UNIVERSITI PUTRA MALAYSIA

THE EFFECT OF CONVERTERS NUMBERS ON THE BLOCKING PROBABILITY PARAMETER OF THE WSW2 SWITCHING FABRIC

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By

AWS ABDULKAREEM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Computer Since

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DEDICATIONS

"To my beloved great father and mother, thank you for all your support in term of spiritual and encouragement"

&

"To my wife, siblings, colleagues and lecturers, thank you for all your support and help"

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Computer Science

THE EFFECT OF CONVERTERS NUMBERS ON THE BLOCKING PROBABILITY PARAMETER OF THE WSW2 SWITCHING FABRIC

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June 2019

Chairman: Mohamed A. Alrshah, PhD

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In the current study, the Wavelength-Space-Wavelength (W-S-W) switching fabrics are considered for performance evaluation purpose. WSW2 architecture, which is derived from Clos switching fabrics, is made up of three phases. In the first and third stages, the converting switches of the bandwidth-variable waveband are contained, while the central phase is made up of bandwidth-variable waveband selective space switches. This design is capable of shifting the optical wavelength of connections within the first and last stages, while the second stage merely forwards the connections in the space domain. The switching fabric is capable of switching the switch m-slot connections occupying the m adjacent slots, $1 \leq m \leq mmax$. Recently, few papers, which have been published in this area, investigated the strict-sense (SSNB) and wide-sense (WSNB) non-blocking conditions of these kind of switching fabrics. A large number of center stage switches and spectrum converters are required by SSNB and WSNB switching fabrics. In this research, an evaluation of the blocking switching fabrics has been done with the aim of

identifying the optimal number of spectrum converters and/or center stage switches. The performance evaluation has been carried out using simulation that is implemented in C++ programming language. Simulation results have provided insights on the relationship between the number of converters and blocking probability of the mentioned switching.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Sarjana Sains Komputer

KESAN BILANGAN PENUKAR KEPADA PARAMETER KEBARANGKALIAN PENYELESAIAN WSW2' SWITCHING FABRIC'

Oleh

AWS ABDULKAREEM

June 2019

Pengerusi: Mohamed A. Alrshah , PhD

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Dalam kajian semasa, Wavelength-Space-Wavelength (W-S-W) switching fabrics dipertimbangkan untuk tujuan penilaian prestasi. Seni bina WSW2, yang berasal dari C switching fabrics Clos, terdiri daripada tiga fasa. Dalam peringkat pertama dan ketiga, jahitan penukaran bandwidth-variable waveband -pemboleh ubah jalur lebar terkandung, manakala fasa pusat terdiri daripada suis ruang pilih-ganti waveband yang berubah-ubah. Reka bentuk ini mampu mengalihkan panjang gelombang optik sambungan dalam peringkat pertama dan terakhir, sementara tahap kedua hanya meneruskan sambungan dalam domain ruang. Fabrik pensuisan berupaya menukar sambungan m-slot suis yang menduduki slot bersebelahan m, $1 \leq m \leq mmax$. Baru-baru ini, beberapa kertas yang telah diterbitkan dalam bidang ini menyiasat syarat-syarat yang tidak menyekat (SSNB) 'strict – sense dan rasa luas (WSNB) wide - sense jenis fabrik beralih ini. Sejumlah besar suis di tahap kedua dan penukar spektrum dikehendaki oleh SSNB dan WSNB beralih fabrik. Dalam penyelidikan ini, penilaian terhadap bahan

suis menyekat akan dilakukan dengan tujuan untuk mengenal pasti bilangan penukar spektrum optimum dan / atau suis pada tahap kedua. Penilaian prestasi akan dijalankan menggunakan simulasi yang dilaksanakan dalam bahasa program C ++. Diharapkan bahawa hasil simulasi akan memberikan gambaran tentang hubungan antara bilangan penukar dan kebarangkalian untuk gagal dari pengunaan switching fabric tersebut.

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I certify that a Thesis Examination Committee has met on 24 June 2019 to conduct the final examination of AWS ABDULKAREEM on his thesis entitled “THE EFFECT OF CONVERTERS NUMBERS ON THE BLOCKING PROBABILITY PARAMETER OF THE WSW2 SWITCHING FABRIC ” in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Computer Science.

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LIST OF ABBREVIATIONS

3G	Third Generation
4G	Fourth Generation
ABC-PTS	Artificial Bee Colony
ACE	Active Constellation Extension
ACI	Adjacent Channel Interference
ADRG	Addition of Random Gaussian Signals
ADSL	Asymmetric Digital Subscriber Line
A/D	Analog to Digital Conversion
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
bps	bit per second
CCDF	Complementary Cumulative Distribution Function
CDMA	Code Division Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
CP	Cyclic Prefix
CR	Clipping Ratio
CF	Crest Factor
D/A	Digital to Analog Conversion
DAB	Digital Audio Broadcasting
dB	decibels
dc	direct current (0 Hz)
DFT	Discrete Fourier Transform
DMT	Discrete Multi-Tone
DSI	Dummy Sequence Insertion
DSR	Dummy Subcarriers Ratio
DVB	Digital Video Broadcasting
Eb/No	Bit Energy-to-Noise Density Ratio
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
HMA	Hybrid Multiplicative-Additive CF Reduction Technique
IBO	Input Back-Off
ICI	Inter-Carrier Interference
IDRG	Insertion of Dummy Random Gaussian Subcarriers
i.i.d.	independent identically distributed
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter-Symbol Interference
ITU-R	International Telecommunication Union-Radio
JTAG	Joint Test Action Group
Mbps	Mega bits per second

MCM	Multi-Carrier Modulation
MDM	Multi-Dimensional Modulation
OBO	Output Back-Off
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Amplifier
Parallel TS-PTS	Parallel Tabu Search
P/S	Parallel-to-Serial Conversion
PMEPR	Peak to Mean Envelope Power Ratio
PAPR	Peak to Average Power Ratio
PC-PTS	PTS-Combining PS and PE
PE-PTS	PTS-Excluding Phase rotating vectors
PRT	Peak Reduction Tones
PSD	Power Spectral Density
PS-PTS	PTS-dominant time-domain Samples selected by Pn
PSK	Phase Shift Keying
P/S	Parallel to Serial
PTS	Partial Transmit Sequences
QAM	Quadrature Amplitude Modulation
QCQP	Quadratically Constrained Quadratic Program
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RC-PTS	Reduced-Complexity-PTS
RMS	Root Mean Square
RRCF	Root Raised Cosine Filter
RS	Reed-Solomon
SBC	Sub Block Coding
SBI-PTS	Subblocks Interleaving-PTS
SC	Single Carrier
SER	Symbol Error Rate
SES	Suboptimal Exhaustive Search
SL	Soft Limiter
SLM	Selected Mapping
SLS	Successive Local Search
SNR	Signal to Noise Ratio
SoC	System on a Chip
S/P	Serial to Parallel
SSPA	Solid State Power Amplifier
SSI	Scrambling with Single IFFT CF Reduction
TI	Tone Injection
TR	Tone Reservation
VHDL	Visual Hardware Design Language
WCDMA	Wide Band Code Division Multiplexing
WLAN	Wireless Local Area Network
ZedBoard	Zynq Evaluation and Development Board

CHAPTER 1

INTRODUCTION

1.1 Overview

The high influx of data traffic increases the needs of high transmission rates. Optical paths of 100 Gb/s can be provided with optical networks between end users. This might change the rate of Gbps to Tbps given the current and future applications and services. This means that the network operators have to make it cost effective and produce a scalable option to transport various traffic streams; one such solution will be the use of elastic optical networks (EONs) (Jinno et al., 2009).

An elastic optical network is a paradigm shift where a flexibility of optical paths on bandwidth has been made possible. Hence the name elastic optical networks, the bandwidth is assigned to the optical channel based on the required transmission speed, distance, quality of the path and the modulation scheme (Gerstel et al., 2012).

Furthermore, even lower traffic can be assigned to the full wavelength capacity of the wavelength routed optical networks. In order to use bandwidth in optical links efficiently, traffic grooming was proposed. Another method is the division of bandwidth in to smaller parts where it is made possible to aggregate the small parts into the large parts in order to make optical paths flexible (Dutta et al., 2008). The International Telecommunication Union (ITU) proposed a 50 GHz grid, which divides the relevant optical spectrum range of 1530–1565 nm (the so-called C-band) into fixed 50 GHz spectrum slots, but it is likely that bit rates greater than 100 Gb/s will not fit into this scheme (ITU-T, 2012).

In the past few years the use of 100-Gb/s has been made commercial. Due to the compatibility with 50 GHz ITU grid which has been used, eliminating the need to replace the grids. Telecom and Datacom industries see a spike in the use of data rate above 100 GB/s and 400 Gb/s. Unfortunately, the spectral width occupied by 400 Gb/s at standard modulation formats is too broad to fit in the 50 GHz ITU grid, Using a high spectral efficiency modulation format would result in short transmission distances. Hence, the use of flexible frequency grid proposed by ITU (Gerstel et al., 2012), allows the flexibility of spectrum assignment in the dense wavelength Multiplexing (DWDM) networks. Figure 1.1 shows both ITU grids, fixed and flexible. Bit rates of 400 Gb/s and 1 Tb/s with standard modulation formats are not supported by fixed grids as it overlaps the 50 GHz grid boundary. Hence, it is optimal to properly size the spectrum for each demand based on the bit rate and the distance of the transmission, instead of forcing all demands to use more spectrum.

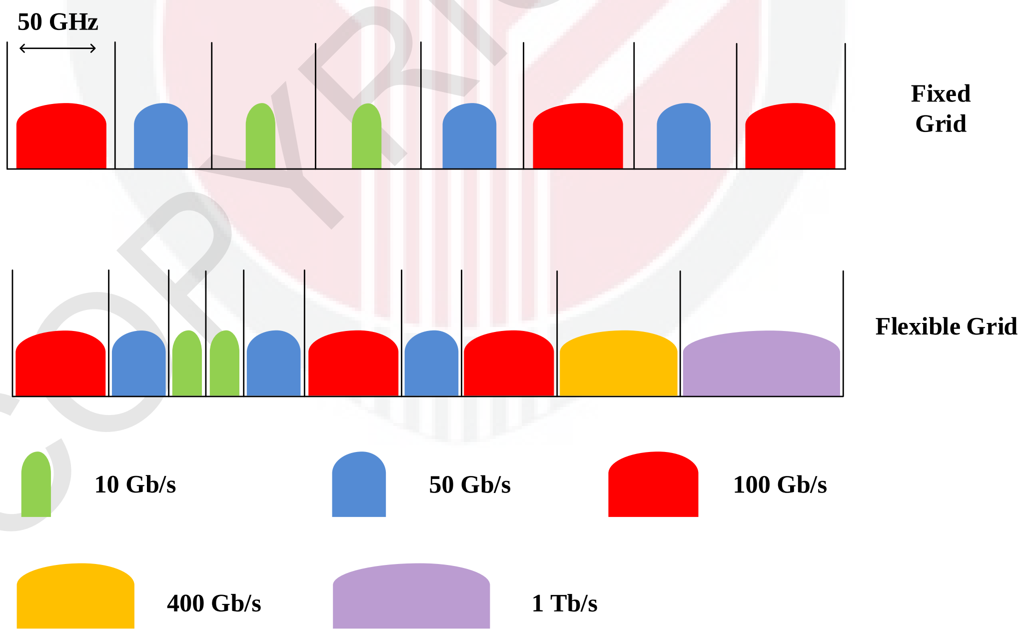

Figure 1.1: ITU fixed and flexible grids.

Elastic optical switches are used to support EONs and optical switches are used to switch connection between fibers. The issue of optical switching and switching fabrics was considered in many books and papers (El-Bawab, 2006; Kabaciński, 2005; Papadimitriou et al., 2007). Proposed switches for EON differ in design, capacity and blocking characteristics. Some researchers considered switches that depend only on Bandwidth-Variable Waveband Space Switch (BV-WSS), which is a device that separate wavelengths multiplexed in a single fiber and forward them into different directions (Finisar, 2015; Hideaki et al., 2016; Yamaguchi et al., 2016). The BV-WSSs elements are further explained in Chapter 3. Since the results of BV-WSS were not satisfactory in terms of the blocking probability, researchers had to come out with another solution. The widely accepted solution is to adapt the principle of staging, where a switching fabric is implemented by means of switching elements organized in stages. When we talk about multi-stage switching fabrics, we have to consider Charles Clos and his well-known paper (Clos, 1953).

Clos published a paper in 1953 that defined the basics of what is known today as Clos switching fabrics (Clos, 1953). In 1953, switching systems were purely electro-mechanical that depended on the principle of space-division, which can be simply defined as separation of switching paths merely in space. The separation of switching paths is further explained in Chapter 2. Clos defined in his paper the number of second stage switches required so that any connecting request from any free input to any free output could be established successfully. V. E. Beneš extended the theory of Clos by introducing the notion "nonblocking in the wide-sense" (WSNB) and refereed to the conditions proposed by Clos as "nonblocking in the strict-sense" (SSNB) (Beneš, 1965; Jajszczyk, 2003). SSNB and WSNB concepts are further extended in Chapter 2. The well-known results of space-division Clos switching fabrics are not valid when we consider a system that operate in slots, such as Time-Division Multiplexing (TDM) or Wavelength-Division Multiplexing (WDM), where each slot in the interstage links is considered as a connecting path. When we compare slot-operating systems with the original principle of Clos, each of the links connecting two consecutive stages in Clos original design corresponds to a single slot in TDM or WDM systems. The definition of the term "free link" in WDM is also different than Clos. In WDM systems, a free input link to an m-slot connection can be defined as a link that has free adjacent slots, and their sum is $\geqslant m$.

The switching fabrics which are nonblocking in the strict-sense require usually a big number of middle stage switches. This might be the reason why Beneš proposed the notion of wide-sense nonblocking in the first place. In WSNB, the switching fabric depends on a certain control algorithm to achieve the nonblocking. What is important in WSNB, the number of middle stage switches is reduced or in some cases is equal to SSNB, where number of middle stage switches (p) is the $\min\{p_{\text{ssnb}}; p_{\text{wsnb}}\}$.

1.2 Motivation

Detailed studies have recently been published on the switching conditions of the strict-sense non-blocking and wide-sense non-blocking of the WSW2 switching fabrics. It is important to note that these need high number of spectrum converters and center stage switches. Therefore, this research will evaluate blocking switch fabrics which utilize less spectrum converters and center stage switches.

1.3 Problem Statement

The number of converters directly affects the blocking probability value. It negatively affects the total performance if this number is reduced, and it increase the cost if it is increased. The question of this research is:

- How to find the optimal number of converters that reduces the blocking probability in W-S-W2 switching fabric while maintaining the cost.

1.4 Research Objectives

The main objective of this research is:

- To find the optimal number of converters that reduces the blocking probability in W-S-W2 switching fabric while maintaining the cost.

1.5 Research Scope

The scope of this research is as follows:

- The reduction in number of converters/switches was done as an effort to reduce the total implementation cost of WSW2 switching fabric, therefor the scope for this work will be specific in Elastic optical networks switching fabrics.

- All experiments are conducted using a simulation developed in C++ programming language.

- This work is only to revisit a previous work, which has been published in (Kabaciński et al., 2018a).

1.6 Research Significance

The significance of this research is in the reduced cost of the WSW2 switching fabrics, where the results of this research might reduce the implementation cost of such switching fabrics by almost 80%.

1.7 Thesis Organization

This research is structured as follows: Chapter 2 presents the background and introduction to switching fabrics and the principle of elastic optical networks. Chapter 3 presents the the research method that is used in this research. It also describes the functions used to implement the simulator and introduces general characteristics of the considered simulator. Chapter 4 introduces the experiments which were done using the simulator along with results and comparisons. Chapter 5 concludes the work and highlights the future works and directions.

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