# DESIGN OF NONBLOCKING HIGH-DENSITY PHOTONIC SWITCHES

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# DEDICATION

**To the permanent residents of my heart and my mind,**

**To my parents, my wife, my brothers and sisters.**

**"*I am every thing I am, because you love me*"**

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# ABSTRACT

Crosstalk, signal attenuation, and nonblocking type are considered the most critical issues that limit the switch density in photonic switches. The research is a theoretical study to develop high-density photonic switch architectures with reduced crosstalk and attenuation and improved nonblocking performance. Four photonic switching networks have been proposed based on lithium niobate ($LiNbO_3$) directional couplers. They are called *N*W*N*, *N*S*N*, SCS, and *N*M*N* networks. Ideas from the theory of circuit switching have been considered and space dilation techniques have been adopted using new approaches. The properties of the proposed networks have been examined and formulated. Comparison with other well-known designs has also been presented and analyzed. All proposed networks suit unicast connections with the *N*M*N* network also capable of multicasting. The *N*W*N* is nonblocking in the wide sense while the others are strictly nonblocking. The optimum switch dimension for the proposed networks was found to be 16. With this size the insertion loss of the *N*W*N*, *N*S*N*, SCS, and *N*M*N* networks is 17, 17, 15, and 21 dB, respectively. This signal attenuation is lower than the constraint of 30 dB beyond which optical amplifiers may be needed. The respective signal-to-noise ratio with this size is 11.549, 11.549, 20, and 13.979 dB, which is also higher than the 11 dB required for achieving a good bit error rate performance. The penalty to achieve these results is more hardware complexity that is reflected by the number of couplers used and the number of waveguide crossovers required. Waveguide crossovers can, however, be reduced if some stages or subnetworks of the switch are fabricated on separate substrates.

# ABSTRAK

Cakapsilang, pelemahan isyarat terhantar dan ciri-ciri tak terhalang adalah isu-isu yang besar yang perlu diambilkira apabila merekabentuk rangkaian pensuisan fotonik. Penyelidikan ini adalah berkaitan kajian tentang teori struktur binaan untuk mengurangkan cakapsilang dan pelemahan serta memperbaiki kebolehupayaan tak terhalang. Empat rangkaian pensuisan fotonik telah direkabentuk berasaskan pengganding berarah lithium niobate ($LiNbO_3$). Mereka dinamakan sebagai rangkaian *N*W*N*, *N*S*N*, SCS, dan *N*M*N*. Idea daripada teori pensuisan litar dan kaedah pengembangan baru telah digunakan. Ciri-ciri rangkaian yang direkabentuk telah diuji dan dirumuskan. Perbandingan keputusan dengan rekabentuk yang telah dikenali dan analisa ciri-cirinya telah dipersembahkan. Semua rangkaian yang dicadangkan memenuhi penyambungan ekasiar. Rangkaian *N*M*N* juga memenuhi penyambungan jenis berbilang siar. Rangkaian *N*W*N* adalah tidak terhalang dalam erti kata deria lebar, manakala rangkaian yang lain langsung tidak terhalang. Ukuran optima suis bagi rangkaian yang telah dicadangkan didapati sebagai 16. dengan saiz ini kehilangan sisipan bagi rangkaian *N*W*N* dan *N*S*N* adalah 17 dB, SCS adalah 15 dB, manakala *N*M*N* adalah 21 dB. Kehilangan sisipan ini adalah lebih rendah daripada had andaian halangan 30 dB, yang mana bagi kehilangan sisipan yang lebih tinggi, penguat adalah diperlukan. Nisbah isyarat-hingar pada saiz ini bagi rangkaian *N*W*N* dan *N*S*N* adalah 11.549 dB, SCS adalah 20 dB, manakala *N*M*N* adalah 13.979 dB. Ini adalah lebih tinggi dari 11 dB yang diperlukan untuk mencapai kadar bit kesilapan yang mempunyai kebolehupayaan yang lebih baik. Namun, perkakas keras yang lebih kompleks diperlukan untuk mencapai keputusan yang telah dipersembahkan. Ini dapat dilihat daripada bilangan pengganding dan pandu gelombang bersilang yang diperlukan. Persilangan pandu gelombang akan dapat dikurangkan jika fabricasi aras atau sub rangkaran bagi suis dilakuhan di atas bahan substrat yang berlainan.

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| | |
|---|---|
| $a$ | The fiber core radius |
| $C(N)$ | Maximum number of crossovers along a path for the *N*S*N* and the SCS switches |
| $CRO_T$ | Maximum number of crossovers along a path for the *N*W*N* switch |
| $d$ | The gap between the waveguides in a directional coupler |
| dB | Decibel unit |
| $D_T$ | Total number of drivers required by the *N*M*N* switch |
| $E$ | Excess loss in passive splitters |
| $i$ | The general input port in a switches |
| $j$ | The stage number in a multistage switching network |
| $k$ | Central modules in a tree-type network |
| K | Number of crosstalk switches in a signal path |
| $l$ | Length of the coupling region in a directional coupler |
| $L$ | The insertion loss in dB of a directional coupler |
| m | Crosstalk intensity of the 2x2 switch |
| $m$ | Number of middle stage switches in the Clos switch |
| n | $\log_2 N$ for a switch of size $N$ |
| $N$ | Switch size |
| $n$ | The average refractive index (section 2.8.2.1) |
| | The input switch size of the first stage of the Clos switch (section 3.6) |
| $o$ | The output port in double crossbar switches |
| $O$ | Output signal in a dilated Benes switch |
| $P_{in}$ | Total input power in dB |
| $P_N$ | Total noise power |
| $P_{out}$ | Total output power in dB |

| | |
|---|---|
| $r$ | The switch size of the middle stage switches in the Clos switch |
| $SE_T$ | Total number of SEs |
| $SiO_2$ | Silicon dioxide |
| $V$ | Number of modes for an optical fiber |
| W | The fiber-to-waveguide coupling loss in dB |
| $w$ | The width of the waveguides in a directional coupler |
| $X$ | Extinction ratio in dB of a directional coupler |
| $\Delta$ | The relative refractive index |
| $\lambda$ | The operating wavelength |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| 2S3 | 2 X 3 Strictly Nonblocking Basic Element |
| 2W3 | 2 X 3 Wide-Sense Nonblocking Basic Element |
| 3S2 | 3 X 2 Strictly Nonblocking Basic Element |
| 3W2 | 3 X 2 Wide-Sense Nonblocking Basic Element |
| 4S4 | 4 X 4 Strictly Nonblocking Switch |
| 4W4 | 4 X 4 Wide-Sense Nonblocking Switch |
| AC | Active Combiner |
| AS | Active Splitter |
| BER | Bit Error Rate |
| B-ISDN | Broadband Integrated Service Digital Network |
| CDMA | Code Division Multiple Access |
| CDMA/CD | Code Division Multiple Access With Collision Detection |
| DC | Directional Coupler |
| DWDM | Dense Wavelength Division Multiplexing |
| E/O | Electrical-To-Optical |
| FBT | Fused Biconical Taper |
| FDDI | Fiber Distributed Data Interface |
| FDM | Frequency Division Multiplexing |
| FDMA | Frequency Division Multiple Access |
| I/O | Input/Output |
| IL | The Insertion Loss Of A Switching Network |
| LAN | Local Area Network |
| MFD | Mode-Field Diameter |
| MIN | Multistage Interconnection Network |
| *N*M*N* | The proposed multicast switch |
| *N*S*N* | The proposed strictly nonblocking network |

| | |
|---|---|
| *N*W*N* | The proposed wide-sense nonblocking network |
| O/E | Optical-To-Electrical |
| PC | Passive Combiner |
| PM | Polarization-Maintaining |
| PS | Passive Splitter |
| RC | Resistor-Capacitor |
| SCS | Single-Crosstalk-Stage Switch |
| SD | Space Division |
| SDM | Space Division Multiplexing |
| SE | Switching Element |
| SNR | Signal-To-Noise Ratio |
| TD | Time Division |
| TDM | Time Division Multiplexing |
| TDMA | Time Division Multiple Access |
| Ti:$Linbo_3$ | Titanium Diffused Lithium Niobate |
| VCI | Virtual Circuit Identifier |
| VLSI | Very Large Scale Integration |
| WAN | Widearea Network |
| WD | Wavelength Division |
| WDM | Wavelength Division Multiplexing |
| WDMA | Wavelength Division Multiple Access |
| WDS | Wavelength Dilated Switch |

# CHAPTER I

# INTRODUCTION

## 1.1 Introduction

The increasing number of users of the Internet has pushed the growing demand for more bandwidth. Multimedia traffic, which combines the voice, data, and video, consumes large amount of bandwidth. There is not enough capacity of transmission in today's networks to support the exponential growth in user's traffic. The traditional copper wire, even coaxial cable, is limited by electronic speeds to a few Gbps. Radio has a total channel bandwidth of 25 GHz which is still insufficient [1]. In contrast fiber can offer a huge bandwidth of nearly 50 Tbps. Optical networks are emerging as a replacement of traditional copper wire networks. Optical networks using optical switches instead of electronic devices along the signal path are also emerging from laboratories into field trials.

In communication networks, switches form an important part that provides a facility for moving data from node to node until they reach their destinations. The basic function of a switch is to forward the data arriving at its inputs to the corresponding outputs while supporting control and management functions.

Within recent years there has been a significant amount of interest in applying the new and developing photonic technology in telecommunications switching networks [1]. As the transmission plant has converted its facilities to fiber, there is an economic interest in completing the optical path through the switching network to the terminal facilities without requiring optical-to-electrical (O/E) and electrical-to-optical (E/O) conversions. The subject of this thesis is optical switching, which will be a crucial technology to avoid O/E and E/O in these networks. Optical switching and its challenging issues are covered in the first two sections of this chapter. In the following sections the problem formulation, the research scope, the contribution and the organization of the thesis are introduced.

## 1.2 Optical Switching

As its name implies, optical switching involves the switching of optical signals rather than electrical signals using optical switching elements or components. The advantages of this technology include: decreased switching time, less cross-talk and interference, increased reliability, increased fault-tolerance, enhanced transmission capacity, economical broadband transport network construction, and flexible service provisioning [2].

Most of these advantages stem from the fundamental properties of light. Light is composed of photons, which are neutral bosons unaffected by mutual interactions. Thus, multiple beams of photons with different frequencies can cross paths without significant interference. Only the switching speed and capacitance of transmitters and receivers limit the speed of optical links [3]. These characteristics are highly desirable in developing high-capacity, flexible communication systems. However, using optical frequencies which is between 100 and 1000 THz, still has some difficulties, especially with optical component design that requires its own technology because of the extremely small wavelength that need micro-metric manipulations [4].

Optical switches can be implemented with either free-space optics or guided wave technology. Free-space optical switches utilize beam splitters, mirrors, and lenses while guided wave switches use structures (fibers or waveguides) within which electromagnetic waves are guided for propagation [3]. In this thesis we consider optical implementation with guided wave technology. Two types of guided wave optical switching system can be identified. The first is a hybrid approach in which optical signals are switched but the switches are controlled electronically implying that the routing must be carried out electronically. The speed of electronic switch control signals can be much less than the bit rate of the optical signals being switched and is limited by factors such as clock skew and RC time constant [3]. This type of switching is usually implemented with electronically controlled optical switching elements (SEs) such as the titanium diffused lithium niobate ($Ti:LiNbO_3$) directional couplers. They are described in chapter II.

The second approach is all-optical switching in which, not only the signals switched are optical, but the switches are controlled optically too. The processing necessary to calculate the switch setting, is also optical. This overcomes the speed mismatch problems associated with the hybrid approach and allows the potential for extremely high bit rates. However, such systems are not likely to become practical in the near future [5]; hence, only the hybrid approach was chosen here because it represents a mature technology.

## 1.3 Optical Switching System Issues

Although optical switches based on directional couplers hold great promises and have demonstrated advantages over their electronic counterparts they also introduce new challenges such as how to deal with the unique problem of crosstalk in the SEs and how to minimize the number of waveguide crossovers [5]. These issues add to the common challenges of switching systems design which include the system architecture, unicast/multicast capability, blocking/nonblocking property, control complexity, number of SEs, number of drivers, system attenuation, and system signal to noise ratio (SNR). These issues are discussed in detail later in the thesis but we highlight them briefly in the following subsections.

### 1.3.1 System Architecture

A large photonic switch needs a good switching architecture to interconnect basic switching elements. To minimise cost and provide good switching performance, the architecture needs to minimise the number of crosspoints, the number of crossovers, the power loss, the crosstalk, and the internal blocking. Several architectures have been proposed for optical switching [3, 8-15]. These architectures have been constructed using various optical switching elements including directional coupler switches. In addition, many of the classical switching architectures found in the electronic and communication domains could be implemented with photonic switching elements in the optical domain [17]. These architectures include Clos, Benes, and crossbar, to name a few.

### 1.3.2 Unicast/Multicast Capability

Two types of switching system architectures can be defined, unicast and multicast. In the unicast (point-to-point) architecture, one input goes to one and only one output channel. In the multicast (point-to-many points) architecture, every output is able to listen to any input, even if other output channels are listening to the same input [12, 17]. Multicast architectures typically have larger attenuations than unicast architectures because the input optical power must be divided among several output channels. In addition to directional couplers, other devices such as splitters and combiners are needed for multicast architectures.

### 1.3.3 Blocking/Nonblocking Property

For a given switching architecture, there might be no route for a required connection even when the destination output port is idle. This is called internal blocking. The internal blocking probability should be reduced to zero to have a nonblocking switching system. There are three conditions of nonblocking. A switching network is *rearrangeably nonblocking* if all permutations are possible but some existing connections may need to be torn down and rearranged to allow the new connection to be added [6]. A switching network is *wide sense nonblocking* if an algorithm exists for setting up the paths in a way that guarantees that any future connection can always be made without requiring rearrangement of existing paths. A switching network is *strictly nonblocking* if any input to any unused output connection can always be made without rearrangement regardless of the connecting algorithm used [6, 17].

### 1.3.4 Control Complexity

As the connecting algorithms become more complex, they require more computational and set-up time. The trend for algorithmic complexity generally moves in the opposite direction where no algorithms are required for strictly nonblocking architectures and significant control and computational complexity are needed for the rearrangeably nonblocking architectures [15].

### 1.3.5 Number of Switching Elements

The total number of SEs (or crosspoints) directly reflects the system design cost. Various architectures require different numbers of SEs for the same switch dimensionality, $N$x$N$, for example. The number of SEs along the signal path (i.e. the number of stages crossed) determines how the signal will be attenuated because of the loss these SEs will insert in the path [5]. Thus, the total number of SEs and the number of stages in a system should be as minimum as possible.

### 1.3.6 Number of Drivers

Most of the architectures require an electronic driver for each directional coupler. Some of the architectures can, however, tie several directional couplers to the same driver circuit. The number of drivers becomes a problem if the cost, power dissipation, or board real estate associated with each driver is large [32].

### 1.3.7 System Attenuation

The number of directional couplers, crossovers, bends, substrates and fibers that a given signal path passes through determines the signal attenuation [7]. Signal attenuation can be compensated for with the addition of optical amplifiers, repeaters or regenerators but this increases the system cost and generates additional noise. It is therefore better to keep the signal attenuation to the minimum.

### 1.3.8 System Signal-to-Noise Ratio

Every directional coupler and crossover that the signal path passes through leaks some optical power (noise) into the desired channel. This undesired noise power or crosstalk should be reduced. In other words, the SNR should be as high as possible for a good bit-error-rate (BER) performance. Here the worst-case SNR is the important parameter [8]. The differential SNR, which is the ratio of the best-case SNR to the worst-case SNR, is usually not relevant.

### 1.3.9 System Crossovers

Much architecture requires the signal paths to cross through one another on the optical substrate between the SEs in order to embed a specific topology. This crossover between waveguides in integrated optics is more costly than its counterpart between two wires in VLSI. Although these passive integrated optical waveguide crossovers appear feasible, they can cause crosstalk, signal attenuation, and increase the manufacturing complexity [9]. Crossovers should therefore be minimized when designing large directional coupler based photonic switching systems.

## 1.4 Problem Formulation

Several switch architectures have been reported for optical switches fabricated on Ti:$LiNbO_3$ directional couplers [7-17]. All proposals considered the crosstalk, attenuation, and nonblocking type as the most critical issues that limit the switch density and try to improve one or more of them at the expense of more hardware. Each issue may single out a different architecture as being better than others. However, the overall optimal architecture depends on the relative weighting a designer would assign to the various issues. Designing directional-coupler-based high-density nonblocking optical switching systems with improved crosstalk, nonblocking, and attenuation properties is still a room for research. The challenge is to develop new switch architectures and to investigate the tradeoffs, which can be made between the performance issues.

## 1.5 Objectives and Scope

The objective of this research is to propose and develop switch architectures for optical switching systems that are nonblocking, have low attenuation, and high SNR (i.e. low crosstalk). Thus the thesis is a theoretical study of optical switching architectures that addresses the nonblocking, SNR, and attenuation issues and investigate how high the density of these switches can reach. The physical implementation of the proposed switch architectures is out of the scope of this work.

## 1.6 Research Methodology

This thesis proposes a class of optical switching systems for unicast communication and one switching system for multicast communication. First, different existing proposals will be reviewed. Second, dilated networks will be studied in more detail and their ability to embed different topologies and to realize connection permutations will be examined. Then algorithms for establishing an arbitrary set of connections will be studied. Based on the finding, new optical switching system models were designed with some necessary modifications to overcome their associated drawbacks. The space dilation technique was applied for unicast systems using new approaches. For multicast systems, however, splitters and combiners were used to ensure the multicasting property. To measure the performance the relevant characteristics are defined and compared with the existing switching systems. The mathematical expressions used are derived based on the methods and assumptions described in the corresponding references [10, 18]. The research methodology is a theoretical approach that will follow these steps:

1. Existing design approaches will be studied carefully:
   The study will cover the network design proposals and their mathematical models as well.
2. The definition of the proposed photonic switching system:
   Here, the definition necessary to describe the topology of the proposed system will be stated.
3. The derivation of the proposed architecture properties:
   This step addresses the characteristics of the system model.
4. Performance analysis will be made for the proposed system:
   The analysis will include nonblocking property, SEs count, SNR, attenuation, and crossover count.
5. Based on the analysis, the proposed systems will be compared with other well-known proposals in the literature.

## 1.7 Contributions Of The Thesis

The work in this research addressed the design issues of photonic switching networks using optical space-division switching networks based on the titanium diffused lithium niobate directional couplers. It focused on the improvement of nonblocking type, the reduction of signal losses, and the increase of SNR.Based on the suggested solutions we provided methods to design high-density nonblocking optical networks.

Three new switch architectures for unicast connection and one for multicast connection have been proposed for photonic switching networks. Their design ideas have been presented and their properties have been derived and formulated. Some characteristics of the proposed networks have been analyzed and compared with other well-known photonic switching network topologies.

For the wide-sense nonblocking network, the *N*W*N*, two new preservable states that guarantee any future connection without bringing the basic elements of the network into a forbidden state have been presented. The construction of the *N*W*N* network from these elements has then been explained.

Two new approaches for applying space dilation concept on lightwave networks have been presented and utilized for designing two basic elements. Based on these elements two new architectures for photonic switching networks have been proposed. They are the strictly nonblocking network, the *N*S*N*, and the single-crosstalk-stage network, the SCS. Both architectures are shown to be nonblocking in the strict-sense. The SCS network has the best SNR among the proposed networks.

For multicast connections the *N*M*N* network is proposed. The *N*M*N* network can realize all possible connection patterns needed for multicasting including the one in which signals can be blocked from reaching the outputs even if they have already been lunched at the inputs of the network.

## 1.8 Thesis Organization

The thesis is organized as follows; chapter two briefly summarizes the important blocks in a communication system and reviews optical networks. It also describes some candidate devices to implement the optical switching system. Chapter three surveys previous work proposed in the literature for nonblocking high density optical space switch architectures and discusses their advantages and disadvantages. In chapter four an alternative architecture for wide sense nonblocking photonic switching is proposed. In chapter five and chapter six two strictly nonblocking photonic switches are introduced with the latter specifically designed to maintain a constant SNR of the switch regardless of its size. In chapter seven a multicast photonic switch is proposed. The design idea for each proposed switch is presented and explained. The properties of these designs are derived and the tradeoffs involved are addressed. Comparisons between the proposed networks and those surveyed in chapter three are made and discussed in chapter eight. This chapter also includes design optimization. Chapter nine concludes the thesis and recommends some possible rooms for future research based on the ideas presented and the studies carried on this thesis.

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