2.2: SONET/SDH levels and data rates [25, 26].

quency through the $c = f\lambda$ relationship, where c is the speed of light in a vacuum, $2.99792458 \times 10^8 ms^{-1}$, f is frequency and λ is wavelength.

When referring to wavelengths in the optical communication context, it is always with reference to the speed of light in a vacuum. Since the index of refraction, n in an optical fiber is typically in the region of 1.4, the actual wavelength in an optical fiber is $\frac{1}{n}$ of the wavelength specified. The frequency of an electromagnetic wave is however independent of the medium through which it propagates, hence the ITU's focus on frequencies in the standardisation of multi-wavelength communication channels.

Table 2.3 only shows 81 standardised frequencies in the 50 GHz spacing grid. The standard does however allow for implementors to extend the end-points of the grid above and below the outer frequencies. The basic prerequisite is that frequencies be integer multiples of the grid spacing factor around the nominal centre frequency of 193.10 THz. Experimental optical networking equipment utilising spacing factors of 25 GHz and even 12.5 GHz have been announced by several companies in the DWDM industry.

50 GHz spacing (THZ)	**100 GHz spacing (THz)**	**Wavelength (nm)**	**50 GHz spacing (THZ)**	**100 GHz spacing (THz)**	**Wavelength (nm)**
196.10	196.10	1528.77	194.05	-	1544.92
196.05	-	1529.16	194.00	194.00	1545.32
196.00	196.00	1529.55	193.95	-	1545.72
195.95	-	1529.94	193.90	193.90	1546.12
195.90	195.90	1530.33	193.85	-	1546.52
195.85	-	1530.72	193.80	193.80	1546.92
195.80	195.80	1531.12	193.75	-	1547.32
195.75	-	1531.51	193.70	193.70	1547.72
195.70	195.70	1531.90	193.65	-	1548.11
195.65	-	1532.29	193.60	193.60	1548.51
195.60	195.60	1532.68	193.55	-	1548.91
195.55	-	1533.07	193.50	193.50	1549.32
195.50	195.50	1533.47	193.45	-	1549.72
195.45	-	1533.86	193.40	193.40	1550.12
195.40	195.40	1534.25	193.35	-	1550.52
195.35	-	1534.64	193.30	193.30	1550.92
195.30	195.30	1535.04	193.25	-	1551.32
195.25	-	1535.43	193.20	193.20	1551.72
195.20	195.20	1535.82	193.15	-	1552.12
195.15	-	1536.22	**193.10**	**193.10**	**1552.52**
195.10	195.10	1536.61	193.05	-	1552.93
195.05	-	1537.00	193.00	193.00	1553.33
195.00	195.00	1537.40	192.95	-	1553.73
194.95	-	1537.79	192.90	192.90	1554.13
194.90	194.90	1538.19	192.85	-	1554.54
194.85	-	1538.58	192.80	192.80	1554.94
194.80	194.80	1538.98	192.75	-	1555.34
194.75	-	1539.37	192.70	192.70	1555.75
194.70	194.70	1539.77	192.65	-	1556.15
194.65	-	1540.16	192.60	192.60	1556.55
194.60	194.60	1540.56	192.55	-	1556.96
194.55	-	1540.95	192.50	192.50	1557.36
194.50	194.50	1541.35	192.45	-	1557.77
194.45	-	1541.75	192.40	192.40	1558.17
194.40	194.40	1542.14	192.35	-	1558.58
194.35	-	1542.54	192.30	192.30	1558.98
194.30	194.30	1542.94	192.25	-	1559.39
194.25	-	1543.33	192.20	192.20	1559.79
194.20	194.20	1543.73	192.15	-	1560.20
194.15	-	1544.13	192.10	192.10	1560.61
194.10	194.10	1544.53			

Table 2.3: ITU frequency grid for wavelength division multiplexing [27].

Chapter 3

Communication traffic engineering

3.1 Statistical nature of communication traffic

In its most elementary form, the basic purpose of any communication network is to satisfy the communication requirements of its customers through the delivery of products and services over limited physical infrastructure. From the physical infrastructure's perspective, these service and product demands are dealt with as communication traffic exhibiting non-uniform statistical behaviour. The fluctuating flows of traffic through a communication network not only influences network management, load balancing, capacity utilisation, and quality of service, but also the way in which the network should have been designed. This results in the familiar chicken-egg dilemma that is best resolved through the use of traffic models and simulation during the network design phase.

Communication networks typically exhibit periodically varying traffic levels that follow daily, weekly and monthly cycles. As the geographical area of large wide-area networks increase and extend over several time zones, the appearance of this kind of periodical behaviour gradually change from a network-wide phenomenon to more localised occurrences. The variation of network traffic as a function of time does however still account for great uncertainty in the utilisation levels of the various links that comprise a network.

3.1.1 Geographical distribution of communication traffic

A strong correlation exists between the add/drop traffic of a network node and its proximity to other network nodes. This is due to the tendency of people to populate metropolitan areas and conduct their economic activities in these metropolitan areas. It is therefore expected for metropolitan areas to contain more network nodes than rural areas, and for these network nodes to have more add/drop traffic than those in rural areas. The add/drop traffic of a network node as well as its proximity to other network nodes should thus be taken into account when designing wide-area networks that provide connectivity between all network nodes.

The concept of communities of interest evolved from the geographical correlation frequently observed between the source and destination in general communication network traffic. To some extent it can even be argued that network designers and operators encourage the seemingly natural occurrence of communities of interest, because of the cost-saving benefits of networking functions such as the proxy and mirror commonly utilised in packet-switched data retrieval applications such as the World Wide Web (WWW).

The clustering of network nodes in such a way as to exploit communities of interest and provide the connectivity associated with wide-area networking, is discussed in section 5.3. The creation of clusters residing on the various levels of the multi-level network model, described in section 4.1, is an intuitive result of the communities of interest concept. It is however important to note that the geographical distribution of communication traffic relates to the network's source-destination pairs' contribution to the total network traffic, as opposed to the geographical proximity of network nodes alone.

3.1.2 Traffic models

The traditional application of traffic models is to assist network operators to estimate the traffic load distribution to be expected if changes in the network should occur. Changes such as network faults or malfunctions can be simulated, allowing for analysis of the resultant impact on the load on protection paths. Another change that can occur in the network might be on the service layer, where traffic models can be used to predict how new services supported over the network would affect its ability to provide required levels of reliability and capacity for delivering existing services.

Theoretical traffic models that attempt to describe actual communication traffic in a network usually have difficulty in obtaining good fit with regards to the marginal probability distribution and autocorrelation function of the empirical time series [28]. Several time series models exist for describing Internet traffic, but are usually limited to specific network topologies and implementations. The late NSFNet was well studied in this regard [29, 30] due to the availability of traffic statistics [31] that assisted in the verification, benchmarking and further development of network traffic models.

Burstiness, described as significant positive autocorrelation in the inter-arrival process, results in increased waiting times without considerably influencing the nett arrival rate.

These are parameters that typically do not behave in such a fashion when generated in theoretical traffic models, hence the motivation for traffic models that can more accurately represent the activity on the channels of modern WDM optical communication networks.

Traffic models are also used when add/drop traffic statistics are unavailable for a wide-area network that is to be designed, or when predictions are required on the influence of planned modifications to the network. Not only the amount of a network node's add/drop traffic is important, but also its geographic distribution. Gravity models using statistics such as regional population and economics can be used to estimate the traffic relationship between all network nodes, from which the estimated add/drop traffic of all network nodes can be calculated.

Gravity models

The simple gravity model, as depicted in figure 3.1, is a popular mathematical tool, inherited from physics where it is used in various of its branches, including the fields of statics, dynamics, and even astronomy. The underlying principle of the gravity model is the weighting of inter-point relationships based on their relative importance in a system of points. In the communication networking context, the points constitute network nodes and the inter-point relationships give an indication of the logical topology as described in section 4.2.2. The relative importance of a network node in a network comprising several network nodes is the key parameter in demand estimation, because it directly determines the logical topology of a network.

With reference to figure 3.1, the meanings of the employed symbols are as follows. W_i is the relative weight of network node i, while W_j is the relative weight of network node j.

In the denominator of the inter-nodal weight expression, a summation of relative nodal weights is made over all network nodes by using k as an index to N total network nodes. The inter-nodal weight expression $W_i \times W_j/(\sum_{k=1}^{N} W_k)^2$ shown in figure 3.1, is evaluated for all combinations of network nodes, indexed by i and j, as per the logical connectivity requirements to be presented in the network's logical topology.

Elaborations on the simple gravity model exist and are referred to as modified gravity models. These models exhibit various weighting preferences and can be customised to suit the requirements of a given problem. A popular modification is the inclusion of a distance parameter to allow for the phenomenon of communities of interest, that form based on geographical proximity. Caution should however be taken in the modification of gravity models to avoid the introduction of bias that can negatively impact on the dynamic range and resolution of the achievable inter-nodal network weights. Relationships ranging from linear to exponential and even polynomial can be achieved for the mapping from node weighting parameters to inter-nodal network weights. The careful selection of the relationship can ensure more robust capacity provisioning, capable of sustaining fluctuations in network load and unbalanced demand growth.

The population-distance model used in the European Optical Network (EON) project [16], is very similar to the gravity model, modified to include the distance metric. The lack of reliable demand estimates from regulatory bodies required the EON network designers to do a demand estimation for the required capacity between points s and p in the network by evaluating the equation

$$D_{s,t} = K \frac{P_s P_t}{distance_{s,t}}, \tag{3.1}$$

where K was a constant of 5.25 Erlang and the units of population P being in millions

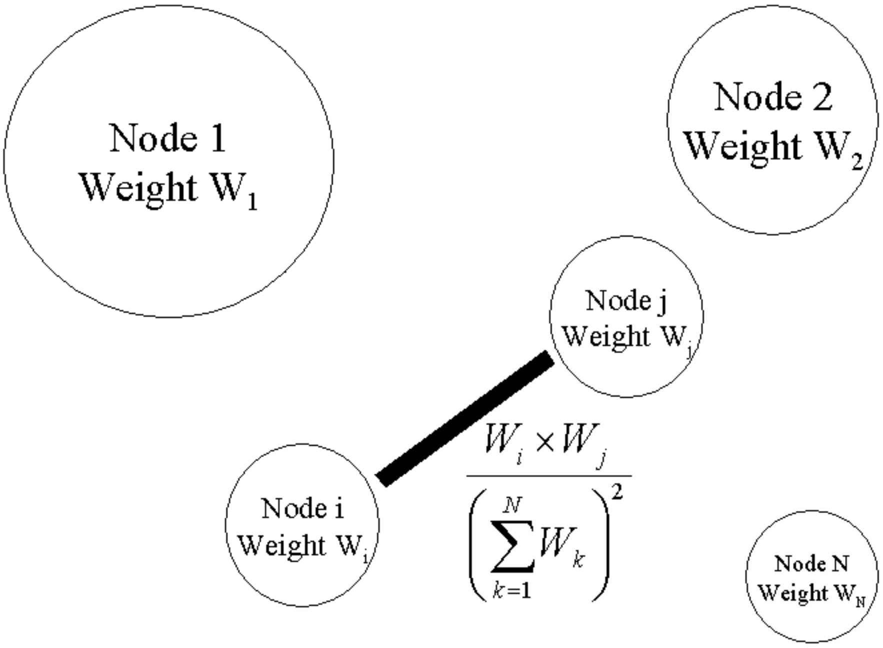


Figure 3.1: The simple gravity model.

and *distance* in kilometres. From the constant K being in Erlang it is easy to deduce the circuit-switched thinking that was still prevalent during the time of the EON project.

3.1.3 From network node weighting to demand matrices

The determination of relative network node weights is crucial for the utilisation of techniques such as the gravity model, which is discussed in section 3.1.2. Various parameters obtained from statistical analysis of a planned communication network's geographical area can be employed in the development of a relative network node weight. Popular parameters include absolute, growth potential, growth trends, and demographic breakdowns of metrics such as population, economic activity, teledensity, and available technology.

Network node weighting functions can be as simple as relative population density or as complex as a non-linear polynomial interaction of numerous parameters. Experience in signal processing and pattern recognition disciplines suggest that less complicated characteristic functions produce results that are comparable to that of complex functions, with the benefit of providing insight into parameter interaction. For this reason, lower-order network node weighting functions with fewer parameters are recommended, since complex functions do not enhance the power of an equation that ultimately contributes to a process based on non-discrete decision mechanisms and evaluation criteria.

Population alone is not a sufficient parameter to use when weighting a network node. Economical activity has been identified as being key to the communication requirements of network nodes. For this reason a modified gravity model has been employed to create the flow distribution and subsequent demand matrices that describe the capacity requirements between all network nodes. The gravity model has been modified to include consideration of geographical positions, thus allowing for community of interest factors to influence the creation of the demand matrix. The demand matrix is populated through the evaluation of the following modified gravity model, where a simple nodal weighting of economic activity has been employed:

$$D_{i,j} = K_1 \frac{E_i \times E_j}{dist_{i,j}}, \tag{3.2}$$

where E_i and E_j indicate the economic activity of nodes i and j, $dist_{i,j}$ is the distance between nodes i and j, and K_1 is a normalising constant chosen in such a way as to ensure that the network capacity requirement is satisfied as follows:

$$C = \sum_{i=1}^{N} \sum_{j=1}^{N} D_{i,j}, \tag{3.3}$$

with network capacity C being the chosen aggregate network capacity requirement of the network under design. With reference to $dist_{i,j}$ of equation 3.2, it is important to note that the distance between two points on a sphere is given by:

$$\begin{aligned} dist_{i,j} = 1.852 \times 180\frac{60}{\pi} \arccos\Bigg(& \sin\frac{lat_i}{180\pi} \sin\frac{lat_j}{180\pi} + \\ & \cos\frac{lat_i}{180\pi} \cos\frac{lat_j}{180\pi} \cos\left(\frac{long_i}{180\pi} - \frac{long_j}{180\pi}\right)\Bigg), \end{aligned} \tag{3.4}$$

where $dist_{i,j}$ is the distance along the surface of the sphere from point i to point j in kilometres, lat_i is the latitude of point i in degrees and $long_j$ is the longitude of point j in degrees.

3.2 Matrices representing network traffic and flow distribution

A traffic matrix mathematically presents the volume of traffic that a communication network carries between its nodes, through the mapping of traffic sources and destinations on a two dimensional matrix. These nodes could be ingress and egress points on a backbone transport network, gateway routers at the edge of an Internet service provider's (ISP's) point-of-presence (PoP), or interfaces to the subnets of an enterprise network. The backbone network is considered core to this investigation into factors influencing wide-area network design, which is why the discussion of matrices that describe network traffic is limited to this context.

The terms *table* and *matrix* are used interchangeably in literature and industry to refer to the method of presenting the flow, interrelation and distribution of communication network traffic, whether in estimated, provisioned, demanded, capacity or actual embodiments. Aspects such as symmetry of network traffic and the differences between intra and inter-nodal traffic are discussed in this section. Flow distribution matrices are also discussed at length, motivated by their importance to logical topologies, as discussed in section 4.2.2.

The structure of the matrices under discussion consists of row and column labels, indicating the network nodes that constitute the sources and destinations of the connections represented at the intersecting cells of the matrix structure. Nodal totals are computed and indicated at the end of each row and column, with a grand total indicated at the intersection of the end row and column. No set standard exists for whether sources or destination should be mapped to rows or columns, but it is important for a network designer to specify the chosen convention when an actual matrix is constructed. The convention of sources along rows and destinations along columns will be followed throughout this document.

3.2.1 Symmetry in network traffic

In communication networks, the relationship between source and destination is often defined by the difference in the amounts of traffic that flows in both directions. A source is typically defined as the node in a logical connection from where high volumes of traffic originate, whereas a destination is defined as the node to where high volumes of traffic travel. Except for special broadcast and multi-cast scenarios, it is customary for bi-directional communication to exist between all source-destination pairs in a communication network. The temporary nature of most communication connections is one of the main reasons for the overhead and handshaking required in connection establishment. The connection management component, as discussed in section 4.3.2, is also responsible for the bi-directional nature of most communication links.

Since bi-directionality has been established to be a characteristic of typical network connections, the matter of symmetry between the volume of traffic generated in the two directions emerge. In a conventional client-server model such as what has become popular in the WWW, the observation of highly asymmetrical traffic can be made. On the other hand, typical circuit-switched applications such as a public switched telephone network (PSTN) are perfect examples of truly symmetrical communication. Since the first commercial implementation of optical fiber technology and subsequent optical networks in the telecommunication industry, optical network traffic is typically thought of as being symmetrical. *The prevalence of this is such that optical network designers seldom consider asymmetrical traffic models when designing wide-area networks.*

An asymmetrical traffic model offers the advantage of having symmetrical traffic as a special case, thus allowing for seamless coexistence with existing symmetrical traffic paradigm. It is therefore suggested that a network design approach that considers the possibility of asymmetrical traffic possesses great advantages above one that blindly assumes the provisioning of conventional voice services.

With the many developments and nearing maturity of voice-over-IP (VoIP) technology, the field of conventional circuit-switched voice telecommunication will be forced to adapt to a more generic packet-switched way of thinking, including acknowledgment of the possible asymmetrical properties of network traffic. The aforementioned broadcast and multi-cast scenarios applicable to video-on-demand (VoD) and other content streaming services also lend themselves to an asymmetrical traffic model.

3.2.2 Intra-and inter-nodal traffic

It is conventional to only consider inter-nodal traffic and not the intra-nodal traffic that never travels on the network level under consideration. For this reason it is typical to find an empty diagonal in the flow distribution matrix, and subsequent demand, capacity and traffic matrices, resulting from not considering traffic that originates from a specific network node and terminates at the same network node. Traffic of this nature is typically handled on a lower level of the multi-level network model, as described in section 4.1, resulting in additional matrices being created in a hierarchical fashion.

Consideration of intra-nodal traffic is justified in special situations such as described in the clustering approach discussed in section 5.3. This is a special application where recursive traversing of the multi-level network model is used to determine the way in which network nodes should best be grouped for load balancing purposes. In such an application it would thus be justified not to have an empty diagonal in intermediate flow distribution matrices, but still in the subsequent demand, capacity and traffic matrices.

3.2.3 Flow distribution matrices

One of the most important applications of the traffic models and node weighting techniques discussed in section 3.1.2 and section 3.1.3 is the development of flow distribution matrices. The design of logical topologies, as described in section 4.2.2, depend on flow distribution matrices that show the relative contributions of all logical connection permutations to the total network traffic capacity that should be provisioned for.

In a simple network consisting of a low number of network nodes it might be possible to represent all traffic flows in a single flow distribution matrix. Medium-sized to large networks usually require the creation of several hierarchical flow distribution matrices in accordance with the multi-level network model as described in section 4.1. However, where many flow distribution matrices are necessary, the prerequisite is given that the sum of all relative nodal flows over all the flow distribution matrices equate to 100%, thus ensuring that all anticipated traffic flows are provided for in a relative yet context-aware manner. Figure 3.2 shows a hierarchical collection of flow distribution matrices where symmetrical traffic demand was assumed.

In order to achieve an aggregate traffic flow of 100%, it is necessary to employ techniques for scaling the individual relative traffic flows that do not introduce unplanned non-linearity into the results of an already potentially non-linear node weighting process. An innovative methodology for creating flow distributions from weighted network nodes through the use of statistical clustering is presented in section 5.3.

The rows and columns of flow distribution matrices represent the sources and destinations of the traffic flows. In symmetrical traffic matrices, as described in section 3.2.1, the column and row totals of the flow distribution matrix separately add up to the same 100% total network capacity. In the case of asymmetrical network traffic a slightly different approach is used where individual cell values add up to the 100% total network capacity due to the inequality of row and column totals.

Table 3.1 shows an elementary flow distribution matrix with asymmetrical traffic as opposed to symmetrical traffic as shown in table 3.2. Each individual cell entry indi-

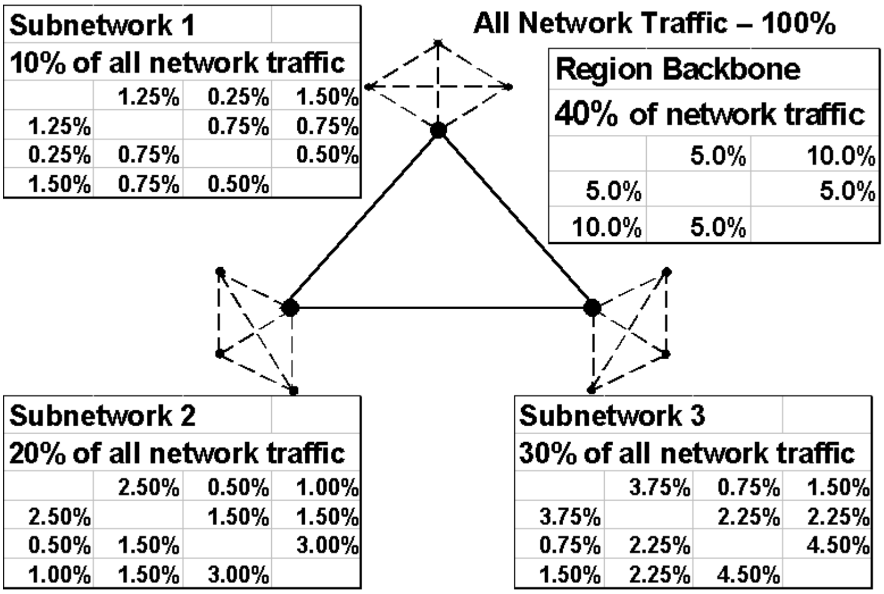
		Destination			
	Nodes	**1**	**2**	**3**	
Source	**1**		19%	8%	**27%**
	2	12%		21%	**33%**
	3	22%	18%		**40%**
		34%	**37%**	**29%**	**100%**

Table 3.1: An elementary flow distribution matrix with asymmetrical traffic.

		Destination			
	Nodes	**1**	**2**	**3**	
Source	**1**		10%	15%	**25%**
	2	10%		25%	**35%**
	3	15%	25%		**40%**
		25%	**35%**	**40%**	**100%**

Table 3.2: An elementary flow distribution matrix with symmetrical traffic.

cates the amount of traffic flow from a specific source node to a specific destination node relative to the total network traffic, where the source nodes can be chosen to be the rows and the destination nodes the columns of the flow distribution matrix. The mapping of source and destination to row and column should always be specified in a flow distribution matrix since a wrong assumption can result in the development of an incorrect logical topology.



All Network Traffic – 100%

Subnetwork 1
10% of all network traffic

	1.25%	0.25%	1.50%
1.25%		0.75%	0.75%
0.25%	0.75%		0.50%
1.50%	0.75%	0.50%	

Region Backbone
40% of network traffic

	5.0%	10.0%
5.0%		5.0%
10.0%	5.0%	

Subnetwork 2
20% of all network traffic

	2.50%	0.50%	1.00%
2.50%		1.50%	1.50%
0.50%	1.50%		3.00%
1.00%	1.50%	3.00%	

Subnetwork 3
30% of all network traffic

	3.75%	0.75%	1.50%
3.75%		2.25%	2.25%
0.75%	2.25%		4.50%
1.50%	2.25%	4.50%	

Figure 3.2: Hierarchical collection of flow distribution matrices assuming symmetrical traffic demand.

3.3 Traffic grooming

When evaluating the cost of contemporary WDM optical networks, it is found that the SONET/SDH multiplexing equipment found in the digital cross-connect systems (DCSs) of the network nodes contribute substantially to the total equipment cost of the network. Figure 3.3 shows a high-level diagram of three network nodes with emphasis on the DCS that interfaces lower data rate traffic streams to the unlabeled optical add-drop multiplexer (OADM) in the middle network node. A number of transceivers are located at the interface between the DCS and OADM and constitutes a dominant cost to be minimised through efficient traffic grooming.

The compilation of a data stream for transmission on a wavelength has become as challenging as the wavelength-division multiplexing function itself. The data rates of the independent traffic streams are substantially lower than that of the optical data rates achieved on a wavelength channel. The term *traffic grooming* refers to the techniques used to combine lower data rate traffic streams onto available wavelength channels to achieve design goals such as cost minimisation and restorability.

Grooming can be seen as the time-domain equivalent of wavelength division multiplexing, with the only exception being that individual traffic streams of various, often different, data rates are combined as opposed to traffic streams of the same data rate. The problem of assigning shared wavelength channels to several individual traffic streams is complex due to the different source and destination combinations of the various individual traffic streams. Figure 3.4 shows how the number of SONET/SDH add-drop multiplexers (SADM) required in the DCS, shown left, can be greatly reduced by implementing wavelength add-drop multiplexer (WADM) functionality, shown right, in the OADM of a network node.

The combination of individual traffic streams into shared wavelength channels requires consideration of several factors including channel capacity, time-domain multiplexing and demultiplexing resolution, near-minimum hop routing, reliability through protection and restoration, and billing complexity. Since traffic grooming operates on the SONET/SDH level, it is not surprising that most research [32, 33, 34] on the topic have focused on traffic grooming in ring topologies, the most popular implementation of SONET, as shown in figure 3.5. Besides the conventional techniques for doing traffic grooming in SONET rings, some novel approaches employing genetic algorithms [35] and simulated annealing [36] have also been proposed.

The creation of concepts such as local and express traffic routes, results from the grooming of communication traffic. The combination of various individual traffic streams onto shared wavelength channels is done in such a way as to minimise the standard deviation of add-drop multiplexing required per wavelength channel. Some channels will be used for short routes, and then re-used in other parts of the network, whereas other chan-

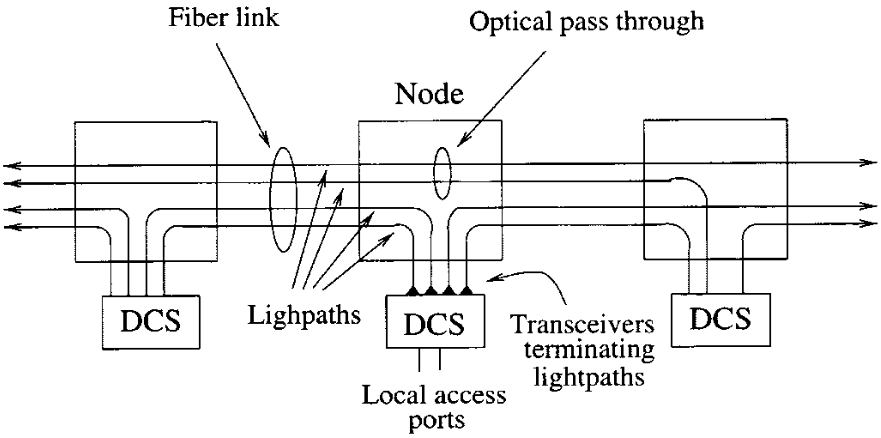


Figure 3.3: Three optical network nodes with emphasis on the interface between DCS and OADM of the middle node [33].

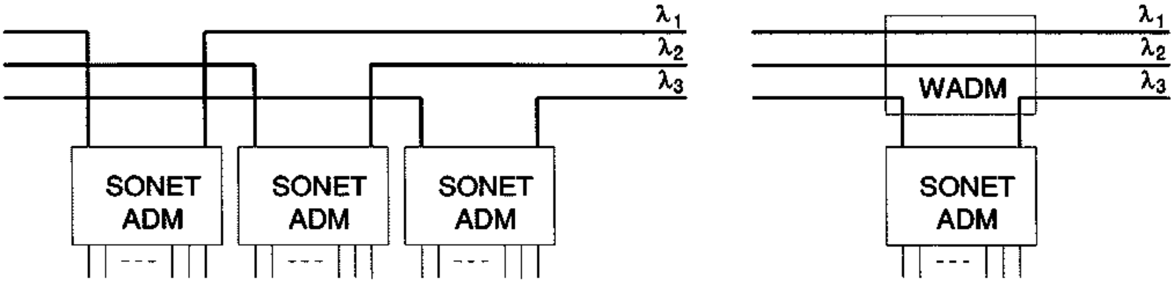


Figure 3.4: Reducing the number of SADMs, shown left, required at a network node through the addition of WADM functionality, shown right [34].

nels will function like express lanes on a highway, where vast geographical distances are covered without allowing for individual traffic streams to exit or join the shared wavelength channel.

3.3.1 The non-trivial nature of the grooming problem

Figure 3.6 shows a simple six-node point-to-point physically connected SONET-over-WDM ring utilising three wavelengths on all the optical links. Note that this network does not contain any true optical nodes, since no traffic can traverse a node without

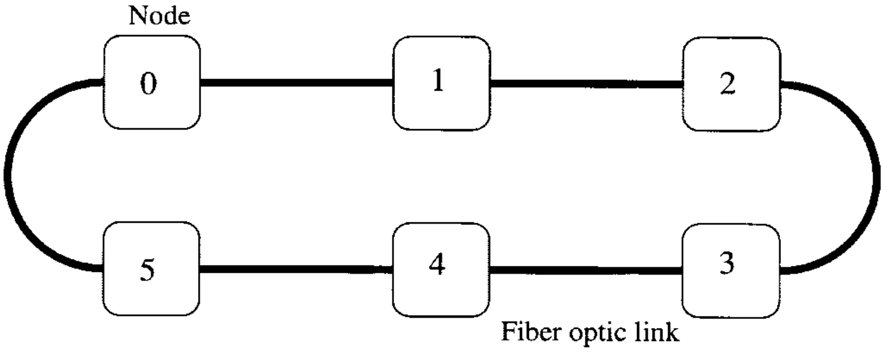


Figure 3.5: Simplified physical topology of a six-node optical SONET-over-WDM ring network [33].

being converted to and from the electronic domain where all processing decisions are made.

The non-trivial nature of the grooming problem can be explained with reference to the network in figure 3.6. Assume the following scenario: each of the three wavelengths in the network carries a SONET OC-48 data stream and it is necessary to extract an OC-3 stream from each of the three wavelengths at a specific network node. This would require all three wavelengths to be received and processed at the network node to obtain three OC-3 data streams that could have easily fitted into the same OC-48 data stream, allowing the other wavelengths to pass through the network node unhindered. In a relatively simple example like this it might seem easy to ensure more appropriate grooming, but complex networks with high numbers of network nodes and varying traffic conditions make this a highly non-trivial problem.

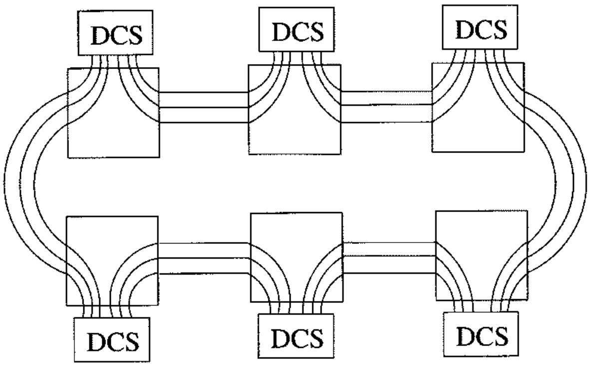


Figure 3.6: Elementary six-node SONET-over-WDM ring with three wavelengths per point-to-point physical link [33].

Chapter 4

Communication network engineering

4.1 Multi-level network model

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

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

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

4.2 Topologies

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

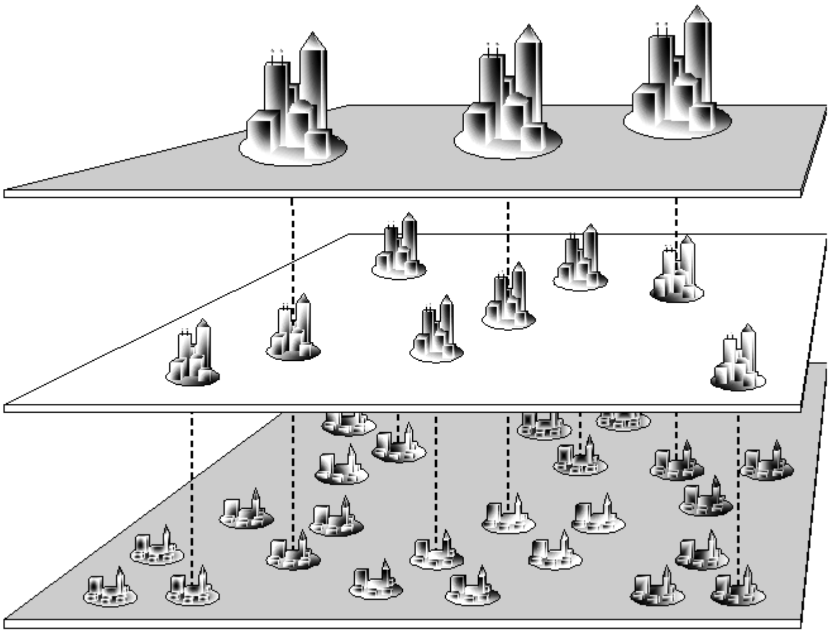


Figure 4.1: The multi-level network model.

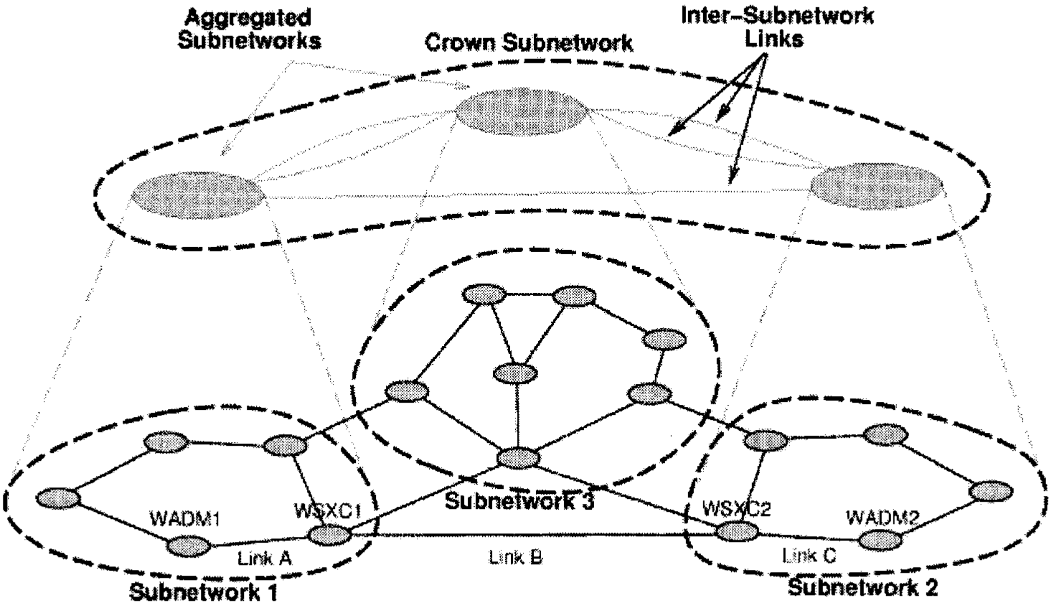


Figure 4.2: Representation of the multi-level network model showing the partitioning and aggregation of subnetworks [37].

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

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

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

4.2.1 Physical topologies

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

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

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

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

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

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

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

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

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

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

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

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

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

Physical topologies of benchmark networks

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

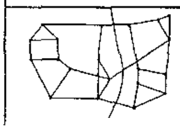
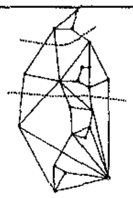
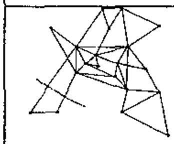
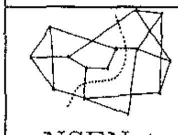
Network	N	L	α	$\overline{H}$	D	W_{LL}	N_λ
 JON	50	84	0.07	5.39	14	209	221
 ARPANet	20	31	0.16	2.81	6	33	33
 UKNet	21	39	0.19	2.51	5	19	22
 EON	20	39	0.2	2.36	5	18	18
 NSFNet	14	21	0.23	2.14	3	13	13

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

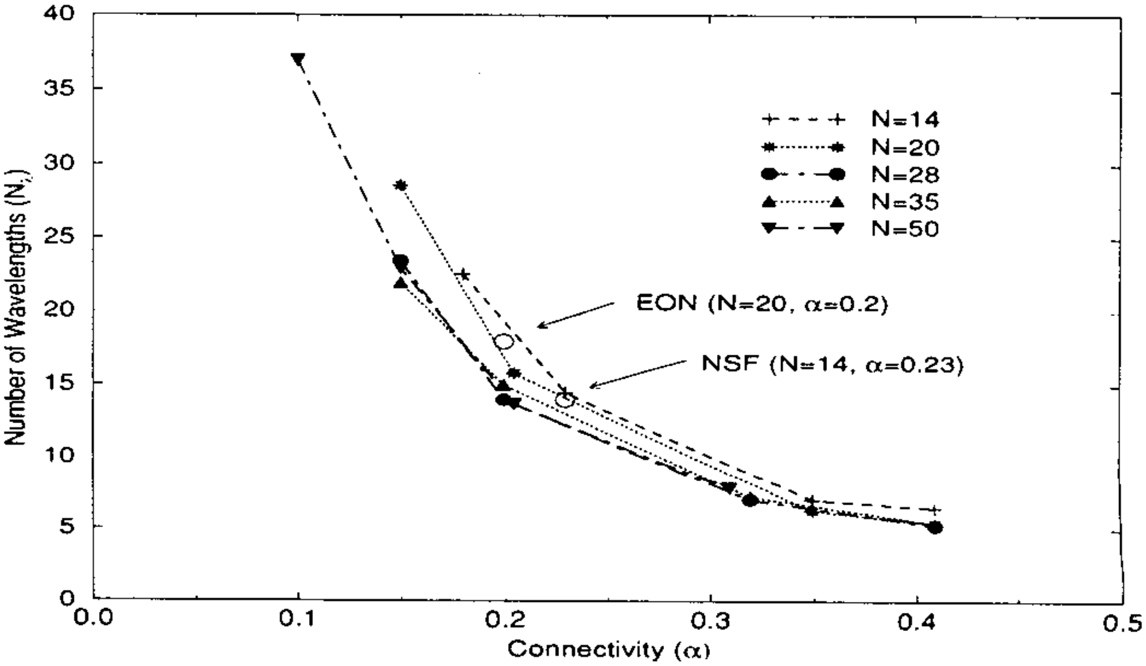


Figure 4.3: The number of wavelengths required in a network as a function of physical connectivity [39].

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

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

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

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

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

4.2.2 Logical topologies

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

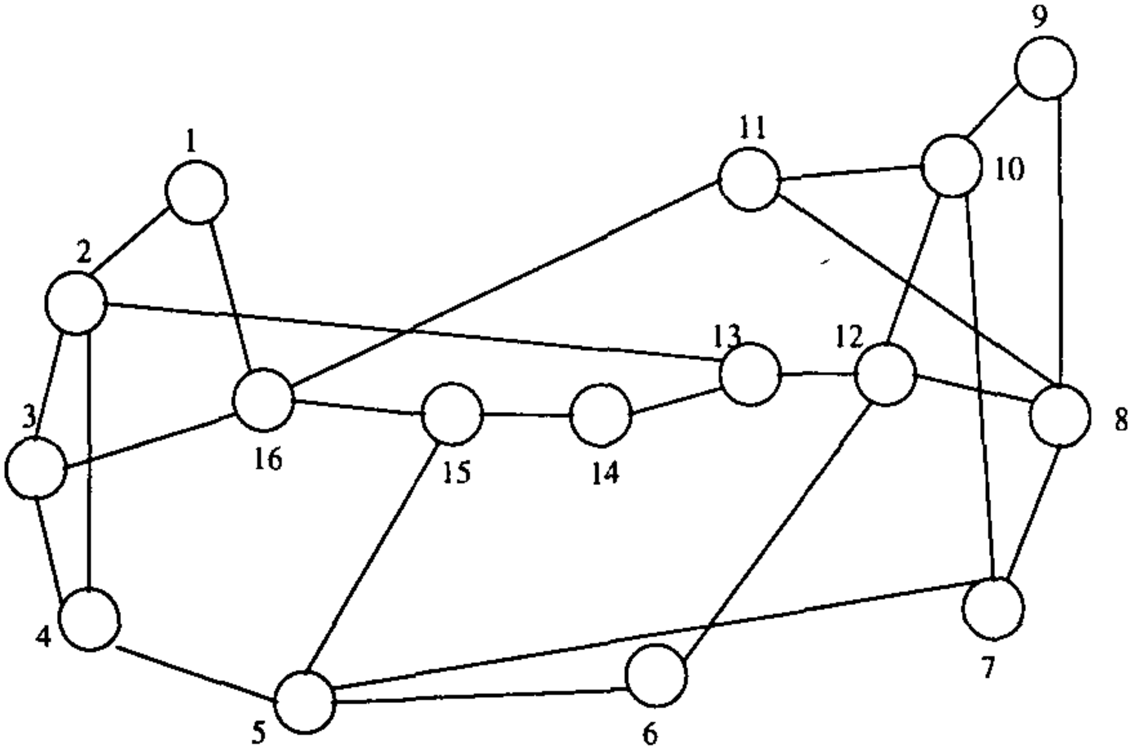


Figure 4.4: Physical topology of NSFNet [42].

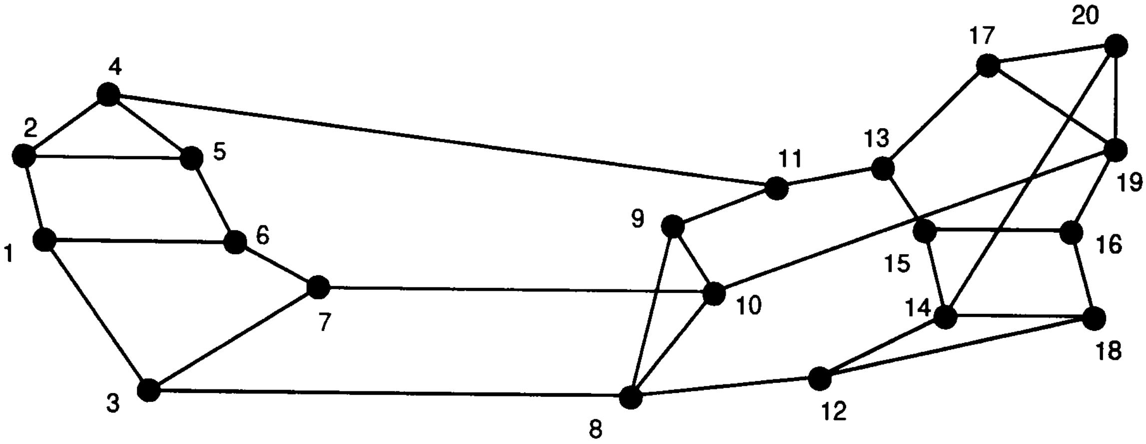


Figure 4.5: Physical topology of ARPANet [24].

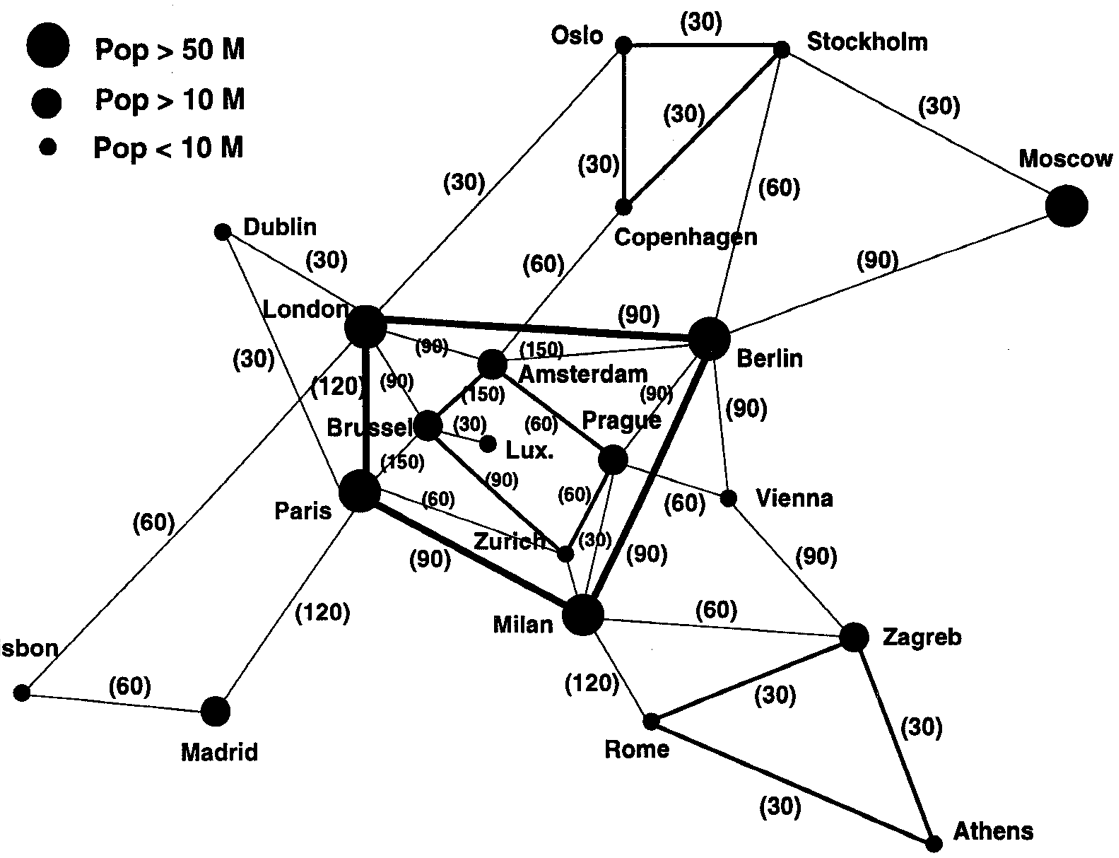


Figure 4.6: Physical topology of EON with link capacities in Gbps indicated in brackets [16].

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

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

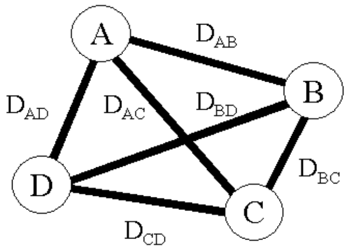
For the development of a demand matrix from a flow distribution matrix it is essential that a reliable estimate for the aggregate traffic of the whole network exists. This is however not a trivial issue, since where the network edge is defined, has a great impact on the aggregate traffic of the network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

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

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

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

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



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

Symmetrical

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

Asymmetrical

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

4.2.3 Virtual topologies

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

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

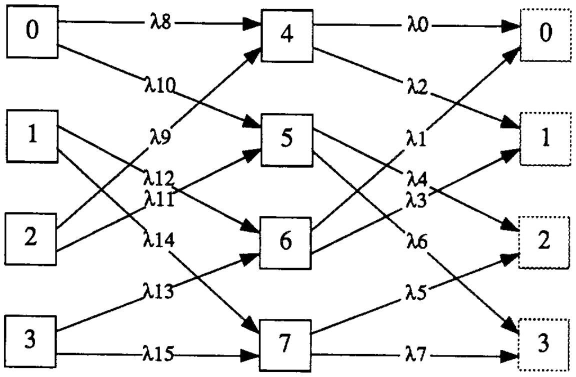


Figure 4.8: A representation of an eight station ShuffleNet virtual topology [7].

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

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

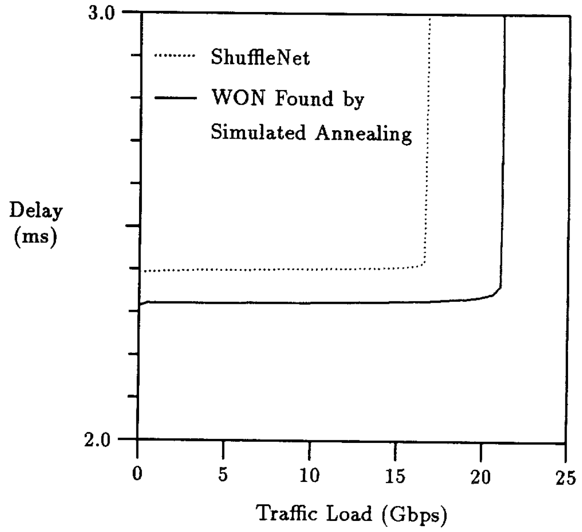


Figure 4.9: Average propagation delay as a function of traffic load for virtual topologies found through ShuffleNet and simulated annealing techniques [7].

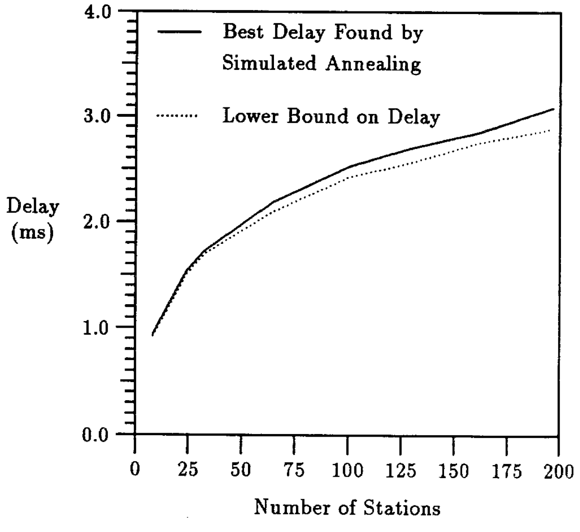


Figure 4.10: Average propagation delay as a function of the number of network nodes for virtual topologies designed through simulated annealing [7].

4.3 Network management

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

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

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

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

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

4.3.1 Physical layer management

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

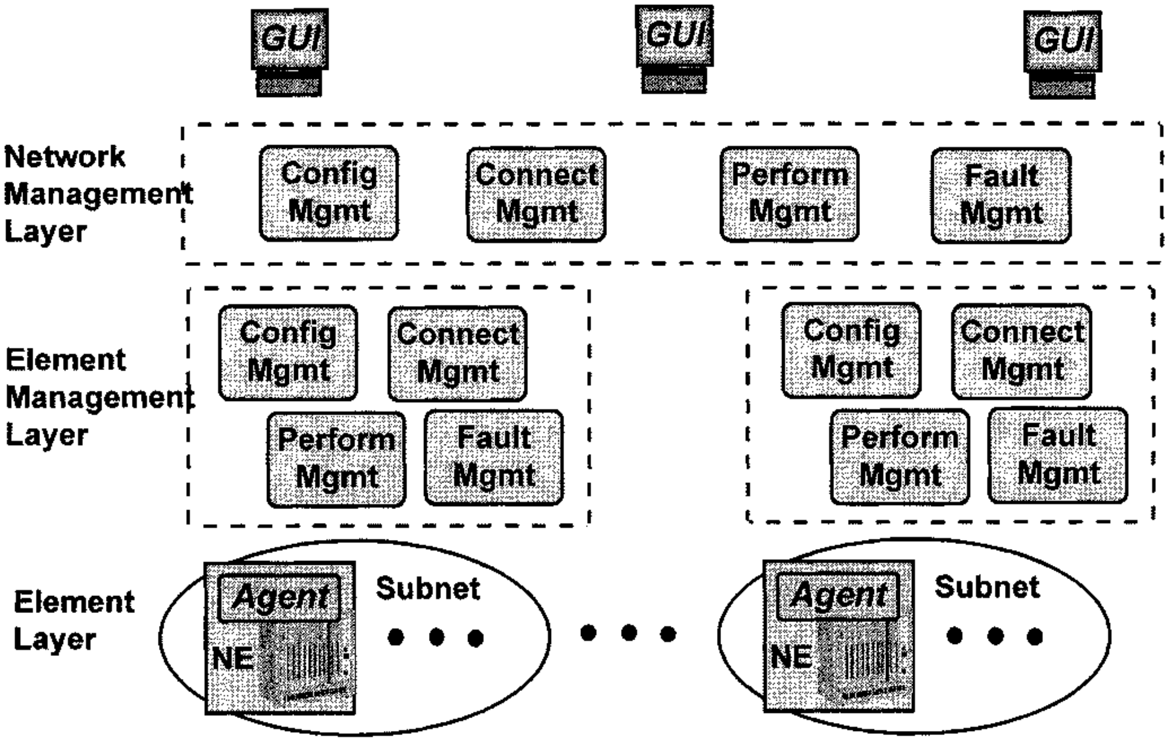


Figure 4.11: MONET network management architecture [37].

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

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

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

4.3.2 Configuration management

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

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

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

4.3.3 Load management

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

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

4.3.4 Restoration management

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

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

4.4 Reliability

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

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

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

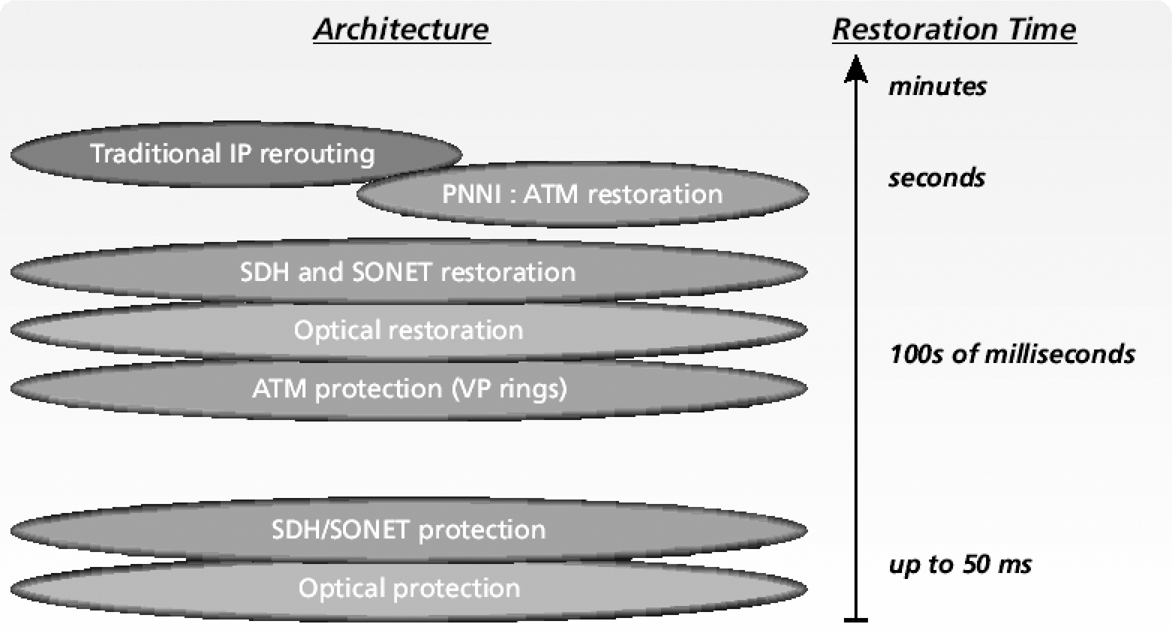


Figure 4.12: Survivability hierarchy for optical networks with relative restoration times [49].

normal network performance.

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

4.4.1 Reliability through protection and restoration

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

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

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

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

Protection methods

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

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

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

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

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

Restoration methods

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

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

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

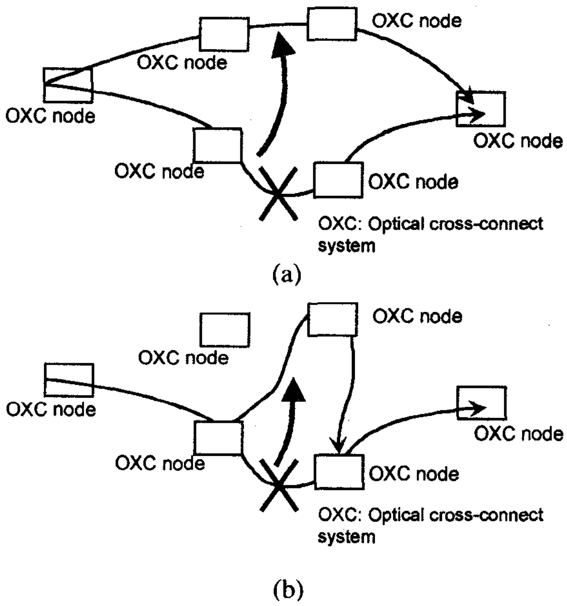


Figure 4.13: The difference between (a) global path switched re-routing and (b) local link switched re-routing in a basic optical network [53].

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

4.4.2 Relative cost of providing for network reliability

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

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

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

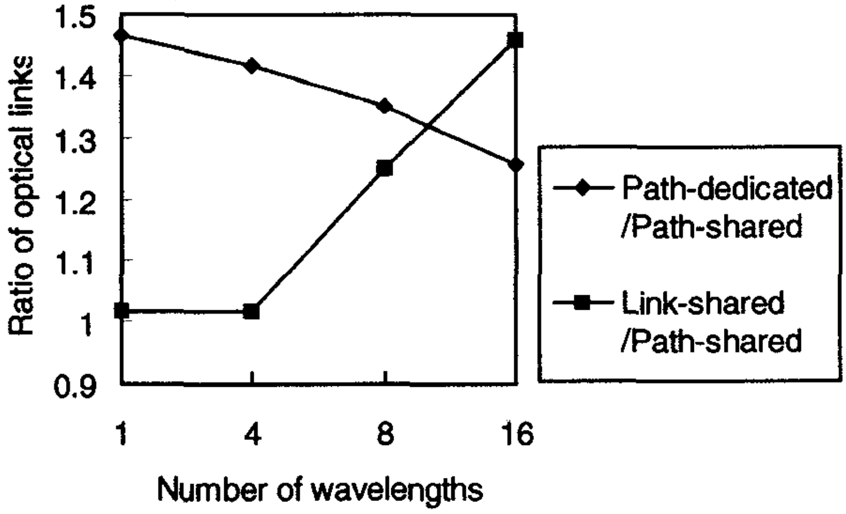


Figure 4.14: Ratio of required optical links as a function of the number of wavelengths [53].

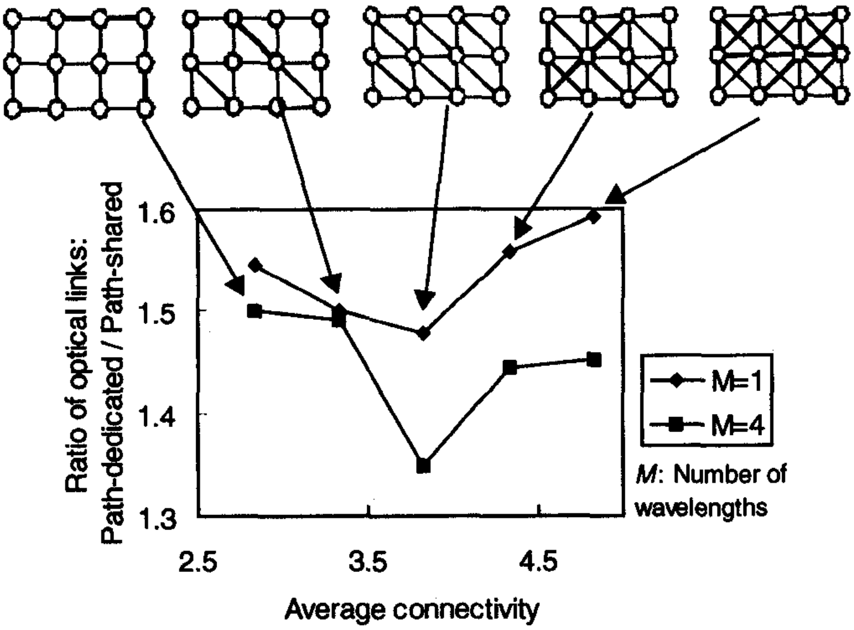


Figure 4.15: Ratio of required optical links as a function of the physical connectivity [53].

4.5 Business modelling

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

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

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

4.5.1 Financial aspects of the optical networking business case

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

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

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

4.5.2 Elasticity as market manipulation tool

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

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

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

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

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

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

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

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

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

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

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

Chapter 5

Wide-area network design

5.1 The network design process

The network design process possesses many stages and seemingly independent processes. The various parts of the design process are normally approached individually due to inherent interaction between the factors that influence the design of wide-area WDM optical networks. There are however many principles and functions that optical network design shares with the design of other communication systems.

The basic characteristics of a communication system are information sources, information destinations and the transport of information between these. The source of an information transport is usually geographically displaced from the destination, hence the need for transport networks. The need therefore exists to establish physical infrastructure between the various nodes of a communication network, to provide logical connectivity that can satisfy the communication demand of the source and destination pairs.

In conjunction with physical connectivity, a communication network requires mechanisms for managing the flow of information over the physical infrastructure to ensure security, reliability and quality of service. The way in which these management functions are implemented is greatly influenced by the underlying technologies and protocols used for data transfer. In this section the network design process will be discussed with reference to optimisation parameters, commercial and proprietary design software, and the integrated design methodology.

5.1.1 Optimisation parameters

There always exist certain expectations from a communication network's users, funders and operators of what the network's characteristics should be. The concept of optimisation and the optimisation parameters that can be optimised for, is key to addressing and managing these expectations. A network can be designed in such a way as to provide for the expectations of one party for a certain period, but as user demand and market conditions change a poorly optimised network may quickly lose its ability to satisfy the requirements of all its stakeholders.

In the keynote address of the international IEEE AFRICON 2002 conference in George, South Africa, Dr. Hiromasa Haneda elaborated at length on the differences between the terms *optimal* and *optimum* and how they should be interpreted in optimisation problems. The crux of the matter was that the term *optimum* should be used with extreme care since it implies superiority of a solution with regard to all conceivable criteria. An optimal solution, on the other hand, forms part of a collection of solutions to a problem, each achieved by an optimisation process with a specific optimisation function being considered. The challenge thus lies in the careful selection of an optimisation function that defines the selected optimisation parameter.

The classic optimisation parameters of any optimisation problem are cost and performance. In the case of cost the aim is to achieve as low a cost as possible, whereas performance has the aim of being as high as possible. These parameters unfortunately have the troublesome characteristic of being mutually destructive, leading to a difficult trade-off situation where an increase in the one, for instance higher performance, has a negative impact on the other, greater cost in this case. Due to the inverse logic nature of cost as optimisation parameter, it is important to note that a positive impact on cost is defined as a lowering in cost, where a negative impact on cost is define as an increase in cost.

One could be tempted to define other optimisation parameters in conjunction with the two fundamental parameters of cost and performance. Parameters such as reliability, capacity, and scalability can however be considered as being performance characteristics since they also typically result in a trade-off situation with the cost parameter. It is therefore important to clearly define the exact composition of the performance metric when it is stated as the aim of an optimisation process.

Capacity is the metric usually associated with performance, where data rates and bandwidth dominate as user-level interpretations of a network's value. It is proposed here that reliability, as discussed in section 4.4, falls in the same category as capacity when considering the performance of a network. This can be justified by the user-level perception of bad network performance usually being due to insufficient reliability or the effects of the processes that attempt to restore network functionality in the event of fault or malfunction.

Scalability of a network relates to the ease with which it can allow for the growth of its user-base, capacity or geographical coverage. When optimising a network design, a situation similar to that of training a neural network can be created. Neural networks should be trained with data that represents the statistical distributions of parameters that will exist under normal operating conditions. The design of communication networks, like the training of neural networks, should avoid over fitting that may inhibit the resultant communication network's ability to cope with changes in its composition not anticipated or accommodated for in the original design process.

A good balance between current and possible future requirements should be maintained to avoid a situation where a network is currently utilised at a very low percentage of its capacity because it was designed to suit possible future requirements. Investors in communication network infrastructure generally demand maximum return on investment in the shortest time frame possible and would thus not be satisfied with a network that operates at very low utilisation levels if a cheaper network operating at higher utilisation levels would have resulted in the same revenue generation and user requirement satisfaction potential.

It is true that some level of interaction between reliability, capacity and scalability exist, but these are superficial when compared to that of the cost parameter on these three performance parameters. For many optimisation problems it would be possible to create an optimisation function that optimises for a combination of these three performance parameters without sacrificing too much compared to when they are considered as individually exclusive optimisation problems.

5.1.2 Commercial and proprietary design software

Network design software tools play an important role in assisting network designers in the design process. These software tools vary from very specific algorithms that require the computational speed of a computer, to involved design suites with extensive user interfaces that guide designers through various stages of the design process.

Many of the software tools are available commercially, but usually at extremely high cost due to the limited market for these tools. Most players in the optical networking industry do however also utilise proprietary software tools that are customised for their specific products offerings and equipped with a wealth of knowledge obtained through years of experience. These tools are seldom mentioned in open literature, or where reference is made to them very limited information about their features and functionality are made public. This can be expected from such a highly competitive industry where trade secrets are often concealed in the value of a mysterious constant or unpublished equipment characteristic.

Network design tools exist for various stages in the design process. The RCA function is responsible for developing the virtual topology from the physical and logical topologies of a network. This problem has received a lot of attention from network designers and researchers and is often mistaken for being the only part of the network design process suited for computer-based solving. As a matter of fact, the RCA function, however important, merely brings the design process to a climax where optimisation can be considered and the design eventually concludes.

In addition to purely network design tools, there exists a type of software tool relevant to the network designer, namely network evaluation tools. Two main categories of network evaluation tools exist, namely: simulation tools and optimisation tools. Simulation tools are used to investigate the behaviour of already designed networks, whether theoretical or practical. Optimisation tools, on the other hand, are used where the values of various network parameters are manipulated in order to optimise a predetermined optimisation function, and often form an integral part of the design process.

Network design tools can be categorised based on the specific function that they perform. These functions include: traffic forecasting, trunk engineering, SONET/SDH transport, signalling network design, access network planning, distribution network planning, and backbone network planning. Commercially available software tools available from around \$20,000 to more than \$500,000 offering various combinations of these design functions include: OPNET by MIL3, COMNET by CACI Products Company, COMPOSIS by AixCom, NetScene by Network Design House, NetMaker by Make Systems, WESTPLAN by Westbay Engineers, AUTONET by NDA Corporation, WinMIND by Network Analysis Center, CANE by ImageNet, NetSuite by NetSuite Development, and NetCracker by NetCracker Technologies.

Figure 5.1 shows the interfacing of the various software modules developed by the CATO project [57]. From this figure it is apparent that the RCA component, here shown as the routing and wavelength assignment function, is one of several network design functions accommodated for in a software-based tool for the design of optical networks. Functions such as restoration and protection, discussed in section 4.4.1, and resource allocation and placement also utilise physical and logical topology inputs and interaction between each other and the RCA function, to produce a virtual network design that can be assessed for optimality.

Another academic tool set for optical network optimisation, modelling and design called NoMAD [58] has been developed as an application of hybrid genetic algorithm and heuristic optimisation techniques to optical network design. Object oriented design methodology makes NoMAD easy to understand, flexible and extensible. The genetic algorithms approach to network design makes use of objective functions and fitness levels to evaluate the mutations of successive generations.

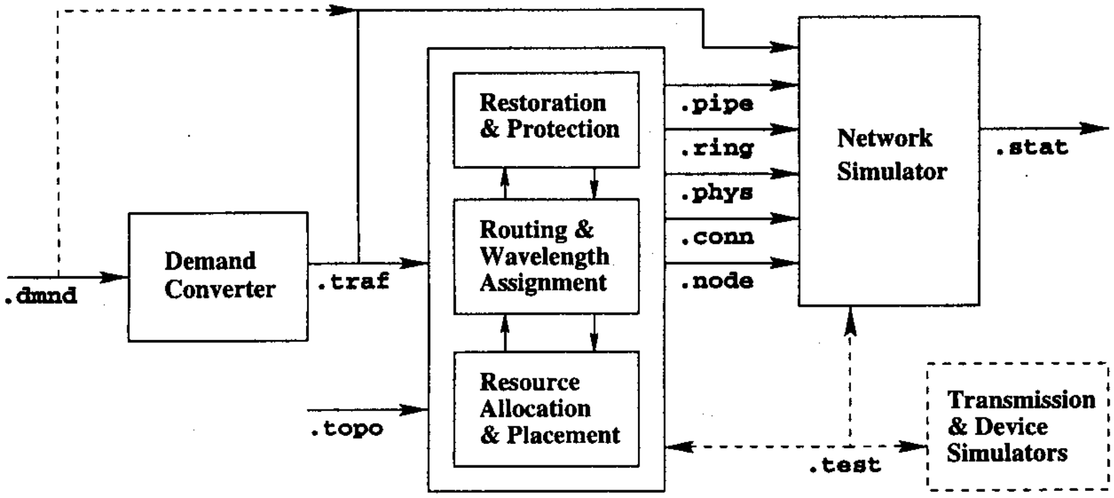


Figure 5.1: High-level diagram of CATO, a computer aided design (CAD) tool for optical networks and interconnects [57].

5.1.3 Integrated design methodology

The network planning and design process is complex with many influencing factors, optimisation parameters, tasks, interactions and dependencies. The scope of a network planning and design methodology depends on the employed evaluation criteria. If a methodology is expected to produce the number of required wavelengths for a given scenario, the RCA function will be sufficient. If the economic viability of VoIP needs to be determined, much greater scope would be required. In the context of enterprise network planning and design the following tasks have been identified [49]:

strategic business modelling is the task responsible for analysis of business requirements and revenue generating opportunities. It identifies applications and services that need to be supported by the network infrastructure under design.

industry and technology trends analysis identifies and analyses the influence of technology trends on business. Phases such as introduction, maturity, acceptability, and standardisation are used to assess technology trends.

strengths, weaknesses, opportunities and threats analysis is the task responsible for assessing the *status quo* in terms of usage and capability of communication infrastructure. Strengths and weaknesses of the current infrastructure are determined in order to identify opportunities and threats.

network architecture planning developes functional architecture models defining key functionalities and their interaction on each other.

network planning and design defines the detail of how the architectural planning objectives and requirements can be satisfied. Optimisation techniques are employed to minimise cost for a specified requirements and constraints scenario.

business justification and transition planning is responsible for the development of strategies for closing the gap between the current and desired communication network infrastructure. Economic tools and methods are used to provide alternatives and justification to communication infrastructure investment.

network infrastructure engineering and implementation is the technical task responsible for the deployment and implementation issues of providing appropriate communication network infrastructure.

The network planning and design task is most relevant to this investigation, although some attention has been given to some of the business aspects on the network planning and design problem as discussed in section 4.5. The main activities of the network planning and design task include: requirement specification, network topology design, network dimensioning, and design analysis and verification.

The requirement specification activity involves the identification and estimation of traffic characteristics and resource requirements. The network topology activity determines the number and positions of network nodes and their interconnections, which can be influenced by constraints imposed by existing infrastructure. Performance and reliability modelling are performed by the network dimensioning activity to determine optimum network configurations under various traffic load conditions. The design analysis and verification activity involves iterative sensitivity analysis to evaluate the robustness of a network design under various conditions and for different scenarios.

Figures 5.2 and 5.3 show the integrated design methodology developed through the research conducted in this investigation. The process commences by taken all the influencing factors into consideration when developing the physical and logical topologies. Conventional approaches rely on subjective decisions, as shown in figure 5.2, by network designers that are familiar with the country or region for which the wide-area network is to be designed. Expert knowledge about the network nodes to be inter-connected and the traffic distributions to be expected between them, characterise the subjective nature of the decision making process. The RCA function has been identified as the integrating process responsible for producing a virtual topology. Capacity, reliability and scalability requirements are satisfied through the recursive optimisation process that eventually terminates the design process.

The level of designer interaction in the design process is indicated in figure 5.2 by the manual and automated domain boundaries on the right. Due to the subjective nature of the decision making process responsible for interpretting the influencing factors in developing the physical and logical topologies, manual interaction is required right up to their initial stages. The RCA function is highly automated through the use of several established computer-based algorithms, although the interpretation of results and optimisation processes are again very manual in nature. It is also important to note that the network designer has to take final responsibility when terminating the design process.

As with most processes, there is always an aim to automate as much of the process as possible. In network design processes an increase in design automation can shorten the design cycle and produce more repeatable results. In order to achieve greater automation in the network design process, it is suggested that the interpretation of influencing factors be automated to effectively minimise designer interaction. Figure 5.3 shows how the design methodology presented in figure 5.2 can be modified to allow for greater design process automation. The *subjective decisions* component is replaced with an *objective decisions* component that should result in greater design process automation, since computer-based decision logic structures are inherently objective.

The concept of objectivity in the context of design process automation is defined as the ability to make decisions based on a set of criteria without allowing bias or prejudice to negatively influence the repeatability of the process. A subjective decision, on the other hand, is defined as being influenced by knowledge not explicitly declared as relevant to the criteria framework, thus resulting in low repeatability due to the unpredictability of designer bias and prejudice.

The contribution of the research conducted in this investigation into the field of wide-area optical network design is in the technique suggested for achieving increased objectivity in the network design process. In section 5.3, clustering is presented as technique for improving objectivity in the network design process through its algorithmic nature and resultant load balancing characteristics.

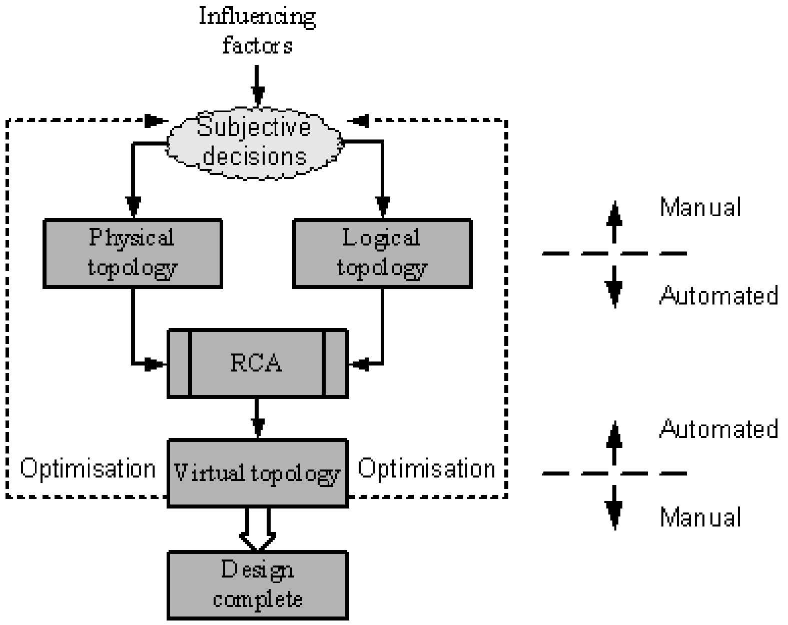


Figure 5.2: Traditional subjective integrated network design methodology.

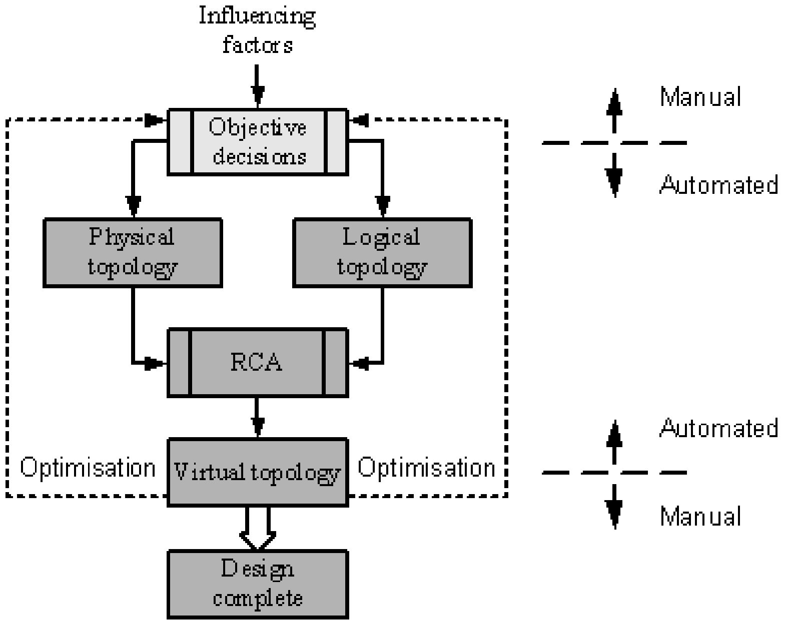


Figure 5.3: Proposed objective integrated network design methodology.

5.2 Methodology for finding hub nodes from economic activity statistics

A methodology was developed for finding hub nodes, clusters and the demand matrix for a network under design by using economic statistics as input to the process. Section 3.1.3 and equation 3.2 in particular show how economic activity can be used as a nodal weight in a modified gravity model. The developed methodology, shown in figure 5.4, applies to any nodal weights and not only economic activity statistics in particular.

In figure 5.4 it can be seen that actual economic activity statistics or a demand matrix generator can be used to generate a full demand matrix. The use of actual economic statistics and geographical coordinates will be demonstrated in chapter 6 and the use of the demand matrix and geographical coordinate generators will be demonstrated in section 5.3.4. The demand matrix reducer will be employed in chapter 6 due to memory constraints, as described by equation 5.1, when implementing the methodology on a computer with finite memory.

The methodology contains an iterative segment where the intra/inter-cluster traffic ratio is used to determine the suitable number of hub nodes. The issue of how many network nodes there should be on the various levels of the multi-level network model, discussed in section 4.1, is non-trivial. One of the attributes of this methodology is its ability to objectively determine the number of nodes required on each of the levels of the multi-level network model.

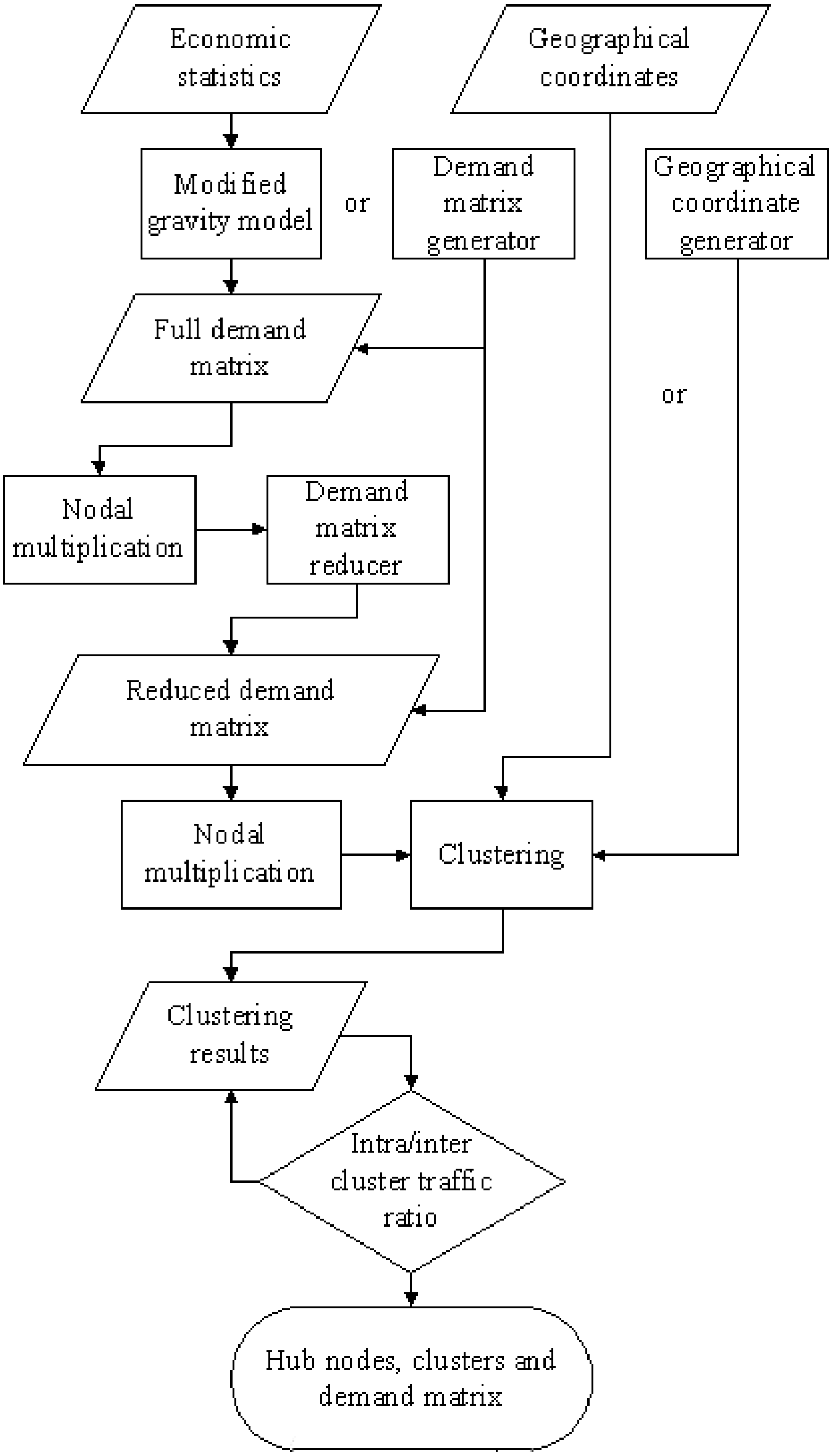


Figure 5.4: Flow diagram of methodology for finding hub nodes from economic statistics.

5.3 Clustering of network nodes

A conventional approach to selecting hub nodes for wide-area optical networks is by means of exhaustive searching. This approach guarantees optimal solutions, but requires vast amounts of time, which make it impractical for network design problems exceeding moderate complexity. The clustering approach to selecting wide-area optical network hub nodes is a statistical pattern recognition technique whereby the number of clusters is reduced one by one through the merging of neighbouring clusters judged most similar based on a selected similarity metric. Although consuming considerably less time than exhaustive searching, this technique has memory requirements that increase non-linearly with the number of network nodes of the network:

$$M \propto \frac{n(n-1)}{2}, \tag{5.1}$$

where M is the required memory and n is the number of physical network nodes being clustered.

There are various well-known similarity metrics, including: shortest distance, largest distance, average distance, and centroid distance. In this implementation of the clustering approach to hub node selection, the employed similarity metric is known as the Ward linkage [59], which can be described as an incremental sum of squares metric. This metric is very well suited to the creation of clusters around hub nodes, due to the way in which it rewards low interference on hub node location when selecting clusters to merge. The two clusters judged to be most similar would be the clusters that minimise the Ward linkage as follows:

$$
\begin{aligned}
s_{Ward}(H) &= min_H \left(\frac{N_i N_j \| \frac{1}{N_i} \sum_{\bar{x} \in H_i} \bar{x} - \frac{1}{N_j} \sum_{\bar{x'} \in H_j} \bar{x'} \|^2}{N_i + N_j} \right) && (5.2) \\
&= min_H \left(\frac{N_i N_j \| \mu_{H_i} - \mu_{H_j} \|^2}{N_i + N_j} \right), && (5.3)
\end{aligned}
$$

where min_H is interpreted as the minimum over all possible combinations of clusters, H is the collection of clusters, x and x' are the nodes of arbitrary clusters in the collection, i and j are cluster indices, N is the number of network nodes in a cluster, and μ_{H_i} is the centroid of cluster i.

During each iteration of the clustering process, two clusters are merged to form one cluster containing all their respective network nodes. Iteration of the clustering process thus reduces the total number of clusters by one cluster per iteration. It is intuitive that clusters would be more similar early in the clustering process than late in the clustering process. Figure 5.5 shows how the value of the similarity metric changes with the number of remaining clusters. In this clustering problem, 1801 clustering iterations were required to end up with one cluster containing all the virtual network nodes that were created from 60 actual network nodes through a process of node multiplication. For the clustering process to consider node weighting, multiple instances of actual network node are created according to its estimated add/drop traffic, resulting in a higher number of virtual network nodes than actual network nodes.

5.3.1 Background to similarity metrics

The purpose of data clustering is to identify clusters that appear naturally in a given data set. When starting a clustering process all data points are regarded as individual

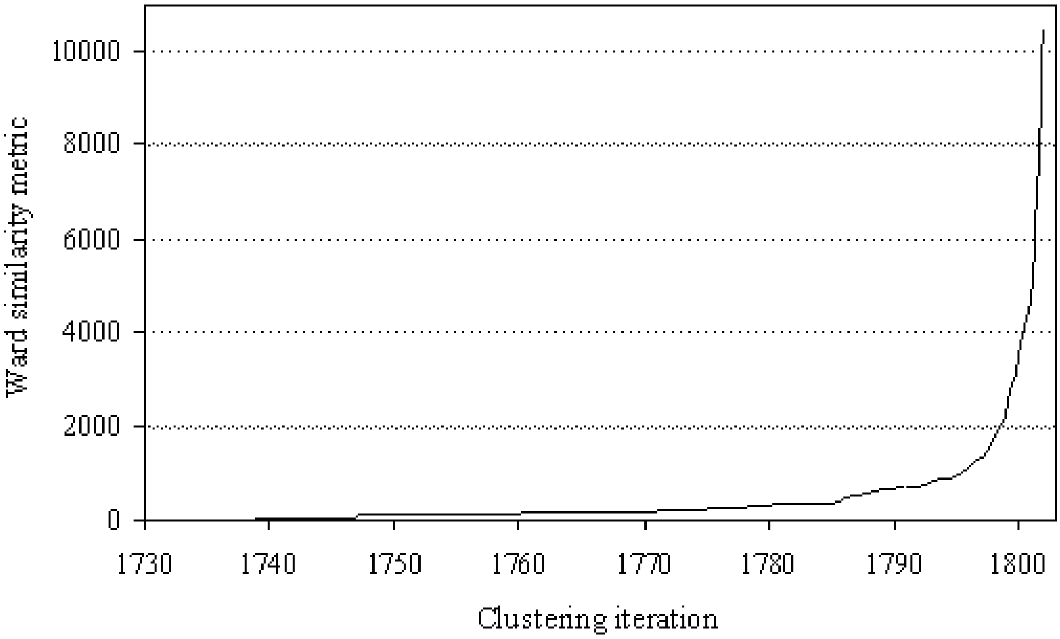


Figure 5.5: The non-zero values of the similarity metric are shown as a function of the number of elapsed clustering iterations.

clusters. Two clusters that are judged to be most similar, based on a chosen metric, are combined to form one new cluster. This process is repeated until the desired number of clusters is reached.

Clustering by implementing the minimum distance s_{min} similarity metric means that two clusters are combined to form one new cluster when the smallest Euclidean distance between data points in the two clusters is smaller than the smallest Euclidean distance between any other two data points from any two different clusters. The s_{min} similarity metric can be expressed as:

$$s_{min}(H) = min_H \left(min_{\bar{x} \in H_i, \bar{x'} \in H_j} \|\bar{x} - \bar{x'}\| \right), \tag{5.4}$$

where min_H is interpreted as the minimum over-all possible combinations of clusters.

Clustering by implementing the maximum distance s_{max} similarity metric means that two clusters are combined to form one new cluster when the largest Euclidean distance between data points in the two clusters is smaller than the largest Euclidean distance between any other two data points from any two different clusters. The s_{max} similarity metric can be expressed as:

$$s_{max}(H) = min_H \left(max_{\bar{x} \in H_i, \bar{x'} \in H_j} \|\bar{x} - \bar{x'}\| \right), \tag{5.5}$$

where min_H is interpreted as the minimum over-all possible combinations of clusters.

Clustering by implementing the average distance s_{avg} similarity metric means that two clusters are combined to form one new cluster when the average Euclidean distance between data points in the two clusters is smaller than the average Euclidean distance between the data points of any other two clusters. The s_{avg} similarity metric can be expressed as:

$$s_{avg}(H) = min_H \left(\frac{1}{N_i N_j} \sum_{\bar{x} \in H_i} \sum_{\bar{x'} \in H_j} \|\bar{x} - \bar{x'}\| \right), \tag{5.6}$$

where min_H is interpreted as the minimum over-all possible combinations of clusters.

Clustering by implementing the centroid distance s_{mean} similarity metric means that two clusters are combined to form one new cluster when the Euclidean distance between the means of the data points in the two clusters is smaller than the Euclidean distance between the means of the data points of any other two clusters. The s_{mean} similarity metric can be expressed as:

$$s_{avg}(H) = min_H \left\| \frac{1}{N_i} \sum_{\bar{x} \in H_i} \bar{x} - \frac{1}{N_j} \sum_{\bar{x'} \in H_j} \bar{x'} \right\|, \tag{5.7}$$

where min_H is interpreted as the minimum over-all possible combinations of clusters.

5.3.2 Clustering of weighted network nodes

The way in which node weighting, as discussed in section 3.1.3, translates into node multiplication ensures that clustering decisions are based on node weights as well as absolute and relative node locations. If, for instance, the nodes that have heavier weights are multiplied by a greater factor than the nodes that have lighter weights, a situation will be created where the clustering process is biased towards heavily weighted network nodes. The opposite might seem to be a better situation, where the gap between heavily and lightly weighted nodes can be reduced through a greater multiplication factor for nodes with lighter weights. Theoretically it would however be preferable to not introduce any bias at the node multiplication stage, since the node weighting stage can be used for this. In practice it might not be possible to avoid bias at the node multiplication stage, since only integer multiples can be created and the nodal weights might not be integer multiples of a common denominator.

The demand matrix developed in section 3.1.3 is used to produce nodal add/drop traffic values. This is done by determining the sum of the values in the row and column of each network node in the demand matrix as follows:

$$w_i = \sum_{j=1}^{N} D_{i,j} + D_{j,i}. \tag{5.8}$$

where w_i is the add/drop traffic of physical network node i, $D_{i,j}$ is the demand between nodes i and j as defined in equation 3.2, and N is the number of network nodes. For a symmetrical demand matrix this would simplify to:

$$w_i = 2\sum_{j=1}^{N} D_{i,j} \propto \sum_{j=1}^{N} D_{i,j}. \tag{5.9}$$

The clustering process is initialised by regarding all network nodes, of which most are multiples resulting from nodal add/drop traffic weighting, as individual clusters. The number of initial clusters is given by:

$$n_{weighted} = K_2 \sum_{i=1}^{N} w_i, \tag{5.10}$$

where w_i is the add/drop traffic of physical network node i and N is the number of physical network nodes. K_2 is a normalisation factor chosen in such a way as to ensure that each physical network node translates into at least one virtual network node. Due to memory considerations when implementing the algorithm this is achieved through the rounding up of normalised individual nodal add/drop traffic and not by normalisation alone as would be theoretically preferable. Equation 5.10 can be interpreted as the number of physical network nodes multiplied by the normalised average nodal add/drop traffic.

5.3.3 Intra/inter-cluster traffic ratio

One of the most important problems to be solved when designing an optical network, and any other communication network for that matter, is that of how many network nodes there should be on each of the levels of the multi-level network model. In the context of wide-area network design the number of backbone nodes is of importance. The developed methodology utilises a metric referred to as the intra/inter-cluster traffic ratio to assist in solving the problem of how many network nodes there should be on each of the levels of the multi-level network model.

The intra/inter-cluster traffic ratio for a specific cluster is defined as follows:

$$R = \frac{\text{traffic with source and destination in cluster}}{\text{traffic with source or destination in other cluster.}} \tag{5.11}$$

For high numbers of clusters this ratio is typically low, since a lot of inter-cluster traffic would exist. For low numbers of clusters this ratio is typically high, since strong communities of interest exist within the clusters resulting in high intra-cluster traffic. Finding the number of clusters for which the intra/inter-cluster traffic ratios are acceptable is thus a justified approach to selecting the number of hub nodes for a specified network level.

Figure 5.6 presents a special case of the multi-level network model, where only three levels exist and no network node can appear on more than two of these levels. Guidelines for selecting suitable intra/inter-cluster traffic ratios when solving the problem of how many network nodes should appear on the various levels of the multi-level network model are given through the 10%, 30% and 60% geographical traffic distribution estimates. Two target intra/inter-cluster traffic ratios can be derived from these guidelines. The first ratio is valid at the interface of the backbone level and regional levels, where the ratio is as follows:

$$R = \frac{30\% + 60\%}{10\%} = 9. \tag{5.12}$$

The second ratio is valid at the interface of the regional level and local levels, where the ratio is as follows:

$$R = \frac{60\%}{30\% + 10\%} = 1.5. \tag{5.13}$$

These target intra/inter-cluster traffic ratios should however only be seen as a guidelines, since the required configuration of multi-level network model levels for a network under design might not be conform to the three level network model presented here.

The means and standard deviations of the different numbers of intra/inter-cluster traffic ratios are used in order to enable comparison between the ratios of different numbers

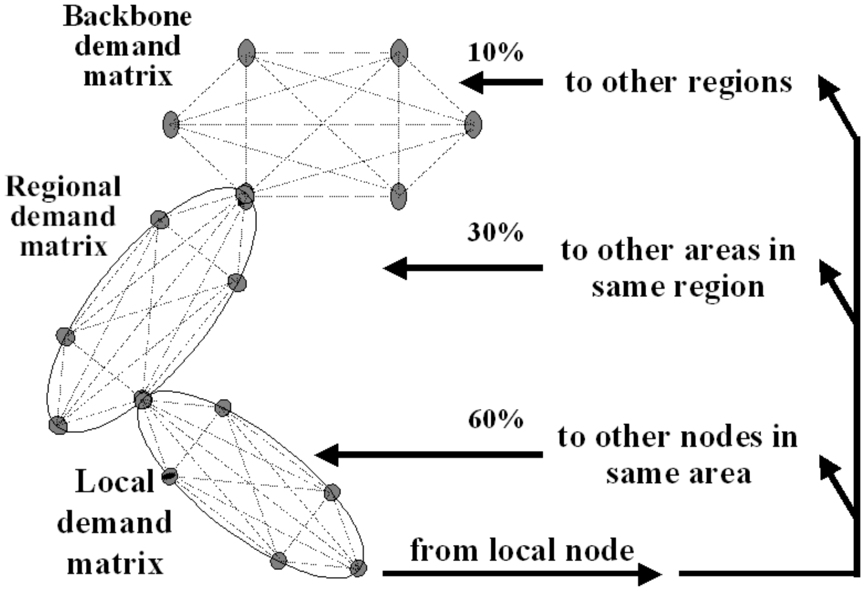


Figure 5.6: Intra/inter-cluster traffic ratios for various levels of a three-level network model.

of clusters. The mean intra/inter-cluster traffic ratio is favourable when it is close to a target value deemed appropriate for the specific network level. Proximity to this target value identifies potentially optimal numbers of clusters. When attempting to find the optimal number of high-level hub nodes, the first incidence of mean intra/inter-cluster traffic ratios above or on and subsequently on or below the target value, are regarded as suitable candidates. The candidate with the lowest standard deviation of the intra/inter-cluster traffic ratios is deemed optimal, since a lower standard deviation would indicate that the clusters have intra/inter-cluster traffic ratios closer to the mean intra/inter-cluster traffic ratio.

5.3.4 Simulation experiment

The purpose of this simulation experiment is to determine how the integrated design methodology presented in section 5.1.3 can be used to evaluate the means and standard deviations of the intra/inter cluster traffic ratios, as described in section 5.3.3, for the following theoretical scenarios:

1. Geographical coordinates generated from a beta distribution with $a = b = 1$ and a demand matrix generated from a beta distribution with $a = b = 0.1$.
2. Geographical coordinates generated from a beta distribution with $a = b = 1$ and a demand matrix generated from a beta distribution with $a = b = 1$.
3. Geographical coordinates generated from a beta distribution with $a = b = 5$ and a demand matrix generated from a beta distribution with $a = b = 0.1$.
4. Geographical coordinates generated from a beta distribution with $a = b = 5$ and a demand matrix generated from a beta distribution with $a = b = 1$.

The beta distribution was employed due to the ease with which an iterative process can be performed on its parameters, resulting in the creation of a potentially wide range of probability distribution functions should the need arise. The statistical nature of the four scenarios defined above are described in the following sections.

Simulation context definition

The simulation was conducted in Matlab using the Statistics Toolbox version 3.0. Definition of the context of the two types of input parameters to the simulation, geographical coordinates and a demand matrix, is important for it determines the context of the simulation.

A square plane spanning 10° by 10°, approximately 1.2×10^6 km^2, was used for the geographical coordinate sets to be generated. This corresponds roughly to the surface-area of a medium-sized country like South Africa, which has a surface area of $1,219,090\ km^2$. The square plane under consideration is purely theoretical and should not be misconstrued as being representative of an irregular shaped country, like most countries tend to be.

For the purpose of this simulation an aggregate network capacity of 1 Tbps was assumed. This value relates to all the traffic between the nodes of the network and not to the traffic that exists at lower levels of the multi-level network model that are beyond the scope of the network design under consideration. In a practical scenario this kind of traffic would for example include a circuit-switched telephone connection established between two telephones connected to the same exchange.

The number of network nodes taken into consideration in this simulation has been set at 60. This value is small enough to allow for the memory-hungry clustering of multiplied virtual network nodes, as described in section 5.3.2, and large enough to ensure meaningful clustering results.

Statistics of the input parameters

The input parameters to the simulation are generated geographical coordinates and a demand matrix. These were generated according to a beta distribution by a random number generator in Matlab. The beta distribution has two parameters of its own, as shown in equation 5.14, and these were chosen to be equal at values of 0.1 and 1 for generating two different demand matrices, and 1 and 5 for generating geographical coordinates on the square plane defined in section 5.3.4.

Figure 5.7 shows the plots of the beta pdf for $a = b = 0.1$, $a = b = 1$, and $a = b = 5$ respectively. Note how $a = b = 1$ results in a uniform distribution and $a = b = 1$ has a similar shape to the normal distribution although it is confined to the range $(0, 1)$. By manipulating the two input parameters of the beta distribution it is possible to create virtually any pdf in the range $(0, 1)$, which makes it well-suited to simulations such as this where various probability distributions are iteratively required. The well-known beta probability distribution function (pdf) is given by:

$$y = f(x|a, b) = \frac{1}{B(a, b)} x^{a-1}(1 - x)^{b-1} I_{(0,1)}(x), \tag{5.14}$$

where a and b are input parameters determining the shape of the beta pdf, x is the value for which probability is evaluated, the indicator function $I_{(0,1)}$ ensures nonzero probability for values of x in the range $(0, 1)$, and $B(\cdot)$ is the Beta function:

$$B(a, b) = \int_0^1 t^{a-1}(1 - t)^{b-1} dt = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a + b)}, \tag{5.15}$$

where $\Gamma(a)$ is the gamma function defined by the integral:

$$\Gamma(a) = \int_0^\infty e^{-t} t^{a-1} dt. \tag{5.16}$$

In order to allow for the comparison of results obtained from the different beta distributions, two random number generator seeds were used, one for the generation of the two different demand matrices and the other for the generation of the two different geographical coordinate sets.

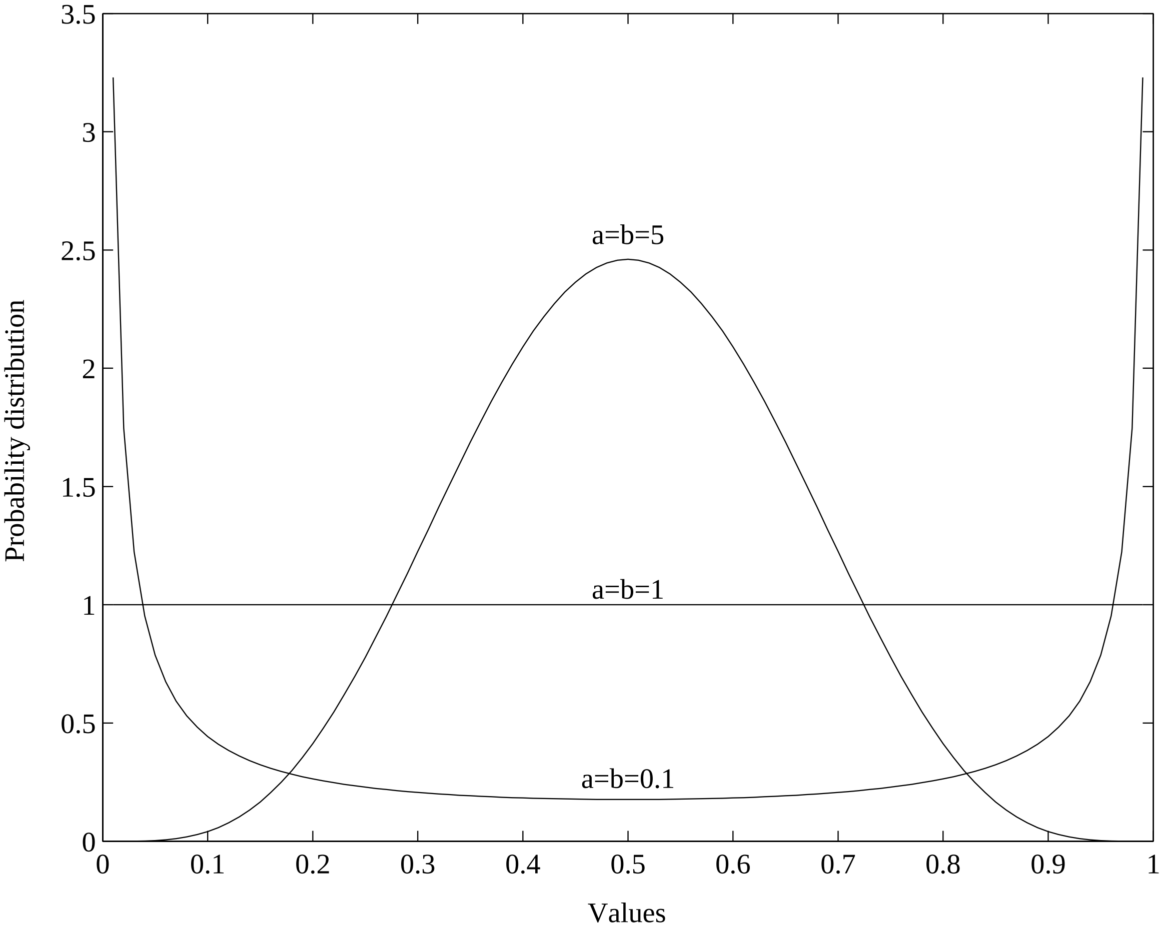


Figure 5.7: Beta probability distribution functions for a=b=0.1, a=b=1, and a=b=5.

Geographical position as input parameter

Two sets of geographical positions for the network nodes to be clustered were generated. The one set was generated from a beta distribution with $a = b = 1$ and the other from a beta distribution with $a = b = 5$. The first set is shown in figure 5.8 where the uniform nature of the coordinate distribution over both latitude and longitude can be observed. The second set is shown in figure 5.9 where the concentration of networks nodes towards the middle of the plane can be observed.

Demand matrix as input parameter

Two demand matrices were generated with nodal add/drop traffic values from beta distributions with $a = b = 0.1$ and $a = b = 1$ respectively. The individual values for the demands between nodes were determined as follows:

$$D_{i,j} = \frac{D_i \times D_j}{C}, \tag{5.17}$$

where D_i is the add/drop traffic of node i, D_j is the add/drop traffic of node j, and C is the chosen aggregate network capacity requirement of the network under design, 1 Tbps in this case. i and j are allowed to be equal, since the 60 nodes considered here are assumed to be above the lowest level of the multi-level network model as defined in section 4.1.

Figures 5.10 and 5.11 show how 8-bin histograms of the nodal add/drop traffic from the generated demand matrices follow the beta distributions from which they were generated. Eight bins were used in the histogram because 8 is the closest integer to

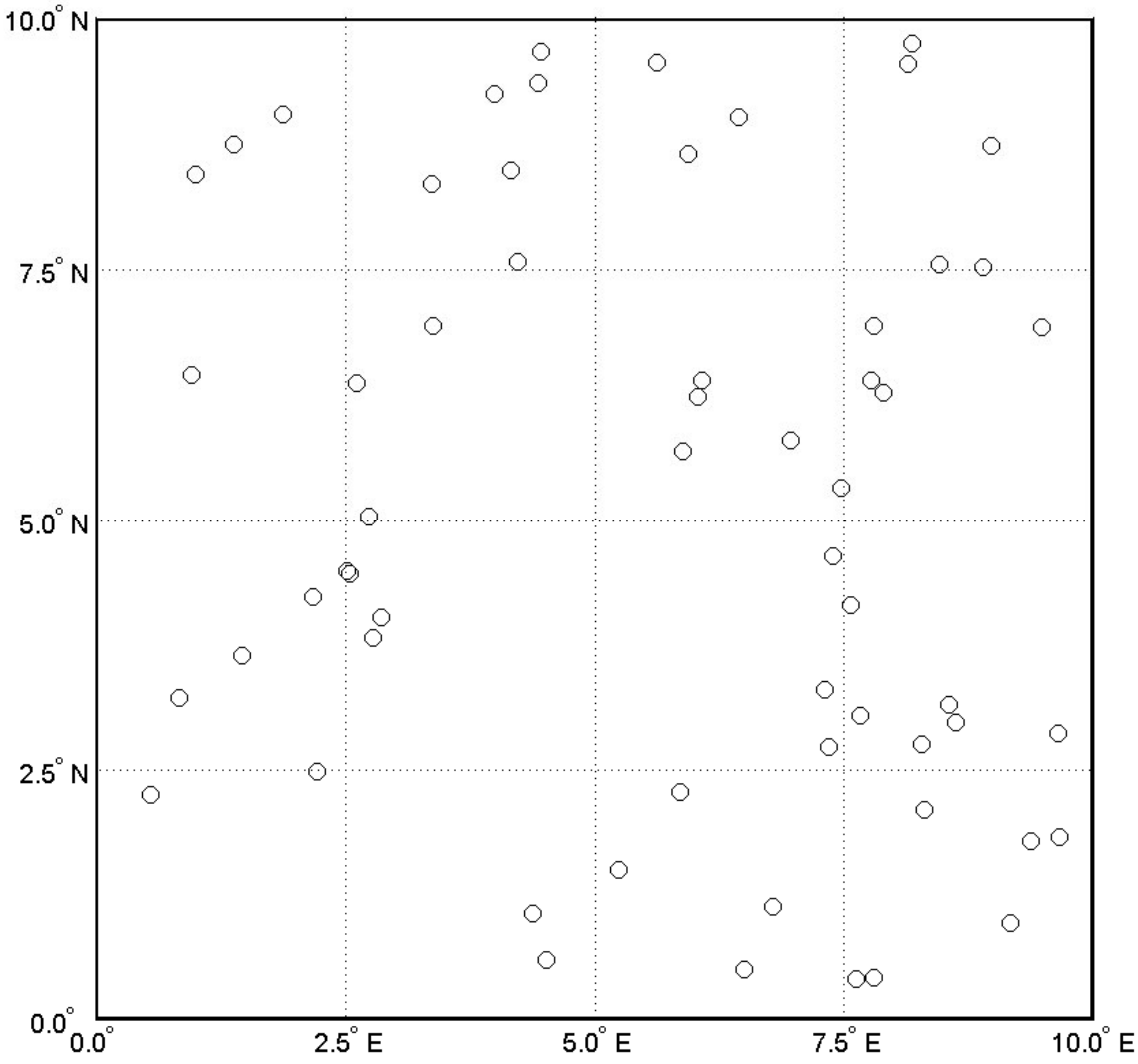


Figure 5.8: Geographical coordinates when generated from beta distribution with $a = b = 1$.

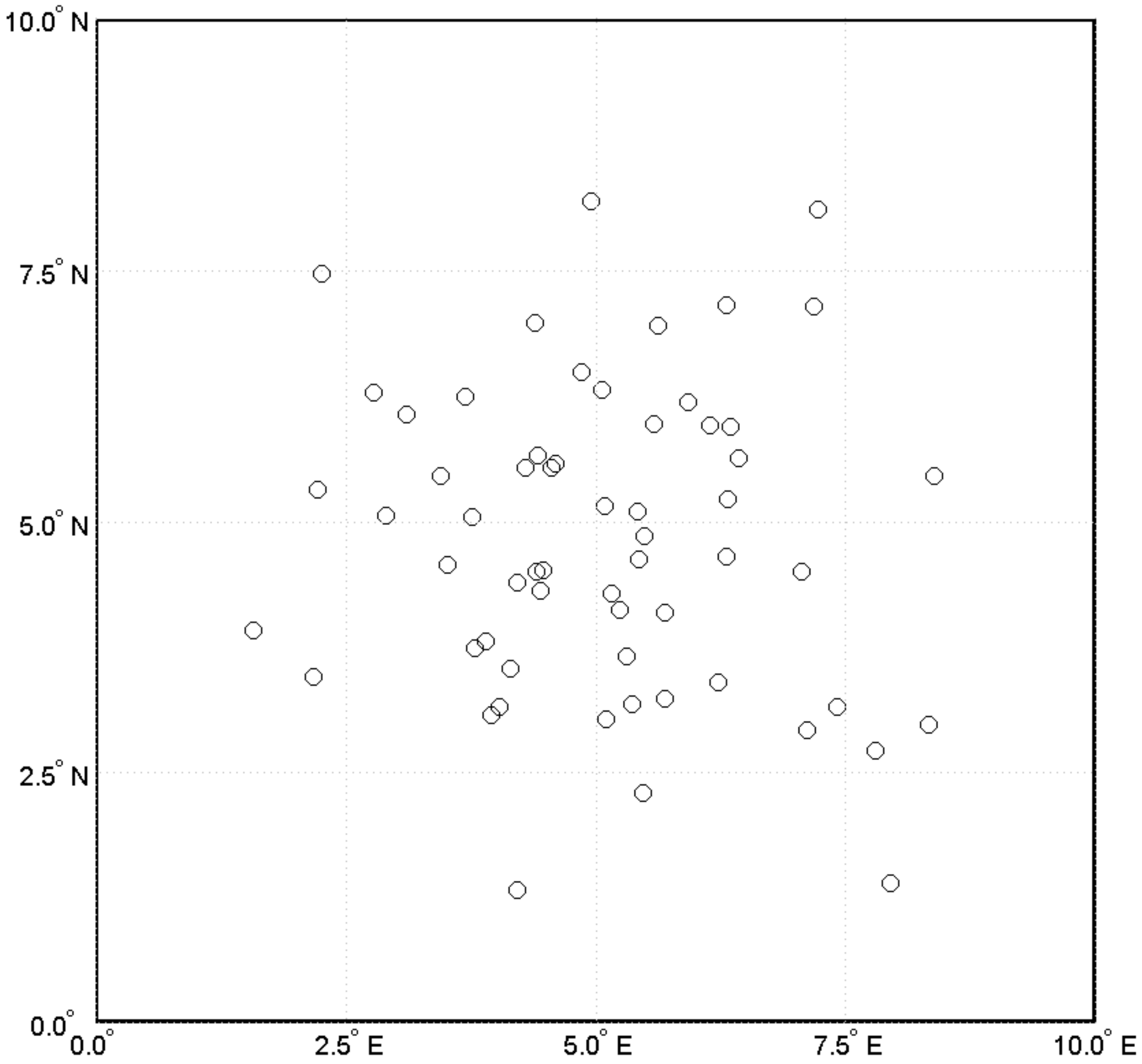


Figure 5.9: Geographical coordinates when generated from beta distribution with $a = b = 5$.

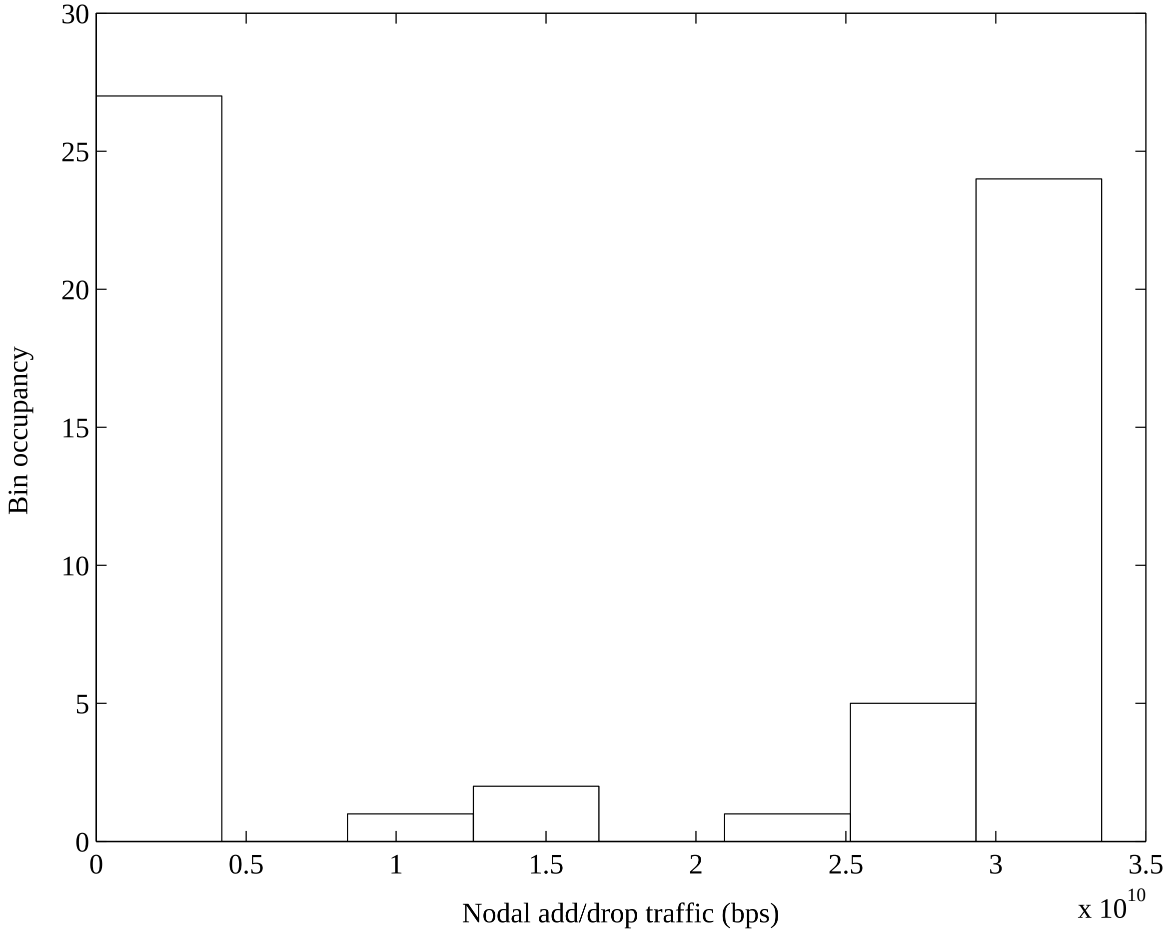


Figure 5.10: Histogram with 8 bins of nodal add/drop traffic when generated from beta distribution with $a = b = 0.1$.

the square root of 60, which is the number of network nodes. The demand matrices generated in this simulation have the constraint of being symmetrical, due to the method by which beta distributed nodal add/drop traffic values are used to generate the demand matrices.

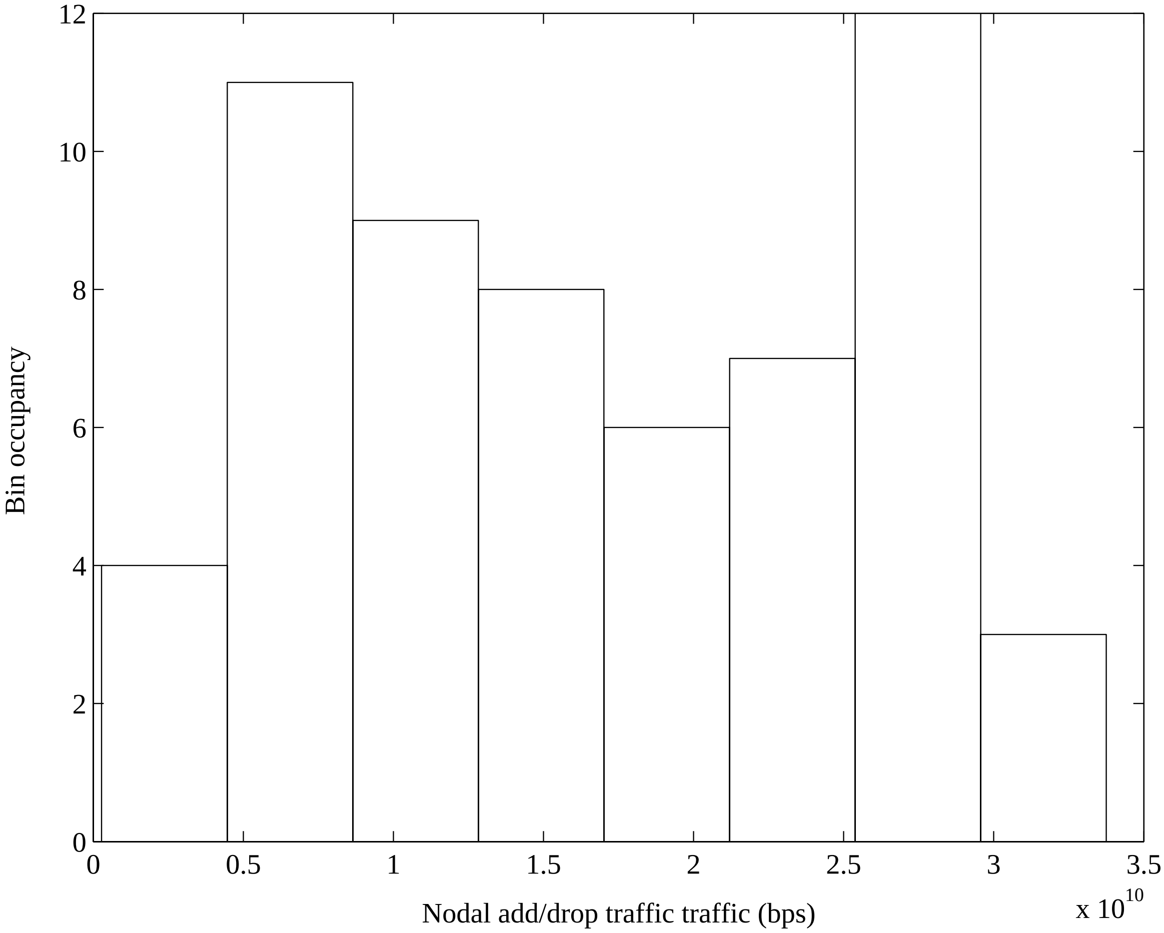


Figure 5.11: Histogram with 8 bins of nodal add/drop traffic when generated from beta distribution with $a = b = 1$.

5.3.5 Results and discussion

Evaluation of intra/inter-cluster traffic ratio

The results obtained for scenarios 1-4, as defined in section 5.3.4, are presented in figures 5.12 to 5.15. The mean intra/inter-cluster traffic ratio value for each number of hub nodes was calculated as follows:

$$\mu_N = \frac{1}{N} \sum_{l=1}^{N} R_m, \tag{5.18}$$

where N is the number of hub nodes for which a mean of the intra/inter-cluster traffic ratios is being calculated, and R_m is the intra/inter-cluster traffic ratio, as defined in section 5.3.3, of cluster m.

The standard deviation value for the intra/inter-cluster traffic ratio for each number of hub nodes was calculated as follows:

$$\sigma_N = \left(\frac{1}{N-1} \sum_{l=1}^{N} \left(R_m - \mu_N \right)^2 \right)^{\frac{1}{2}}, \tag{5.19}$$

where N is the number of hub nodes for which a standard deviation of the intra/inter-cluster traffic ratios is being calculated, R_m is the intra/inter-cluster traffic ratio, as defined in section 5.3.3, of cluster m, and μ_N is the mean intra/inter-cluster traffic ratio for N hub nodes as defined in equation 5.18.

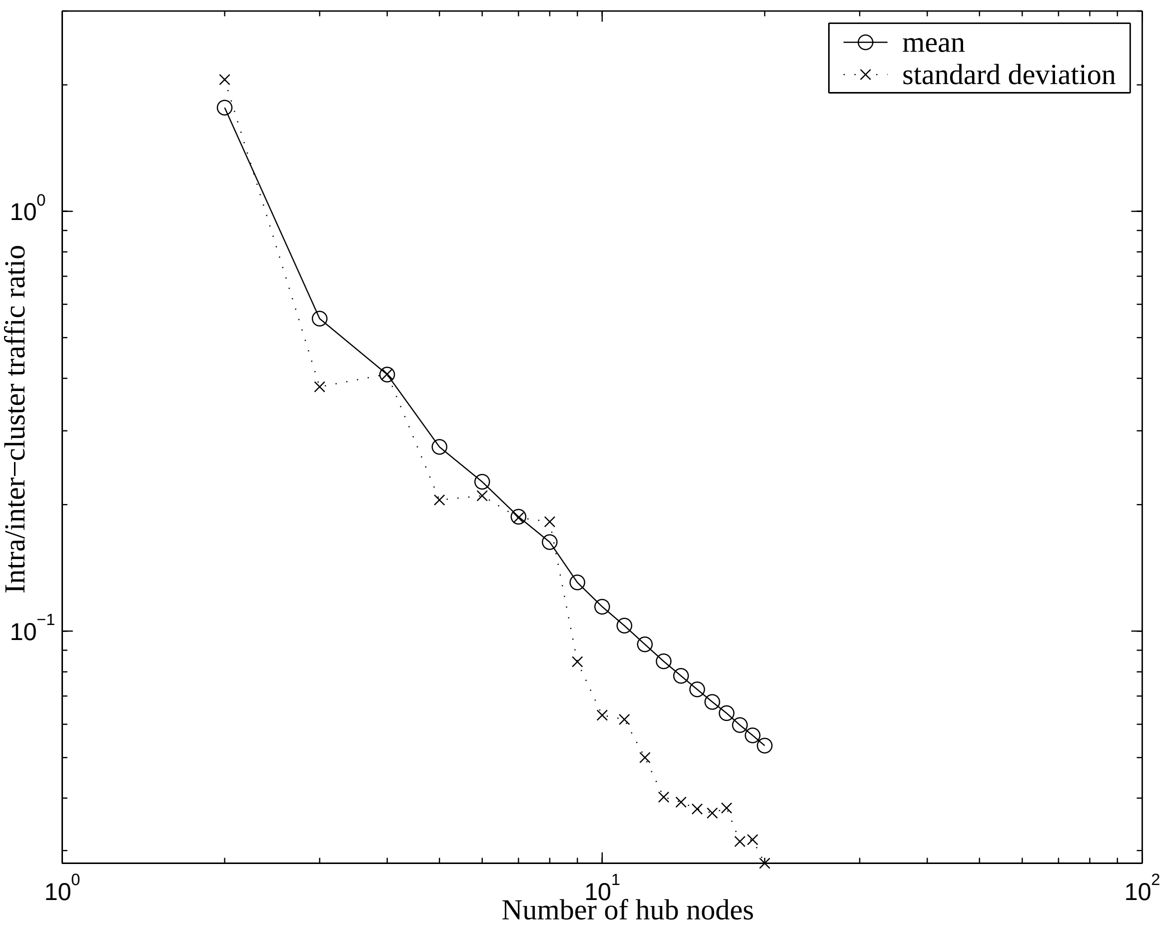


Figure 5.12: Means and standard deviations of the intra/inter-cluster traffic ratio as a function of the number of hub nodes, for scenario 1 as defined in section 5.3.4.

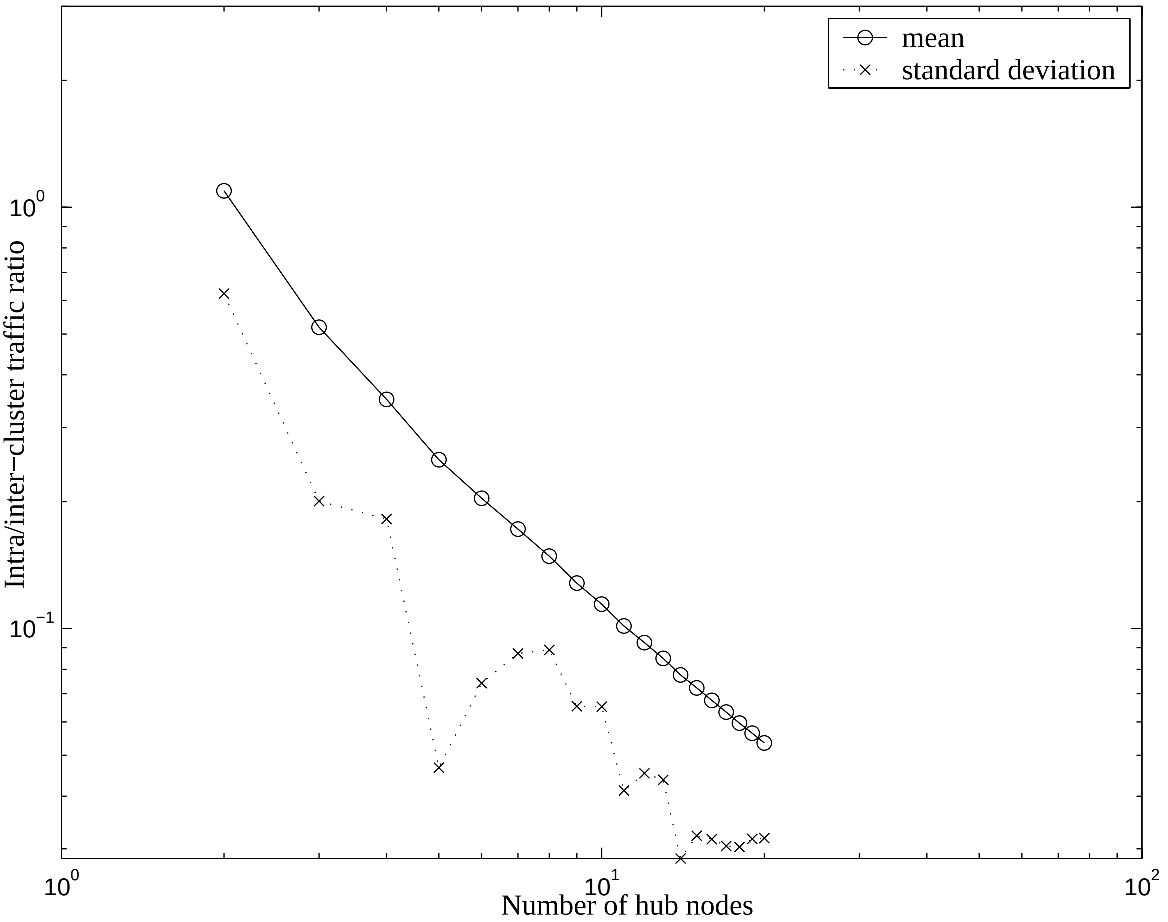


Figure 5.13: Means and standard deviations of the intra/inter-cluster traffic ratio as a function of the number of hub nodes, for scenario 2 as defined in section 5.3.4.

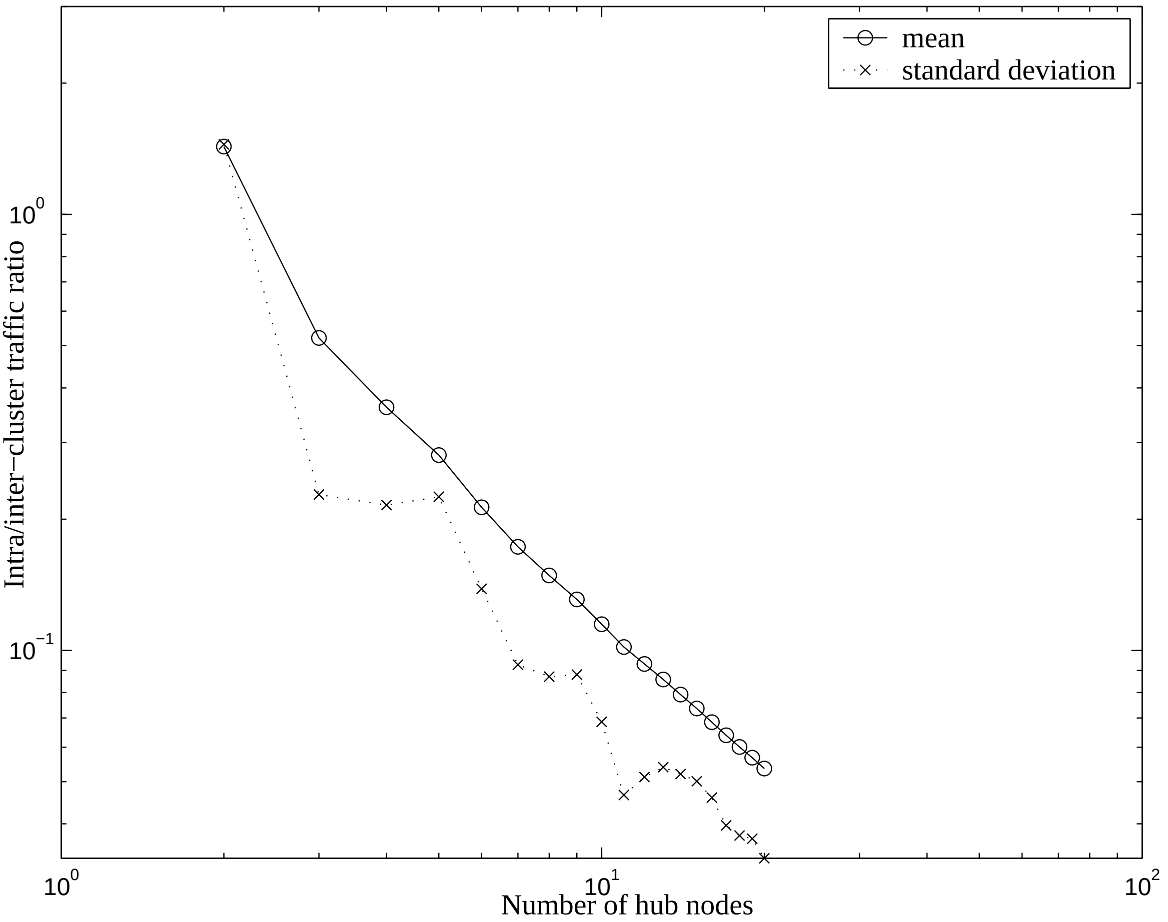


Figure 5.14: Means and standard deviations of the intra/inter-cluster traffic ratio as a function of the number of hub nodes, for scenario 3 as defined in section 5.3.4.

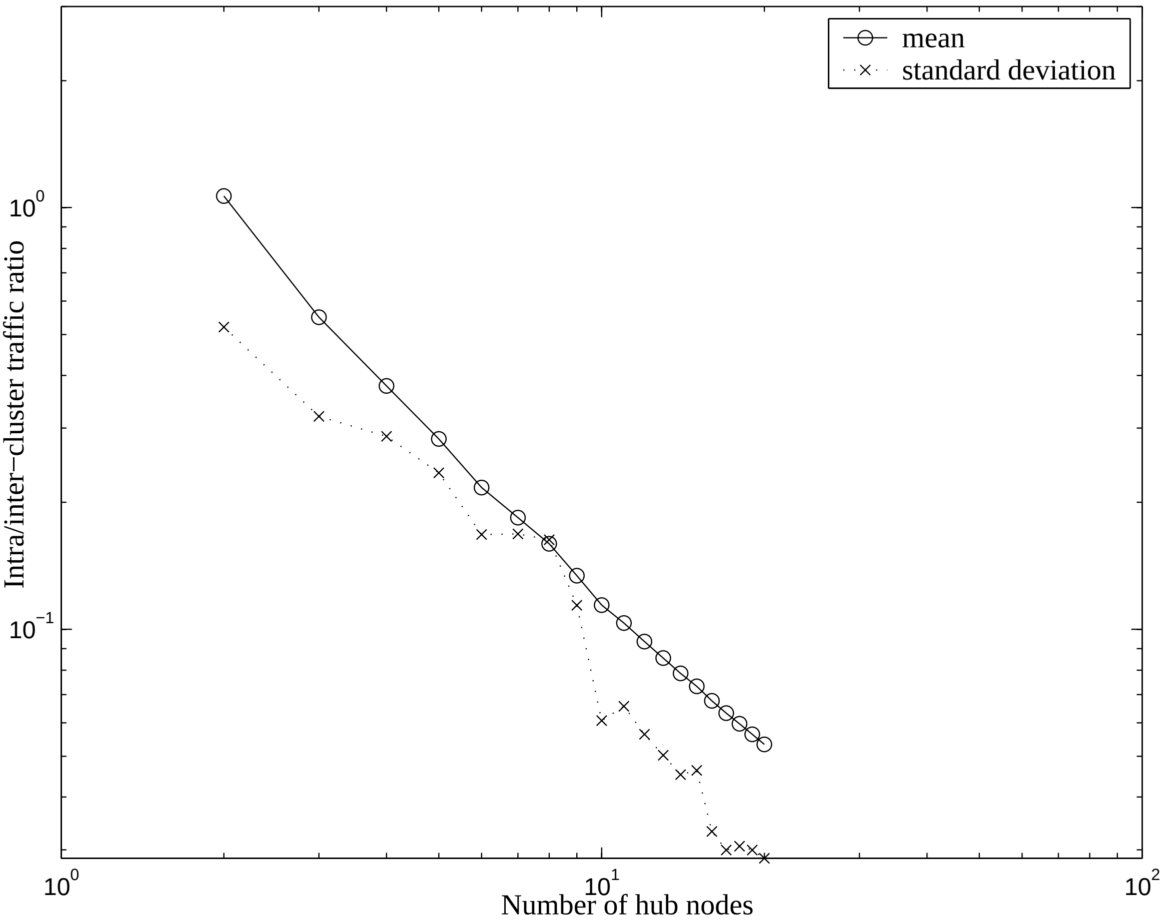


Figure 5.15: Means and standard deviations of the intra/inter-cluster traffic ratio as a function of the number of hub nodes, for scenario 4 as defined in section 5.3.4.

Discussion

In order to determine the number of hub nodes required on the backbone level of the multi-level network model for each of the four scenarios, as defined in section 5.3.4, the results obtained in section 5.3.5 have to be evaluated against a target or preferable intra/inter-cluster traffic ratio. The guidelines provided in the discussion of section 5.3.3 were considered in selecting the target intra/inter-cluster traffic ratio to be 0.5. This target value is lower than the value of 1.5 recommended in section 5.3.3 for the selection of hub nodes on the second level of the multi-level network model.

Table 5.1 shows the number of hub nodes required on the backbone level of the multi-level network model for each of the four scenarios outlined in section 5.3.4, for various target intra/inter-cluster traffic ratios, including the target of 0.5.

The scenarios are quite evenly matched when it comes to the number of backbone hub nodes required at different intra/inter-cluster traffic ratio targets. The results obtained in this experiment can thus not be used to identify any trends about the sensitivity of the number of hub nodes to the distributions of the nodal add/drop traffic or geographical coordinates. It can however be seen that the required number of hub nodes decreases as the target intra/inter-cluster traffic ratio increases.

Scenario	$R_t = 0.2$	$R_t = 0.5$	$R_t = 0.8$
1	7	3	3
2	7	3	3
3	6	4	3
4	7	4	3

Table 5.1: The number of backbone level hub nodes for each of the four scenarios, defined in section 5.3.4, according to various target intra/inter-cluster traffic ratios indicated by R_t.

Chapter 6

Demonstration of network design methodology

6.1 Scope

The scope of the design methodology demonstration in this chapter is defined as follows: The developed integrated design methodology, as presented in section 5.1.3, has as its most novel component the clustering approach to finding hub nodes from economic statistics, as presented in section 5.2. The use of this clustering approach in finding the number and positions of hub nodes on the backbone level of the multi-level network model, as presented in section 4.1, will be demonstrated.

In contrast to the simulation experiment presented in section 5.3.4, this demonstration will utilise actual economic activity statistics and geographical coordinates. The network to be designed will cover the whole of South Africa and is designed with an aggregate network capacity of 1 Tbps. This capacity refers to the sum of all logical connections that the network would be able to carry simultaneously.

As indicated in figure 5.4, a demand matrix reducer function is performed due to the memory constraints discussed in section 5.3. Results for the network under design will be presented for the following implementation configurations:

1. Demand matrix reducer limited to 1 MB of memory and clustering function limited to 1 MB of memory.
2. Demand matrix reducer limited to 1 MB of memory and clustering function limited to 8 MB of memory.
3. Demand matrix reducer limited to 8 MB of memory and clustering function limited to 1 MB of memory.
4. Demand matrix reducer limited to 8 MB of memory and clustering function limited to 8 MB of memory.

These scenarios were chosen due to the coverage that they afford to the problem space of how much memory to allow. The vast amount of time required to run these scenarios, several hours in some cases, made the use of scenarios requiring greater amounts of memory impractical. In the discussion section at the end of the chapter it would also be interesting to note that the obtained results exhibit asymptotic behaviour, which seems to indicate that consideration of greater memory scenarios would not provide significantly different results.

6.2 Input statistics

The economic activity metric used to weigh the network nodes, as described in section 3.1.3, was the remuneration of employees and turnover according to the levies received by district councils, metropolitan councils and regional councils by magisterial district published by Statistics South Africa [60]. Due to the sheer volume of statistics, table 6.1 only shows the 20 most economically active magisterial districts. Figure 6.1 shows a 29 bin logarithmic histogram of the economic activity of the 349 magisterial districts.

One global demand matrix was initially generated with nodal add/drop traffic values determined by a modified gravity model, as described in section 3.1.3, with 1 Tbps as the chosen aggregate network capacity requirement of the network under design.

Figure 6.2 shows how a 39 bin logarithmic histogram of the nodal add/drop traffic from the generated demand matrix follows the distribution of economic activity, shown in figure 6.1, on which it is based. The greatest nodal add/drop traffic was calculated for Johannesburg at 242.5 Gbps and the smallest nodal add/drop traffic was calculated for Mutale at 9.6875 kbps. The generated demand matrix has the constraint of being symmetrical, due to the modified gravity model used in its creation.

Geographical coordinates for the main town or city of each of the 349 magisterial districts in South Africa, shown in figure 6.3, were obtained from *www.gpswaypoints.co.za.*

A demand matrix reduction function is utilised to circumvent memory limitations, as discussed in section 5.3, when implementing the methodology on a computer with finite memory. For the network under design it has been decided that 50 super network nodes will be created from the original 349 network nodes representing the magisterial districts of South Africa. These super nodes are allowed to contribute intra-nodal traffic to the demand matrix, since they represent several other network nodes.

When reducing the original matrix a clustering process is used to aggregate network nodes to the new super network nodes. This clustering process has been designed to utilise limited amounts of memory by managing the node multiplication process, which is discussed in section 3.1.3. Results will be presented for where the memory for the demand matrix reduction process was limited to 1 MB and 8 MB respectively. The greatest and smallest add/drop traffic values of the reduced demand matrix's super nodes are presented in table 6.2.

6.3 Results

6.3.1 Evaluation of intra/inter-cluster traffic ratio

The results obtained for the 4 implementation configurations, as defined in section 6.1, are presented in figures 6.4 to 6.7. The mean intra/inter-cluster traffic ratio value for each number of hub nodes was calculated by using equation 5.18. The standard deviation value for the intra/inter-cluster traffic ratio for each number of hub nodes was calculated by using equation 5.19.

6.3.2 Discussion

In order to determine the number of hub nodes required on the backbone level of the multi-level network model for each of the four implementation configuration, as defined in section 6.1, the results obtained in section 6.3.1 have to be evaluated against a target

District	**Employees (R1000m/yr)**	**Institutions (R1000m/yr)**	**Total income (R1000m/yr)**
Johannesburg	48.5	262.1	310.7
Pretoria	31.2	148.7	179.9
Durban	20.7	119.7	140.4
Randburg	16.9	105.8	122.7
Cape	14.8	81.2	96.0
Germiston	7.6	58.6	66.3
Port Elizabeth	9.2	51.8	61.0
Kempton Park	6.8	48.8	55.7
Lower Umfolozi	5.0	33.0	38.1
Rustenburg	5.2	31.9	37.2
Bellville	3.8	28.9	32.7
Highveld Ridge	3.4	26.3	29.8
Pinetown	3.9	24.0	28.0
Wynberg	4.3	23.0	27.4
Goodwood	2.6	23.9	26.5
East London	4.7	19.8	24.5
Pietermaritzburg	6.4	18.1	24.5
Witbank	3.5	20.3	23.8
Middelburg MP	3.6	20.0	23.6

Table 6.1: The 20 most economically active magisterial districts in South Africa [60].

Memory used	**Greatest add/drop traffic**		**Smallest add/drop traffic**	
(MB)	**Node**	**Gbps**	**Node**	**Mbps**
1	Johannesburg	473.4	Molteno	18.5
8	Johannesburg	242.5	Edenburg	27.6

Table 6.2: The add/drop traffic values for the super nodes created by the demand matrix reducer, utilising either 1 MB or 8 MB of memory.

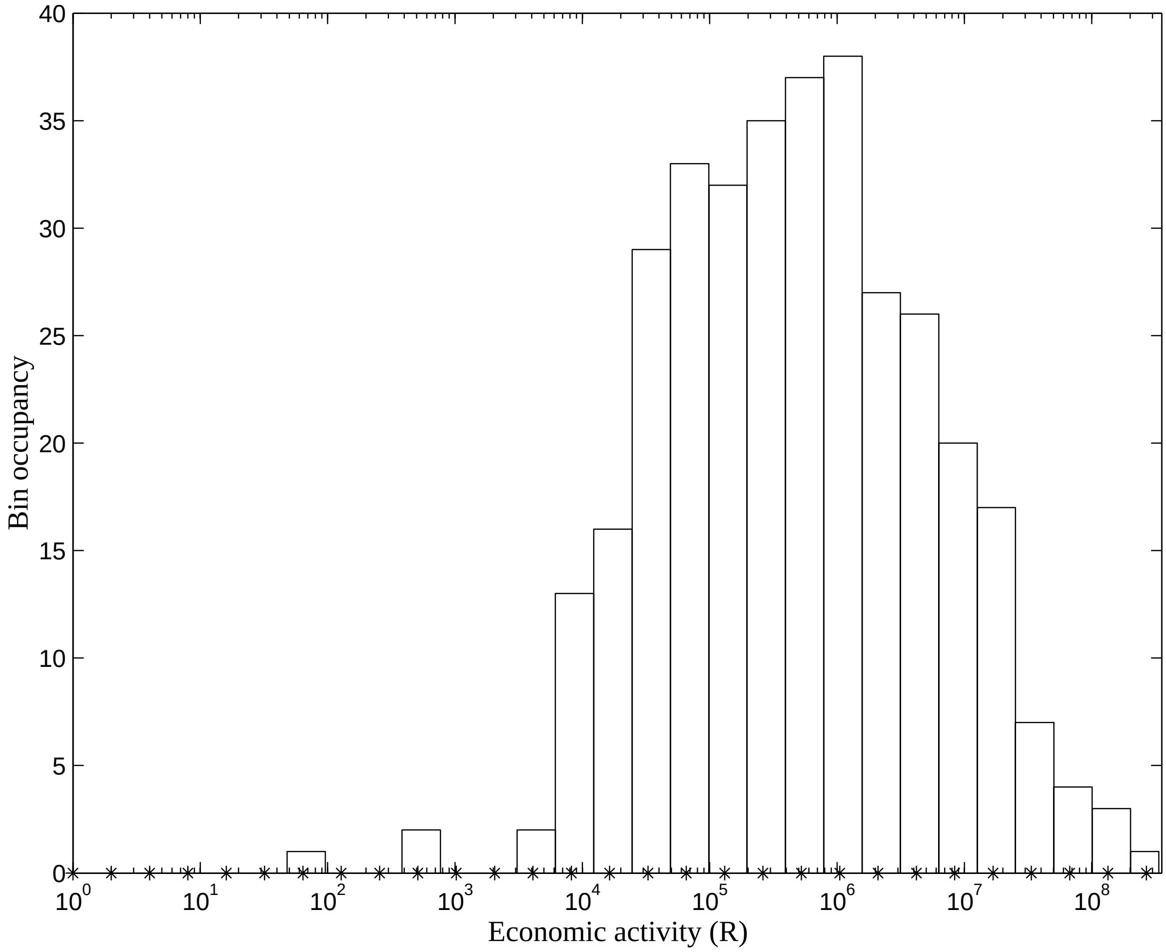


Figure 6.1: Histogram with 29 bins on a logarithmic x-axis, showing the distribution of economic activity over the magisterial districts of South Africa.

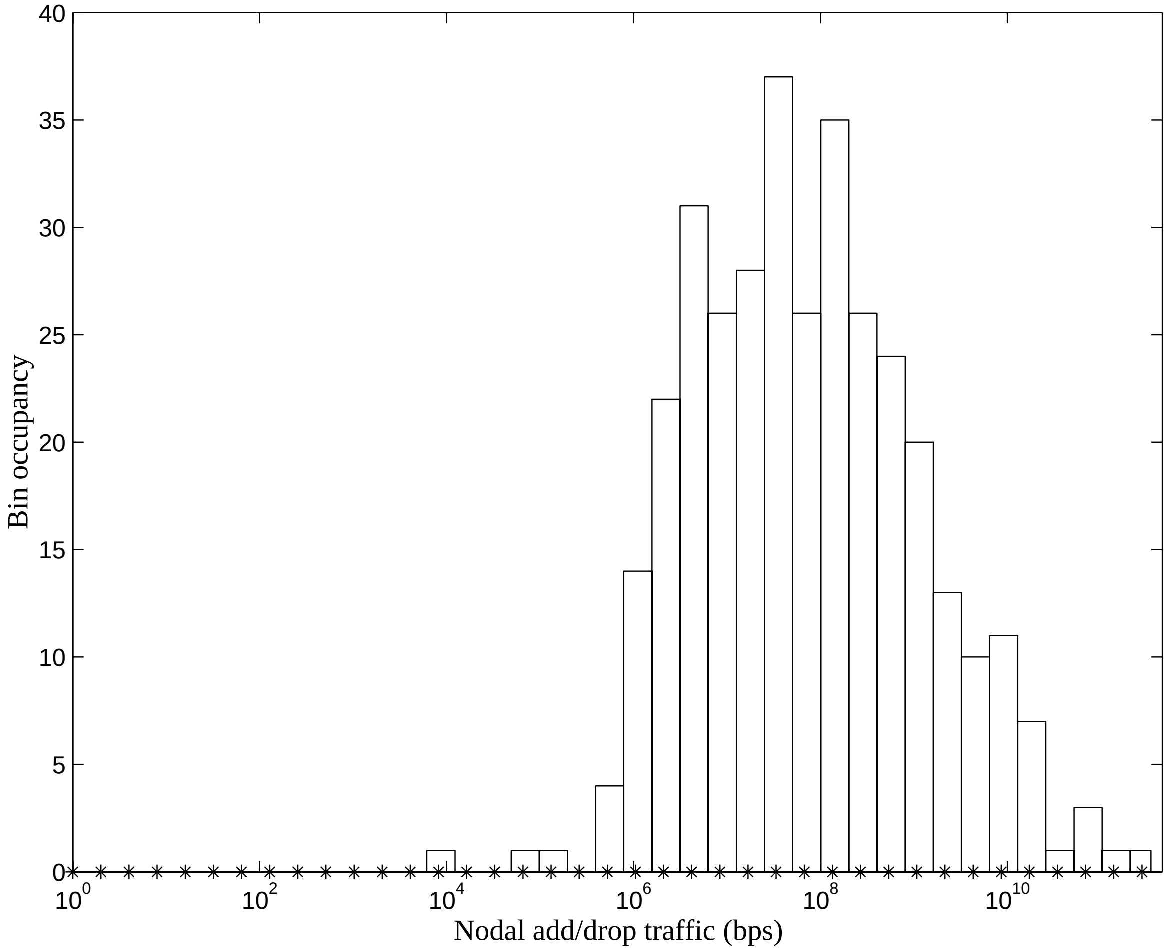


Figure 6.2: Histogram with 39 bins on a logarithmic x-axis, showing estimated nodal add/drop traffic over the magisterial districts of South Africa.

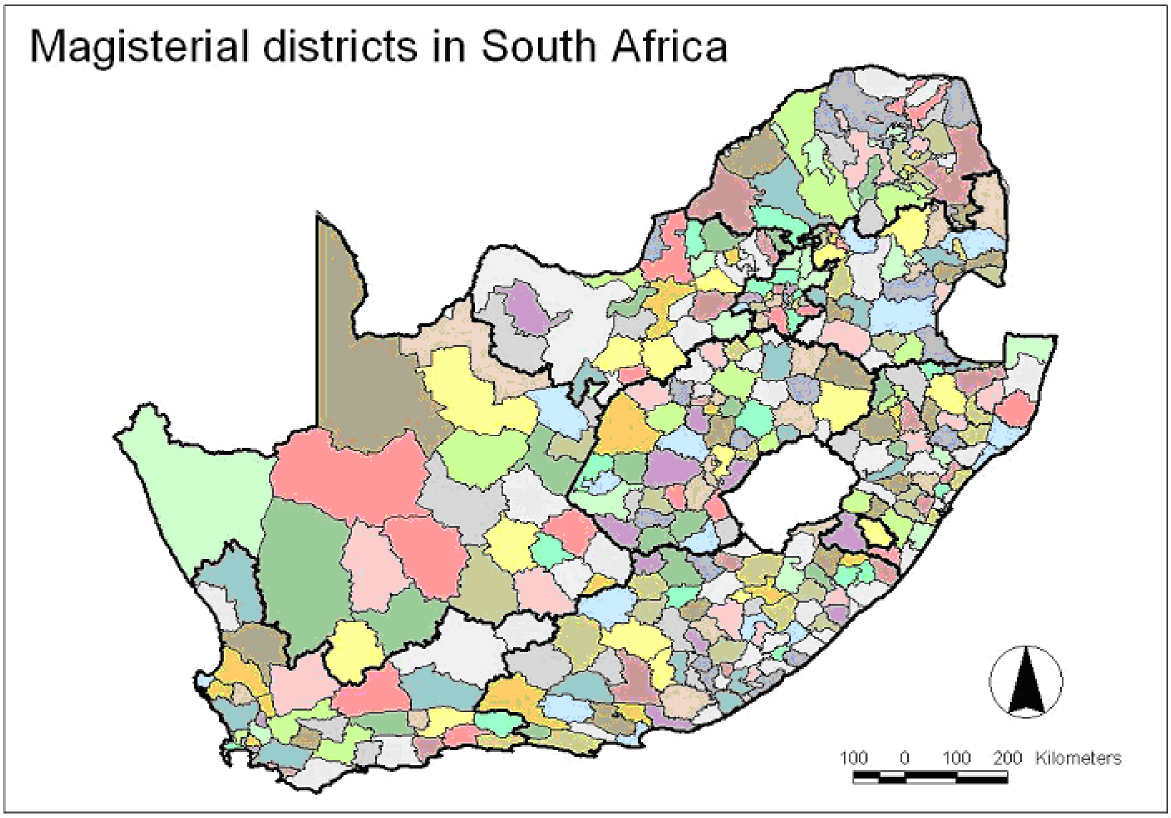


Figure 6.3: Map of South Africa indicating its 349 magisterial districts [61].

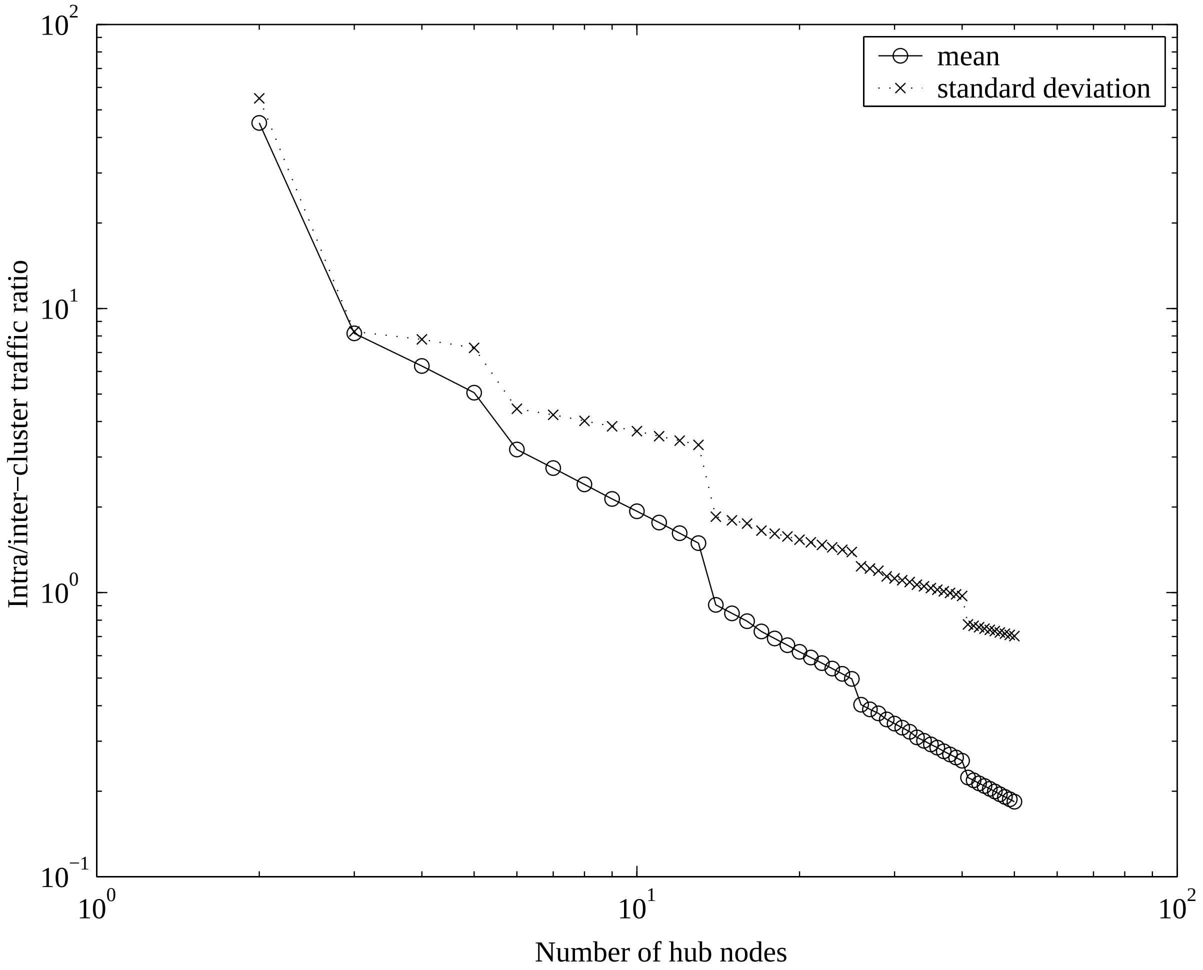


Figure 6.4: Means and standard deviations of the intra/inter-cluster traffic ratio as a function of the number of hub nodes, for implementation configuration 1 as defined in section 6.1.

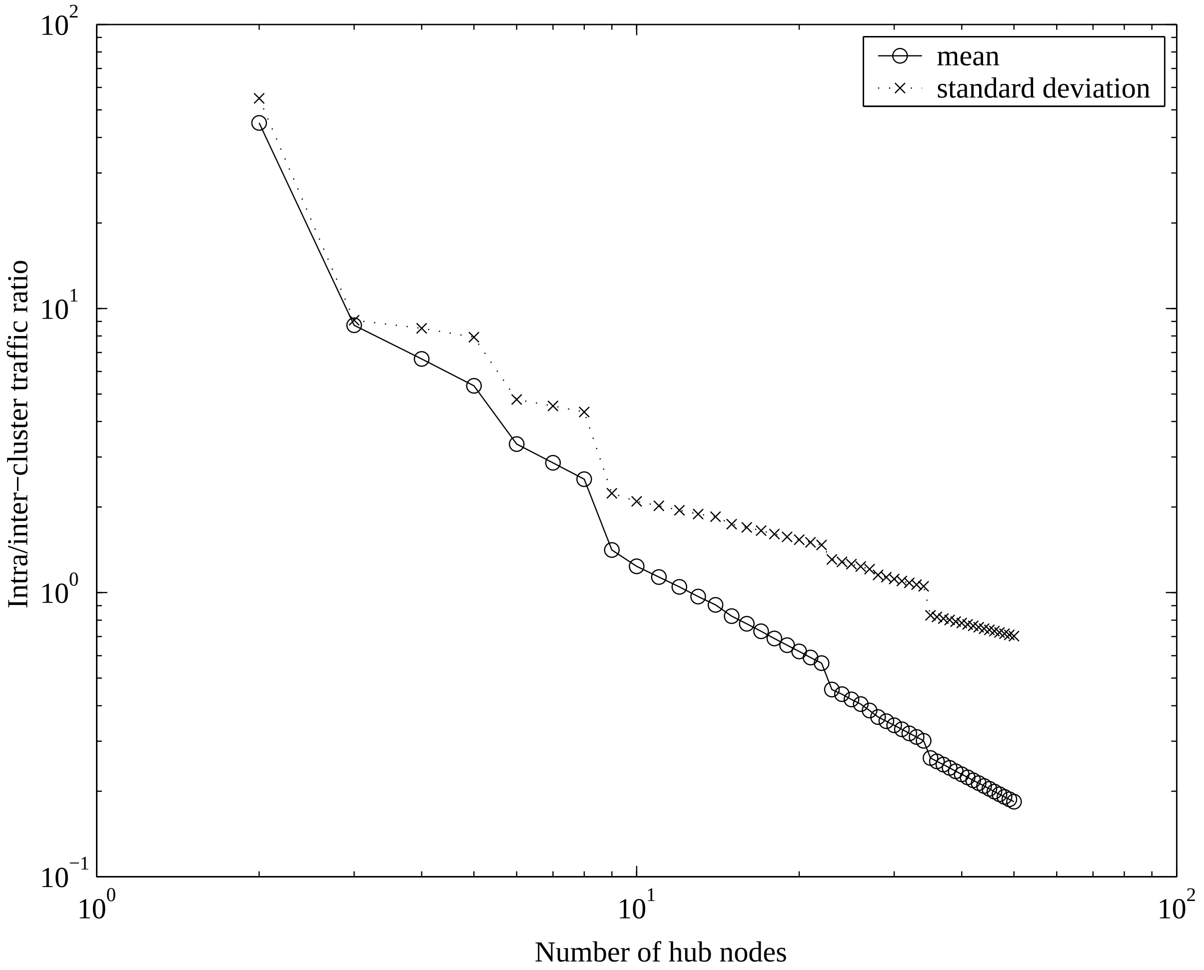


Figure 6.5: Means and standard deviations of the intra/inter-cluster traffic ratio as a function of the number of hub nodes, for implementation configuration 2 as defined in section 6.1.

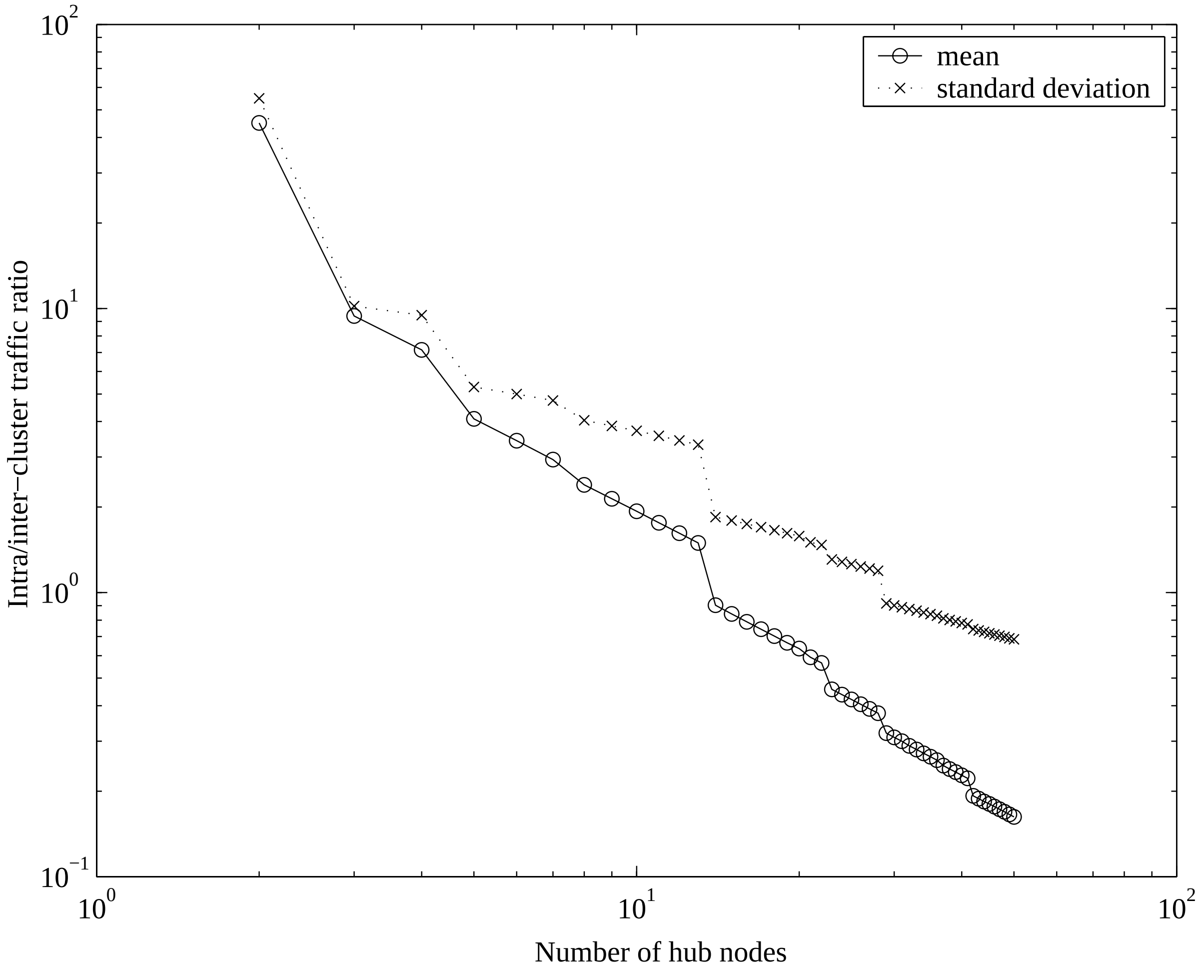


Figure 6.6: Means and standard deviations of the intra/inter-cluster traffic ratio as a function of the number of hub nodes, for implementation configuration 3 as defined in section 6.1.

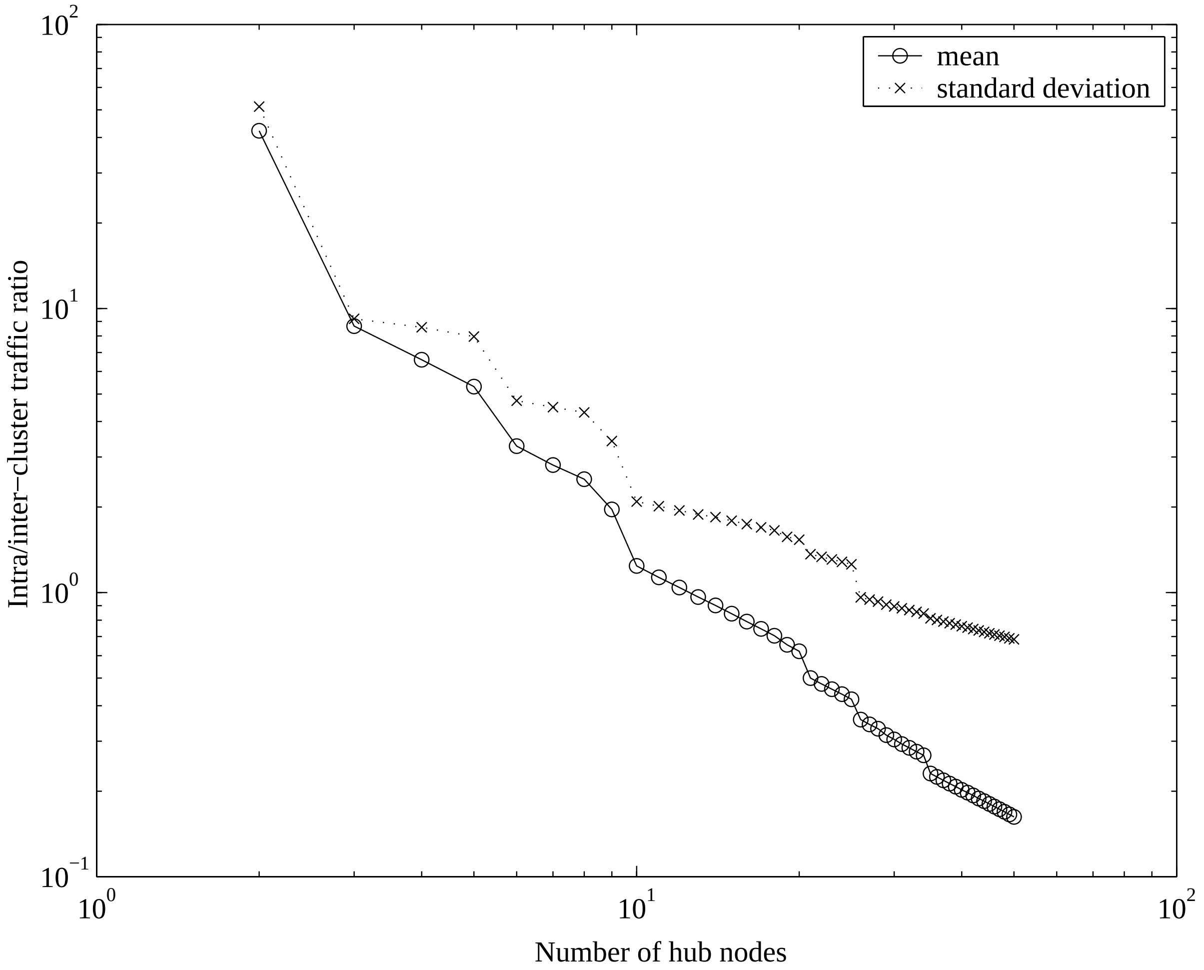


Figure 6.7: Means and standard deviations of the intra/inter-cluster traffic ratio as a function of the number of hub nodes, for implementation configuration 4 as defined in section 6.1.

Implementation configuration	$R_t = 1$	$R_t = 5$	$R_t = 9$
1	14	6	3
2	13	6	3
3	14	5	4
4	13	6	3

Table 6.3: The number of backbone level hub nodes for each of the four implementation configurations, defined in section 6.1, according to various target intra/inter-cluster traffic ratios indicated by R_t.

or preferable intra/inter-cluster traffic ratio. The guidelines provided in the discussion of section 5.3.3 were considered in selecting the target intra/inter-cluster traffic ratio to be 5. This target value is lower than the value of 9 recommended in section 5.3.3 for the selection of hub nodes on the backbone level of the multi-level network model.

Table 6.3 shows the number of hub nodes required on the backbone level of the multi-level network model for each of the four implementation configurations outlined in section 6.1, for various target intra/inter-cluster traffic ratios, including the target of 5. As expected it can be seen that the number of hub nodes required decreases as the target intra/inter-cluster traffic ratio increases.

The implementation configurations are quite evenly matched when it comes to the number of backbone hub nodes required at different intra/inter-cluster traffic ratio targets. It is thus not possible to identify any trends about the sensitivity of the number of hub nodes to the amount of memory available for the demand matrix reduction and clustering processes.

6.3.3 Clustering results

The backbone hub nodes and their corresponding clusters are shown in figures 6.8 to 6.11 and tables 6.4 to 6.7 for the 4 implementation configurations defined in section 6.1. The network nodes with the large circles around them are hub nodes of the backbone network, and the similarly shaded nodes in their vicinity belong to the same cluster. Only the networks designed for the target intra/inter-cluster traffic ratio of 5 are shown.

Three of the four figures show a network comprising of 6 backbone hub nodes. It is interesting to note that non of the implementation configurations resulted in identical network designs. The two implementation configuration pairs that utilised the same amounts of memory in the demand matrix reduction function had the same 50 network nodes. The difference in the memory limit for the clustering process also influenced the selection of hub nodes and creation of clusters. Of these four implementation configurations, the one that utilised the most memory in both the demand matrix reduction and clustering processes is regarded as the best, since it could have solved the problem with more resolution than any of the others.

It is however satisfying to observe that the network designed by the implementation configuration that was most severely limited by memory constraints, performed very good and managed to produce a solution very similar to that found by using a lot more memory. The effective implementation and successful operation of the demand matrix reduction function have been identified as the reasons for the success of the network design methodology under limited memory conditions.

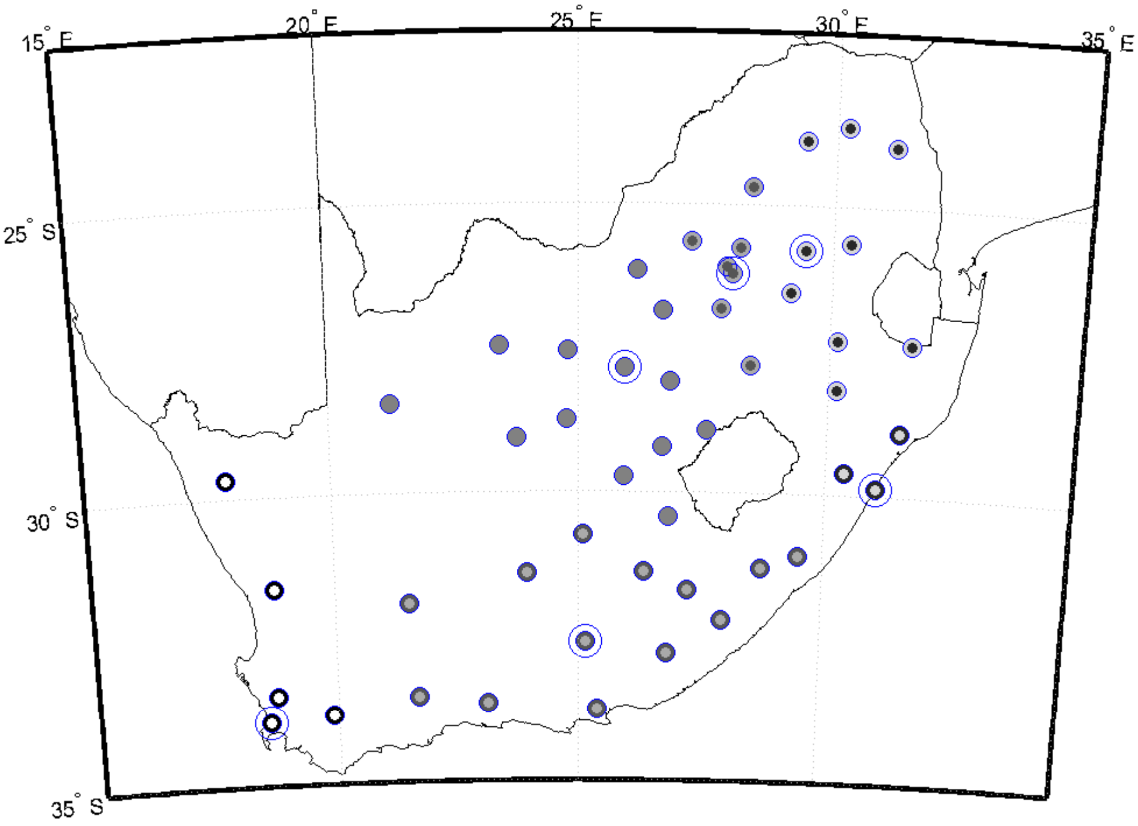


Figure 6.8: A map of South Africa showing the backbone hub nodes and clusters for the network designed according to implementation configuration 1, as defined in section 6.1.

	Hub node	**1**	**2**	**3**	**4**	**5**	**6**
1	Durban	X	1.571	1.753	15.192	3.449	1.842
2	Goodwood		X	0.961	5.712	0.917	1.713
3	Hoopstad			X	13.253	1.443	0.805
4	Johannesburg				X	27.446	4.723
5	Middelburg MP					X	0.797
6	Pearston						X

Table 6.4: The hub nodes and resultant symmetrical backbone demand matrix, in Gbps, for the network designed according to implementation configuration 1, as defined in section 6.1.

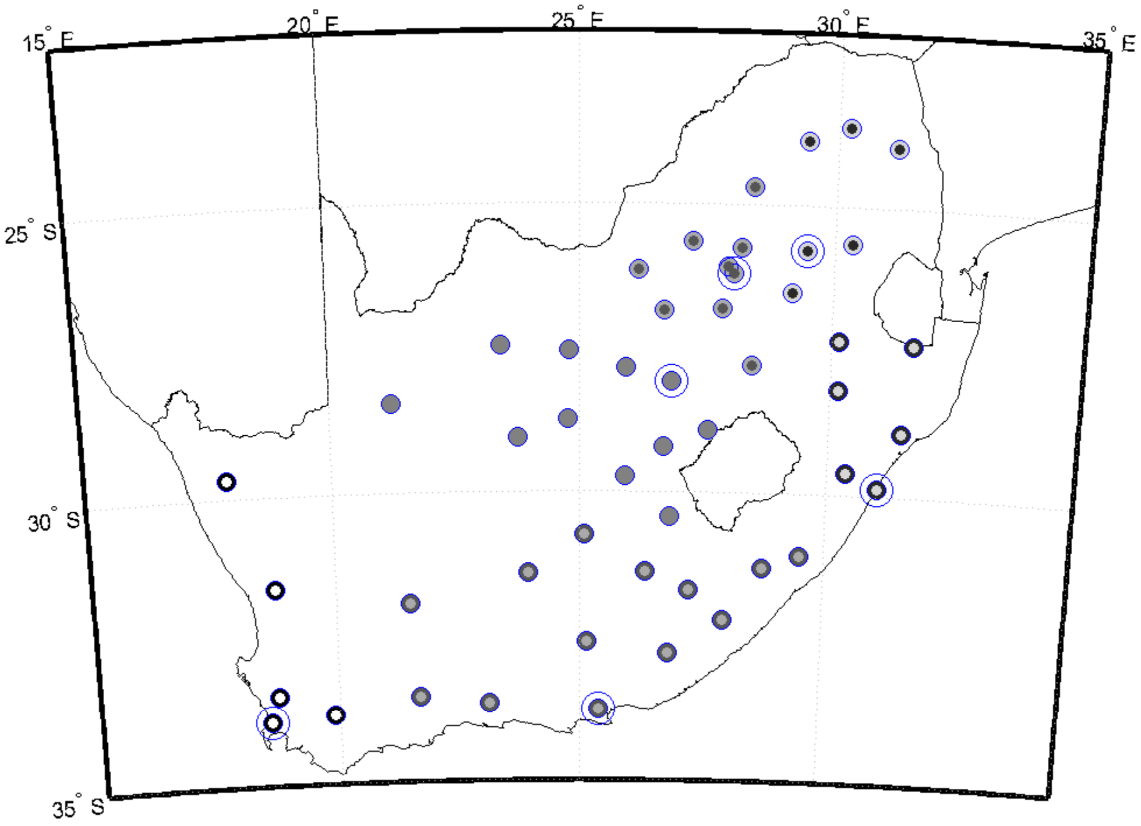


Figure 6.9: A map of South Africa showing the backbone hub nodes and clusters for the network designed according to implementation configuration 2, as defined in section 6.1.

	Hub node	**1**	**2**	**3**	**4**	**5**	**6**
1	Durban	X	1.735	18.610	2.996	2.005	1.426
2	Goodwood		X	5.942	0.753	1.713	0.731
3	Johannesburg			X	25.051	4.910	7.556
4	Middelburg MP				X	0.634	0.747
5	Uitenhage					X	0.619
6	Virginia						X

Table 6.5: The hub nodes and resultant symmetrical backbone demand matrix, in Gbps, for the network designed according to implementation configuration 2, as defined in section 6.1.

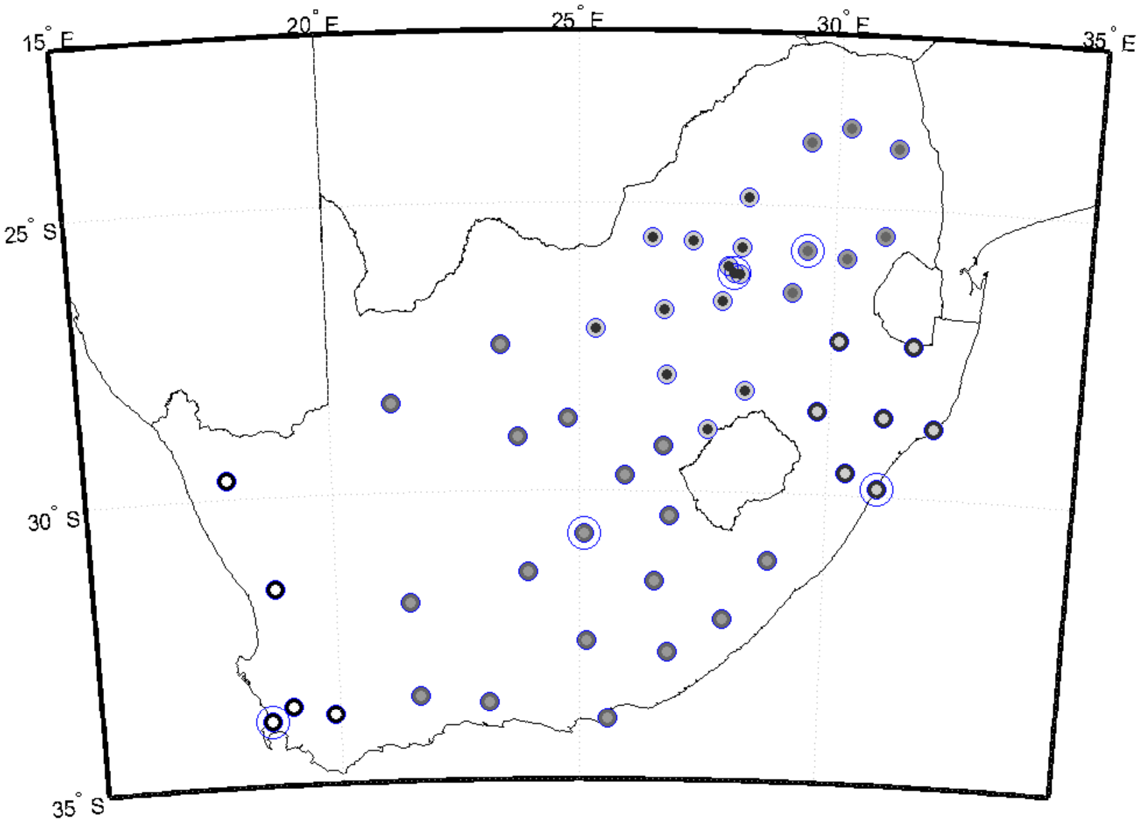


Figure 6.10: A map of South Africa showing the backbone hub nodes and clusters for the network designed according to implementation configuration 3, as defined in section 6.1.

	Hub node	**1**	**2**	**3**	**4**	**5**
1	Colesberg	X	2.781	2.201	8.964	1.047
2	Durban		X	1.714	18.687	2.941
3	Goodwood			X	6.184	0.773
4	Johannesburg				X	25.957
5	Middelburg MP					X

Table 6.6: The hub nodes and resultant symmetrical backbone demand matrix, in Gbps, for the network designed according to implementation configuration 3, as defined in section 6.1.

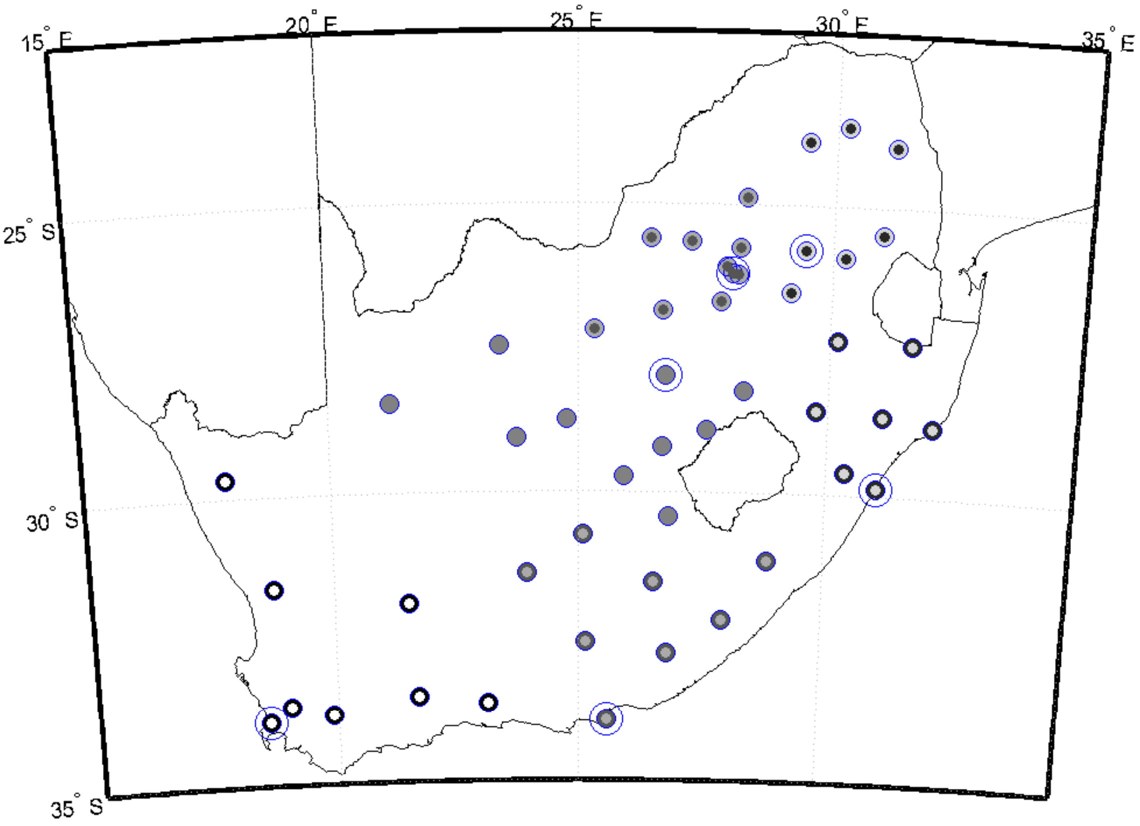


Figure 6.11: A map of South Africa showing the backbone hub nodes and clusters for the network designed according to implementation configuration 4, as defined in section 6.1.

	Hub node	**1**	**2**	**3**	**4**	**5**	**6**
1	Durban	X	1.901	17.914	2.941	1.800	1.567
2	Goodwood		X	6.534	0.850	1.484	0.808
3	Johannesburg			X	25.513	4.305	7.954
4	Middelburg MP				X	0.575	0.839
5	Port Elizabeth					X	0.554
6	Welkom						X

Table 6.7: The hub nodes and resultant symmetrical backbone demand matrix, in Gbps, for the network designed according to implementation configuration 4, as defined in section 6.1.

Chapter 7

Conclusion

Recent developments in the field of optical communication technology have paved the way for a whole new generation of services and products. Steadily-increasing network capacity can barely keep up with the demand for more communication bandwidth. New applications such as voice-over-IP and video-on-demand are but two examples of what will characterise the communication networks of tomorrow.

Communication traffic and the management thereof have become extremely important topics. The establishment of new levels of reliability, through techniques known as protection and restoration, will continue to converge with the other management functions required to maintain acceptable levels of operation from a communication network. Concepts such as price elasticity of user demand have been identified as tools that can by employed for market manipulation. The business development challenge in optical networking technology is to ensure that the services are created that will require the high-technology infrastructure and extreme performance that characterises optical communication networks.

An integrated methodology was developed and presented for the design of wide-area WDM optical networks. The methodology aims to promote enhanced interaction between the various problem solving functions that have thus far operated in relative isolation. The definition of the three topologies: physical, logical, and virtual facilitate in the process of creating some common ground on which network designers and researchers can actively partake and interact within the same frame of reference.

The intra/inter-cluster traffic ratio promises to be a very useful tool in selecting the number and positions of the hub nodes on the various levels of the multi-level network model. This approach to decision-making promotes beneficial networking principles such as load balancing and hierarchical design. Two target intra/inter-cluster traffic ratios have been identified for use in determining the hub nodes of the backbone and regional levels of the multi-level network model. These target values are in the ranges 5-9 and 0.5-1.5 for the backbone and regional levels respectively.

Most conventional approaches to the design of wide-area optical networks assume hub nodes and their clusters to be known. A given demand matrix is then used to design the physical topology of the network and do the routing and channel assignment accordingly. The applicability of the clustering approach to the design of wide-area optical networks precedes this in the real-world design process, where the hub nodes and demand matrix have to be determined prior to the design of a physical topology or the routing and channel assignment. Following these steps, optimisation of criteria such as cost and performance would result in several iterations of the design process to converge to a solution that optimises the selected criteria. The proposed clustering approach to the design of wide-area optical networks addresses the establishment of a logical topology as well as identification of the hub nodes that are crucial to the design of a physical topology.

The introduced methodology can be a valuable tool to a network designer due to the increase objectivity that it provides to the design process and the reproducibility of the obtained results. These characteristics come at the cost of reliable statistics being required together with a lot of processing power and memory to satisfy the greedy nature of the clustering process with regards to system resources.

References

[1] M. C. Brain and P. Cochrane, “Wavelength-routed optical networks using coherent transmission,” in *Proc. IEEE ICC*, (Philadelphia), pp. 26–31, Jun. 1988.

[2] G. R. Hill, “A wavelength routing approach to optical communications networks,” in *Proc. IEEE INFOCOM*, (New Orleans), pp. 354–362, Mar. 1988.

[3] S. Baroni and P. Bayvel, “Wavelength requirements in arbitrarily connected wavelength-routed optical networks,” *J. Lightwave Technol.*, vol. 15, pp. 242–251, Feb. 1997.

[4] R. A. Barry and P. A. Humblet, “On the number of wavelengths and switches in all-optical networks,” *IEEE Trans. Commun.*, vol. 42, pp. 583–591, Feb.-Apr. 1994.

[5] J. Doucette and W. D. Grover, “Influence of modularity and economy-of-scale effects on design of mesh-restorable DWDM optical networks,” *IEEE J. Select. Areas in Commun.*, vol. 18, pp. 1912–1923, Oct. 2000.

[6] B. Mukherjee, D. Banerjee, S. Ramamurthy, and A. Mukherjee, “Some principles for designing a wide-area WDM optical network,” *IEEE/ACM Trans. Networking*, vol. 4, pp. 684–696, Oct. 1996.

[7] J. A. Bannister, L. Fratta, and M. Gerla, “Topological design of the wavlength-division optical network,” in *Proc. IEEE INFOCOM*, (San Francisco), pp. 1005–1013, Jun. 1990.

[8] R. J. Vetter, K. A. Williams, and D. H. C. Du, “Topological design of optically switched WDM networks,” in *Proc. LCN*, (Minneapolis), pp. 114–127, Oct. 1991.

[9] Y. Hu and M. Mezhoudi, “Cost effectively design an optical network based on optical signal noise ratio (OSNR) requirement,” in *Proc. NFOEC*, (Baltimore), pp. 1035–1042, Jul. 2001.

[10] R. Ramaswami and K. N. Sivarajan, “Design of logical topologies for wavelength-routed all-optical networks,” in *Proc. IEEE INFOCOM*, (Boston), pp. 1316–1325, Apr. 1995.

[11] L. Rapp and H. Jäger, “Physical and network aspects concerning the number of wavelengths in WDM systems,” in *Proc. Int’l Zurich Seminar on Broadband Communication*, (Zurich), pp. 63–68, Feb. 1998.

[12] T. K. Tan and J. K. Pollard, “Determination of minimum number of wavelengths required for all-optical WDM networks using graph colouring,” *IEE Electron. Lett.*, vol. 31, pp. 1895–1897, Oct. 1995.

[13] D. Banerjee and B. Mukherjee, “Wavelength-routed optical networks: Linear formulation, resource budgeting tradeoffs, and a reconfiguration study,” in *IEEE/ACM Trans. Networking* (598-607, ed.), (5), 8, Oct. 2000.

[14] D. R. Hjelme, A. Royset, and B. J. Slagsvold, “How many wavelengths does it take to build a wavelength routed optical network?,” in *Proc. ECOC*, (Oslo), pp. 27–30, Sep. 1996.

[15] O. Gerstel, P. Lin, and G. Sasaki, "Combined WDM and SONET network design," in *Proc. IEEE INFOCOM*, (New York), pp. 734–743, Mar. 1999.

[16] T. El-Bawab, M. O'Mahony, and A. Jayasumana, "A European multiwavelength optical network," in *Proc. ISCC*, (Alexandria), pp. 568–573, Jul. 1997.

[17] A. D. Gazendam and F. W. Leuschner, "Statistical clustering in the design of logical topologies for wide-area optical networks," in *Proc. IEEE AFRICON*, (George), pp. 209–210, Oct. 2002.

[18] T. E. Stern and K. Bala, *Multiwavelength optical networks: a layered approach.* Addison-Wesley, 1999.

[19] R. C. Alferness, H. Kogelnik, and T. H. Wood, "The evolution of optical systems: Optics everywhere," *Bell Labs Tech. J.*, pp. 188–202, Jan.-Mar. 2000.

[20] A. M. Glass, D. J. DiGiovanni, T. A. Strasser, A. J. Stentz, R. E. Slusher, A. E. White, A. R. Kortan, and B. J. Eggleton, "Advances in fiber optics," *Bell Labs Tech. J.*, pp. 168–187, Jan.-Mar. 2000.

[21] Anritsu Corporation, *MS9720A WDM network tester datasheet: No. MS9720A-E-A-1-(3.00)*, February 2000.

[22] A. D. Gazendam, "The application of MEMS technology in optical routers," tech. rep., University of Pretoria, South Africa, 2001.

[23] A. N. Netravali, "When networking becomes second nature: the next 25 years...and beyond," *Bell Labs Tech. J.*, pp. 203–214, Jan.-Mar. 2000.

[24] R. Ramaswami and K. N. Sivarajan, "Optimal routing and wavelength assignment in all-optical networks," in *Proc. IEEE INFOCOM*, (Toronto), pp. 970–979, Jun. 1994.

[25] American National Standards Institute, Inc., *T1.105-1995 Synchronous Optical Network (SONET) - Basic description including multiplex structure, rates, and formats*, Oct. 1995.

[26] International Communication Union, *Recommendation G.707/Y.1322 - Network node interface for the synchronous digital hierarchy (SDH)*, Oct. 2000.

[27] International Communication Union, *Recommendation G.692 - Optical interfaces for multichannel systems with optical amplifiers*, Oct. 1998.

[28] G. Klaoudatos, M. Devetsikiotis, and I. Lambadaris, "Automated modeling of broadband network data using the QTES methodology," in *Proc. IEEE ICC*, (Vancouver), pp. 397–403, Jun. 1999.

[29] N. K. Groschwitz and G. C. Polyzos, "A time series model of long-term NSFNET backbone traffic," in *Proc. IEEE ICC*, (New Orleans), pp. 1400–1404, May 1994.

[30] S. Basu, A. Mukherjee, and S. Klivansky, "Time series models for internet traffic," in *Proc. IEEE INFOCOM*, (San Francisco), pp. 611–620, Mar. 1996.

[31] K. C. Claffy, G. C. Polyzos, and H.-W. Braun, "Traffic characteristics of the T1 NSFNET backbone," in *Proc. IEEE INFOCOM*, (San Francisco), pp. 885–892, Mar. 1993.

[32] R. Dutta and G. N. Rouskas, "On optimal traffic grooming in WDM rings," in *Proc. ACM SIGMETRICS*, (Cambridge), pp. 164–174, Jun. 2001.

[33] O. Gerstel, R. Ramaswami, and G. H. Sasaki, "Cost-effective traffic grooming in WDM rings," *IEEE/ACM Trans. Networking*, vol. 8, pp. 618–630, Oct. 2000.

[34] X. Zhang and C. Qiao, "An effective and comprehensive approach for traffic grooming and wavelength assignment in SONET/WDM rings," *IEEE/ACM Trans. Networking*, vol. 8, pp. 608–617, Oct. 2000.

[35] H.-W. Tzeng, J.-L. Chen, and N.-K. Chen, “Traffic grooming in WDM networks using genetic algorithm,” in *Proc. SMC*, (Tokyo), pp. I.1003–1006, Oct. 1999.

[36] J. Wang, V. R. Vemuri, W. Cho, and B. Mukherjee, “Improved approaches for cost-effective traffic grooming in WDM ring networks: Non-uniform traffic and bidirectional ring,” in *Proc. IEEE ICC*, (New Orleans), pp. 1295–1299, June 2000.

[37] B. J. Wilson, N. G. Stoffel, J. L. Pastor, M. J. Post, K. H. Liu, T. Li, K. A. Walsh, J. Y. Wei, and Y. Tsai, “Multiwavelength optical networking management and control,” *J. Lightwave Technol.*, vol. 18, pp. 2038–2057, Dec. 2000.

[38] Y. Wang and Y. Yang, “Multicasting in a class of multicast-capable WDM networks,” in *Proc. IEEE ICCCN*, (Las Vegas), pp. 184–191, Oct. 2000.

[39] S. Baroni, P. Bayvel, and J. E. Midwinter, “Influence of physical connectivity on the number of wavelengths in dense wavelength-routed optical networks,” in *Proc. OFC*, (San Jose), pp. Tu.25–26, Feb. 1996.

[40] C. Zhou and Y. Yang, “Multicast communication in a class of wide-sense nonblocking optical WDM networks,” in *Proc. IEEE ICCCN*, (Lafayette), pp. 321–328, Oct. 1998.

[41] S. Baroni and P. Bayvel, “Key topological parameters for the wavelength-routed optical network design,” in *Proc. ECOC*, (Oslo), pp. 2.277–280, Sep. 1996.

[42] V. Anand and C. Qiao, “Dynamic establishment of protection paths in WDM networks, part I,” in *Proc. IEEE ICCCN*, (Las Vegas), pp. 198–204, Oct. 2000.

[43] J. Cao, S. Vander Wiel, B. Yu, and Z. Zhu, “A scalable method for estimating network traffic matrices from link counts,” tech. rep., Bell Laboratories, Lucent Technologies, 2001.

[44] R. Chaki and U. Bhattacharya, “Design of a new scalable topology for multihop optical networks,” in *Proc. IEEE TENCON*, (Kuala Lumpur), pp. II.482–487, Sep. 2000.

[45] M. W. Maeda, “Management and control of transparent optical networks,” *IEEE J. Select. Areas in Commun.*, vol. 16, pp. 1008–1023, Sep. 1998.

[46] A. W. Bragg and W. Chou, “Real-time computation of empirical autocorrelation, and detection of non-stationary traffic conditions in high-speed networks,” in *Proc. IEEE ICCCN*, (Las Vegas), pp. 212–219, Sep. 1995.

[47] W. S. Cleveland and D. X. Sun, “Internet traffic data,” *J. American Statistical Association*, vol. 95, no. 451, pp. 979–985, 2000.

[48] American National Standards Institute, Inc., *T1.105.01-2000 Synchronous Optical Network (SONET) - Automatic Protection Switching*, Mar. 2000.

[49] E. Drakopoulos, “Enterprise network planning and design: Methodology and application,” white paper, Bell Laboratories, Lucent Technologies, 1999.

[50] S. Baroni, P. Bayvel, and R. J. Gibbens, “Restoration capacity for resilient wavelength-routed optical transport networks,” in *Proc. IEEE/LEOS Summer Topical Meetings*, pp. 31–32, 1998.

[51] O. Crochat and J.-Y. Le Boudec, “Design protection for WDM optical networks,” *IEEE J. Select. Areas in Commun.*, vol. 16, pp. 1158–1165, Sep. 1998.

[52] S. Gangxiang, S. K. Bose, C. Tee Hiang, and L. Chao, “Designing wdm optical network for reliability: Routing light paths efficiently for path protection,” in *Proc. OFC*, (Baltimore), pp. Th.50–52, Mar. 2000.

[53] T. Shiragaki and H. Saito, "Optimum protection architectures for reliable dense-WDM lightwave networks," in *Proc. IEEE ICC*, (Atlanta), pp. 181–186, Jun. 1998.

[54] I. Rubin and J. Ling, "Failure protection methods for optical meshed-ring communications networks," *IEEE J. Select. Areas in Commun.*, vol. 18, pp. 1950–1960, Oct. 2000.

[55] S. Baroni, P. Bayvel, R. J. Gibbens, and S. K. Korotky, "Analysis and design of resilient multifiber wavelength-routed optical transport networks," *J. Lightwave Technol.*, vol. 17, pp. 743–758, May 1999.

[56] D. Mitra and Q. Wang, "Generalized network engineering: Optimal pricing and routing for multi-service networks," tech. rep., Bell Laboratories, Lucent Technologies, 2001.

[57] A. Fumagalli, I. Cerutti, M. Tacca, D. Montgomery, I. Chlamtac, and K. Pathak, "CATO: Trans-layer dense wavelength division multiplexing (DWDM) network optimization," in *Proc. OFC*, (Baltimore), pp. 378–380, Mar. 2000.

[58] M. C. Sinclair, "NoMaD: an optical network optimisation, modelling and design toolset," tech. rep., Department of Electrical Systems Engineering, University of Essex, UK, 1998.

[59] J. H. Ward, "Hierarchical grouping analysis for applications," *J. American Statistical Association*, vol. 58, pp. 236–244, 1963.

[60] Statistics South Africa, *Statistical release P9149: Remuneration of employees and turnover according to the levies received by district councils, metropolitan councils and regional councils by magisterial district - Quarter ended 31 March 2001*, June 2001.

[61] P. Schmitz and T. Stylianides, “Mapping crime levels and court efficiency per magisterial district in South Africa,” in *Proc. International Crime Mapping Research Conference*, (Denver), Dec. 2002.

Bibliography

- M. Ali, *Transmission-efficient design and management of wavelength-routed optical networks.* Kluwer Academic Publishers, 2001.
- R. Bhandari, *Survivable networks: algorithms for diverse routing.* Kluwer Academic Publishers, 1999.
- Edited by G. De Marchis and R. Sabella, *Optical networks: design and modelling.* Kluwer Academic Publishers, 1999.
- D. Derickson, *Fiber optic test and measurement.* Prentice Hall PTR, 1998.
- W. Goralski, *Optical networking & WDM.* Osborne/McGraw-Hill, 2001.
- G. Keiser, *Optical fiber communications.* McGraw-Hill, 2000.
- J.M. Senior, *Optical fiber communications: principles and practice.* Prentice Hall, 1985.
- Edited by K.M. Sivalingam and S. Subramaniam, *Optical WDM networks: principles and practice.* Kluwer Academic Publishers, 2000.
- T.E. Stern and K. Bala, *Multiwavelength optical networks: a layered approach.* Addison-Wesley, 1999.