

# 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 evo-

lution 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 topolo-

gies (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 by 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.