Dynamic Routing and Spectrum Allocation in Elastic Optical Networks

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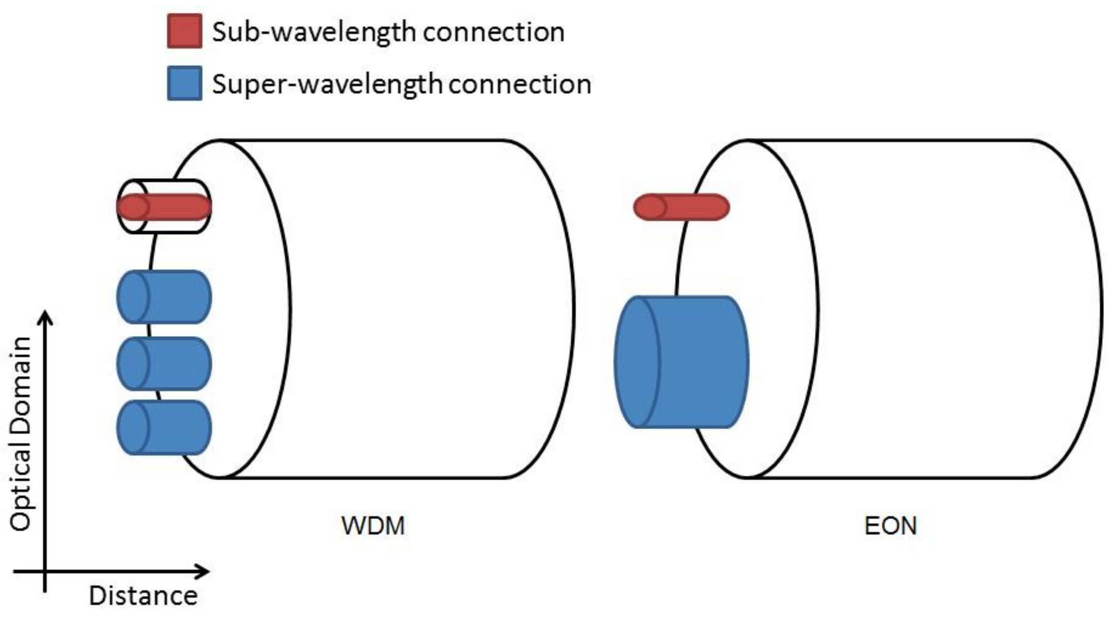

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Contents

List of Figures

Abbreviations and Symbols

Abbreviations

ACN	Avoid Close Neighbors
ADM	Add/Drop Multiplexer
ADSL	Asymmetric Digital Subscriber Line
AR	Adaptive Routing
BLR	Burst Loss Rate
BP	Blocking Probability
BPSK	Binary Phase Shift Keying
BV	Bandwidth-Variable
BV-OXC	Bandwidth Variable Optical Cross-Connect
BV-WSS	Bandwidth Variable Wavelength Selective Switche
B&S	Broadcast-and-Select
CSA	Constant Spectrum Allocation
CW	Continuous Wave
DAD	Dynamic Alternate Direction
DARPA	Defense Advanced Research Projects Agency
DFB	Distributed Feedback
DP-BPSK	Dual Polarization Quadrature Phase Shift Keying
DSF	Dispersion Shifted Fiber
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
E/O	Electro/Optical

EON	Elastic Optical Network
EuON	European Optical Network
FAR	Fixed Alternate Routing
FB	Feedback-based
FDLs	Fiber Delay Line
FF	First Fit
FPA	First-Possible Aggregating
FR	Fixed Routing
FS	Frequency Slot
HT	Holding Time
IAT	Inter-Arrival Time
IDA	Iterative-Defragmentation Algorithm
IETF	Internet Engineering Task Force
ILP	Integer Linear Programming
JIT	Just In Time
LAN	Local Area Network
LCoS	Liquid Crystals on Silicon
LCP	Least Congested Path
LiNbO3	Lithium Niobate
LL	Least Loaded
LSS	Lowest Starting Slot
LU	Least Used
MEMS	Microelectromechanical Systems
MG-OXC	Multi Granular Optical Cross Connect
MP	Min Product
MSP	Modified Dijkstra's Shortest Path
MU	Most Used
M$\sum$	MAX SUM
NSFnet	National Science Foundation Network
OBS	Optical Burst Switching
OCS	Optical Circuit Switching

O/E/O	Optical/Electrical/Optical
O/E	Opto/Electrical
OFDM	Orthogonal Frequency Division Multiplexing
OPS	Optical Packet Switching
OXC	Optical Cross Connect
R	Random wavelength assignment
RAM	Random Access Memory
RCL	Relative Capacity Loss
RF	Random Fit
RMLSA	Routing, Modulation Level and Spectrum Allocation
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RSA	Routing and Spectrum Allocation
Rsv	Wavelength Reservation
RWA	Routing and Wavelength Allocation
SA	Spectrum Allocation
SCPVS	Spectrum-Constraint Path Vector Searching
SF	Smallest Fit
SLE	Static Lightpath Establishment
SMF	Single Mode Fiber
TDM	Time Division Multiplexing
Thr	Protecting Threshold
TWC	Tunable Wavelength Converter
VoIP	Voice over the Internet Protocol
WDM	Wavelength Division Multiplexing
WSS	Wavelength-Selective Switche
WXC	Wavelength Cross-Connect

Symbols

c	Maximum utilized frequency slot
C	Capacity of a FS in Gb/s

d	Destination
D	L-by-W matrix
D_{lj}	Number of assigned fibers on link l and wavelength j
E	Set of (point-to-point) single-fiber links
f_{cs}	Channel spacing
f_i	Starting frequency slot
f_{sd}	Integer that denotes the starting frequency for connection (s,d)
$f(\alpha, N)$	Number of shared TWCs at each element inside the switch
F	Spectral granularity of the OFDM transmitters and WXCs
F_{ij}^{sdw}	All connection requests from s to d on link ij and wavelength w
G	Guard band separates adjacent spectrum paths
$G(i, j)$	Splitting section gain
L	Number of links
M	Number of fibers per link
M_l	Number of fibers on link l
N	Number of nodes
P	Set of all potential paths for the connection request in ψ
P_{sd}	Set of candidate paths for (s,d)
$r(\psi, l, j)$	Number of fibers on which wavelength j is unused on link l
$r(\psi, p, j)$	Path capacity on wavelength j
$R(\psi, p)$	Path capacity
s	Source
S_p	Set of available wavelengths along the selected paths p
T_i	Required bandwidth of connection i
T_{sd}	Number of FSs required for the communication between s and d
V	Set of nodes
W	Number of wavelengths per fiber
x_p	Boolean variable that denotes the utilization of path $p \in P$
α	Sharing factor
$\delta_{sd,s'd'}$	Boolean variable that indicates the place of a connection
λ_{sdw}	All connection requests from s to d on any wavelength w

Λ	Traffic matrix
Λ_{sd}	All connections needed between source s and destination d
$\pi(p)$	Set of links comprising path p
ψ	Current network state
$\psi'(j)$	Next state of the network if wavelength j is assigned
$\Omega(\psi, p)$	Set of all possible wavelengths on path p

Resum

Degut a l'augment de serveis emergent com la distribució de vídeo d'alta definició o les xarxes socials, el volum de tràfic IP ha crescut de manera exponencial durant els darrers temps. S'espera que aquest creixement no s'aturi sinó que continuï de manera imparable degut als constants avenços tecnològics. Alguns exemples d'això poden ser els processadors multi-nucli, la virtualització o el "cloud computing" que donaran suport a una nova generació de e-Science i d'aplicacions Grid per les quals caldran fluxes de dades des de 10 Gb/s fins al Terabit per segon. La conseqüència esperable és que els operadors de xarxes de telecomunicacions requeriran una nova generació de transport òptic en el futur proper, per donar servei a aquests grans i heterogenis volums de tràfic d'una manera econòmicament eficient i escalable.

Com a resposta a les creixents necessitats de capacitat i de diferents granularitats de tràfic de la Internet del Futur s'ha proposat l'arquitectura coneguda com "Elastic Optical Network" (EON). Trencant el rígid entramat de les xarxes WDM tradicionals, on s'ha de reservar tot un canal òptic per a cada comunicació, mitjançant les EON s'aconsegueix incrementar la flexibilitat en l'aprovisionament de connexions. per fer-ho, depenent del volum de tràfic s'assigna la quantitat adient de l'espectre òptic a cada connexió. I, anant encara un pas més enllà, per desfer la rigidesa dels canals convencionals de les xarxes amb multiplexació per divisió en longitud d'ona (WDM), les connexions òptiques en les EON poden expandir-se o contraure's de manera elàstica segons els requeriments d'ample de banda en cada moment. D'aquesta manera, les peticions de connexió que arriben poden ésser servides de manera eficient pel que fa a l'espectre que utilitzen. Aquest avenç tecnològic implica però alguns reptes a nivell de xarxa, especialment pel que fa a l'establiment eficient de les connexions. De manera similar a com succeeix en les xarxes WDM, una connexió ha d'ocupar la mateixa part de l'espectre en tots els links que la conformen, acomplint el principi de "continuïtat en l'espectre". A més a més, tot l'ample de banda de la connexió ha d'estar assignat de manera adjacent, acomplint el principi de "contigüitat en l'espectre". Per aconseguir aquests objectius, el problema de l'encaminament i assignació de l'espectre (RSA) ha merescut una gran atenció dels investigadors en els darrers anys, amb especial èmfasi a escenaris dinàmics, és a dir, en la fase d'operació de la xarxa. En aquest cas, els processos d'arribada i mort de les connexions són aleatoris i la xarxa ha d'acomodar en temps real el tràfic ofert. Tot i els grans esforços dedicats a aquest tema, queden encara alguns punts a resoldre. Aquesta Tesi està dedicada a alguns d'aquests

temes oberts en l'àmbit de les xarxes EON: 1) l'agregació dinàmica de connexions de granularitat inferior a la longitud d'ona, 2) la correlació entre la granularitat del tràfic i les polítiques de desfragmentació de l'espectre, i, 3) utilitzar la fragmentació espectral per a una millor assignació de connexions d'ample de banda canviant en el temps. El primer tòpic analitza la possibilitat d'agregar connexions originades a la mateixa font però amb diferents destinacions dins d'una EON, amb l'objectiu d'estalviar recursos tant pel que fa a nombre d'equips transmissor utilitzats com a l'espectre utilitzat. S'ha proposat un nou algorisme que millora ambdós paràmetres, així com una arquitectura pels nodes de la xarxa que permet utilitzar l'algorisme d'agregació proposat de manera eficient des del punt de vista del cost. S'aconsegueix una considerable millora pel que fa a la utilització de l'espectre a més d'una significativa reducció en el nombre de transmissors per node que es requereixen. El problema de la fragmentació espectral en les EONs s'ataca en la segona aportació d'aquesta Tesi. S'ha aconseguit demostrar la correlació entre l'òptima (és a dir mínima) periodicitat de les accions de desfragmentació i la granularitat del tràfic suportat. S'ha proposat un nou algorisme per a una desfragmentació eficient, l'objectiu del qual és consolidar l'espectre disponible en les fibres tan com sigui possible, al mateix temps que es redueix el nombre de connexions que has de ser reubicades en la xarxa. Es demostra que, en una EON, es pot configurar de manera òptima la periodicitat de les desfragmentacions si es coneix la granularitat de les connexions a transportar. Finalment, en el tercer gran apartat de la Tesi, s'estudia la possibilitat d'utilitzar la fragmentació espectral en les EON per a una millor assignació dels recursos quan el tràfic és variant en el temps. En aquest context, s'ha proposat i validat un algorisme d'assignació de l'espectre (SA) que incrementa de manera intencionada la fragmentació espectral de la xarxa. En aquesta proposta, l'espectre assignat a cada nova connexió s'ubica al bell mig del buit espectral més gran que es troba en tota la ruta, amb l'objectiu de deixar tan espai com sigui possible entre les diferents connexions. Aquest espai és després utilitzat per a connexions que requereixen, al llarg de la seva existència, més espectre del que se'ls ha assignat inicialment (incrementen el seu ample de banda). Els resultats obtinguts mitjançant simulacions mostren significants millores en termes de Probabilitat de Bloqueig (BP) en la xarxa quan s'utilitza l'algorisme proposat.

Després d'una introducció a la Tesi, el Capítol 2 ofereix una revisió de l'evolució de les xarxes òptiques de transport, tot introduint el concepte de xarxa òptica elàstica (EON). El Capítol 3 se centra en l'estudi dels mètodes d'encaminament i assignació de longitud d'ona en xarxes WDM convencionals, i la seva evolució cap al problema de l'assignació d'espectre (RSA) en EONs. El Capítol 4 detalla els estudis i les contribucions fetes en el tema d'agregació de connexions de granularitat inferior a la longitud d'ona en EONs. L'algorisme proposat, així com l'arquitectura de node que permet aplicar-lo es presenten en aquest Capítol. El problema de la fragmentació espectral en EONs i llurs solucions es revisen a fons en el Capítol 5. La correlació entre la periodicitat de les desfragmentacions espectrals i la granularitat del tràfic ofert s'estudien aquí. El Capítol 6 detalla el problema de servir connexions variants en el temps en EONs. Algunes polítiques proposades fins ara es revisen, i tot seguit se'n proposa una que, en certs aspectes, millora les prèvies.

Finalment, cal destacar que aquest treball ha rebut el suport del Govern de la Generalitat de Catalunya, a través d'una beca FI-AGAUR, i que s'ha realitzat en el marc del projecte del Ministerio de Educación Ciencia i Deporte espanyol ELASTIC (TEC2011-27310).

Resumen

Debido al aumento de servicios emergentes como la distribución de vídeo de alta definición o las redes sociales, el volumen de tráfico IP ha crecido de manera exponencial durante los últimos tiempos. Se espera que este crecimiento no se pare sino que continúe de manera imparable debido a los constantes adelantos tecnológicos. Algunos ejemplos de esto pueden ser los procesadores multi-núcleo, la virtualización o el "cloud computing" que darán servicio a una nueva generación de aplicaciones de e-Science y de Grid para las cuales serán necesarios flujos de datos desde 10 Gb/s hasta Terabits por segundo. La consecuencia esperable es que los operadores de redes de telecomunicaciones requerirán una nueva generación de transporte óptico en el futuro cercano, para dar servicio a estos grandes y heterogéneos volúmenes de tráfico de una manera económicamente eficiente y escalable.

Como respuesta a las crecientes necesidades de capacidad y de diferentes granularidades de tráfico de la Internet del Futuro, se ha propuesto la arquitectura conocida como "Elastic Optical Network" (EON). Rompiendo el rígido entramado de las redes con multiplexación por división en longitud de onda (WDM) tradicionales, donde se tiene que reservar todo un canal óptico para cada comunicación, mediante las EON se consigue incrementar la flexibilidad en el aprovisionamiento de conexiones. Para hacerlo, dependiendo del volumen de tráfico se asigna la cantidad adecuada del espectro óptico a cada conexión. Y, yendo todavía un paso más allá, para deshacer la rigidez de los canales convencionales de las redes WDM, las conexiones ópticas en las EON pueden expandirse o contraerse de manera elástica según los requerimientos de ancho de banda en cada momento. De este modo, las peticiones de conexión que llegan pueden ser servidas de manera eficiente en cuanto al espectro que utilizan. Este adelanto tecnológico implica sin embargo algunos retos a nivel de red, especialmente en lo que se refiere al establecimiento eficiente de las conexiones. De manera similar a como sucede en las redes WDM, una conexión debe ocupar la misma parte del espectro en todos los links que la conforman, cumpliendo el principio de "continuidad espectral". Además, todo el ancho de banda de la conexión tiene que estar asignado de manera adyacente, cumpliendo el principio de "contigüidad espectral". Para conseguir estos objetivos, el problema del encaminamiento y asignación del espectro (RSA) ha merecido una gran atención de los investigadores en los últimos años, con especial énfasis en escenarios dinámicos, es decir, en la fase de operación de la red. En este caso, los procesos de llegada y finalización de las conexiones son aleatorios

y la red tiene que acomodar en tiempo real el tráfico ofrecido. A pesar de los grandes esfuerzos dedicados a este tema, quedan todavía algunos puntos a resolver. Esta Tesis está dedicada a algunos de estos temas abiertos en el ámbito de las redes EON: 1) la agregación dinámica de conexiones de granularidad inferior a la longitud de onda, 2) la correlación entre la granularidad del tráfico y las políticas de desfragmentación del espectro, y, 3) utilizar la fragmentación espectral para una mejor asignación de conexiones de ancho de banda variante en el tiempo. El primer tópico analiza la posibilidad de agregar conexiones originadas en la misma fuente pero con diferentes destinos dentro de una EON, con el objetivo de ahorrar recursos tanto en cuanto a número de equipos transmisores utilizados como en el espectro utilizado. Se ha propuesto un nuevo algoritmo que mejora ambos parámetros, así como una arquitectura para los nodos de la red que permite utilizar el algoritmo de agregación propuesto de manera eficiente desde el punto de vista del coste. Se consigue una considerable mejora en cuanto a la utilización del espectro además de una significativa reducción en el número de trasmisores por nodo que se requieren. El problema de la fragmentación espectral en las EONs se ataca en la segunda aportación de esta Tesis. Se ha conseguido demostrar la correlación entre la óptima (es decir, mínima) periodicidad de las acciones de desfragmentación y la granularidad del tráfico soportado. Se ha propuesto un nuevo algoritmo para una desfragmentación eficiente, el objetivo del cual es consolidar el espectro disponible en las fibras tanto como sea posible, al mismo tiempo que se reduce el número de conexiones que deben ser reubicadas en la red. Se demuestra que, en una EON, se puede configurar de manera óptima la periodicidad de las desfragmentaciones si se conoce la granularidad de las conexiones a transportar. Finalmente, en el tercer gran apartado de la Tesis, se estudia la posibilidad de utilizar la fragmentación espectral en las EON para una mejor asignación de los recursos cuando el tráfico es variante en el tiempo. En este contexto, se ha propuesto y validado un algoritmo de asignación del espectro (SA) que incrementa de manera intencionada la fragmentación espectral de la red. En esta propuesta, el espectro asignado a cada nueva conexión se ubica en medio del vacío espectral más grande que se encuentra en toda la ruta, con el objetivo de dejar tanto espacio como sea posible entre las diferentes conexiones. Este espacio es después utilizado para conexiones que requieren, a lo largo de su existencia, más espectro del que se les ha asignado inicialmente (incrementan su ancho de banda). Los resultados obtenidos mediante simulaciones muestran significantes mejoras en términos de Probabilidad de Bloqueo (BP) de la red cuando se utiliza el algoritmo propuesto.

Después de una introducción a la Tesis, el Capítulo 2 ofrece una revisión de la evolución de las redes ópticas de transporte, introduciendo el concepto de red óptica elástica (EON). El Capítulo 3 se centra en el estudio de los métodos de encaminamiento y asignación de longitud de onda en redes WDM convencionales, y su evolución hacia el problema de la asignación de espectro (RSA) en EONs. El Capítulo 4 detalla los estudios y las contribuciones hechas en el tema de agregación de conexiones de granularidad inferior a la longitud de onda en EONs. El algoritmo propuesto, así como la arquitectura de nodo que permite aplicarlo, se presentan en este Capítulo. El problema de la fragmentación espectral en las EONs y sus soluciones se revisan a fondo en el Capítulo 5. La correlación

entre la periodicidad de las desfragmentaciones espectrales y la granularidad del tráfico ofrecido se estudian aquí. El Capítulo 6 detalla el problema de servir conexiones variantes en el tiempo en EONs. Algunas políticas propuestas hasta ahora se han revisado, y a continuación se propone una que, en algunos aspectos, mejora las previamente publicadas.

Finalmente, hay que destacar que este trabajo ha recibido el apoyo del Gobierno de la Generalitat de Catalunya, a través de una beca FI-AGAUR, y que se ha realizado en el marco del proyecto ELASTIC (*TEC2011-27310), del Ministerio de Educación Ciencia y Deporte Español.

Summary

Triggered by emerging services such as high-definition video distribution or social networking, the IP traffic volume has been exponentially increasing to date. Furthermore, the traffic growth rate will not stop here due to the day by day technology advances. For example, new hardware advances such as multicore processing, virtualization and network storage will support new generation e-Science and grid applications, requesting data flows of 10 Gb/s up to terabit level. The predictable consequence is that network operators will require a new generation of optical transport networks in the near future, so as to serve this huge and heterogeneous volume of traffic in a cost-effective and scalable manner. In response to these large capacity and diverse traffic granularity needs of the future Internet, the Elastic Optical Network (EON) architecture has been proposed. By breaking the fixed-grid spectrum allocation limit of conventional Wavelength Division Multiplexing (WDM) networks, EONs increase the flexibility in the connection provisioning. To do so, depending on the traffic volume, an appropriate-sized optical spectrum is allocated to a connection in EONs. Furthermore, unlike the rigid optical channels of conventional WDM networks, a lightpath can expand or contract elastically to meet different bandwidth demands in EONs. In this way, incoming connection requests can be served in a spectrum-efficient manner.

This technological advance poses additional challenges on the networking level, specifically on the efficient connection establishment. Similar to WDM networks, an elastic optical connection must occupy the same spectrum portion between its end-nodes, that is, ensuring the so called spectrum continuity constraint. In addition, the entire bandwidth of the connections must be contiguously allocated, also referred as the spectrum contiguity constraint. The Routing and Spectrum Allocation (RSA) problem in elastic optical networks has grabbed a lot of attention lately, putting more emphasis on dynamic network scenarios. There, connection arrival and departure processes are random and the network has to accommodate incoming traffic in real time. Despite all efforts at studying the dynamic RSA problem from different perspectives, there are still some issues which need to be addressed.

This thesis is devoted to the study of three still open issues in the EONs literature, 1) dynamic source aggregation of sub-wavelength connections, 2) correlation between traffic granularity and defragmentation periodicity and 3) using spectrum fragmentation to better allocate time-varying connections. The first issue deals with the possibility of aggregation of same source but different destination sub-wavelength connections in EONs, aiming to obtain both transmitter and spectrum usage savings. A novel algorithm for dynamic source aggregation of connections is proposed. Moreover, a novel node architecture enabling the realization of the proposed source aggregation scheme in a cost-effective way is introduced. A considerable improvement in the network spectrum utilization, as well as a significant reduction in the number of necessary transmitters per node is shown. The spectral fragmentation problem in elastic optical networks is addressed with the second issue. A correlation between the optimal (i.e., minimum) spectrum defragmentation periodicity in the network with the granularity of the supported traffic is investigated. A novel algorithm for efficient spectrum defragmentation is proposed, aiming to consolidate the available fiber spectrum as much as possible, while limiting the number of re-allocated active connections. It is shown that the spectral defragmentation periodicity can be effectively configured by having knowledge of the offered traffic granularity. The last issue is about lightpath adaptation under time variable traffic demands in EONs. Specifically, the possibility of utilizing the spectral fragmentation to increase the spectrum allocation capabilities of EONs is explored. In this context, a heuristic Spectrum Allocation (SA) algorithm, which intentionally increases the spectral fragmentation in the network is proposed and validated. In the proposal, the spectrum assigned to each new connection is in the middle of the largest free spectral void over the route, aiming to provide considerable spectral space between adjacent connections. These free spectral spaces are then used to allocate time-varying connections without requiring any lightpath re-allocation. The obtained simulation results show a significant improvement in terms of network Blocking Probability (BP) when utilizing the proposed algorithm.

After an introduction to the thesis, chapter 2 initially reviews the optical transport network evolution. Then, the elastic optical networks are introduced. Chapter 3 focuses on the Routing and Wavelength Allocation (RWA) problem in conventional WDM networks and its solutions, followed by the RSA problem in EONs. Chapter 4 details the issue of source aggregation of sub-wavelength connections. The proposed algorithm as well as the enabling node architecture is presented in this chapter. The spectral fragmentation problem and its current solutions are deeply discussed in chapter 5. The correlation between spectral defragmentation periodicity and the traffic granularity is presented in this chapter. Chapter 6 details the problem of serving time-varying connections. Some available policies are initially reviewed, and then the proposed heuristic SA algorithm is presented.

It shall be mentioned that the work reported in this thesis has been supported by the Government of Catalonia and the European Social Fund through a FI-AGAUR research scholarship grant and by the Spanish National project ELASTIC (TEC2011-27310).

Dedicated to my brilliant, loving and supportive fiancee, Atieh,
my thoughtful, angelic and beautiful mother, Fariba,
my always encouraging, faithful father, Hassan,
my caring, and kind-hearted sister, Niloofar,
and the memory of my grandma, Mahin.

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Chapter 1

Introduction

By emerging new services such as high-definition video distribution and real-time video communication, the IP traffic volume has been multiplied to date, however, the traffic growth rate will not stop here due to the day by day technology advances, and its fast increase will be expected for the years to come. Meanwhile, new hardware technology advances such as multicore processing, virtualization, network storage, I/O convergence will support new generation of e-Science and grid applications. These applications generate data flows of 10 Gb/s up to terabit level. The predictable consequence in the near future is that the network operators will require a new generation of optical transport networks to serve this huge and heterogeneous volume of traffic in a cost-effective and scalable manner. In response to these large capacity and diverse traffic granularity needs of the future Internet, the Elastic Optical Network (EON) architecture has been proposed. By breaking the fixed-grid spectrum allocation limit of conventional WDM networks, EONs increase the flexibility in the connection provisioning. To do so, depending on the traffic volume, an appropriate-sized optical spectrum is allocated to connections in EON. Furthermore, unlike the rigid optical channels of conventional WDM networks, a lightpath can expand or contract elastically to meet different bandwidth demands in EON. In this way, incoming connection requests can be served in a spectrum-efficient manner.

This technological advance poses additional challenges on the networking level, specifically on the efficient connection establishment. Similar to Wavelength Division Multiplexing (WDM) networks, an elastic optical connection must occupy the same spectrum portion between its end-nodes, that is, ensuring the so called spectrum continuity constraint. In addition, the entire bandwidth of the connections must be contiguously allocated, also referred as the spectrum contiguity constraint. The new contiguity constraint adds a degree of complexity to the conventional Routing and Wavelength Allocation (RWA) problem. As a matter of fact, the available RWA proposals for WDM networks are no longer directly applicable in EON. A new routing and resource allocation scheme has to be developed, namely Routing and Spectrum Allocation (RSA). The RSA problem has grabbed a lot of attention lately, putting more emphasis on dynamic network scenarios.

There, connection arrival and departure processes are random and the network has to accommodate incoming traffic in real time.

The traffic accommodation in EON is realized using Bandwidth-Variable (BV) transmitters which are capable to support flexible central frequency tuning and elastic spectrum allocation. To do so, the bandwidth of transmitters is discretized in spectrum units (i.e. 12.5 GHz), referred as Frequency Slot (FS). For example, the 50, 100 and 400 GHz transmitter's bandwidth correspond to 4, 8 and 32 FSs, respectively. The spectrum variability of lightpaths is achievable by tuning the number of allocated FSs. The incoming traffic is mapped onto individual BV transmitters generating the appropriate-sized optical lightpaths between end-nodes. However, the capacity of a transmitter may remain underutilized when the traffic demands are lower than the transmitter's full capacity. In simple words, despite the crucial role of BV transmitters in increasing the spectrum efficiency of network, their full capacity cannot be utilized efficiently. It is therefore essential to introduce a solution for maximizing the capacity utilization of BV transmitters.

In addition, upon tear down of connections, their allocated spectral resources are released, and could be assigned to new connection requests. In a dynamic traffic scenario, the random connection arrival and departure in the network leads to the fragmentation of the spectral resources. Therefore, in medium and high loaded network scenarios, the possibility of finding sufficient contiguous spectrum to establish a connection over such a fragmented spectrum can be very low, leading to connection request blocking despite having enough, but non-contiguous, spectrum resources. In light of this, there is an increasing demand from network operators to be able to periodically reconfigure their networks, aiming to improve the spectrum utilization. This operation is called spectrum defragmentation. During the defragmentation operation, the available fragmented spectrum bands are consolidated by reconfiguring active connections, i.e., changing their routes, or assigning them a different portion of spectrum or both, while maintaining the imposed continuity and contiguity constraints. However, the traffic granularity, namely, the offered load to the network and the average bit-rate of the connections, has a direct effect on the spectrum fragmentation experienced at network links. Such effect can also affect the efficacy of a periodic spectrum defragmentation to keep an acceptable network performance. In particular, a deep analysis of the relationship between the traffic granularity and the defragmentation periodicity can allow a network operator to find the optimal defragmentation interval yielding the desired network performance, but requiring the minimum active connection disruptions and network control and management burden.

Besides this, the spectral voids between adjacent connections (due to the spectrum fragmentation) are traditionally considered as a problem. However, this statement not always applies. Considering the near future technology advances (e.g. high capacity bandwidth variable transponders) and the exponential increase of network traffic, it is foreseeable to have large intervals between the establishment and the release of connections. Thus, during such relatively long periods, the bit-rate demand of any connection may fluctuate following short- and mid- term traffic variations. As long as connections required bandwidth may grow over time, free spectral voids are crucial to accommodate additional bandwidth demands without requiring the re-allocation of the already established connections (an existing connection can easily adapt to transmission rate fluctuations if it has free spectral spaces around it). Therefore, an alternative approach could consist in deliberately leaving space between connections.

This thesis is devoted to the study of the aforementioned issues. To this end, each individual chapter deals with a specific issue. Along this process, the problem under study is stated, followed by a review of related existing work in the literature. Next, contributions addressing the identified issue are provided and further validated by simulation evaluations. Finally, main achievements in each chapter are highlighted.

1.1 Overview of the thesis

This thesis is structured into two background chapters, the evolution of optical transport networks (chapter 2) and the problem of routing and resource allocation in them (chapter 3), one chapter concerning the dynamic source aggregation of sub-wavelength connections (chapter 4), one chapter aiming at the correlation between traffic granularity and defragmentation periodicity (chapter 5), and one chapter detailing the possibility of using spectrum fragmentation to better allocation of time-varying connections (chapter 6).

Chapter 2, entitled *The evolution of optical networking*, offers a historical perspective on the evolution of optical networks. The value proposition of optical transport networks as well as their critical network elements and their enabling technologies is discussed. Also, the current status of these networks from a commercial deployment as well as the next-generation research point of view is highlighted. Being EON main objective of this thesis, the chapter places an emphasis on explanation of its fundamentals. This leads to conclude on the appropriateness of EON as a promising solution for high-speed optical transmission, able to provide superior flexibility and scalability in spectrum allocation towards the seamless support of diverse services along with the rapid growth of Internet traffic.

Chapter 3, *From RWA to RSA: routing and spectral resource allocation*, reviews the routing and wavelength allocation problem in conventional WDM networks and its available solutions. Then the concept of frequency slot as a strong tool for converting available RWA solutions to RSA algorithms is introduced. Next, an Integer Linear Programming (ILP) example of RSA problem is reviewed. Such an ILP formulation is led to precise solutions; however, it is time-consuming and complex. In light of this, some famous heuristic RSA algorithms are introduced.

Chapter 4, *Source aggregation: towards full transmitter capacity utilization*, presents the important role of source aggregation in better resource utilization of EONs. Considering the ever-increasing growth of IP traffic, transport networks must be dimensioned with more and more transmitters which is neither spectrum nor cost efficient. By aggregating same source but different destination sub-wavelength connections, both transmitter and spectrum usage savings can be obtained. In this context, limitations in current source aggregation algorithms are identified. Later, a novel algorithm for dynamic source aggregation of connections is proposed and further validated. Moreover, a novel node architecture enabling the realization of the proposed algorithm in a cost-effective way is introduced.

Chapter 5, *Intelligent defragmentation: defragmentation periodicity and traffic granularity*, concentrates on the spectral fragmentation issue in EONs. The particular focus is on the network periodic defragmentation, the most usual operation in elastic optical networks. For intelligent defragmentation mechanism design, the impact of traffic granularity on the performance of operation is deeply analyzed and quantified. To this end, a novel defragmentation algorithm aiming to consolidate the available fiber spectrum as much as possible, while limiting the number of re-allocated active connections is proposed. Then, supported by extensive simulation results, it is shown that the spectral defragmentation periodicity can be effectively configured by having knowledge of the offered traffic granularity.

Chapter 6, *Efficient time-varying connection serving*, focuses on lightpath adaptation under time variable traffic demands in EON. Specifically, the possibility of utilizing the spectral fragmentation to increase the spectrum allocation capabilities of EONs is explored. In this context, a heuristic Spectrum Allocation (SA) algorithm, which intentionally increases the spectral fragmentation in the network is proposed and validated. With this algorithm, the spectrum assigned to each new connection is in the middle of the largest free spectral void over the route, aiming to provide considerable spectral space between adjacent connections. These free spectral spaces are then used to allocate time-varying connections without requiring any lightpath re-allocation. The obtained simulation results show a significant improvement in terms of network blocking probability when utilizing the proposed algorithm.

Finally, chapter 7 summarizes this thesis and opens future lines of research.

Chapter 2

The evolution of optical networking

This chapter provides a historical perspective on the evolution of optical networks. It discusses the value proposition of optical networks as well as their critical network elements and enabling technologies. Several network evolutionary steps are identified, ranging from the first point-to-point fiber optic connections at megabit per second rates over several kilometers to today's multi-terabit ultralong-haul dense wavelength division multiplexed systems and optical networking beyond 100G, with the emphasis on the elastic optical networks. Despite all benefits of conventional WDM networks, such as the elimination of costly, power- and space- consuming Optical/Electrical/Optical (O/E/O) regenerators and automated remote provisioning of optical paths, they still suffer from one major problem, the low bandwidth efficiency due to their rigid large granularity. Full wavelength capacity has to be dedicated for establishing a connection between end-nodes, even when the traffic between the nodes is not sufficient to fill the entire capacity of the wavelength. It means wasting the residual bandwidth of wavelength. Providing finer granularity than a wavelength, namely sub-wavelength, would certainly have an economical advantage. In addition, it is possible that the requested end-to-end capacity be higher than a wavelength. In this case, several wavelengths are grouped and allocated according to the request. Spectrum guard bands are necessary between adjacent wavelengths in such groups for de-multiplexing purpose. This can be easily translated to poor spectral utilization. Aiming to break the fixed-grid spectrum allocation limit of conventional WDM networks, the novel spectrum efficient and scalable optical transport network architecture, called elastic optical network is introduced. Depending on the traffic volume, an appropriate-sized optical spectrum is allocated to connections in EON. Furthermore, unlike the rigid optical channels of conventional WDM networks, a lightpath can expand or contract elastically to meet different bandwidth demands. In this way, incoming connection requests can be served in a spectrum-efficient manner. In view of this, current chapter deeply outlines the general characteristics of EON as a promising solution for future high-speed optical transport.

2.1 The evolution of wavelength multiplexed optical networks

Over the last decade, optical networks have gone through an extensive and rapid evolution [TMK+12, Alf12]. With estimated exponential traffic growths, future networks have to boost their capacity. The channel capacity will need to be increased beyond 100G per channel or higher, together with an increase of spectral efficiency. Additionally, the dynamic functionality of networks should be enhanced, allowing for dynamic re-optimization. This section illustrates the evolution optical networks have gone through so far. Further, it reveals the still long road ahead to the final objective of having robust, efficient and easy-to-maintain optical network architectures.

2.1.1 Early efforts in WDM and optical switching

The early attempts for optical transmission system deployment go back to late 1970s, where a revolution in telecommunications networks began, spawned by the use of a relatively unassuming technology: fiber optic cable. The first optical transmission system was commercially demonstrated in 1980 at a line rate of 45 Mb/s [Jac95]. It was a single wavelength system, made up of a cascade of optical links - a transmitter, a fiber line, and a receiver - each followed by an electronic regenerator to overcome transmission loss and mitigate signal distortion in the fiber. In that era, as greater capacity was needed, new systems with higher bit rate, requiring faster lasers and receivers, were deployed.

By the early 1990s, and after several generations and many important device innovations, the operation of optical transmission systems at ∼2 Gb/s became possible. These networks were designed to carry smooth voice traffic. However, fax and some data services were beginning to drive more traffic on the network. Moreover, the growth of multinational companies around the world put increased pressure on the transoceanic undersea transmission facilities that had moved to optical fiber in 1988 on the TAT-8 undersea system [Abb08]. The traditional solution was to increase the link bit rate, typically by a factor of 4. That was a number, which had generally been large enough to handle demand for some time (typically ∼7 years) while not being overly demanding of advances in electronics. Motivated by the economic concerns, the cost of optical transmission scaled sub-linearly with respect to its capacity so that as optical networks moved to higher capacity to meet demands, the cost per bit was decreased.

By migration of optical transmission systems to higher bit rates (∼10 Gb/s), beside the problem of transmission loss, signal impairments on the fiber due to fiber dispersion (both chromatic and polarization), became an important issue. By setting the transmission wavelength around 1.5 μm, the lowest loss wavelength region of silicon fiber, the required signal level for detection purpose at higher bit rates was obtained. Despite this great achievement, unfortunately, this wavelength region was not well-matched with non-zero dispersion window of standard Single Mode Fiber (SMF). One potential solution was to design fiber in such a way that the lowest loss wavelength region coincided with that of minimum dispersion window, which was referred to as the Dispersion Shifted Fiber (DSF) [Kar00]. However, following this research line was not so easy.

Moreover, emerging such enormous transmission capacity placed a tremendous burden on the electronic devices at each node that must somehow process carried information. Considering the traffic growth and possible migration of optical transmission systems to ultra-high bit rates made the electronic bottleneck a serious problem. Due to these concerns, keeping the single wavelength architecture for optical transport networks did not appear very effective.

The technical community was certainly aware of WDM as another way to increase the capacity on the fiber. As a matter of fact, based on multi-wavelength microwave systems, WDM was proposed very early in the evolution of optical transmission systems. Under WDM, the optical spectrum available in the fiber is carved up into a number of non-overlapping wavelength (or frequency) bands, with each wavelength supporting a single communication channel operating at whatever rate one desires, e.g., peak possible electronic speed. In this way, WDM avoided the problematic transmission impairments incurred by higher bit rates as well as escaping the need to drive to higher speed electronics.

Key technology breakthroughs to enable wavelength multiplexing were single frequency lasers and passive wavelength multiplexing devices. The emitting wavelength of laser was roughly set at fabrication (and then temperature tuned) to a wavelength that matched to the passive wavelength multiplexing device. It is instructional to note that this matchup between the generated wavelength at lasers (channels) and multiplexer (wavelength alignment) is functionally equivalent to time synchronization in Time Division Multiplexing (TDM) systems [Bit11]. A great advantage is that wavelength alignment is achieved in design and fabrication of the components rather than with active electronics as in the case of TDM. It means less complexity and energy consumption. Note also that the wavelength multiplexing process is independent and unaffected by the bit rate carried on the wavelengths.

The main obstacle for commercial viability of WDM transmission systems prior to the availability of the optical amplifier was the cost of electrical regenerators. In primary WDM systems, optical propagation loss compensation was still achieved by electrical regeneration (as had been the case with single-channel systems). Each wavelength in the WDM system would have to be de-multiplexed and regenerated electrically, the operation so called O/E/O regeneration. The N regenerators were required at each regeneration site to restore optical signals. In this sense, the implementation cost to upgrade the transmission system would increase roughly proportionately to the capacity increase. That was not acceptable in the marketplace, so WDM remained a future technology.

The late 1980s, the pre-optical amplifier era (the absence of optical gain), was witness a flurry of research activity on WDM networks, but mostly focused on potential Local Area Network (LAN) applications, which was much in vogue at that time, rather than core telecom networks [Aca87]. In this period, most of the optical LAN research was based upon the idea of sharing access on a fiber using WDM and utilization of coherent detection. Interestingly, because of the intended LAN application, the per user bandwidth target was that of a single end user and therefore modest (∼50 Mb/s). Despite all efforts, since the very narrow band optical filters that allow efficient use of the spectrum were not available, coherent detection development was not successful at the moment. Moreover, the extra (∼10 dB) sensitivity of coherent detection relative to direct detection provided an additional margin to the network loss budget. While this application for WDM has not yet been shown to provide cost-effective value in the market place, its interest drove some very interesting and ultimately useful research on wavelength selective devices and tunable lasers.

Along with mentioned ideas and driven by analogies to microwave systems, early researchers demonstrated basic optical switches, both bulk and integrated, that when connected to a fiber could, under electrical control, dynamically switch out (drop) or switch in (add) a particular wavelength onto the fiber while leaving other wavelengths on the fiber unaltered, i.e., provide a wavelength add/drop functionality [AS78]. The research on optical switching technology received significant interest and activity in the late 1980s and early 1990s. It is one of the most important technologies that underpin today's optical networks. In general, optical switches are able to switch the path of the information signal carried by a particular wavelength in optical domain. In their simplest implementation, an optical switch is a wavelength add/drop multiplexer. Under electrical control, this device is able to switch a particular wavelength onto or off a fiber while leaving unaffected all other wavelengths on the fiber. More complex version of optical switches is the Optical Cross Connect (OXC) switch fabric, which uses a switching matrix to switch a particular wavelength from one of N input fiber routes to any of N output fiber routes (e.g. Reconfigurable Optical Add/Drop Multiplexers (ROADM) [GBS+10]). Typically, this involves a combination of wavelength de-multiplexing, optical space switching, and wavelength multiplexing.

The type of optical switch that is widely used in optical networks is a space division, physical path switch, in which the optical wavelength carrying the encoded signal is switched between one of two or more paths. The electro-optic, thermal or electromechanical effects are used to actuate the switching function. The result is that once the switch reconfigures the optical path, the wavelength that is carried over it can have information-bearing capacity of arbitrary rates. Therefore, these optical add/drop or cross connect network elements are working for any bit rate being carried by the wavelength. This is a powerful advantage for optical switching in transport networks.

Many efforts were done to realize space division switching elements, including cascaded 2-by-2 switches to form relatively large N-by-N switch arrays. These large switch arrays were capable to preform electrically controlled optical switching between an array of input fibers and an array of output fibers. Optical switch fabrics based upon Lithium Niobate (LiNbO3) directional couplers were particularly advanced and served as a useful platform to demonstrate potential optical switching applications [MMA+96]. Such researches opened up a horizon for the replacement of high rate electrical digital cross connects with optical cross connect fabrics. At that time, electrical cross connects were used for maximum channel bit rates of about 45 Mb/s. Both the electrical switching fabrics and the electrical cables between switching stages were getting large and power hungry. In contrast, optical switching showed some advantage in terms of energy and space savings, especially as the signals to be switched approached several hundreds of megabits per second. Such advantages provided a useful opportunity to develop optical switching fabrics and gain experience and understanding with the cross connect applications in transport networks generally.

2.1.2 The emergence of the optical amplifier

At the very heart of the motivation, justification, and evolution of the WDM transmission systems and ultimately WDM optical transport networks is the enormous value proposition of the optical amplifiers. The fact that a single optical amplifier in line with the transmission fiber and pumped by Continuous Wave (CW) optical power source can simultaneously amplify multiple wavelengths makes wavelength division multiplexing not only economical viable but also economical valuable. It is worth to mention that, such functionality is done with very high efficiency and, without causing any mixing or distortion between the signals being carried on the different amplified wavelengths. Moreover, the fiber amplifier can provide amplification for signals being carried on the wavelengths that have essentially arbitrarily bit rates. This is an enormously important and valuable feature of optical amplifiers that enables the ability to upgrade optical transmission systems to higher per wavelength bit rates without the need to replace amplifiers.

The earliest and most successful optical fiber amplifier is the Erbium Doped Fiber Amplifiers (EDFA). They are realized by doping erbium atoms into silicon fibers. When pumped with an intense laser source in the 0.98- or 1.4- μm region, EDFA provides optical gain over a roughly 40-nm bandwidth centered around 1.55 μm. This output range is fortuitously well matched to the loss minima of single mode transmission fiber. Gain of 20-30 dB is achievable with reasonable pump power and is sufficient to compensate for loss of a $\sim$100-km span.

With these gain characteristics, the EDFA is an ideal amplifier for high capacity WDM transmission systems. Long-haul transmission systems, including undersea networks were the first natural application areas. By upgrading the capacity of already available undersea network through simply increasing the bit rate of the land-based transmitters and receivers, the first commercial systems were deployed in 1995. The first deployment was able to multiplex and amplify 8-wavelength, each at 2.5 Gb/s, between two end nodes.

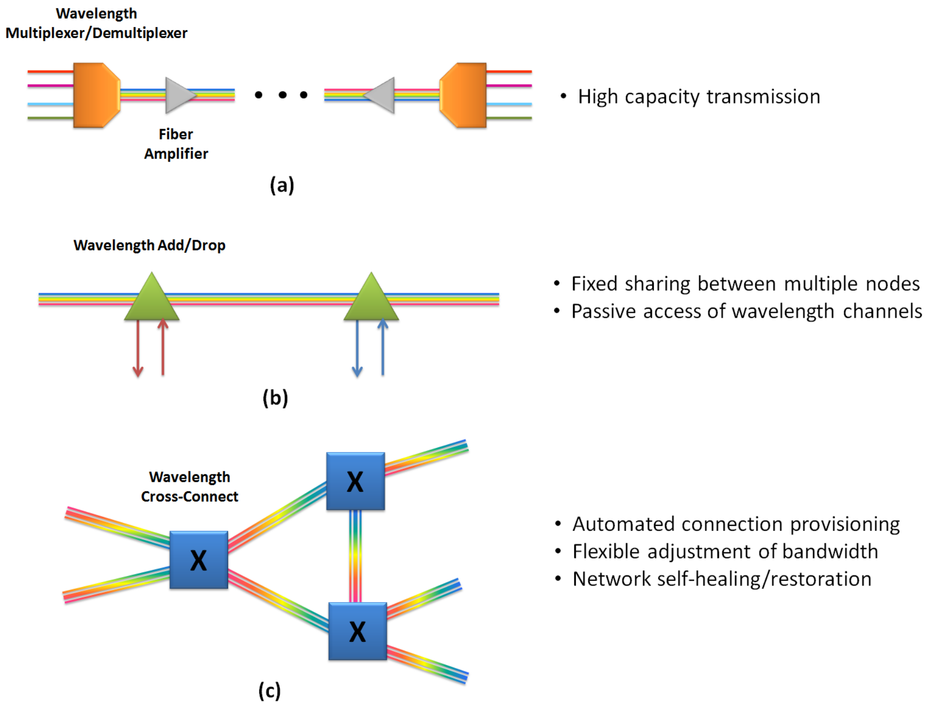


FIGURE 2.1: Evolution of optical networks (a) WDM/Point-to-Point transport (b) fixed WDM/Multipoint network (c) reconfigurable WDM/Multipoint network.

However, by introducing more advanced technologies, the possibility of multiplexing 16 and 32, etc., to meet the substantial bandwidth capacity growth became feasible. Together, deployment of WDM along with the replacement of single channel regenerators with multi-wavelength fiber amplifiers dramatically increased the network capacity in a cost-effective manner.

2.1.3 The optical transport network vision

While optical transmission benefited from availability of optical amplifier, complementary optical switching capability were largely absent from the first-generation network nodes. These nodes were typically the major cities at which traffic is sourced, terminated, and electrically switched. Figure 2.1(a) shows a schematic view of a first-generation WDM system between two endpoints. In this system, to perform the switching functionality, all the incoming traffic on the node initially had to go through an Opto/Electrical (O/E) conversion in order to process the control information and switch the data accordingly. Then, the outgoing traffic had to be converted again to the optical domain (i.e. Electro/Optical (E/O)) before the transmission. Regardless of the traffic type, in this primary WDM system, transponders were necessary at network nodes for every incoming wavelength and for every outgoing wavelength.

The large number of required transponders yielded nodal solutions that were expensive, required a lot of power and space, and that presented reliability issues. It also required the electronic switch fabric, which was difficult to scale, to grow in concert with the network traffic. The recognition of this nodal ”electronic bottleneck” was one impetus for the all-optical vision, where a network connection could be maintained in the optical domain from source to destination.

In the shown system at Figure 2.1(a), it may happen that the link connecting two end-points carries much more traffic than what just required between those two nodes (the drop traffic). This type of traffic is the ”bypass” traffic which represents the connection between node pairs on either side of these two nodes. By distinguishing between these two types of traffic that enter a node, an alternative and much better approach can be obtained as shown in Figure 2.1(b). In this approach, instead of doing a full de-multiplex of all wavelengths at each of the nodes along the route, the wavelength or wavelengths destined for this node drop off and the rest pass through.

Such an all-optical functionality realized with the help of Add/Drop Multiplexers (ADM). As stated previously, there had been many research activities to explore the feasibility of such functionality in the optical domain. Clearly, this technology enabled the removal of a tremendous amount of electronics from the network, and the attendant cost, power, space, and reliability burdens. Furthermore, ADMs, by operating on wavelengths, were more scalable than their electronic counterparts. Another benefit of the second-generation of WDM network was the provisioning time for a new connection which was greatly decreased, as E/O and O/E conversions needed to be done only at the endpoints, in oppose to at every node along the path as the first-generation WDM networks. It is also worth to mention that, optical amplifiers were still used in the second-generation WDM networks to compensate both propagation loss and the wavelength ADM loss. This technology opened up a horizon for the rapid development of multi-point networks.

Along with the development of multi-point optical networks, some necessary conditions were suggested. First, the information-bearing wavelengths launched at one end node of the chain should be able to transmit over the entire length without being too distorted or noisy to be detected. As a matter of fact, in the first sight, direct amplifying signals in the optical domain fulfilled this requirement. However, optical amplification of signals for traveling over longer distances required modulation format least susceptible to transmission impairments (i.e. no chirp in the modulated signal). Such a requirement was achieved with the help of external electro-optic modulation. This ability of externally modulated signals to travel very long distances without distortion brought great value to optical networks and really assured an important place for optical modulators in the marketplace.

The other condition was that the cost of the ADM must be sufficiently small. Roughly, the cost of the ADM plus the optical amplifier should be less than that of a simple splitter/combiner pair plus the cost of the N electrical regenerators, where N is the total number of wavelengths on the fiber. Moreover, since it was necessary to ensure that the optical signals could travel without noise accumulation and distortion over the multipoint network some additional elements, such as, e.g., dispersion compensating fiber had to be considered. Despite this fact that the cost of a single add/drop multiplexer and its supplementary devices was a way greater than a single splitter/combiner pair plus electrical regenerators, since an amplified WDM transmission system was able to send data over several thousand miles (instead of several hundred miles in the case of regenerated system), it was concluded that amplified WDM transmission system could provide a good business case.

Once we understand the value of wavelength add/drop multiplexers in a linear network, including a ring, it is not a big step to see that the same value proposition applies to mesh-based architectures (Figure 2.1(c)). In a mesh network, any node can be connected directly to several other nodes. Each node must not only capture and disseminate its own data, but also serve as hops for other nodes, that is, it collaborates in data transmission over the network. In this sense, any node in a mesh network should be able to perform two functionalities, first, capturing the traffic terminating at the node and second, route the wavelength directly as they carry the high bit rate signals. Here OXC can provide value in the same way as the ADM, eliminating costly regenerators. Without the optical switching layer, the signals would have to first be detected and then de-multiplexed down to an electrical TDM rate. Next, a digital cross-connect fabrics should be available to switch them. Finally, this data have to be multiplexed back together to the line rate to be put on a wavelength onto the new route, which is totally impractical.

Such a vision (Figure 2.1) highlighted the value of WDM optical networks for the funding agencies and companies in Europe, the United States and Japan. The European Framework Programs funded several generations of OXC and WDM network projects which were very successful in bringing together teams from universities and industry across Europe. While Japan had initially taken the path to single-channel high bit rate optical communication and, as a result, deployed dispersion shifted fiber to mitigate signal distortion issues at bit rates beyond 2.5 Gb/s, it was considerable interested in WDM network research. In the United States, the Defense Advanced Research Projects Agency (DARPA) funded several generations of WDM and optical switching programs, including both LAN and core network programs. Despite the geographical diversity of all these efforts, it was concluded that WDM transmission would break into commercial deployment very soon [MMA+90].

Commercial deployment of the point-to-point WDM transmission systems came in 1995. First systems included only eight channels at 2.5 Gb/s but, to stay ahead of perceived demand, 16 wavelength systems, a total capacity of 40 Gb/s, were deployed in 1997. Global research programs to enable reconfigurable WDM networks were ongoing in the second half of the 1990s. As indicated earlier, WDM was driven by the market of growing demand for capacity. This included demand for inter-continental capacity over undersea communication system for multi-national companies building operations around the globe. That led to the first undersea fiber amplified WDM transmission system deployment in 1996.

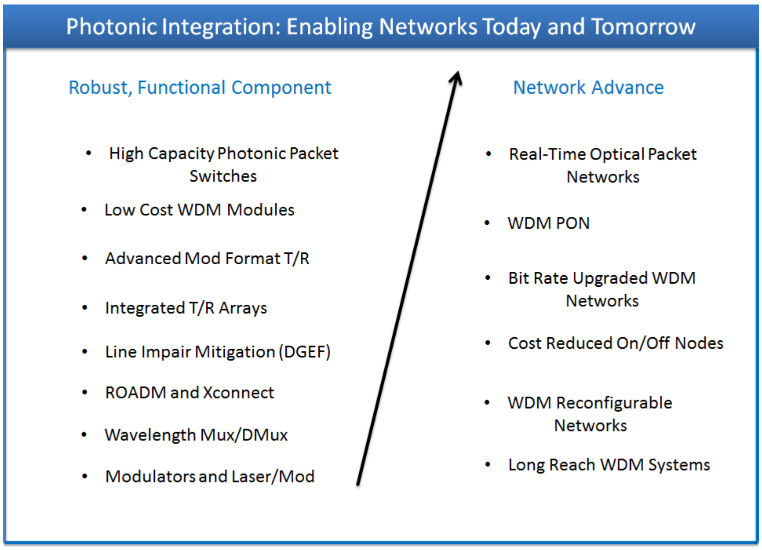


FIGURE 2.2: Evolution of technologies to enable optical networks.

The Internet was also beginning to become part of the public vocabulary in the mid-1990s. While still very much a research area, Voice Over the Internet Protocol (VoIP) promised to use packet technology to allow voice to be easily carried as a relatively low bandwidth service on the data network.

The growing sense that data and the Internet would likely change the model of communications in the future resulted in a tidal wave of activity both research and business in the late 1990s and early 2000s. There was a real communication boom, especially in the United States after the turn of the millennium. New communication companies sprung up to compete with the established providers who were just depend on the outdated voice-based businesses. New entrants into long-haul networks took advantage of the enormous potential of WDM networks to offer bandwidth wholesale for Internet providers. It was a great motivation booster to bring more optical communications, including the new WDM systems, to the business.

Quite naturally, new component companies, aiming to provide the underlying technologies for reconfigurable WDM networks -wavelength multiplexer/de-multiplexers, optical switching fabrics, and tunable lasers vastly founded. Those startup companies had the benefit of research results generated over the prior 10-15 years from government funded programs and vertically integrated industrial research labs such as Bellcore, NTT Labs, Siemens Labs, Bell Labs, etc. Figure 2.2 shows the evolution of technologies to enable optical networks.

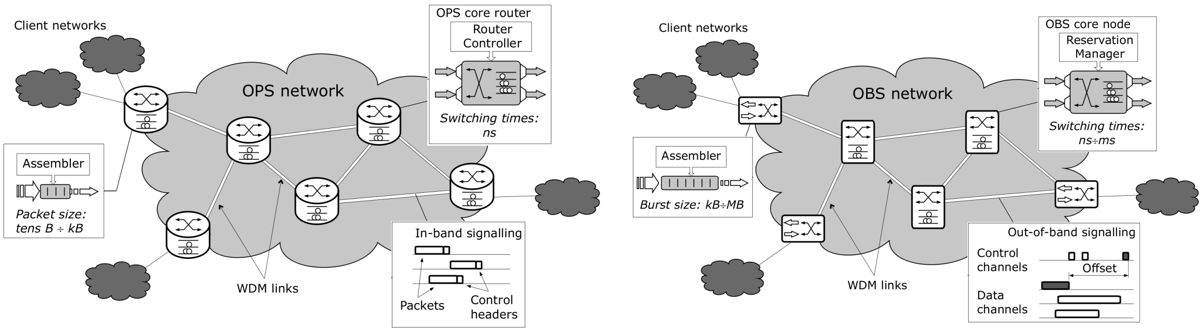
By early 2000s, 10-Gb/s systems were readily available and 40-Gb/s systems were being researched. The first WDM network products, including fully reconfigurable wavelength add/drop, were deployed in 2004. Also, as a result of the continued growth of data, including video content, reconfigurable WDM optical networks began to be deployed in metropolitan scale networks in 2007. Growing capacity demand within metro networks for video and the need to cost effectively manage that bandwidth with applications such as YouTube and Facebook has continued to drive the deployment and upgrade of metro WDM networks. This includes the latest upgrade to 100 Gb/s per wavelength and beyond.

2.2 Elastic optical network: architecture, benefits, and enabling technologies

As mentioned already, by emerging new services such as high-definition video distribution and real-time video communication, the IP traffic volume has been multiplied to date. The sustained growth of data traffic volume is also expected for the years to come [CIS13]. Meanwhile, new hardware technology advances such as multicore processing, virtualization, network storage, I/O convergence will support new generation of e-science and grid applications. These applications generate data flows of 10 Gb/s up to terabit level. The predictable consequence in the near future is that the network operators will require a new generation of optical transport networks to serve this huge and heterogeneous volume of traffic in a cost-effective and scalable manner.

To serve this ever-growing demand for more transmission capacity, high-tech innovations have enabled long-distance Dense Wavelength Division Multiplexed (DWDM) transmission with per-channel bandwidth of 100 Gb/s. Thanks to this technological advancement, optical signals can travel multiple hubs without experiencing significant loss. It provides many advantages, such as cost, power- and space- consumption reduction as well as automated remote provisioning of optical paths. However, the stranded bandwidth due to the rigid large granularity of DWDM networks limits their bandwidth utilization. Full wavelength capacity has to be dedicated for establishing a connection between an end-node pair, even when the traffic between the nodes is not sufficient to fill the entire capacity of wavelength, which means wasting the residual bandwidth of the wavelength. Providing finer granularity than a wavelength, namely sub-wavelength, would certainly have an economic advantage. In contrast, it is possible that the requested end-to-end capacity be higher than a wavelength. In this case, several wavelengths are grouped and allocated according to the request. Spectrum guard bands are necessary between adjacent wavelengths in such groups for de-multiplexing purpose. Therefore, current accommodation of super-wavelength data traffic is not spectral efficient. These requirements opened up a window toward next-generation optical transport network deployment.

Several proposals including Optical Packet Switching (OPS) [Yoo06a] and Optical Burst Switching (OBS) [QY99] have been introduced. These proposals offer traffic accommodation in a spectral efficient manner. In OPS networks, all-optical data packets (composed of an optical header and an optical payload) are statistically-multiplexed in the DWDM optical layer, so that each wavelength of each link in the network is shared amongst all packets belonging to all source-destination demands (Figure 2.3(a)). As a matter of



(a) (b)

FIGURE 2.3: (a) OPS and (b) OBS network scenarios [Per09].

fact, OPS aims to translate the electronic packet-switching operation to the optical domain, which provides better network resource utilization than previous transport network proposals. Nevertheless, OPS deployment comes up against severe technological limitations [DGSB01]. First, no optical Random Access Memories (RAM) exists to date, which restricts packet store-and-forward operations as in electric IP routers. The only way to delay packets in the optical domain is by means of Fiber Delay Lines (FDLs). However, these devices are bulky and only provide deterministic delays. In addition, optical header processing is also infeasible today. Although alternative solutions that perform O/E packet header conversion have been proposed, electronic processing do not keep pace with optical transmission speed. Furthermore, as optical packets are very short, a stringent synchronization between the optical header and payload would be required. All these issues prevent OPS realization at least in a short to mid-term future.

To relax the need for optical RAM, OBS network has been proposed as a suitable candidate for next-generation all-optical networks. In an OBS network, traffic is firstly aggregated in edge nodes and afterwards sent as bursts along buffer-less optical networks (Figure 2.3(b)). In this way, OBS provides dynamic sub-wavelength switching of data. As a matter of fact, OBS network can be viewed as a compromise between the yet unfeasible OPS and the mostly static Optical Circuit Switching (OCS) networks (i.e. aforementioned WDM networks). The main difference between OBS and OPS is in the sense that OBS control information is sent separately in a reserved optical channel and in advance of the data payload. These control signals are then processed electronically to allow the timely setup of an optical light path to transport the soon-to-arrive payload. The time difference between the control signal and data payload is known as offset time. OBS network provides more bandwidth flexibility than conventional OCS networks but requires fast optical switches and advanced control technology. The enabling technologies to fulfill these requirements are not mature enough. Therefore, OBS is still considered as a long-term solution. A deep study on a hybrid OBS/OCS solution is detailed in appendix A of this thesis.

Despite the mentioned long-term solutions, the sustained growth of data traffic volume

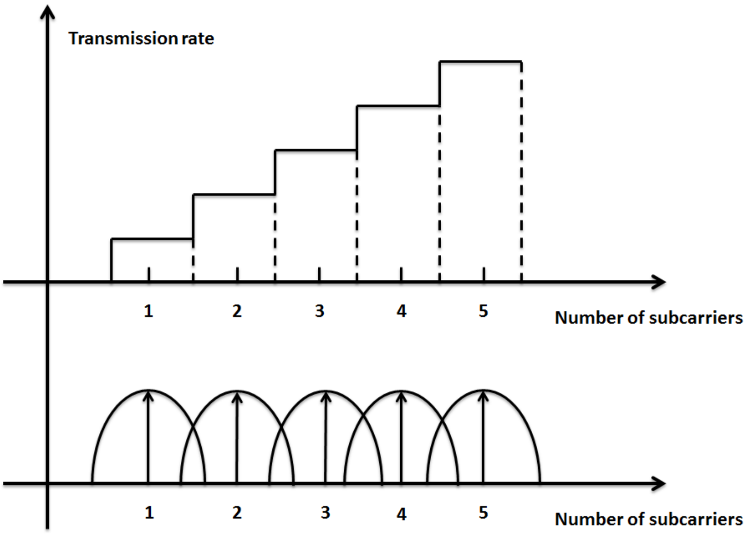


FIGURE 2.4: Variable bandwidth transmission using OFDM sub-carriers.

yet calls for an efficient and scalable middle-term solution. Two important breakthrough technologies created a chance to fulfill this requirement. The first technology advancement is the optical Orthogonal Frequency Division Multiplexing (OFDM) [SBT08]. In OFDM the data is transmitted over multiple orthogonal sub-carriers. This technology has been widely implemented in various systems, such as wireless LAN and Asymmetric Digital Subscriber Line (ADSL). Many extensive research efforts have focused on an optical version of OFDM as a means to overcome transmission impairments [LDA07, KTJ10]. Besides the advantages of low symbol rate of each sub-carrier and coherent detection that mitigate the effects of physical impairments, OFDM also brings unique benefits in terms of spectral efficiency, allowing the spectrum of adjacent sub-carriers to overlap due to their orthogonal modulation. In this sense, OFDM enables elastic bandwidth transmission realized by allocating a variable number of low-rate sub-carriers for a transmission (Figure 2.4).

The other crucial enabling technology which changed the face of optical transport networks is BV-Wavelength Cross-Connect (WXC) [RSM+05, KTJ10, JTK09a]. With the help of WXCs, the signal transmitted over the optical path (using the spectrum determined by the volume of client traffic) is routed towards the receiver. Every BV WXC on the route allocates a cross-connection with the corresponding spectrum to create an appropriate-sized end-to-end optical path. To do so, the BV WXC has to configure its switching window in a contiguous manner according to the spectral width of the incoming optical signal. Microelectromechanical Systems (MEMS)- or liquid crystal-based Wavelength-Selective Switches (WSS) can be used as BV WXC. To avoid interference effects that would deteriorate the signal quality of edge sub-carriers, adjacent optical paths require appropriate spectrum separation, implemented by spectrum guard bands [KTY+09]. Figure 2.5 presents an schematic diagram of WXC.

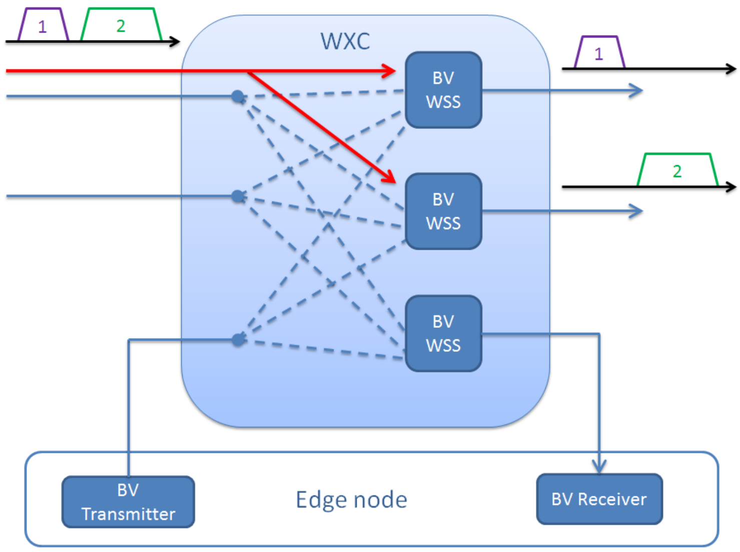


FIGURE 2.5: Bandwidth variable WXC.

By introduction of these enabling technologies, a novel spectrum efficient and scalable optical transport network architecture, known as elastic optical network, has been proposed [JTK+09c]. In EON, depending on the traffic volume, an appropriately-sized optical spectrum is allocated to every connection. It means that, unlike the rigid bandwidth of the conventional fixed-bandwidth optical path in WDM networks, an optical path in EON expands and contracts according to the traffic volume and user request, if necessary. Such elasticity in optical spectrum allocation significantly improves the spectrum efficiency and scalability of the network. It provides unique features such as segmentation and aggregation of spectral resources, efficient accommodation of multiple data rates, as well as elastic variation of allocated resources [JTK09b]. Figure 2.6 illustrates these features and a detailed discussion for each of them is given in the following.

- **Sub-wavelength accommodation:** As shown in Figure 2.6(a), current WDM networks allocate a full wavelength capacity to a lightpath, even if the supported traffic demand is not sufficient to fill the entire wavelength capacity (sub-wavelength connections). This operation leads to inefficient utilization of network spectral resources. EON provides a new mechanism for cost-effective sub-wavelength (in other words, fractional bandwidth) connectivity service. EON allocates just enough optical bandwidth to accommodate the client traffic, as shown in Figure 2.6(b). At the same time, every node on the route of the optical path allocates a cross-connection with the appropriate spectrum bandwidth to create an appropriately-sized end-to-end optical path. In this way, with an efficient use of network resources, the cost-effective provisioning of sub-wavelength connections is achieved.

- **Super-wavelength accommodation:** The other important feature targets traffic demands greater than a wavelength capacity. In WDM networks, multiple independent channels are traditionally allocated for serving this type of connection

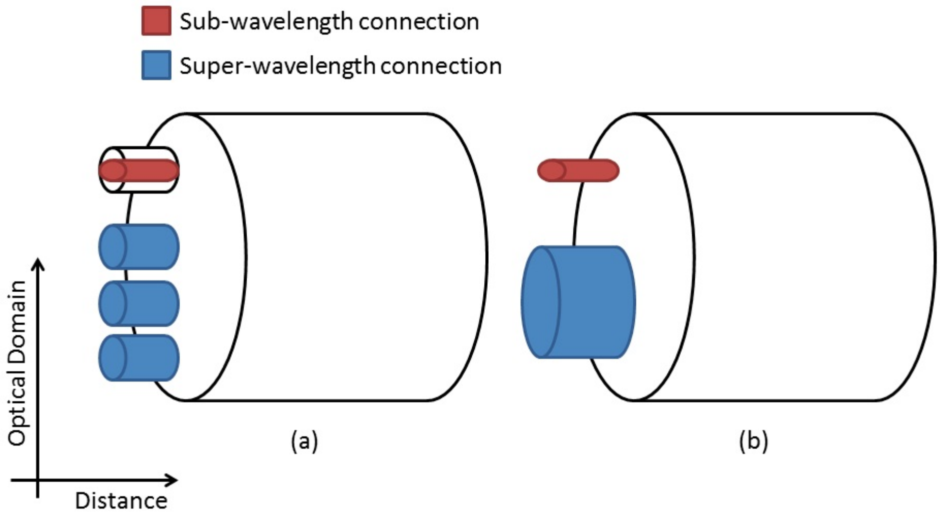


Figure 2.6: Spectrum assignment in (a) WDM network (b) EON.

requests (i.e. super-wavelength connections). Note as well, that spectral guard bands are necessary between adjacent channels for switching purposes, which further increases the spectrum overhead (Figure 2.6(a)). To provide better spectrum utilization, as shown in Figure 2.6(b), elastic optical networks tightly tailor the allocated spectrum to the specific demand requirements, regardless of the total (sub- or super-wavelength) bandwidth they require.

- **Multiple data rate accommodation:** As shown in Figure 2.6, EON enables spectrally-efficient direct accommodation of mixed data bit rates in the optical domain because of the flexible assignment of spectrum. In contrast, WDM networks with fixed grid can lead to stranding of the optical bandwidth due to the excess frequency spacing for lower bit rate signals. In this way, EON supports various data rates including possible future ones in a highly spectrum-efficient manner.

The EON technology introduces a new degree of freedom in optical networking. This emerging technology is still in its infancy. An EON installation today might be expensive with the risk of poor reliability. At first sight, the existing DWDM installations may still look suffice to cover traffic needs in the nearby future. If traffic follows a slow growth path, this is the preferred solution. However, if it grows faster than expected (which is quite possible), the operators will end up either losing money, since they are not able to route all traffic, or they will be putting in a next-generation optical network -presumably EON this time- earlier than they would have needed to, also leading to additional costs [TVC+13]. In light of this, it would be a wise decision to follow up the gradual migration of technology toward fully elastic optical networks. Therefore, more research and investment on EON is definitely necessary.

Despite the fact that EON delivers many benefits, its introduction poses additional challenges on the networking level, specifically on the efficient connection establishment.

Similar to WDM networks, an elastic optical connection must occupy the same spectrum portion between its end-nodes, that is, ensuring the so called spectrum continuity constraint. In addition, the entire bandwidth of the connections must be contiguously allocated, also referred as the spectrum contiguity constraint. The new contiguity constraint adds a degree of complexity to the conventional RWA problem. As a matter of fact, the available RWA proposals for WDM networks are no longer directly applicable in EONs. A new routing and resource allocation scheme has to be developed, namely routing and spectrum allocation. The RSA problem grabbed a lot of attention lately, putting more emphasis on dynamic network scenarios. There, connection arrival and departure processes are random and the network has to accommodate incoming traffic in real time. This problem and its possible solutions will be detailed in the next chapter.

2.3 Chapter summary

This chapter has provided a comprehensive explanation of optical network evolution all through the years. After a long journey full of challenges, pragmatic realizations, and major technological advances, WDM networks have reached its current vibrant state, achieving great savings in cost and power consumption, while enabling ease of network operation and graceful upgradability. More advances are still needed to continue to cope with the explosive growth of future networks.

OPS and OBS networks are two possible solutions for providing spectrum efficient and cost effective transport optical networks. However, since their high technological requirements, they are considered as long-term future network scenarios. In turn, EON has recently appeared as a promising technology for short- to mid- term optical transport networks. EON realizes the promise of efficient transport by using OFDM flexible-rate transponders and bandwidth-variable WXCs. This network architecture enables sub- and super-wavelength accommodations in highly spectrum-effective manner, as well as provides cost-effective fractional bandwidth service. Dynamic bandwidth variation of elastic optical path creates new business opportunities for network operators offering cost-effective and highly-available connectivity service through time-dependent bandwidth sharing, energy efficient network operation, and highly survivable restoration with bandwidth squeezing.

While EON introduced a new degree of freedom to the future optical transport networks, it poses additional challenges on the networking level, specifically on the efficient connection establishment. In view of this, the RSA problem in EON will be detailed in the next chapter.

Chapter 3

From RWA to RSA: routing and spectral resource allocation

As highlighted in the previous chapter, optical networks employing wavelength division multiplexing offer the promise of meeting the high bandwidth requirements of emerging communication applications, by dividing the huge transmission bandwidth of an optical fiber ($\sim$5 terabits per second) into multiple communication channels with bandwidths ($\sim$10 gigabits per second) compatible with the electronic processing speeds of the end users. Therefore, there has been great interest in WDM networks consisting of wavelength routing nodes interconnected by optical fibers. Such networks carry data between access stations in the optical domain without any intermediate optical to/from electronic conversion. To be able to send data from one access node to another, one needs to establish a connection in the optical layer similar to the one in a electrical circuit-switched network. This process consists of determining a path in the network between the two nodes and allocating a free wavelength on all of the links on the path. Such an all-optical path is commonly referred to as a lightpath and may span multiple fiber links without any intermediate electronic processing, while using one WDM channel per link. The entire bandwidth on the lightpath is reserved for this connection until it is terminated, at which time the associated wavelengths become available on all the links along the route.

Since lightpaths are the basic building block of this network architecture, their effective establishment is crucial. It is thus important to provide routes to the lightpath requests and assign wavelengths to each of them in a way that optimizes a certain performance metric (e.g. network blocking probability). This is known as RWA problem. The wavelengths assigned must be such that no two lightpaths that share a physical link use the same wavelength on that link. Moreover, in networks without wavelength converters, the same wavelength must be used on all links of the lightpath (i.e. wavelength continuity constraint). The RWA problem is critically important in increasing the efficiency of wavelength-routed optical networks. With a good solution of this problem, more customers can be accommodated by the given system, and fewer customers need to be rejected during periods of congestion. Numerous research studies have been conducted on the RWA problem. In this chapter some of them are reviewed.

With the emergence of the EON technology, as a promising solution for future high-speed optical transport, new technical challenges have introduced; like the efficient resource allocation of elastic lightpaths. Similar to WDM networks, an elastic optical connection must occupy the same spectrum portion between its end-nodes, that is, ensuring the spectrum continuity constraint. In addition, the entire bandwidth of the connections must be contiguously allocated, referred as the spectrum contiguity constraint. The new contiguity constraint adds a degree of complexity to the conventional RWA problem. Furthermore, the available RWA proposals for WDM networks are no longer directly applicable in EONs. A new routing and resource allocation scheme has to be developed, namely RSA problem. In light of this, this chapter, after reviewing the RWA problem and its available solutions, puts an emphasis on the evolution of RWA problem toward RSA. Next, an example of the ILP formulation as a way to find the accurate answer of the problem is presented. Also, some heuristic algorithms for solving the RSA problem in an easier way are detailed.

3.1 Routing and wavelength assignment problem

The introduction of WDM technology changed the face of optical telecommunications forever. Within a fairly short period, this technology gained acceptance as a cost efficient mean to handle the ever-increasing bandwidth demands of network users. In a WDM network, end users communicate with one another via all-optical WDM channels, which are referred to as lightpaths. A lightpath is used to support a connection in the network, and it may span multiple fiber links. In the absence of wavelength converters, a lightpath must occupy the same wavelength on all the fiber links through which it traverses; this property is known as the wavelength continuity constraint. Figure 3.1 illustrates a WDM network in which lightpaths have been set up between pairs of nodes on different wavelengths.

The problem of setting up lightpaths by routing and assigning a wavelength to each connection is called the RWA problem. This problem has been widely studied [ZJM00]. As stated previously, the wavelength continuity constraint is the main issue in the RWA problem. Typically, the RWA problem can be categorized under three operational scenarios: 1) static, 2) incremental, and 3) dynamic. In a static scenario, the entire set of connection requests between node pairs is known in advance. Solutions aim to minimize network resources (number of transmitters or the number of fibers in the network) for serving the given set of connections in a global fashion. Alternatively, setting up as many as possible of the given connection requests in a given topology fixing the number of wavelengths per fiber is the other type of static RWA problem. In the incremental-traffic case, connection requests arrive sequentially. A lightpath is established for each connection

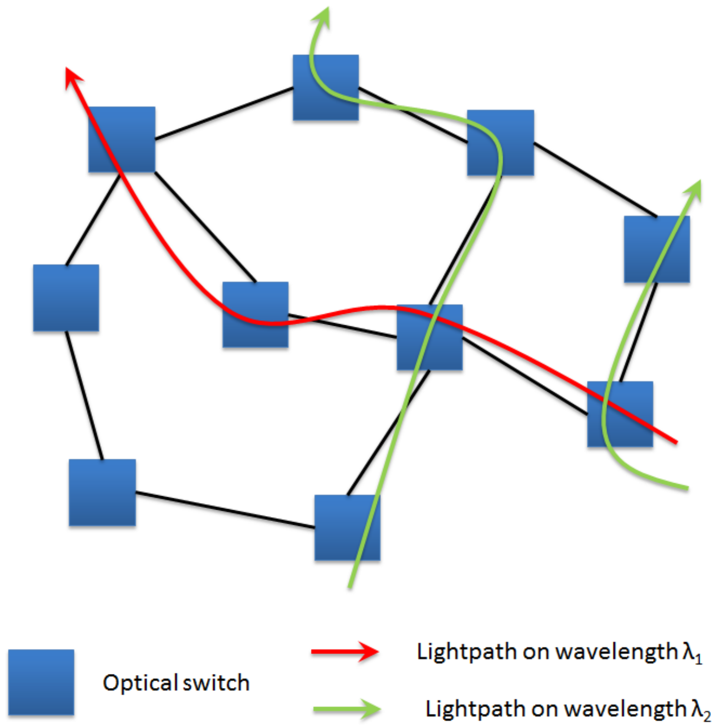


FIGURE 3.1: A WDM network with lightpath connections.

request, and it remains in the network indefinitely. Again the objective is to maximize the number of served connections in the network. In the dynamic scenario, a lightpath is also set up for each connection request as it arrives. However, each lightpath is released after some finite amount of time (connection holding time). Minimizing the amount of blocked connections, or maximizing the number of connections that are established in the network at any time are main objectives of this case.

While it is possible to translate and accurately solve all abovementioned operational RWA scenarios into ILP formulations, this approach is very complex and time-consuming [Muk97]. Alternatively, it is possible to break the RWA problem into two sub-problems, 1) routing and 2) wavelength assignment, and solve them separately. Each of these sub-problems itself can be solved in an exact fashion using some techniques such as ILP formulations. However, to provide faster and easier solution for them, it is convenient to employ heuristic algorithms. A heuristic solution, in general, is a technique designed for solving a problem more quickly when classic methods are too slow, or for finding an approximate solution when classic methods fail to find any exact solution. This is achieved by trading optimality, completeness, accuracy, or precision for speed. In light of this, initially an example of ILP formulation of RWA problem is presented, then a brief review of some famous heuristics solutions for each sub-problem is detailed.

3.1.1 Joint RWA problem

In this section, as an example of ILP formulation, the static RWA problem, also known as the Static Lightpath Establishment (SLE) problem is addressed. The detailed solution of this problem can be found in [ZJM00]. As stated previously, in such a problem lightpath requests are known in advance, and the routing and wavelength assignment operations are performed off-line. The typical objective is to minimize the number of wavelengths needed to set up a certain set of lightpaths for a given physical topology. As stated, SLE problem can be formulated as an ILP in which the objective function is to minimize the flow in each link, which, in turn, corresponds to minimizing the number of lightpaths passing through a particular link. Let λ_{sdw} denote the traffic (number of connection requests) from any source s to any destination d on any wavelength w. It is assumed that two or more lightpaths may be set up between the same source-destination pair, if necessary, but that each of them must employ a distinct wavelength; hence, $\lambda_{sdw} \leq 1$. It means that $\lambda_{sdw} = 1$, if there is a lightpath between s to d using wavelength w and otherwise $\lambda_{sdw} = 0$. Let F_{ij}^{sdw} denote the traffic (number of connection requests) from source s to destination d on link ij and wavelength w. $F_{ij}^{sdw} \leq 1$ since a wavelength on a link can be assigned to only one path. Given a network physical topology, a set of wavelengths, and the traffic matrix Λ in which Λ_{sd} denotes the number of connections needed between source s and destination d, the problem can be formulated as follows:

$$Minimize : F_{max} \tag{3.1}$$

such that, for all (s,d) pairs:

$$F_{max} \geq \sum_{s,d,w} F_{ij}^{sdw} \qquad \forall ij \tag{3.2}$$

$$\sum_{i} F_{ij}^{sdw} - \sum_{k} F_{jk}^{sdw} = \begin{cases} -\lambda_{sdw} & \text{if s = j} \\ \lambda_{sdw} & \text{if d = j} \\ 0 & \text{otherwise} \end{cases} \qquad \forall j \tag{3.3}$$

$$\sum_{w} \lambda_{sdw} = \Lambda_{sd} \tag{3.4}$$

$$F_{ij}^{sdw} = 0, 1 \qquad \forall ij, \ \forall w \tag{3.5}$$

$$\sum_{s,d} F_{ij}^{sdw} \leq 1 \qquad \forall ij, \ \forall w \tag{3.6}$$

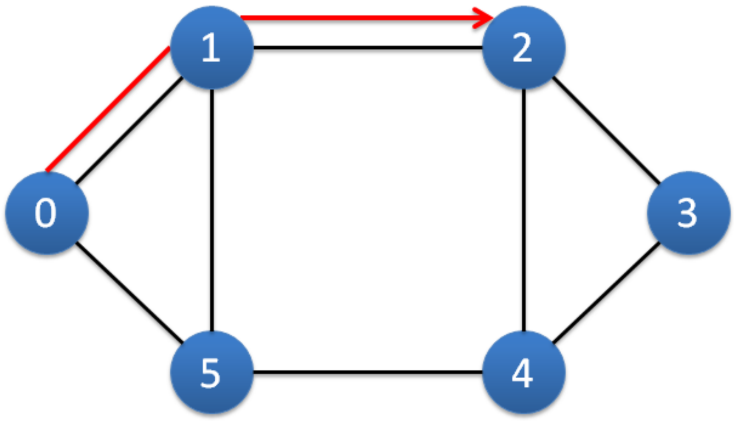


FIGURE 3.2: Fixed shortest-path route from Node 0 to Node 2.

The problem as formulated above is NP-complete [EIS76]. It can be solved using techniques developed in [Muk97]. The result of this formulation is the minimum number of wavelengths needed to set up a certain set of lightpaths for a given physical topology. Beside the presented formulation, there exist many other ILP formulations for RWA problem. In [JMT06] many of them have been reviewed. Since the ILP formulation is out of the main focus of this thesis, future studies on this topic are left to the reader. Only it is important to note that solving such complex equations is hard and time consuming. Specially, in a dynamic traffic scenario where the connection arrival and departure processes are random and the network has to accommodate incoming traffic in real time, using such a complex formulation in order to accommodate incoming traffic to the network is totally impractical. Alternatively, as mentioned previously, it is possible to break down the problem into two sub-problems and solve them individually using heuristic algorithms. Maybe in this way a bit of results accuracy is missed but the easier calculations and faster response time is gained. In the following, some of the famous heuristic algorithms for solving each sub-problem is presented.

3.1.2 The routing sub-problem

As mentioned above, although combined routing and wavelength assignment is a hard problem, it can be simplified by decoupling the problem into two separate sub-problems: the routing and the wavelength assignment sub-problems. In this subsection, various approaches to routing connection requests are reviewed.

- **Fixed Routing (FR):** The most straightforward approach to routing a connection is to always choose the same fixed route for a given source-destination pair. One example of such an approach is fixed shortest-path routing. The shortest-path route for each source-destination pair is calculated off-line using standard

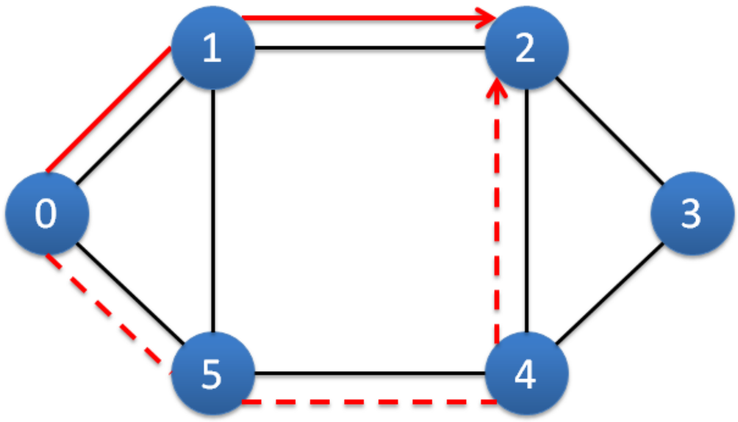


FIGURE 3.3: Primary (solid) and alternate (dashed) routes from Node 0 to Node 2.

shortest-path algorithms, such as Dijkstra's algorithm [JAE+12] or the Bellman-Ford algorithm [ABNG91], and any connection between the specified pair of nodes is established using the pre-determined route. In Figure 3.2, the fixed shortest-path route from Node 0 to Node 2 is illustrated. This approach to routing connections is very simple; however, the disadvantage of such an approach is that, if resources (wavelengths) along the path are tied up, it can potentially lead to high blocking probabilities in the dynamic case, or may result in a large number of wavelengths being used in the static case. Also, fixed routing may be unable to handle fault situations in which one or more links in the network fail. To handle link faults, the routing scheme must either consider alternate paths to the destination, or must be able to find the route dynamically. Note that, in Figure 3.2, a connection request from Node 0 to Node 2 will be blocked if a common wavelength is not available on both links in the fixed route, or if either of the links in the fixed route is cut.

- **Fixed Alternate Routing (FAR):** This approach considers multiple routes between a source node s and a destination node d. To do so, each node in the network has to maintain a routing table that contains an ordered list of routes to each destination node. These routes may include the shortest-path route, the second-shortest-path route, the third-shortest-path route, etc. A primary route between a source node s and a destination node d is defined as the first route in the list of routes to node d in the routing table at node s. The first alternate route between s and d is any route that does not share any links (is link-disjoint) with the first route in the routing table at s. In the same way, the second alternate route is any route that does not share any links with already existing routes (primary and the first alternate routes) in the routing table of s. In this sense, given some critical issues such as topology of the network and the nodal degree, there exists a maximum number of possible routes between s and d. In practice, it is possible to limit the number of calculations (for example to 2 [Ram98]), in order to accelerate the process and reduce the complexity. Figure 3.3 illustrates a primary route (solid

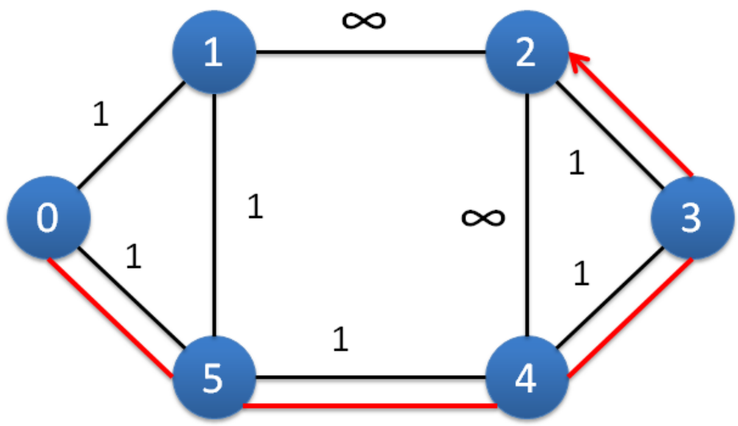


FIGURE 3.4: Adaptive route from Node 0 to Node 2.

line) from Node 0 to Node 2, and an alternate route (dashed line) from Node 0 to Node 2.

When a connection request arrives, the source node attempts to establish the connection on each of the routes from the routing table in sequence, until a route with a valid wavelength assignment is found. If no available route is found from the list of alternate routes, then the connection request is blocked and lost. In most cases, the routing tables at each node are ordered by the number of fiber link segments (hops) to the destination. Therefore, the shortest path to the destination is the first route in the routing table. When there are ties in the distance between different routes, one route may be selected at random. Fixed-alternate routing provides simplicity of control for setting up and tearing down lightpaths and it may also be used to provide some degree of fault tolerance upon link failures. Another advantage of fixed-alternate routing is that it can significantly reduce the connection blocking probability compared to fix routing. As mentioned before, it has also been shown that, for certain networks, having as few as two alternate routes provide significantly lower blocking probabilities than having full wavelength conversion at each node with fixed routing [Ram98].

- **Adaptive Routing (AR):** In adaptive routing, the route from a source node to a destination node is chosen dynamically, depending on the network state. The network state is determined by the set of all connections that are currently in progress. One form of adaptive routing is adaptive shortest-cost-path routing, which is well-suited for use in wavelength-converted networks [ZM04]. Under this approach, each unused link in the network has a cost of 1 unit, each used link in the network has a cost of ∞, and each wavelength-converter link has a cost of C units. If wavelength conversion is not available, then $C = \infty$. When a connection arrives, the shortest-cost path between the source node and the destination node is determined. If there are multiple paths with the same distance, one of them is chosen randomly. By choosing the wavelength-conversion cost C appropriately, we can ensure that wavelength-converted routes are chosen only when wavelength-continuous paths are not available. In shortest-cost adaptive routing, a connection is blocked only when there is no route (either wavelength-continuous or wavelength-converted) from the source node to the destination node in the network. Adaptive routing requires extensive support from the control and management protocols to continuously update the routing tables at the nodes. An advantage of adaptive routing is that it results in lower connection blocking than fixed and fixed-alternate routing. For the network in Figure 3.4, if the links (1, 2) and (4, 2) in the network are busy, then the adaptive-routing algorithm can still establish a connection between Nodes 0 and 2, while both mentioned the fixed-routing protocol and the fixed-alternate routing protocols would block the connection.

Another form of adaptive routing is Least Congested Path (LCP) routing [CY94]. Similar to alternate routing, for each source-destination pair, a sequence of routes is pre-selected. Upon the arrival of a connection request, the least congested path among the pre-determined routes is chosen. The congestion on a link is measured by the number of wavelengths available on the link. Links that have fewer available wavelengths are considered to be more congested. The congestion on a path is indicated by the congestion on the most congested link in the path. If there is a tie, then shortest-path routing may be used to break the tie. An alternate implementation is to always give priority to shortest paths, and to use LCP only for breaking ties. Both combinations are examined through simulation in [LS00], and it has been shown that using shortest-path routing first and LCP second works better than using LCP alone.

A disadvantage of LCP is its computational complexity. In choosing the least-congested path, all links on all candidate paths have to be examined. A variant of LCP is proposed in [LS00] which only examines the first k links on each path (referred to as the source's neighborhood information), where k is a parameter to the algorithm. It has been shown that, when $k = 2$, this algorithm can achieve similar performance to fixed-alternate routing. It is also shown in [LS00] that LCP performs much better than fixed-alternate routing.

This was a brief review on the most famous and practical solutions available for the routing sub-problem. As mentioned previously, beside the routing sub-problem, there exists the wavelength assignment sub-problem which can directly affect the performance of the network. In the next subsection, the most common solutions for this sub-problem are introduced.

3.1.3 The wavelength assignment sub-problem

In this subsection, the problem of wavelength assignment is reviewed. The objective of a solution for this sub-problem is to assign a wavelength to each lightpath such that no two lightpaths share the same wavelength on a given fiber link. One approach to solving this problem is to formulate it as a graph-coloring problem [Muk97]. While this approach leads to a complete and accurate solution, it is time-consuming and complex. As mentioned previously, heuristic algorithm are powerful and strong alternatives. In this subsection, 10 most important and famous heuristics are briefly reviewed, namely 1) Random, 2) First Fit, 3) Least Used/SPREAD, 4) Most Used/PACK, 5) Min Product, 6) Least Loaded, 7) MAX SUM, 8) Relative Capacity Loss, 9) Wavelength Reservation, and 10) Protecting Threshold. These heuristics can all be implemented as on-line algorithms and can be combined with different routing schemes. The first eight schemes attempt to reduce the overall blocking probability for new connections, while the last two approaches aim to reduce the blocking probability for connections that traverse more than one link. In the discussions, the following notation and definitions are used:

- L: Number of links.
- M_l: Number of fibers on link l.
- M: Number of fibers per link if all links contain the same number of fibers.
- W: Number of wavelengths per fiber.
- $\pi(p)$: Set of links comprising path p.
- S_p: Set of available wavelengths along the selected paths p.
- D: L-by-W matrix, where D_{lj} indicates the number of assigned fibers on link l and wavelength j. Note that the value of D_{lj} varies between 0 and M_l.
- Load: For dynamic traffic, the holding time is exponentially distributed with a normalized mean of one unit, and connection arrivals are Poisson; thus, load is expressed in units of Erlangs.

Here is the description of the wavelength assignment heuristics.

- **Random wavelength assignment (R):** This scheme first searches the space of wavelengths to determine the set of all wavelengths that are available on the required route. Among the available wavelengths, one is chosen randomly (usually with uniform probability).
- **First Fit (FF):** In this scheme, all wavelengths are numbered. When searching for available wavelengths, a lower-numbered wavelength is considered before a higher-numbered wavelength. The first available wavelength is then selected. This scheme requires no global information. The idea behind this scheme is to pack all of the in-use wavelengths toward the lower end of the wavelength space so that continuous longer paths toward the higher end of the wavelength space will have a higher

probability of being available. This scheme performs well in terms of blocking probability and fairness, and is preferred in practice because of its small computational overhead and low complexity. Similar to Random, FF does not introduce any communication overhead because no global knowledge is required.

- **Least Used (LU)/SPREAD:** LU selects the wavelength that is the least used in the network, thereby attempting to balance the load among all the wavelengths. This scheme ends up breaking the long wavelength paths quickly; hence, only connection requests that traverse a small number of links will be serviced in the network. The performance of LU is worse than Random, while also introducing additional communication overhead (e.g., global information is required to compute the least-used wavelength). The scheme also requires additional storage and computation cost; thus, LU is not preferred in practice.

- **Most Used (MU)/PACK:** MU is the opposite of LU in that it attempts to select the most-used wavelength in the network. It outperforms LU significantly [SB97]. The communication overhead, storage, and computation cost are all similar to those in LU. MU also slightly outperforms FF, doing a better job of packing connections into fewer wavelengths and conserving the spare capacity of less-used wavelengths.

- **Min Product (MP):** MP is used in multi-fiber networks [JA96]. In a single-fiber network, MP becomes FF. The goal of MP is to pack wavelengths into fibers, thereby minimizing the number of fibers in the network. MP first computes

$$\prod_{l \in \pi(p)} D_{lj} \tag{3.7}$$

for each wavelength j, i.e., $1 \leq j \leq W$. If we let X denote the set of wavelengths j that minimizes the above value, then MP chooses the lowest-numbered wavelength in X. As shown in [SB97], MP does not perform as well as the multi-fiber version of FF in which the fibers, as well as the wavelengths, are ordered. MP also introduces additional computation costs.

- **Least Loaded (LL):** The LL heuristic, like MP, is also designed for multi-fiber networks [KA98]. This heuristic selects the wavelength that has the largest residual capacity on the most-loaded link along route p. When used in single-fiber networks, the residual capacity is either 1 or 0; thus, the heuristic chooses the lowest-indexed wavelength with residual capacity 1. Thus, it reduces to FF in single-fiber networks. LL selects the minimum indexed wavelength j in S_p that achieves

$$\max_{j \in S_p} \min_{l \in \pi(p)} (M_l - D_{lj}) \tag{3.8}$$

In [KA98], it is shown that LL outperforms MU and FF in terms of blocking probability in a multi-fiber network.

- **MAX SUM (M$\sum$):** $M\sum$ [BS97] was proposed for multi-fiber networks but it can also be applied to the single-fiber case. M$\sum$ considers all possible paths (lightpaths with their pre-selected routes) in the network and attempts to maximize the remaining path capacities after lightpath establishment. It assumes that the traffic matrix (set of possible connection requests) is known in advance, and that the route for each connection is pre-selected. These requirements can be achieved since the traffic matrix is assumed to be stable for a period of time, and routes can then be computed for each potential path on the fly.

  To describe the heuristic, a number of notations is introduced. Let ψ be a network state that specifies the existing lightpaths (routes and wavelength assignments) in the network. In M$\sum$, the link capacity on link l and wavelength j in state ψ, $r(\psi, l, j)$, is defined as the number of fibers on which wavelength j is unused on link l, i.e.,

$$r(\psi, l, j) = M_l - D(\psi)l_j \tag{3.9}$$

  where $D(\psi)$ is the D matrix in state ψ.

  The path capacity $r(\psi, p, j)$ on wavelength j is the number of fibers on which wavelength j is available on the most-congested link along the path p, i.e.,

$$r(\psi, p, j) = \min_{l \in \pi(p)} r(\psi, l, j) \tag{3.10}$$

  The path capacity of path p in state ψ is the sum of path capacities on all wavelengths, i.e.,

$$R(\psi, p) = \sum_{j=1}^{max} \min_{l \in \pi(p)} c(\psi, l, j) \tag{3.11}$$

  Let

  - $\Omega(\psi, p)$ be the set of all possible wavelengths that are available for the lightpath that is routed on path p, and
  - $\psi'(j)$ be the next state of the network if wavelength j is assigned to the connection.

  M$\sum$ chooses the wavelength j that maximizes the quantity

$$\sum_{p \in P} R(\psi'(j), p) \tag{3.12}$$

  where P is the set of all potential paths for the connection request in the current state. Once the lightpath for the connection has been established, the network state is updated and the next connection request may be processed.

- **Relative Capacity Loss (RCL)**: RCL was proposed in [ZQ98] and is based on M$\sum$. M$\sum$ can also be viewed as an approach that chooses the wavelength j that minimizes the capacity loss on all lightpaths, which is

$$\sum_{p \in P}(R(\psi'(j) - (R(\psi'(j), p)) \tag{3.13}$$

where ψ is the network state before the lightpath is set up. Since only the capacity on wavelength j will change after the lightpath is set up on wavelength j, M$\sum$ chooses wavelength j to minimize the total capacity loss on this wavelength, i.e.,

$$\sum_{p \in P}(r(\psi'(j) - (r(\psi'(j), p)) \tag{3.14}$$

On the other hand, RCL chooses wavelength j to minimize the relative capacity loss, which can be computed as

$$\sum_{p \in P}(R(\psi'(j) - (r(\psi'(j), p))/(r(\psi, p, j) \tag{3.15}$$

RCL is based on the observation that minimizing total capacity loss sometimes does not lead to the best choice of wavelength. When choosing wavelength i would block one lightpath p_1, while choosing wavelength j would decrease the capacity of lightpaths p_2 and p_3, but not block them, then wavelength j should be chosen over wavelength i, even though the total capacity loss for wavelength j is greater than the total capacity loss for wavelength i. Thus, RCL calculates the Relative Capacity Loss for each path on each available wavelength and then chooses the wavelength that minimizes the sum of the relative capacity loss on all the paths. Both M$\sum$ and RCL can be used for non-uniform traffic by taking a weighted sum over the capacity losses. RCL has been shown to perform better than M$\sum$ in most cases [ZJM00].

So far, the wavelength assignment schemes that have been described attempt to minimize the blocking probability. However, considering that longer lightpaths have a higher probability of getting blocked than shorter paths, some schemes attempt to protect longer paths. These schemes are wavelength reservation and protecting threshold [BK95]. They differ from other wavelength assignment schemes in two ways: First, they do not specify which wavelength to choose, but instead specify whether or not the connection request can be assigned a wavelength under the current wavelength usage conditions. Hence, they cannot work alone and must be combined with other wavelength assignment schemes. Second, other schemes aim at minimizing the overall blocking probability for all connection requests, while the Rsv and Thr schemes attempt to protect only the connections that traverse multiple fiber links (multihop connections). Therefore, when these two schemes are used, the overall blocking probability performance in the network may be higher, but a greater degree of fairness can be achieved, in that connections that traverse multiple fiber links will not have significantly higher blocking probabilities than connections that traverse only a single fiber link.

- **Wavelength Reservation (Rsv):** In Rsv, a given wavelength on a specified link is reserved for a traffic stream, usually a multihop stream. For example, in Figure 3.2, wavelength λ_1 on link (1, 2) may be reserved only for connections from Node 0 to Node 3; thus, a connection request from Node 1 to Node 2 cannot be set up on λ_1 link (1, 2), even if the wavelength is idle. This scheme reduces the blocking for multihop traffic, while increasing the blocking for connections that traverse only one fiber link (single-hop traffic) [BK95].
- **Protecting Threshold (Thr):** In Thr, a single-hop connection is assigned a wavelength only if the number of idle wavelengths on the link is at or above a given threshold [BK95].

This was a brief review of available and most common solutions for RWA problem. Nevertheless, apart from the effectiveness of these solutions, by introduction of EON technology and the crucial need to fulfill the spectrum contiguity constraint, the aforementioned wavelength assignment approaches are not directly applicable in EON. A transformation in typical RWA problem has to be occurred to make its solutions compatible with EON. The next section focuses on this transition.

3.2 Toward RSA

While adaptive spectrum resource allocation in EON promises high spectrum efficiency and scalability for future optical transport networks, it poses additional challenges on the networking level, specifically on the efficient connection establishment. Similar to WDM networks, an elastic optical connection must occupy the same spectrum portion between its end-nodes, that is, ensuring the so called spectrum continuity constraint. In addition, the entire bandwidth of the connections must be contiguously allocated, also referred as the spectrum contiguity constraint. In very simple words, the emergence of EON technology changed the conventional understanding of optical channel. This issue is depicted in Figure 3.5. As it is shown, in WDM networks, operators do not need to distinguish the optical channel itself and the spectral resources allocated on a given route. They only need to specify a central frequency for the optical channel when establishing the end-to-end optical connection (Figure 3.5(a)). In contrast, the central frequency and the width of the spectral resource allocated to an optical path are variable parameters in EON, as shown in Figure 3.5(b). In simple words, beside the optical channel itself, network operators need to be aware of the dedicated end-to-end spectral resource to a connection in elastic optical networks. Quite naturally, it can be inferred

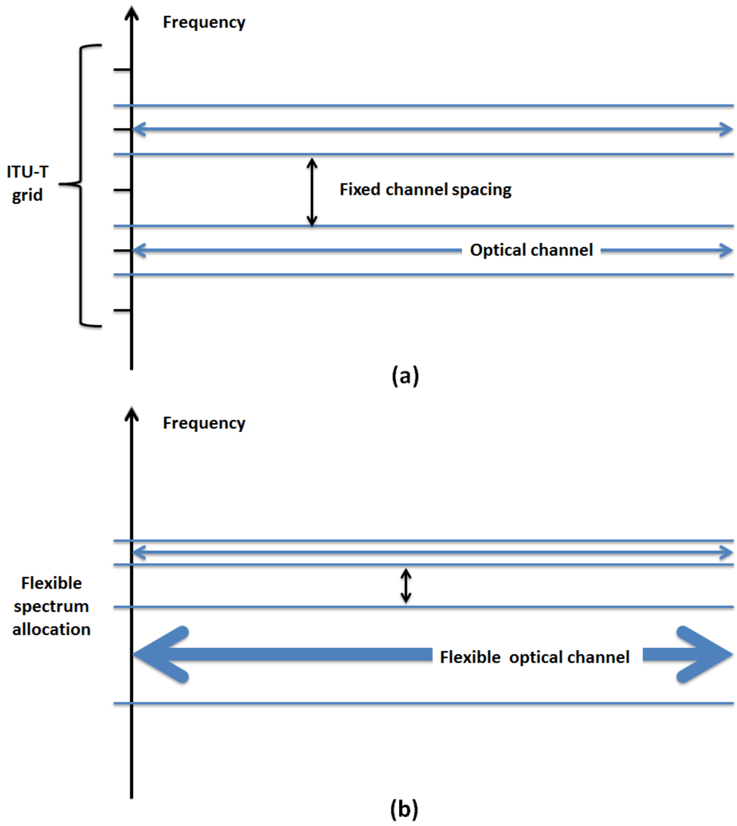


FIGURE 3.5: Optical channel (a) WDM network (b) EON supporting elastic spectrum allocation.

that a flexible spectrum resource designation scheme against the current WDM frequency grid has to be introduced. In the following, initially the current ITU-T frequency grid and the wavelength label under standardization at the Internet Engineering Task Force (IETF) are reviewed. Then the concept of frequency slot as a powerful scheme for flexible spectrum resource designation is introduced.

3.2.1 The current ITU-T WDM frequency grid

The current ITU-T WDM frequency grid specified in G.694.1 [G.694.1] is anchored to 193.1 THz, and supports various channel spacing of 25 GHz, 50 GHz, and 100 GHz as shown in Figure 3.6(a). An optical frequency f on the grid with a channel spacing of f_{cs} can be designated as $f = 193.1 + nf_{cs}$ (THz), where integer n is a frequency grid number. To make this idea practical, wavelength labeling in the signaling message in optically routed networks is undergoing standardization at the IETF, aiming to ensure the global wavelength continuity [IETF+11]. A WDM wavelength label under standardization carries the information on the channel spacing and the number n. Despite the functionality of such channel spacing in WDM systems, since elastic optical channels do not have fixed boundaries, the present standard is useless for EON. One promising way to address this

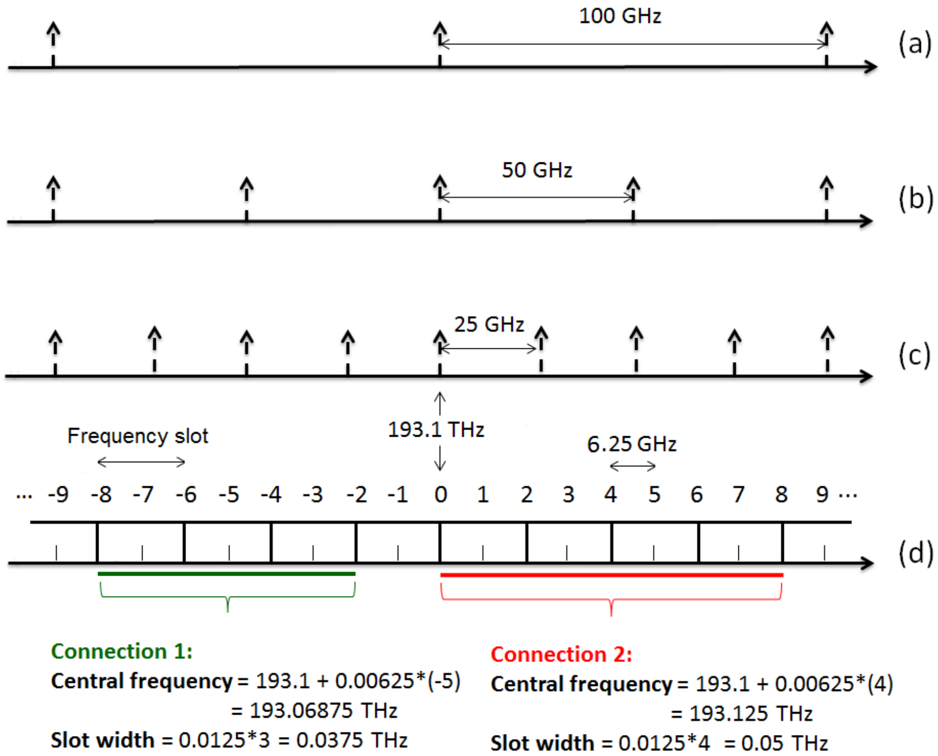


FIGURE 3.6: Spectral resources designation schemes (a) ITU-T frequency grid with channel spacing 100 GHz (b) ITU-T frequency grid with channel spacing 50 GHz (c) ITU-T frequency grid with channel spacing 25 GHz (d) frequency slot.

issue is to introduce the concept of a frequency slot instead of the current frequency grid. In this approach the spectral resource of an optical path can be allocated by assigning the necessary number of contiguous FSs, considering the client signal spectrum width, and an effective filter bandwidth throughout the route.

3.2.2 Frequency slot concept

As mentioned previously, in order to realize flexible spectrum allocation, a new frequency grid scheme has to be defined. In this scheme, in addition to central frequency of different channels, the frequency ranges allocated to each channel has to be indicated. As a matter of fact, considering both continuity and contiguity constraints the frequency range allocated to a channel must be unavailable to other channels. In light of this, the concept of frequency slot has been introduced. According to this idea, the available optical bandwidth is discretized in spectrum units (i.e. 12.5 GHz), referred as frequency slots. For example, the 1, 2 and 5 THz optical bandwidth correspond to 80, 160 and 400 FSs, respectively. The spectrum variability of lightpath is achievable by tuning the number of allocated FSs to the connection. Each connection is defined by its nominal central frequency and its slot width. In order to make calculations easier, a labeling scheme has been proposed [JTK+09c]. In the double-sided half slot labeling scheme, for every 6.25 GHz of spectrum an index is dedicated as shown in Figure 3.6(d). In light of this, the central frequency of a connection is equal to 193.1 THz + $n\times$ 0,00625 THz, where n is the central index and the slot width is equal to the number of allocated FSs to the connection multiplied by 12.5 GHz (the size of one slot in Hz). For example, considering connection 1 in the Figure 3.6(d), the central frequency is 193.1 + 0.00625 $\times$ (-5) = 193.06875 THz and the slot width is 0.0125 $\times$ 3 = 0.0375 THz.

As it is discussed above, FS concept introduced a way for dividing the spectrum domain into small sections. In light of this, by assigning the necessary number of contiguous FSs, considering the client signal spectrum width and an effective filter bandwidth throughout the route, a new connection can be established in the network. At first sight, it may look totally different from the way that connections are served in WDM networks. However, by applying some modifications in the available RWA solutions, it would be possible to utilize them in EONs as well. In the following, available solutions for RSA problem are reviewed. In this way, initially an exemplary ILP formulation of RSA problem is presented. Next, some famous RSA heuristic algorithms (including modified versions of RWA heuristics) are briefly reviewed.

3.3 Routing and spectrum allocation problem

In this section, based on the study at [CTV10a], a typical EON as presented in Figure 3.7 is considered. The spectral granularity of the transmitters and WXCs is one FS corresponding to F GHz of spectrum. The capacity of a FS is equal to C Gb/s. Although C can adapt depending on the modulation level used, i.e., BPSK, QPSK, 8-QAM, or higher, for this study a constant C is assumed. To route the paths through the BV WXC a guard band of G FSs has to separate adjacent spectrum paths. To realize traffic accommodation, as stated above the transmitter's bandwidth is discretized in FS. The transmitters can be tuned to utilize a number of FS forming a continuous spectrum equal to the bandwidth demand of a connection request. Serving a connection i that requires T_i FSs is translated to finding a starting frequency slot f_i after which it can use T_i contiguous FSs (in addition to the guard bands).

A network topology is represented by a connected graph $G = (V, E)$. V denotes the set of nodes, which is assumed to be equipped with bandwidth variable WXCs. E denotes the set of (point-to-point) single-fiber links. Let $N =\mid V \mid$ and $L =\mid E \mid$ denote the number of nodes and the number of links of the network. Here the planning version of the RSA problem is assumed, thus a priori known traffic matrix is available. Assuming a constant FS capacity C, a bandwidth demand of B_i can be mapped to a demand of T_i FSs (e.g. $T_i = \lceil B_i/C \rceil$, for a given C). Thus, the traffic scenario is given in the form of a matrix of non-negative integers T, called the spectrum traffic matrix. Then T_{sd} denotes the number of FSs required for the communication between source s and destination d.

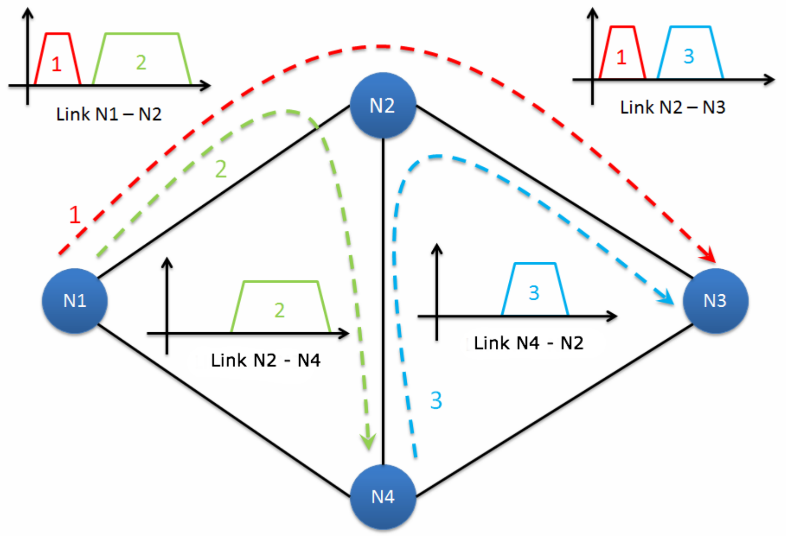


FIGURE 3.7: Typical EON.

It is also assumed that for connection (s,d) a continuous spectrum (a continuous set of FSs) is utilized, so that T_{sd} FSs are allocated over a single path that connects (s,d).

In the following the joint RSA problem which deals with the problem of routing and spectrum allocation simultaneously is presented.

3.3.1 Joint RSA problem

In this subsection the joint RSA problem is considered. To solve the problem, for each commodity (s,d) a set of k paths is initially pre-calculated. Let P_{sd} be a set of candidate paths for (s,d) and $P = \bigcup_{(s,d)} P_{sd}$ be the total set of candidate paths.

Variables:

- x_p : Boolean variable that denotes the utilization of path $p \in P$ (x_p equals to 0 if path p is not utilized, and 1 if p is utilized).
- f_{sd} : Integer variable that denotes the starting frequency for connection (s,d). Assuming $T_{total} = \sum_{(s,d)} T_{sd}$, we have $0 \le f_{sd} < T_{total}$.
- $\delta_{sd,s'd'}$: Boolean variable that equals 0 if the starting frequency of connection (s',d') is smaller than the starting frequency of connection (s,d) (i.e. $f_{s'd'} < f_{sd}$), and 1 otherwise (i.e., $f_{sd} < f_{s'd'}$).
- c : Maximum utilized frequency slot.

ILP routing and spectrum allocation formulation:

minimize c

subject to the following constraints:

- Cost function

  For all (s,d) pairs :

$$c \geq f_{sd} + T_{sd} \tag{3.16}$$

- Single path routing constraints

  For all (s,d) pairs :

$$\sum_{p \in P_{sd}} = 1 \tag{3.17}$$

- Starting frequencies ordering constraints

  For all commodities (s,d) and (s',d') that have $p_i \in P_{sd}$ and $p_j \in P_{s'd'}$, with p_i and p_j sharing at least one common link l $(\forall(s,d),(s',d') : \exists p_i \in P_{sd} \bigcap \exists p_j \in P_{s'd'} \bigcap \ (l \in p_i \bigcap l \in p_j))$, the following constraints are employed:

$$\delta_{sd,s'd'} + \delta_{s'd',sd} = 1 \tag{3.18}$$

$$f_{s'd'} - f_{sd} < T_{total}.\delta_{sd,s'd'} \tag{3.19}$$

$$f_{sd} - f_{s'd'} < T_{total}.\delta_{s'd',sd} \tag{3.20}$$

  Constraints 3.18 - 3.20 ensure that either $\delta_{sd,s'd'} = 1$, meaning that the starting frequency f_{sd} of connection (s,d) is smaller than the starting frequency $f_{s'd'}$ of (s',d') (i.e., $f_{sd} < f_{s'd'}$), or $\delta_{s'd',sd} = 1$ (i.e., $f_{sd} > f'_{s'd}$). Note that f_{sd} and $f_{s'd'}$ are bounded by constant T_{total}, so their difference is always less than T_{total}.

- Spectrum continuity and non-overlapping spectrum allocation

  For all commodities (s,d) and (s',d') that have $p_i \in P_{sd}$ and $p_j \in P_{s'd'}$, with p_i and p_j sharing at least one common link l, the following constraints are employed:

$$f_{sd} + T_{sd} + G - f_{s'd'} \leq (T_{total} + G).(1 - \delta_{sd,s'd'} + 2 - x_{pi} - x_{pj}) \tag{3.21}$$

$$f_{s'd'} + T_{s'd'} + G - f_{sd} \leq (T_{total} + G).(1 - \delta_{s'd',sd} + 2 - x_{pi} - x_{pj}) \tag{3.22}$$

  When one (or both) of the paths p_i and p_j is not utilized ($x_{pi} \neq 1$ or $x_{pj} \neq 1$), then we do not have to consider the overlapping of their spectrum. In this case, constraints 3.21 and 3.22 are deactivated (hold always, irrespectively of f_{sd} and $f_{s'd'}$), since the right hand side of the constraints take a value larger than T_{total}, which is always higher than the left hand side.

  Now, assume that both paths p_i and p_j are utilized (x_{pi}=1 and x_{pj}=1). Then one of the constraints 3.21 or 3.22 are activated according to the values of $\delta_{sd,s'd'}$ and

$\delta_{s'd',sd}$. In particular, constraint 3.21 is activated when $\delta_{sd,s'd'}$ =1 (that is when $f_{sd} < f_{s'd'}$), in which case 3.21 becomes:

$$f_{sd} + T_{sd} + G \leq f_{s'd'} \tag{3.23}$$

Ensuring that the spectrum used by the two connections (s,d) and (s',d') do not overlap. When $\delta_{sd,s'd'}$ =1, then $\delta_{s'd',sd}$=0, and constraint 3.22 is deactivated, since 3.22 becomes:

$$f_{s'd'} + T_{s'd'} - f_{sd} \leq T_{total} \tag{3.24}$$

Which holds always irrespectively of f_{sd} and $f_{s'd'}$.

In a similar manner, constraint 3.22 is activated when $\delta_{s'd',sd}$ =1 (i.e., when $f_{sd} > f_{s'd'}$) and constraint 3.21 is deactivated. In this way, constraints 3.21 and 3.22 ensure that the spectrum allocated to connections that utilize paths that have a common link do not overlap.

The above ILP algorithm finds the paths p (corresponding to x_p =1) and the starting frequencies f_{sd} of the connections over those paths so as to minimize the total used spectrum c. Spectrum continuity constraint is translated to non-overlapping spectrum allocation. Thus, the starting frequencies of the connections that utilize a common link are ordered so that their allocated spectrum do not overlap (accounting also for the required guard bands G in-between).

The presented formulation is an example of exact solutions for the RSA problem. As mentioned previously, such solutions are time-consuming and complex. However, similar to RWA problem, there exist several heuristic RSA algorithms. In these heuristic algorithms the joint RSA problem is decomposed into two main sub-problem 1) routing and 2) spectrum allocation. The routing sub-problem is literally the same as it was presented earlier in this chapter, so the presented heuristics are also used in this case. Besides this, with the help of FS concept and considering the contiguity constraint, it would be possible to translate current wavelength allocation heuristics to spectrum allocation ones. In the following some of them are reviewed.

3.3.2 RSA heuristic algorithms

To solve the RSA problem efficiently, several heuristic algorithms have been proposed. In general they can be designed as one-step or two-step approaches [GLMM12].

- **Two-step approach:**

  As mentioned above, the RSA problem can be partitioned into routing and spectrum assignment sub-problems and solved sequentially. Regarding routing, besides the algorithms previously discussed for RWA, a load balanced routing which determines the routing by balancing the load within the network to potentially minimize the spectrum usage in the network has been presented in [JKT+10]. It was shown that shortest path routing outperforms load-balanced routing in regard to minimizing the total spectrum resources used in the network, while load-balanced routing achieves better performance with the objective to minimize used spectrum index in the network [JKT+10].

After routing, spectrum allocation problem can be solved using one of the following algorithms:

- **First Fit (FF):** In this scheme as it has been presented in [THS+11b], all spectrum slots are numbered. With pre-calculated k shortest paths, ordered from the shortest route to the longest one, this algorithm searches for the necessary consecutive slots in ascending order of the spectrum slot index. It selects the first found route and slots fulfilling the requirements of connection request. As stated, this algorithm is the modified version of FF heuristic algorithm for WDM networks [ZJM00].
- **Random Fit (RF):** Besides the mentioned FF algorithm, there are many other spectrum allocation algorithms that are using the principles of RWA heuristic algorithms. One of them is the RF algorithm [RCC+12]. With the same route ordering procedure as FF, the random fit accommodates the new connection in randomly selected spectrum portion with enough space along the first found route.
- **Smallest Fit (SF):** The only difference between SF and two other mentioned algorithms is that the connection request is placed in the smallest available spectral band along the first found route.
- **Lowest Starting Slot (LSS):** As presented in [CTV10b], for each candidate route, this algorithm searches for the first consecutive slots feasible for the new request in ascending order of the slot index. It selects the path with the lowest starting slot among the set of candidate paths. This algorithm supports void filling, in the sense that voids of size greater than the requested slots can be utilized. Compared to the FF which is quick and simple, the LSS algorithm might have better spectrum utilization because of its void-filling capability.

In a network planning problem (i.e. static scenario), the problem of ordering connection demands for a given traffic matrix becomes also an important issue. As a matter of fact, different ordering approaches may result in different spectrum utilization. Several ordering policies have been proposed in [CTV10b]: 1) Most-subcarriers-first ordering, which orders the connection demands in decreasing order of their requested bandwidth, and serves them with the highest bandwidth first; 2) Longest-path-first ordering, which orders connection demands in descending order of the number of links their shortest paths use, and serves the connection that has the longest path first; 3) simulated annealing meta-heuristic, which finds a near-optimum ordering based on previously mentioned ordering approaches (i.e. 1 and 2). Simulation results indicate that the best available solution is simulated annealing ordering approach [CTV10b].

- **One-step approach:**

  Two different algorithms using a one-step approach have been proposed in [WLH+11], namely Modified Dijkstra's Shortest Path (MSP) and Spectrum-Constraint Path Vector Searching (SCPVS). These algorithms find the route and the available contiguous spectrum simultaneously. MSP is implemented by checking the available spectrum in the Dijkstra's shortest-path algorithm, and SCPVS builds a path-vector tree with spectrum constraint to search the global optimal route.

3.4 Chapter summary

This chapter has addressed the problem of routing and spectrum allocation in all-optical transport networks. In general, a solution to this problem indicates a route and allocated spectrum resource for incoming connection requests as to optimize a certain performance metric (e.g. network blocking probability). To start with, the RWA problem has been reviewed. This problem can be categorized under three operational scenarios: static, incremental, and dynamic. In a static scenario, the entire set of connection requests between node pairs is known in advance. Solutions aim to minimize network resources (number of wavelengths or the number of fibers in the network) for serving the given set of connections in a global fashion. Alternatively, setting up as many as possible of the given connection requests in a given topology with the fixed number of wavelengths per fiber is the other type of static RWA problem. In the incremental-traffic case, connection requests arrive sequentially. A light path is established for each connection request, and it remains in the network indefinitely. Again the objective is to maximize the number of served connections in the network. In the dynamic scenario, a lightpath is also set up for each connection request as it arrives. However, each lightpath is released after some finite amount of time (connection holding time). Minimizing the amount of connection blocking, or that maximizes the number of connections that are established in the network at any time is the main objective of this case.

Being the dynamic operational scenario the main focus of this thesis, more emphasis has been put on it. Two possible approaches for solving the dynamic RWA problem have been introduced, namely the exact solution using ILP formations and estimated solution utilizing heuristic algorithms. The ILP formulation leads to a precise solution of the problem. However, this approach is very complex and time-consuming. Alternatively, it is possible to break the RWA problem into two sub-problems, 1) routing and 2) wavelength assignment, and solve them separately. The heuristic algorithms provide a strong tool for solving each sub-problem in an easy and fast way. A heuristic is a technique designed for solving a problem more quickly when classic methods are too slow, or for finding an approximate solution when classic methods fail to find any exact solution. This is achieved by trading optimality, completeness, accuracy, or precision for speed. In this context, some famous routing and wavelength allocation algorithms have been reviewed.

By emerging the EON technology some technical and operational challenges, specifically, efficient resource allocation for connections has been posed on the optical networking level. Similar to WDM networks, an elastic optical connection must occupy the same spectrum portion between its end-nodes, that is, ensuring the spectrum continuity constraint. In addition, the entire bandwidth of the connections must be contiguously allocated, also referred as the spectrum contiguity constraint. This new constraint adds a degree of complexity to the conventional RWA problem. Consequently, the available RWA proposals for WDM networks are no longer directly applicable in EONs. A new routing and resource allocation scheme have to be developed, namely routing and spectrum allocation. In light of this, the evolution of RWA problem toward RSA has been reviewed. In this way, the concept of FS as a strong and helpful tool for translating RWA solutions for EONs introduced. In light of this, an ILP formulation of RSA problem as well as some famous heuristic solutions have been reviewed.

Chapter 4

Source aggregation: towards full transmitter capacity utilization

So far we have seen that EON technologies arise as promising solutions for future high-speed optical transmission, since they can provide superior flexibility and scalability in spectrum allocation towards the seamless support of diverse services along with the rapid growth of Internet traffic. To realize an elastic optical network, several key optical technologies are used. One of the crucial components is BV transmitters. They should support flexible central frequency tuning and elastic spectrum allocation, which can be achieved thanks to recent technology advances [SYMY08]. To realize traffic accommodation, as mentioned, the bandwidth of transmitters is discretized in spectrum units (i.e. 12.5 GHz), referred as frequency slots. For example, the 50, 100 and 400 GHz transmitter's bandwidth correspond to 4, 8 and 32 slots, respectively. The spectrum variability of lightpaths is achievable by tuning the number of allocated frequency slots. The incoming traffic is mapped onto individual BV transmitters generating the appropriately-sized optical lightpaths between end-nodes. However, the capacity of a transmitter may remain underutilized when the traffic demands are lower than the transmitter's full capacity. In simple words, despite the crucial role of BV transmitters in increasing the spectrum efficiency of network, their full capacity cannot be utilized efficiently. It is therefore essential to introduce a solution for maximizing the capacity utilization of BV transmitters. In light of this, the aggregation of same source but different destination sub-wavelength connections has been recently introduced for elastic optical networks [Ger10, WC12, ZQ98], aiming to obtain both transmitter and spectrum usage savings. Roughly speaking, this proposal tries to aggregate multiple sub-wavelength connections into one transmitter and serve them as a whole over the network. In this chapter, a novel algorithm for dynamic source aggregation of connections is proposed. Moreover, a novel node architecture enabling the realization of the proposed source aggregation in a cost-effective way is introduced. The obtained results demonstrate considerable improvement in the network spectrum utilization, as well as a significant reduction in the number of necessary transmitters per node.

4.1 Source aggregation in elastic optical networks

Traffic aggregation in elastic optical networks tries to combine as much as possible traffic demands between a source-destination pair and establish a connection with an appropriately-size spectrum between them. For example, the author in [Ger10] introduced the concept of optical tunnel for elastic optical networks. It was shown that elastic optical networks have higher spectrum efficiency than WDM networks. However, the problem of inefficient utilization of transmitter's capacity was still unsolved.

This problem initiates a vast research on the possibility of using the residual capacity of a transmitter for establishing new connections to different destinations. On one hand, the idea of sliceable transmitter was proposed in [JST+11, GJLY12, KTT+10, TGS+11, GFS+11]. Sliceable transmitters are multi-flow, multi-rate and multi-reach transmitters. Multiple connections can be provided using a single type of these transmitters, where each connection is supported by a different contiguous subset of frequency slots. To distinguish one connection from another, spectral guard bands must be placed between them. On the other hand, authors in [DBK10, MYT+10, Shi11] showed the possibility of designing and realizing cost-effective sliceable components to receive different subsets of contiguous frequency slots which correspond to one or multiple connections. These papers have shown the possibility of using the full capacity of a transmitter for establishing connections from one source to different destinations. However, using such devices will increase the cost and complexity of the network. In addition, the full capacity of a transmitter will not be used since spectral guard bands are still necessary between different connections originating from the same transmitter.

Furthermore, authors in [WC12] studied the possibility of traffic multicasting in elastic optical networks. They proposed point-to-multipoint connections to be provided using one transmitter and employing Broadcast-and-Select (B&S) switching at intermediate nodes. The saving of spectrum resources compared with the traditional WDM optical networks was demonstrated. The paper has shown the potential of sending traffic demands to multiple destinations in elastic optical networks. However, using the B&S mechanism at network nodes increases their complexity, cost and energy consumption. Moreover, the optical signal experiences spectral penalties due to the internal optical signal splitting.

Authors in [ZQ98, ZLM12] introduced a new perspective to source aggregation in elastic optical networks. They proposed aggregation of multiple connections (which may have different destinations) into a single regular bandwidth variable transmitter and switching them as a whole over the network. Since the aggregated traffic demand is supported by a regular BV-transmitter, spectral guard bands are not necessary between adjacent connections inside the resulting optical tunnel. Therefore, such a source aggregation approach can provide a simple and cost-effective way for increasing transmitter capacity utilization. However, as the connections of an optical tunnel can have different destinations, to establish an individual connection some capability should be added to network nodes. Indeed, when a connection needs to be separated from the optical tunnel at any intermediate node, the node should be able to split the original optical tunnel into multiple tunnels. In addition, guard bands should be added at both sides of the separated optical tunnels spectrum, so that they can be switched at subsequent nodes. Same as previous work in [WC12], they employed B&S switching to achieve this functionality, which unfortunately increases the cost and complexity of network nodes. Introducing less complex and more cost-effective node architectures able to provide the aforementioned functionality is one of the motivations of current study that will be explained in the next section.

Abovementioned studies on the benefits of the source aggregation in the planning phase of elastic optical networks show a significant improvement in terms of spectrum efficiency and number of required transmitters. However, there is no clear vision on the benefits of such a proposal in a dynamic network scenario. As a matter of fact, the random nature of connection arrivals and departures in such a scenario adds more difficulty to source aggregation. To the best of our knowledge, authors in [ZMM13] initiated this research line by proposing a new RSA algorithm which provides a spectrum reservation scheme for non-fully utilized transmitters. The pre-reserved spectrum portions of high-capacity transmitters are used for allocating possible future connections. In this way, they provided better transmitter capacity utilization. However, introducing a reservation scheme leads to inefficient use of available spectrum. In this chapter, a novel heuristic algorithm that provides dynamic source aggregation in elastic optical networks without any spectrum pre-reservation is proposed. This algorithm is detailed later in section 4.3.

4.1.1 Principles and benefits

Thanks to the spectrum flexibility provided by the BV transmitters, optical signals with arbitrary spectrum bandwidth can be accommodated in elastic optical networks. In this way, such networks can provide efficient utilization of spectrum resources. To make the idea more clear, an exemplary elastic optical network is shown in Figure 4.1(a). In this network enough frequency slots are allocated to incoming connection requests supported by two different BV transmitters. Note that the capacity of transmitters is not fully used if the traffic demand is lower than the transmitter capacity. In addition, as the filter characteristic of network nodes has gradual boundaries, the guard bands are necessary between adjacent connections to avoid any data mixing and information loss [KTY+09]. The typical size of single guard band is equal to one frequency slot [ZLM12]. Therefore, besides inefficient utilization of transmitter capacity, a portion of spectral resources remain unused due to the guard band necessity.

In light of the above, the basic idea of source aggregation proposals is to group multiple connections with same source into one transmitter and switch them as a whole over the network. This group of connections is called an optical tunnel. In this way, such proposals can provide better utilization of the transmitter capacity. Moreover, since guard bands are only necessary between different optical tunnels for switching purposes, better bandwidth utilization is also achievable. As highlighted in Figure 4.1(a), both connections 1 and 2

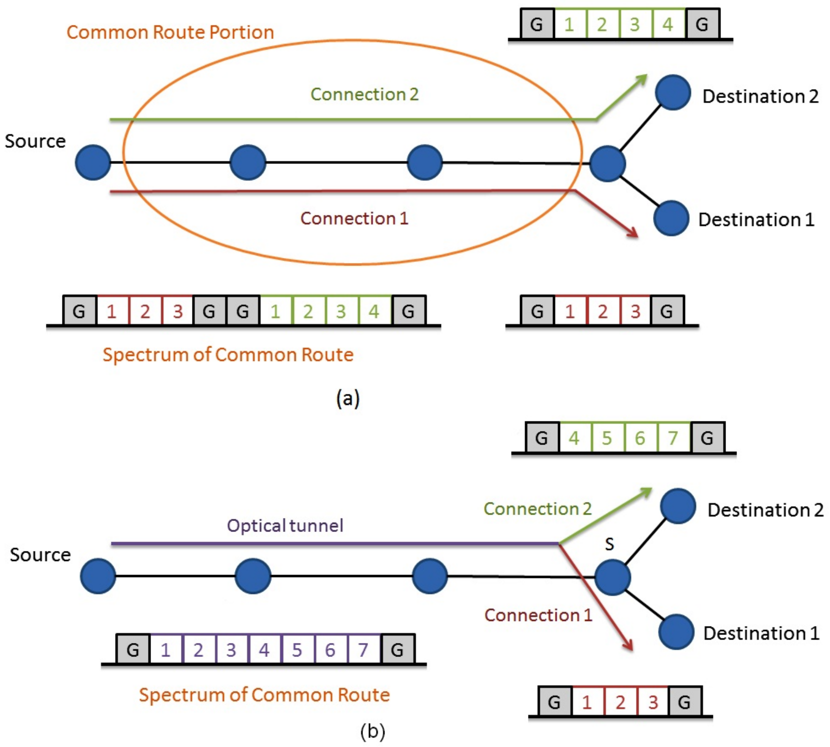


FIGURE 4.1: Two exemplary EONs (a) without source aggregation (b) with source aggregation.

share a portion of their routes from source to destination. By aggregating traffic demands over this common route portion, spectrum savings as well as better transmitter capacity utilization can be achieved. Figure 4.1(b) illustrates the idea. As shown, both connections can be grouped in a single optical tunnel over the common route portion. Since the traffic demand over resulting optical tunnel is assumed less than the whole available spectrum of a transmitter, it can be established using only one transmitter instead of two transmitters as in Figure 4.1(a). In addition, a portion of the spectrum equal to a couple of guard bands (2 frequency slots) has been saved in this example. At the end of common route portion, each connection can be extracted from the optical tunnel and continue its way to the destination. As mentioned before, guard bands are necessary at both sides of the individual connections, once extracted from the optical tunnel. In Figure 4.1(b), frequency slot 4 in the optical tunnel is treated as a signal slot in connection 2, and as a guard band slot in connection 1. In order to provide such functionality, special node architecture has to be employed. The proposed node architecture will be detailed in the next section.

4.2 Enabling node architecture

To realize the proposed source aggregation functionality, some capabilities should be added to the network nodes. An intermediate node should be able to drop a specific

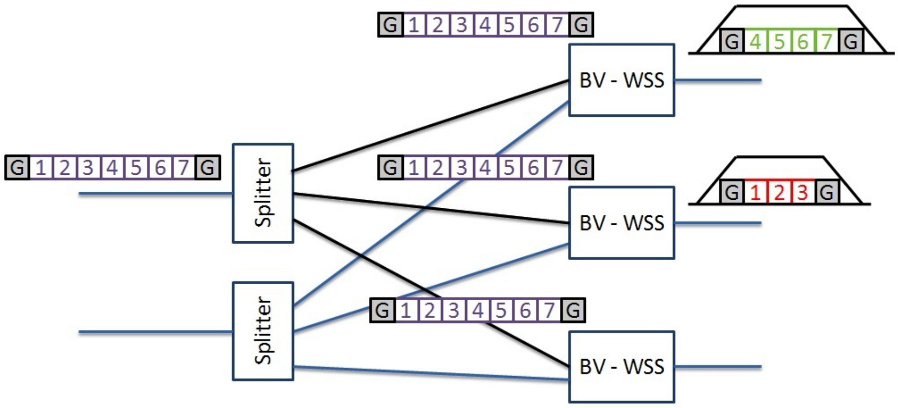


FIGURE 4.2: Broadcast and Select node architecture.

portion of an optical tunnel (corresponding to one or multiple connections) to an outgoing port, while the remaining part of it continues to another outgoing port. In general, providing this functionality for a network node will increase its cost and complexity, since Bandwidth Variable Wavelength Selective Switches (BV-WSS) should be used in the node architecture. Authors in [ZLM12] employed the B&S architecture shown in Figure 4.2. In this architecture, the spectrum of the incoming optical tunnel is broadcasted to all outgoing ports, and filtered by different BV-WSS to form desirable spectrums at each outgoing port. Although this is an easy architecture for an optical node, it has some drawbacks. Firstly, this node architecture is neither scalable nor cost-effective. Secondly, spectrum of optical tunnels will suffer from the internal optical signal splitting. In fact, internal optical signal splitting decreases the energy level of optical signal, which may lead to difficulties in signal detection at the receiver side and worst signal to noise ratio [Agr13].

To address these problems, it is desirable to reduce the number of BV-WSS in the node architecture. In this section a new architecture, called shared splitting architecture, is proposed. As illustrated in Figure 4.3, the architecture consists of two main sections, switching section and splitting section. The Bandwidth Variable Optical Cross-Connect (BV-OXC) module switches portions of spectrum without any signal splitting. To do so, the BV-OXC should be able to configure its spectral switching window in a continuous manner according to the spectral width of incoming optical signal. Thanks to the advancement in Liquid Crystals on Silicon (LCoS) WSS technology, BV-OXCs with these features are available nowadays [RSM+05]. In addition, the proposed node should also be able to drop a specific spectrum portion of the optical tunnel to an outgoing port, while the remaining part of it continues to another outgoing port. As shown in Figure 4.3, the splitting section of the node performs this functionality. In this section, a shared BV-WSS is employed to filter the broadcasted signals and to send the appropriated spectral bands to their desired outgoing ports. In contrast to the previously proposed architecture, no BV-WSS (which are relatively expensive devices) are placed per outgoing port in our proposal; instead they are moved from the output ports to the splitting section. Therefore, the number of necessary BV-WSS per node is reduced significantly which leads

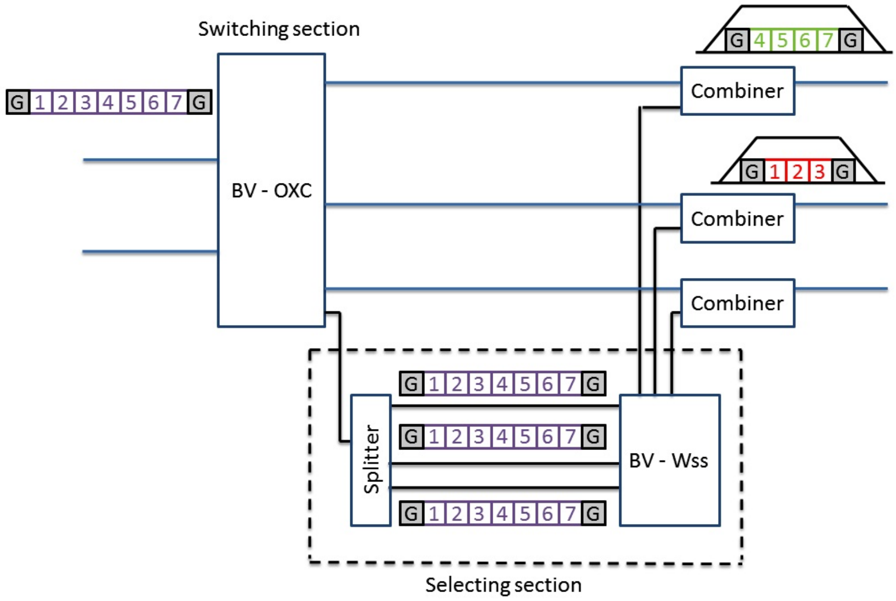


FIGURE 4.3: Shared splitting node architecture.

to considerable cost and energy savings in the network nodes. In addition, the spectral penalty due to optical signal splitting is minimized, since the shared section splits the optical signal in an on-demand fashion. Note, however, that the introduction of such a shared section in the node architecture may lead to collisions. To solve this issue, few parallel splitting sections in the node can be considered, allowing optical signals to be switched without experiencing any blocking. To start with, two parallel splitting sections per node have been assumed, aiming to keep the performance and cost of the node in a reasonable level. However, the detailed study about the effects of network topology on the number of necessary splitting sections in the nodes is left for the end of this chapter.

4.3 Dynamic optical path aggregation algorithm

In this section, a dynamic RSA algorithm that applies the proposed source aggregation concept is presented. The aim of such an algorithm is to minimize the spectrum and transmitter usage in the network simultaneously. To do so, the algorithm tries to aggregate incoming traffic demands with already existing connections in the network. It is worth to mention that the capability of dynamic source aggregation adds more complexity to the conventional RSA problem, since a single transmitter is used for establishing multiple connections. As a matter of fact, besides the contiguity and continuity constraints existent in typical RSA problem [CTV10b], aggregated traffic should use a consecutive number of frequency slots within the transmitter's spectral range. Thus, the maximum number of aggregated connections is limited by the maximum capacity of transmitters. Considering these issues, the First-Possible Aggregating (FPA) algorithm has been developed. The FPA algorithm maximizes the transmitter capacity utilization of the network by aggregating same-source sub-wavelength connections over their common route. Also, it improves the spectrum utilization of the network by reducing the number of required guard bands between connections. These features can be easily translated to more established connections over the network and a lower number of required transmitters per node.

First-Possible Aggregating Algorithm:

1. Calculate the shortest path for the incoming connection request. Set the calculated shortest path as the candidate route to allocate the connection request.

2. Select already existing connections in the network with the same source and following a route that shares some links with the candidate route calculated in step 1.

3. Calculate the residual capacity of the transmitters which are supporting the connections selected in step 2. Set the candidate transmitter as the first one with enough idle capacity to aggregate the incoming connection to the already allocated connection. The transmitters are supposed to be able to dynamically adjust their central frequency to the middle of the aggregated optical tunnel.

4. Check the spectrum continuity and contiguity constraints for establishing the connection using the candidate transmitter over the candidate route.

5. If the constraints satisfied, perform source aggregation and establish the connection, otherwise set the next possible transmitter with enough capacity as the candidate transmitter and go back to step 4.

6. If there is no possibility for establishing the connection over the candidate route, calculate the next disjoint shortest path. Set the calculated path as the candidate route and go back to step 2.

7. If there is no possibility for source aggregation, establish the incoming connection request without source aggregation by using a separate transmitter and employing k-shortest path routing and first-fit spectrum assignment.

8. If there is no possibility for establishing the connection at all, drop the connection request.

In this way, the FPA algorithm provides the capability of dynamic source aggregation in a simple manner. The next section presents the simulation results of the proposal.

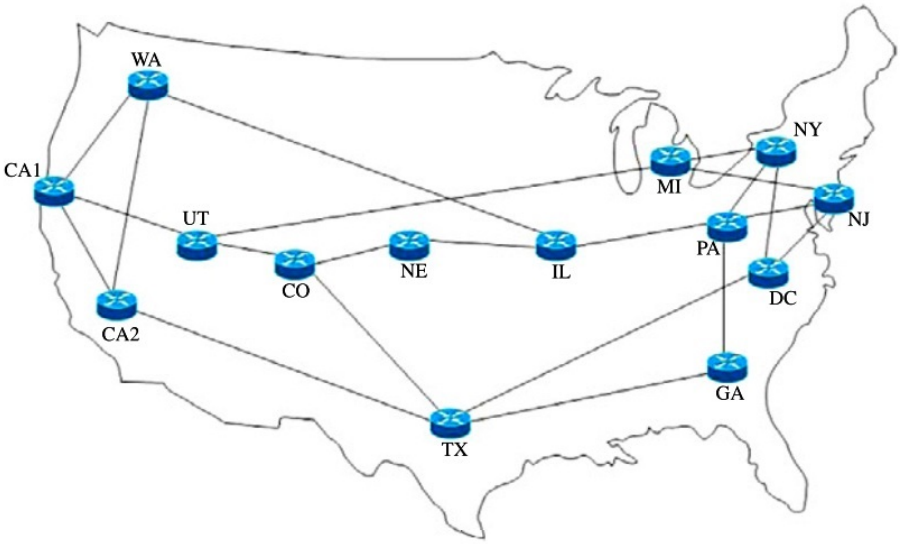


FIGURE 4.4: The topology of NSFnet.

4.4 Simulation results

The performance of the proposed FPA source aggregation algorithm is evaluated through extensive discrete event simulation studies. As a benchmark the non-aggregating scenario (i.e., a conventional elastic optical network using a k-Shortest Path computation algorithm with a First-Fit slot assignment, starting with the shortest computed path [CTV10b]) is considered. The 14-node National Science Foundation Network (NSFnet) (shown in Figure 4.4) topology has been selected for the simulation purposes. Total optical spectrum of 1.5 THz per link and the spectrum slot size of 12.5 GHz [JTK+09c] is assumed. By adopting an appropriate modulation format (e.g., Dual Polarization Quadrature Phase Shift Keying (DP-BPSK) [XPDY12]), each spectrum slot has a capacity of 12.5 Gb/s. The full capacity of a transmitter is 100 Gb/s which supports 8 frequency slots. The guard band size is assumed to be 2 frequency slots [ZLM12]. In addition, according to the asymmetric nature of today's Internet traffic uni-directional connections between end nodes were considered. The traffic generation follows a Poisson distribution process, so that different offered loads are obtained by keeping the mean Holding Time (HT) of the connections constant to 200s, while modifying their mean Inter-Arrival Time (IAT) accordingly (i.e., offered load = HT/IAT). Traffic demands for each source-destination pair are randomly generated by normal distribution over the range of 12.5 Gb/s (1 frequency slot) to 100 Gb/s (8 frequency slots). The average traffic demand is used to study the relationship between aggregation efficiency and service granularity.

Regarding the traffic load, a load from 5 up to 10 Erlang per node have been offered (total offered traffic to the network ranging from 70 to 140 Erlang). The average demand of each connection request is assumed to be 55 Gb/s. Hence, the total traffic generated per node ranges from 275 Gb/s to 550 Gb/s in this study. In addition, 10 transmitters per node are assumed. As stated previously, having enough number of parallel splitting sections in

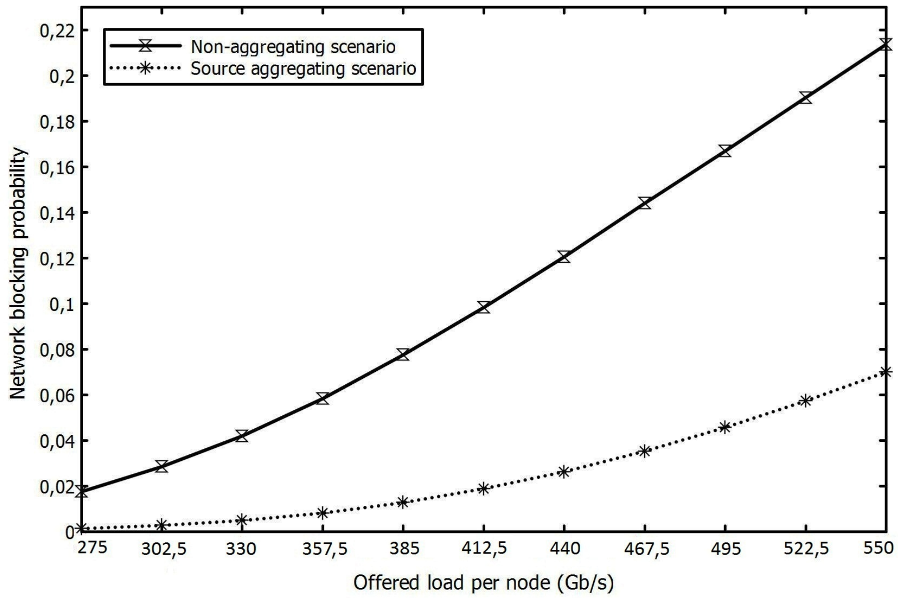


FIGURE 4.5: Network blocking probability for different offered loads.

the proposed structure to avoid any collision is crucial. Considering the current topology and traffic values, as mentioned previously, initially two parallel splitting sections per node are assumed. It is worth to mention that this configuration leads to significantly cheaper network nodes compared to existing node architectures. That is, by taking the average nodal degree of NSFnet topology (which is 3) into account and considering one BV-WSS per output port in a B&S node architecture, the relative cost of current network nodes is reduced by 33% using the proposed node architecture. More detailed evaluation to find the optimum number of parallel splitting sections per node is presented later in this chapter.

Figure 4.5 shows the network blocking probability achieved in both source aggregating and non-aggregating scenarios. From the results, we observe that source aggregation case outperforms the non-aggregating scenario in the entire offered load range. For example, it achieves about one order of magnitude improvement for heavy loads (550 Gb/s per node) with respect to the non-aggregating scenario (the solid line). Indeed, besides increasing the transmitter capacity usage and providing more flexibility for establishing connections over the network, there is another reason for this significant improvement: the proposed algorithm can arrange aggregated connections together as much as possible, which leads to lower spectrum fragmentation [PJJW11] and thus more possibilities for establishing new connections over the network.

Figure 4.6 shows the effect of traffic granularity on the performance of the aforementioned scenarios for a fixed offered load per node of 7 Erlang (i.e., medium load network scenario). We observe that the source aggregating scenario achieves significant blocking probability reduction compared to non-aggregating case for small traffic demands per connection request. The reason is that finding non-fully used transmitter capacities for aggregating

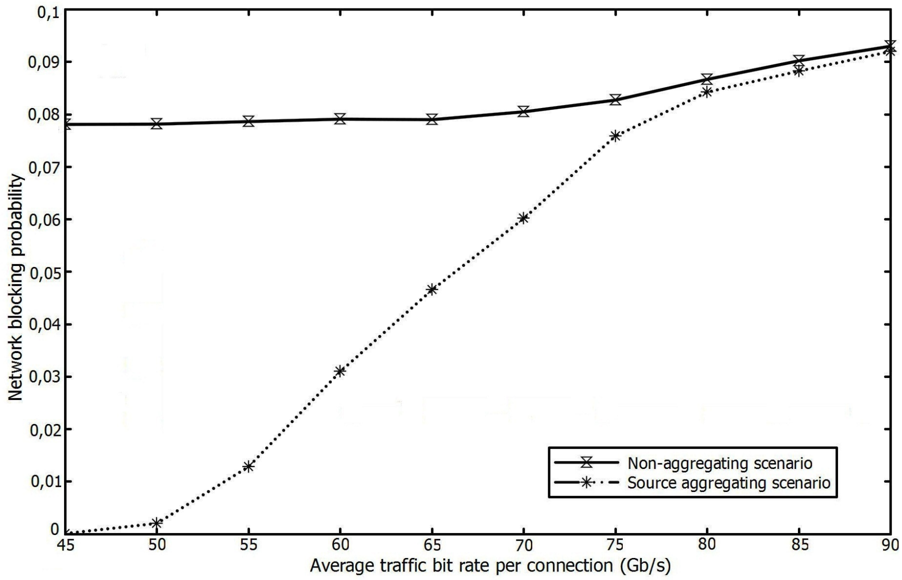


FIGURE 4.6: Network blocking probability for different average traffic bit rates.

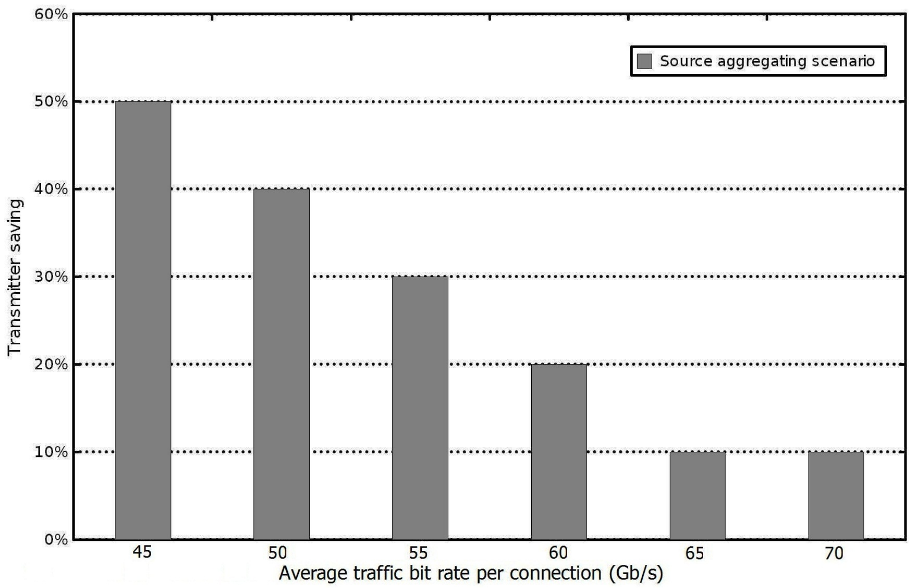


FIGURE 4.7: Transmitter savings for different average traffic bit rates.

traffic demands is easier in this region. As stated previously, the number of aggregated connections in a transmitter is limited by its maximum capacity. Thus, the blocking probability of network increases as the traffic demand per connection request grows. For average bit rate requests greater than 70 Gb/s, we observe that all results converge together. In this case, no extra spectrum savings can be achieved by the proposal, since all connections are served with separate transmitters.

Figure 4.7 illustrates the transmitter savings of the source aggregating scenario versus the non-aggregating scenario for total generated traffic per node ranging from 315 Gb/s to 490 Gb/s (considering the same offered traffic per node of 7 Erlang as pervious case). According to the results, source aggregation can reach the same blocking probability performance

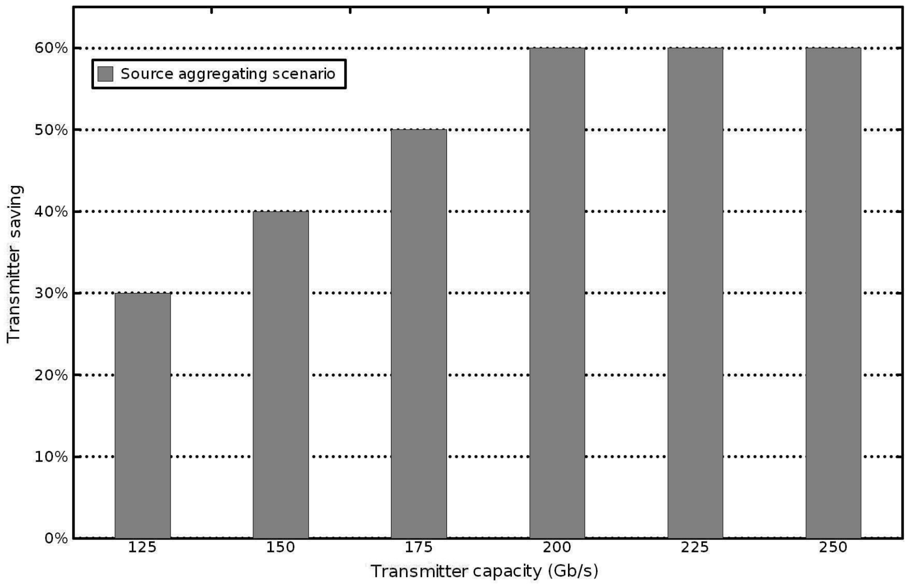


FIGURE 4.8: Transmitter savings for different transponder capacities.

as non-aggregating scenario, while it achieves 50% transmitter savings under low traffic load (i.e., for obtaining similar blocking probability performance as non-aggregating scenario, just half number of transmitters per node is required using the proposal). Similarly to the previous study, this result shows that aggregating connections in one transmitter cannot provide significant benefits for high traffic loads (bit rate demands greater than 70 Gb/s per connection).

Figure 4.8 compares the transmitter savings using source aggregating algorithm for different transmitter capacities under the fixed offered load (385 Gb/s) condition. We observe that for similar blocking probability performance, the transmitter savings grow as the transmitter capacity increases, since more traffic demands can be aggregated. However, when the transmitter capacity reaches a certain threshold no extra savings can be achieved. This is because all the same-source connections have already been aggregated together. This result shows that selecting an appropriate capacity value of transmitters should be carefully considered during the network design.

So far, we have seen the benefits of applying the dynamic aggregation of same source but different destination sub-wavelength connections in elastic optical networks. However, as mentioned previously, the performance and feasibility analysis of the proposal needs more efforts, which are addressed in the rest of this chapter. One crucial step is to select an appropriate network model. In light of this, in the next section, the network model which is used for this purpose is initially introduced. Then, the results of evaluations which have been obtained through extensive discrete event simulation studies are presented.

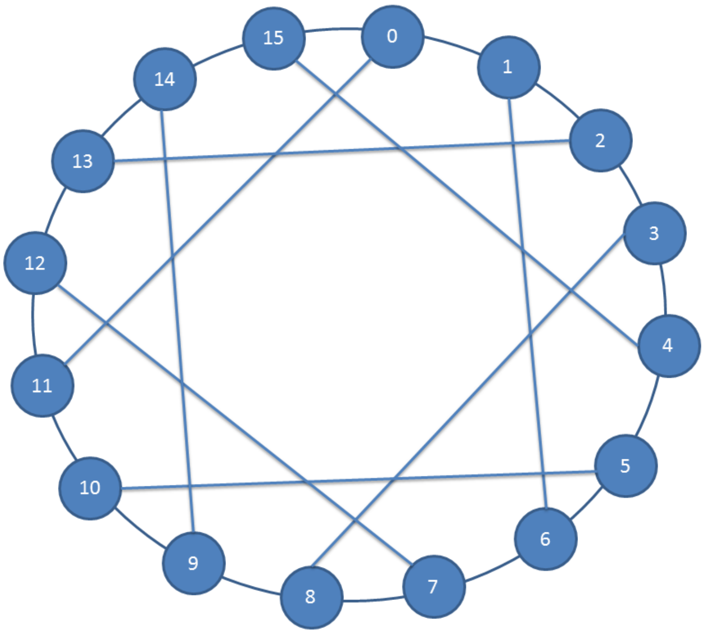


FIGURE 4.9: 16 node $D3T(1, 15, 5)$ chordal ring network.

4.5 Nodal degree and the performance of source aggregation

The main objective of this section is to investigate the role of nodal degree on the effectiveness of source aggregation. Besides this, the influence of network size in terms of number of nodes on the performance of the proposal is also studied. Keeping these two objectives in mind, the selection of the network model becomes a crucial task. One good option is the chordal rings topology [RFL05]. Based on this possibility, in this section, 3 different families of chordal rings with nodal degrees between 3 and 5 are considered. Each member of a family may consist of different number of nodes but all of them have the same nodal degree. A general degree three topology family is represented by $D3T(w1, w2, w3)$ and it is basically a bi-directional ring network, in which each node has a link to the previous node, a link to the next node and an additional bi-directional link. $w1$,$w2$, and $w3$ are called chord lengths. The number of nodes (N) in a chordal topology is assumed to be even, and they are indexed as $0, 1, 2, ..., N-1$. Each odd-numbered node i ($i = 1, 3, ..., N-1$), in addition to its next $((i+1)\ mod\ N)$ and previous $((i+(N-1))\ mod\ N)$ nodes, is connected to a node $(i+w)\ mod\ N$, where w is a positive odd number. Considering the general notation of the degree three topology, a chordal ring family is simply represented by $D3T(1, N-1, w)$.

In a more general form, for a given nodal degree n, each odd-numbered node i ($i = 1, 3, ..., N-1$) is connected to the nodes $(i + w1)\ mod\ N$, $(i + w2)\ mod\ N$, ..., $(i + wn)\ mod\ N$, where the chord lengths, $w1, w2, ..., wn$ are assumed to be positive odd, with $w1 \leq N-1, w2 \leq N-1, ..., wn \leq N-1$, and $wi \neq wj$, $\forall i \neq j$ and $1 \leq i, j \leq n$. In this sense, the general degree n topology family is represented by $DnT(w1, w2, ..., wn)$.

Figure 4.9 shows an 16 node $D3T(1, 15, 5)$ chordal ring network as an example. As it is illustrated, in this example the nodal degree of all nodes is 3.

4.5.1 Performance evaluation

Once again the performance of the proposed FPA source aggregation algorithm is evaluated through extensive discrete event simulation studies. The obtained results are compared with the non-aggregating scenario (i.e., a conventional elastic optical network using a k-Shortest Path computation algorithm with a First-Fit slot assignment, starting with the shortest computed path [CTV10b]). Chordal ring family of $D3T(1, 15, 5)$, $D4T(1, 15, 5, 13)$ and $D5T(1, 15, 7, 3, 9)$ have been selected for this purpose. As mentioned previously, the nodal degree in these families are 3, 4 and 5, respectively. 16 nodes in each network is considered. Total optical spectrum of 1.5 THz per link and the spectrum slot size of 12.5 GHz is assumed [JTK+09c]. As mentioned earlier, by adopting an appropriate modulation format (e.g., DP-BPSK [XPDY12]), each spectrum slot has a capacity of 12.5 Gb/s. The full capacity of a transmitter is 100 Gb/s, so it supports 8 frequency slots. The guard band size is assumed to be 2 frequency slots [ZLM12]. In addition, according to the asymmetric nature of today's Internet traffic uni-directional connections between end nodes were considered. The traffic generation follows a Poisson distribution process, so that different offered loads are obtained by keeping the mean HT of the connections constant to 200s, while modifying their mean IAT accordingly (i.e., offered load = HT/IAT). Traffic demands for each source-destination pair are randomly generated with normal distribution over the range of 12.5 Gb/s (1 frequency slot) to 100 Gb/s (8 frequency slots). The average traffic demand is used to study the relationship between aggregation efficiency and service granularity.

Regarding the traffic load, values from 4.5 up to 6 Erlangs per node (total offered traffic to the network ranging from 72 to 96 Erlangs) have been offered. The average demand of each connection request is assumed to be 55 Gb/s. Hence, the total traffic generated per node ranges from 247.5 Gb/s to 330 Gb/s in this study. In addition, 10 transmitters per node are assumed. As stated previously, having enough number of parallel splitting sections in the proposed structure to avoid any collision is crucial. In light of this, in the first study, the main focus is on the influence of the number of parallel splitting sections in the performance of the proposed FPA source aggregation algorithm.

In order to quantify the benefits due to the increase of parallel splitting sections, the splitting section gain $G(i, j)$, is defined as follows:

$$G(i, j) = [(BP(i) - BP(j))/BP(i)] \times 100 \quad (4.1)$$

where $BP(i)$ is the network blocking probability in the network with i parallel splitting sections per node and $BP(j)$ is the network blocking probability of the same network but

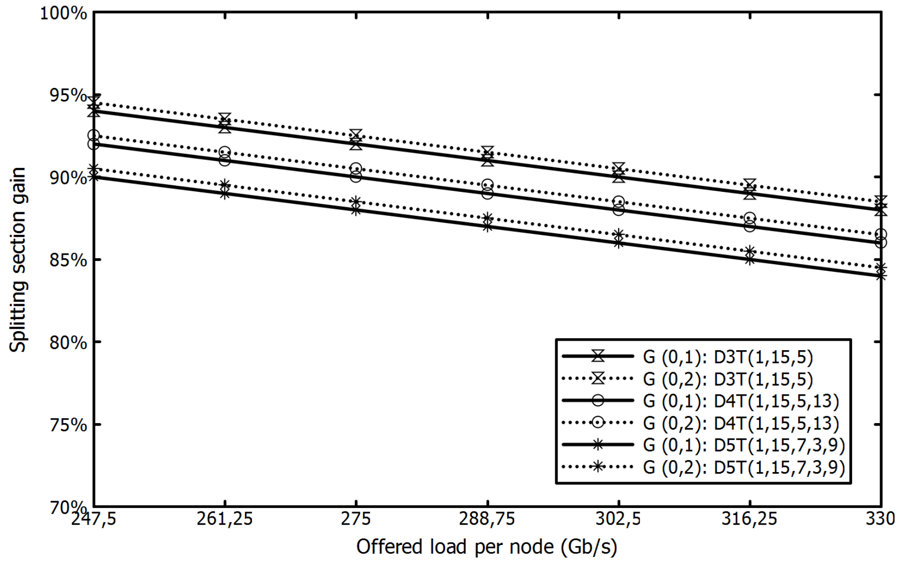


FIGURE 4.10: Splitting section gain due to the increase of the number of parallel splitting sections per node from 0 to 1 and from 0 to 2 in three different topologies with 16 nodes and nodal degrees ranging from 3 to 5, as function of offered load per node.

with j parallel splitting sections per node (same total spectrum per link, same number of nodes, etc). In simple words, $G(i,j)$ shows the changes in the network performance in terms of blocking probability by increasing the number of parallel splitting sections per node from i to j.

Figure 4.10 shows the splitting section gain achieved in three different topologies with 16 nodes and nodal degrees ranging from 3 to 5, $D3T(1,15,5)$, $D4T(1,15,5,13)$ and $D5T(1,15,7,3,9)$ respectively. From the results, we observe that by changing the number of parallel splitting sections in the proposed shared splitting node architecture from 0 to 1 significant improvement in the blocking probability of networks under study is achieved. This is quite reasonable conclusion, since with 0 splitting sections per node (standard EON), it is not possible to realize source aggregation in the network (as mentioned previously, the First-Fit slot assignment is applied in the standard EON case). By introduction of at least one splitting section in the network nodes, realization of source aggregation becomes possible which increases the transmitter capacity usage and provides more flexibility for establishing connections over the network. As illustrated in Figure 4.10, introduction of more parallel splitting sections per node can slightly change the performance of the network. Therefore, it can be inferred that one splitting section per node is sufficient to keep the performance and cost of the node in a reasonable level. To better quantifying the cost reduction, one can easily compare the cost of already available *B&S* node architecture with the proposed shared architecture. To do so, by taking the nodal degree of networks under study into account and considering one BV-WSS per output port in a B&S node architecture, the relative cost reduction using the proposed node architecture is calculated as follows:

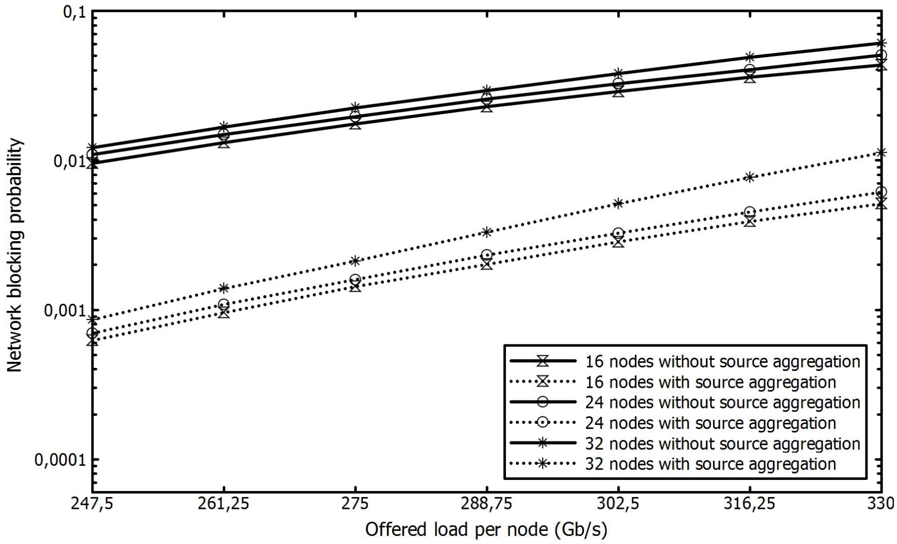


FIGURE 4.11: Network blocking probability for different offered loads in the topology family of $D3T(1, 15, 5)$ with 3 different number of nodes 16, 24 and 32.

$$Cost\ reduction = [(N_{B\&S} - N_{Shared})/N_{B\&S}] \times 100 \tag{4.2}$$

where $N_{B\&S}$ is the number of BV-WSS in the B&S node architecture and N_{Shared} is the number of parallel splitting sections in the proposed node architecture (which is 1 according to the above discussion). Considering the equation 4.2, the relative cost is reduced by 66% in the case of $D3T(1, 15, 5)$ ([(3-1)/3] $\times$ 100), 75% in the case of $D4T(1, 15, 5, 13)$ ([(4-1)/4] $\times$ 100) and 80% in the case of $D5T(1, 15, 7, 3, 9)$ ([(5-1)/5] $\times$ 100) using the proposed node architecture. Based on this discussion, the number of splitting sections per node in the proposed node architecture is fixed on one for the rest of this study.

Figure 4.11 shows the bandwidth blocking probability achieved in both source aggregating and non-aggregating scenarios for the topology family of $D3T(1, 15, 5)$ with 3 different number of nodes 16, 24 and 32. From the results, we observe that the source aggregation case outperforms the non-aggregating scenario in all three study cases and the entire offered load range. For example, it achieves about one order of magnitude improvement for light loads (261.25 Gb/s per node) with respect to the corresponding non-aggregating scenarios (the solid line). It is worth to mention that by increasing the number of nodes in the network, the relative improvement in the performance of the network decreases. The reason is that in such network the chance for having long distance connections (connections spanning more hops) is increased. Considering the existence of spectrum fragmentation in network links, the proposed algorithm cannot aggregate connections as it did in smaller networks.

Figure 4.12 shows the effect of traffic granularity on the performance of the aforementioned scenarios for a fixed offered load per node of 5 Erlang (i.e., medium load network scenario)

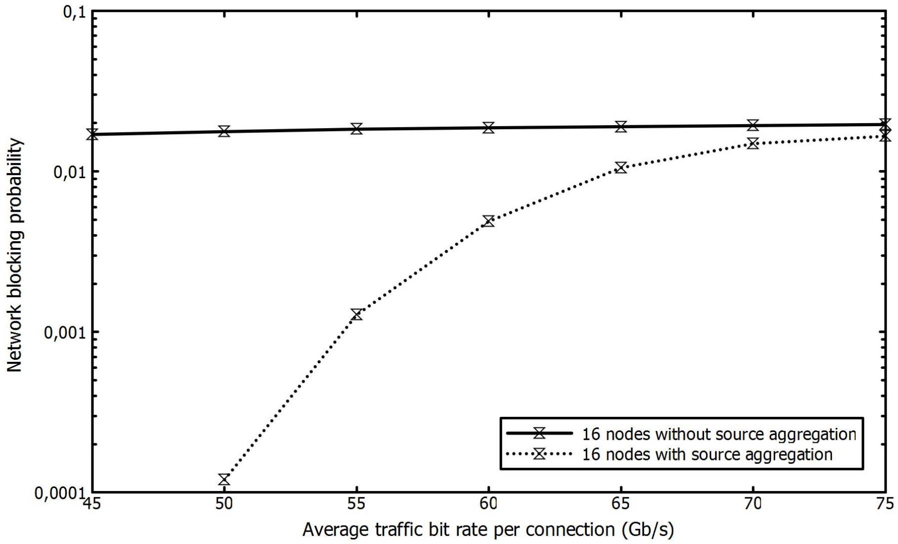


FIGURE 4.12: Network blocking probability for different average traffic bit rates in the topology family of $D3T(1, 15, 5)$ with 16 nodes.

in the $D3T(1, 15, 5)$ topology with 16 nodes. We observe that the source aggregating scenario achieves significant blocking probability reduction compared to non-aggregating case for small traffic demands per connection request. The reason is that finding non-fully used transmitter capacities for aggregating traffic demands is easier in this region. Previously we stated that the number of aggregated connections in a transmitter is limited by its maximum capacity. Thus, the blocking probability of network increases as the traffic demand per connection request grows. For average bit rate requests greater than 70 Gb/s, we observe that all results converge together. In this case, no extra spectrum savings can be achieved by the proposal, since all connections are served with separate transmitters.

Figure 4.13 illustrates the relative cost savings of the source aggregating scenario versus the non-aggregating scenario in the $D3T(1, 15, 5)$ topology with 16 nodes and for total generated traffic per node ranging from 225 Gb/s to 350 Gb/s (considering the same offered traffic per node of 5 Erlang as pervious case). According to the results, source aggregation can reach the same blocking probability performance as non-aggregating scenario, while it achieves 50% transmitter savings under low traffic load (i.e., for obtaining similar blocking probability performance as non-aggregating scenario, just half number of transmitters per node is required using the proposal). Similarly to the previous study, this result shows that aggregating connections in one transmitter cannot provide significant benefits for high traffic loads (bit rate demands greater than 70 Gb/s per connection).

According to this result, source aggregation achieves significant transmitter savings of 10% - 50% respecting to the non-aggregating scenario. Adding this value with the 66% nodal cost reduction comparing to the available B&S architecture, made the presented proposal an effective and cost efficient solution to improve spectrum utilization in EONs.

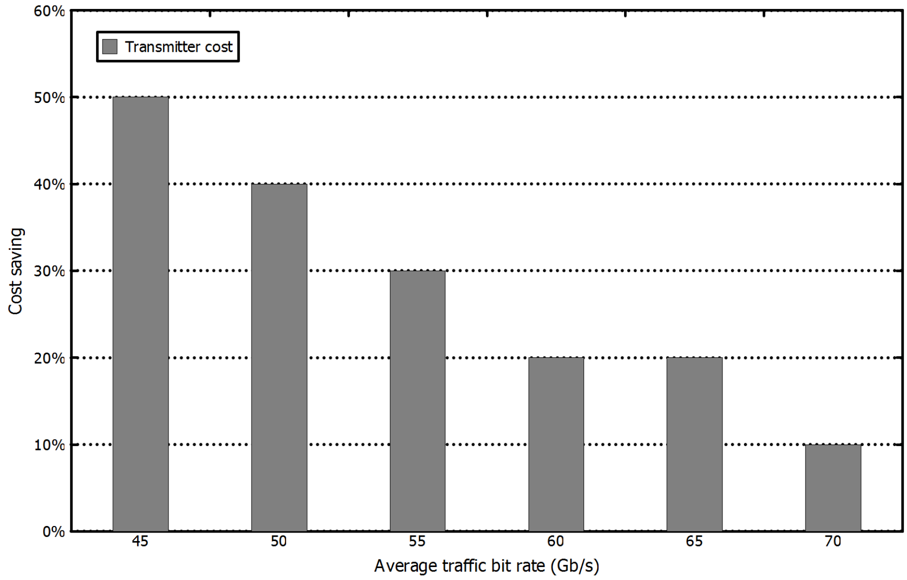


FIGURE 4.13: Relative cost savings for different average traffic bit rates in the topology family of $D3T(1, 15, 5)$ with 16 nodes.

4.6 Chapter summary

In elastic optical networks, heterogeneous traffic demands are typically supported by a single type of BV transmitters, which is not always spectrum and cost efficient. In light of this, the current chapter has introduced the aggregation of same source but different destination sub-wavelength connections for EONs, aiming to obtain both transmitter and spectrum usage savings. Heretofore, much effort has undertaken the realization of such an idea in a cost effective manner. However, almost no works have been successful. The complexity and inefficiency of proposed algorithms plus the cost of equipment-level requirements were the main obstacles. As a matter of fact, providing a cost-effective way (especially for sub-wavelength traffic demands) to realize the idea of source aggregation needed more research and analysis.

To begin, this chapter has initially reviewed the principles and benefits of the source aggregation proposal. There, it has been highlighted that the basic idea of source aggregation is to group multiple connections with same source into one transmitter and switch them as a whole over the network. Spectrum savings as well as better transmitter capacity utilization are the main achievements of the proposal. Also it has been shown that at the end of common route portion, the necessary guard bands are added at both sides of the individual connections, once extracted from the optical tunnel.

To realize the proposed source aggregation functionality, some capabilities should be added to the network nodes. The only available solution in the literature, B&S architecture, has been reviewed with enough detail in this chapter. As it has been highlighted, this solution was not cost effective. To provide an alternative cheaper solution, the proposed shared splitting architecture has been introduced. In this architecture, the number of necessary BV-WSS per node is reduced significantly leading to considerable cost and energy savings in the network nodes. In addition, the spectral penalty due to optical signal splitting has been minimized, since the shared section splits the optical signal in an on-demand fashion.

Moreover, in this chapter a novel dynamic source aggregation algorithm (i.e. FPA algorithm) which supports grouping of multiple sub-wavelength connections with the same source into a single transmitter has been introduced. In contrast to the previous solutions, the FPA algorithm removed the need of pre-reserving spectrum portions of high-capacity transmitters in order to allocate possible future connections. As a matter of fact, by introduction of this proposal, an easy and straightforward way to realize source aggregation functionality has been provided.

Performance evaluations were made to compare the spectrum usage and transmitter saving benefits of source aggregation and non-aggregating scenarios. Besides this, the feasibility and performance of the dynamic source aggregation algorithm has been verified. Our results show that source aggregation achieves significant transmitter and cost savings, with better or equal spectrum utilization compared to non-aggregating case.

Chapter 5

Intelligent defragmentation: periodicity vs. traffic granularity

While elastic optical network technologies have emerged as promising solutions for future ultra-high speed optical transmission, the unavoidable spectral fragmentation problem that appears in such networks significantly degrades their performance. As a matter of fact, upon tear down of connections in EONs, their allocated spectral resources are released, and could be assigned to new connection requests. In a dynamic traffic scenario, the random connection arrival and departure process in the network leads to the fragmentation of the spectral resources. Therefore, in medium and high loaded network scenarios, the possibility of finding sufficient contiguous spectrum to establish a connection over such fragmented spectrum can be very low, leading to connection request blocking despite having enough, but non-contiguous, spectrum resources. In light of this, there is an increasing demand from network operators to be able to periodically reconfigure their networks, aiming to improve the spectrum utilization [CTV10a]. This operation is called spectrum defragmentation.

During the defragmentation operation, the available fragmented spectrum bands are consolidated by reconfiguring active connections, i.e., changing their routes, or assigning them a different portion of spectrum or both, while maintaining the imposed continuity and contiguity constraints [WM12]. However, the traffic granularity, namely, the offered load to the network and the average bit-rate of the connections, has a direct effect on the spectrum fragmentation experienced at network links. Such effect can also affect the efficacy of a periodic spectrum defragmentation to keep an acceptable network performance. In particular, a deep analysis of the relationship between the traffic granularity and the defragmentation periodicity can allow a network operator to find the optimal defragmentation interval yielding the desired network performance, but requiring the minimum active connection disruptions and network control and management burden.

In light of this, the present chapter focuses on analyzing the correlation between the optimal (i.e., minimum) spectrum defragmentation periodicity in the network with the

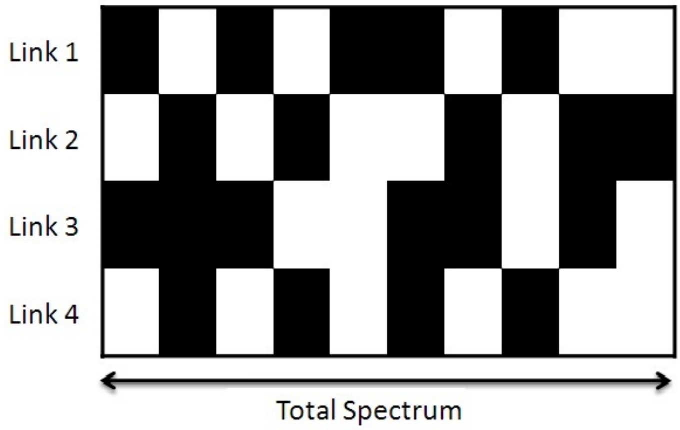


FIGURE 5.1: Scattered spectral fragments in four links of a typical EON.

granularity of the supported traffic. For this purpose, a novel algorithm for efficient spectrum defragmentation is initially introduced. The proposed algorithm aims to consolidate the available fiber spectrum as much as possible, while limiting the number of re-allocated active connections. Then, supported on extensive simulation results, it is shown that the spectral defragmentation periodicity can be effectively configured by having knowledge of the offered traffic granularity.

5.1 Spectral defragmentation

As mentioned earlier, in a dynamic scenario, the spectral resources allocated to connections are released for future requests upon tear down. The randomness in the connection setup and tear down processes leads to fragmentation of the spectral resources in the network. Figure 5.1 shows scattered spectral fragments in four links of a typical elastic optical network. As shown, the available spectrum in the network links is fragmented into small non-contiguous spectral bands. The spectrum fragmentation significantly decreases the probability of finding enough contiguous spectrum for establishing new incoming connections, especially those traversing multi-hop paths (e.g., traversing links 1 to 4 in Figure 5.1) and/or requesting large amounts of bandwidth. In fact, new connection requests can be blocked in spite of having enough spectral resources if these are non-contiguous. Since an efficient utilization of the limited spectral resources in the network is an important issue for network operators, this problem has grabbed the research community attention. To address it, the proposal of spectral defragmentation strategies has appeared in the literature [GYK+11, THS+11a, WYGY11, YWG+12]. In general, spectral defragmentation means arranging the spectral resources in order to consolidate the available spectral fragments contiguously, so that they can be used for serving new incoming connection requests. Spectral defragmentation reduces connection blocking probability, and maximizes the service capacity of the network. In addition, it enables better network maintenance, more efficient network restoration and enhances the quality of service for a given spectral capacity.

In a very general perspective, the defragmentation operation can be realized following two main approaches, periodic and dynamic. The goal of the periodic approach is to confine all occupied spectral resources in the network to one side of available optical spectrum in certain time intervals. In this sense, the periodic defragmentation requires to have knowledge of entire network at each operation event. By the periodic occurrence of defragmentation operation the overall level of spectrum fragmentation in the network decreases. Despite this achievement, such an operation poses a considerable amount of processing task on the network control plane. In the second approach, the defragmentation process is reactively triggered to avoid the blocking of incoming connections. In this case, spectral defragmentation is performed on some links of the network instead of entire network, each time. This significantly reduces the number of required processing task per defragmentation event.

Moreover, to realize connection re-allocations in both previously mentioned approaches, two main mechanisms are commonly used: 1) end-to-end connection re-allocation and 2) partial re-allocation of connection using wavelength converters. In the first mechanism, a connection or a bunch of connections that are needed to be re-allocated in the defragmentation process are entirely moved from their original to new spectrum portions. These new assigned portions of spectrum may either be in the current path of connection or in a new path between the end nodes of connection. In either case, for each connection re-allocation, it is necessary to satisfy both continuity and contiguity constraints. As a matter of fact, the end-to-end connection re-allocation grantees cost and energy efficiency of defragmentation process in the expense of increasing its complexity. In contrast, it is possible to use wavelength converters in order to partially re-allocate a connection along its path. In this sense, to consolidate the spectrum of a link or links, instead of reallocating the entire connection between its end nodes, the necessary portion of connection is only re-allocated over the desired link or links. At the end of defragmented region, the spectrum of connection is returned to its original state using another wavelength converter. Once again it is very important to take both continuity and contiguity constraints into account for each re-allocation. In this way, the complexity of process reduces significantly. However, to realize such an idea, it is necessary to equip all network nodes with the expensive active optical devices (i.e. wavelength converters).

Authors in [PJJW11] introduced the spectral defragmentation problem for the first time. They formulated it and proposed heuristic algorithms for spectral defragmentation operation. A scalable node architecture for realizing the spectral defragmentation proposal was also presented in [GYK+11] by the same authors. They showed a proof-of-principle experimental demonstration of spectral defragmentation in their studies. These studies clearly illustrated the benefits of spectral defragmentation in reducing the blocking probability of elastic optical networks. However, when the network has to be re-configured to perform defragmentation, existing active connections may be disrupted. Achieving a disruption-minimized spectrum optimization is a major challenge in spectral defragmentation. To address this, a disruption-minimized spectrum defragmentation algorithm in distance adaptive elastic optical networks was proposed [THS+11a], which uses a make-before-break re-routing scheme.

In addition, dynamic on-demand lightpath provisioning using spectral defragmentation was studied in [WYGY11]. A spectral defragmentation algorithm, as well as the corresponding node architectures with wavelength conversion to support on-demand lightpath provisioning was proposed. The same authors continued their work in [YWG+12] by introducing new heuristic defragmentation algorithms based on an auxiliary graph approach for elastic optical networks. Besides, a new routing and spectrum assignment algorithm which maximizes spectrum utilization in elastic optical networks was presented in [SHK+11]. Authors introduced a metric that quantifies the consecutiveness of the common available spectrum slots among relevant fibers. The first test-bed demonstration of an elastic optical network was presented in [SHK+11]. Authors used a real-time adaptive control plane for their test-bed that adjusts the modulation format and spectrum-positioning to maintain high QoS and spectral efficiency. Finally, a field-trial experiment of flexible spectrum switching and spectral defragmentation was presented in [AIZ+11].

The aforementioned studies on the benefits of spectral defragmentation of elastic optical networks show a significant improvement in terms of spectrum efficiency and number of interrupted connections during the reconfiguration operation. However, there is no clear vision on the effects of traffic granularity on the defragmentation operation in a dynamic scenario. Authors in [YZZ+12] focused on the problem from the defragmentation operation interval perspective. They proposed a defragmentation algorithm based on a factor that indicates the occupation of the spectrum in a link or in the network. In this sense, by comparing the proposed factor with a given threshold, their algorithm is able to link the traffic granularity with the defragmentation interval. However, since the threshold is an arbitrary value in this study, and the whole available spectrum of network links is not considered for calculating the defragmentation factor, there is still a long way to go before really finding a correlation between traffic granularity and spectral defragmentation. In this chapter, the deep analysis of such correlation is targeted. For this purpose, a novel heuristic defragmentation algorithm, called Iterative-Defragmentation Algorithm (IDA) is initially proposed. The aim of IDA is to increase the network spectrum utilization, while minimizing the number of re-allocated connections during the defragmentation operation. Then, through extensive simulation studies the correlation between traffic granularity and spectral defragmentation process is studied. Such a study can open up a new horizon toward intelligent defragmentation process.

5.2 Iterative defragmentation algorithm

The primary objective of the IDA algorithm is to maximize the consolidation of spectrum, followed by the secondary objective to minimize the number of re-allocated connections during the operation. To achieve the first objective, after establishing a certain number of connections over the network, all existing connections are confined in the lowest part of the spectrum. In this way, the existing connections are processed one-by-one in descending order according to their position in the spectrum (i.e., connections allocated in the highest parts of the spectrum are processed first), also meeting the second objective. The proposed algorithm is as follows:

Iterative-Defragmentation Algorithm:

1. Make a list of all the existing connections in the network and arrange them in descending order based on the connection operating spectrum.
2. Pick up the first connection from the ordered list and record its route in the network.
3. Check the spectrum status of the recorded route in Step 2.
4. If a lower available portion of spectrum is found, re-allocate the connection (in a make-before-break fashion) in the lowest possible part of the spectrum. Else, do not reconfigure the connection and go to Step 5.
5. Pick the next unprocessed connection in the list and repeat steps 2-4.
6. Repeat steps 1-5 for a number of iterations.

All possible existing connections in the network are re-allocated in the lowest available portion of spectrum on their route after the first iteration. However, since the generation of spectral fragments is a random process in a dynamic network scenario, which depends on many factors such as the load offered to the network, average bit-rate demand per connection or average path length, applying only one defragmentation iteration may not result in the higher spectrum consolidation. For example, consider the 3-node simple network shown in Figure 5.2(a) with the initial link spectral state shown in Figure 5.2(b). As seen, there exist some connections in the network with different path length and bandwidth. The defragmentation operation tries to re-allocate existing connections in the lowest available portion of spectrum on their routes. Since some of these connections have smaller spectral requirements and short path length, there is more chance for them to be re-allocated (e.g., connections D or F). Meanwhile, as mentioned before, both continuity and contiguity spectrum constraints should be met when reallocating the connections, making some connections, such as E and G, to have lower defragmentation chances. In the event of defragmentation, existing connections are ordered as follows: G, F, E, D, C,

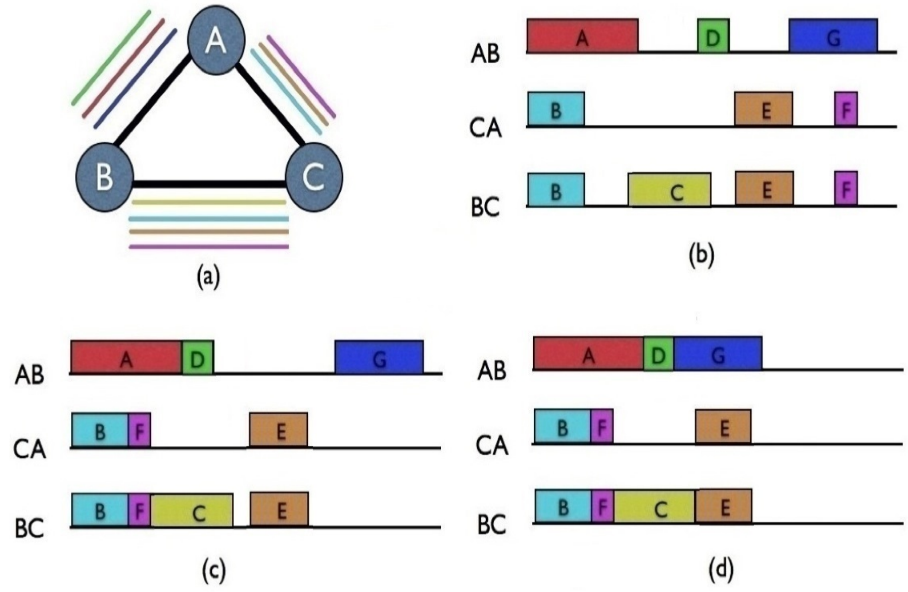


FIGURE 5.2: Illustrative Example (a) 3-node simple network (b) initial link spectral state (c) link after the first iteration (d) link spectral state after the second iteration.

A, B. According to the spectral status, connections F, E, D and C can be re-configured on their paths since all links in their paths (for example (A, B) for connection D and (B, C) for connection C) have sufficient continuous spectrum available at a lower portion of the spectrum. However, connection G cannot be re-allocated due to the spectral conflicts. As shown in Figure 5.2(c), the existing connections are confined after the first iteration; However, it is still possible to consolidate the connections even more. In the second iteration, the ordered list is updated as follows: G, E, C, D, A, F, B. Figure 5.2(d) shows the spectral state of network, in which connections G and E are re-allocated to a lower spectrum portion. As shown, the second iteration optimally confines the existing connections in terms of spectral resources.

The number of re-allocations in the first iteration (Figure 5.2(c)) is 4, while in the second iteration (Figure 5.2(d)) it is 2. In general, by allowing more iterations in IDA, a more consolidated spectrum can be achieved, but at expenses of increasing the network control and management burden. Moreover, since the re-allocation of connections follows a make-before-break approach to avoid connection disruption, which is performed sequentially, the number of iterations impacts directly on the total defragmentation time. With this in mind, the effect of number of iterations on the performance of IDA will be investigated in the next section, together with the analysis of the correlation between traffic granularity and defragmentation periodicity in elastic optical networks.

5.3 Simulation Results

To analyze the correlation between traffic granularity and defragmentation in elastic optical networks, a network scenario where IDA defragmentation is performed on a periodic basis (hereafter referred as periodic defragmentation) is simulated. Moreover, two additional scenarios are simulated for benchmarking purposes: 1) No-defragmentation, namely, a basic elastic optical network scenario without defragmentation capabilities; 2) On-demand defragmentation, where defragmentation is reactively executed upon blocking of an incoming connection request. In this case, considering all possible k-Shortest Paths between incoming connection end-nodes and starting from the first shortest path, the possibility of serving incoming connection request over the kth shortest path (after the re-allocation of those active connections supported on any link along the path) is checked. The first possible shortest path is defragmented. The defragmentation algorithm works identically as IDA, but only selecting those active connections supported on any link along the first possible shortest path. Nonetheless, note here that connections must be re-allocated end-to-end. Hence, although the algorithm focuses on one path only, changes can also affect other network links. Regarding the RSA algorithm for allocating new incoming connections, all scenarios run a typical k-Shortest Path with first-fit slot assignment [CTV10b].

The 14-node NSFnet topology (Figure 4.4) has been selected for the simulations. A total optical spectrum of 1 THz per link is assumed. This spectrum is discretized in units of 12.5 GHz, referred as frequency slots [JTK$^+$09c]. In addition, according to the asymmetric nature of today's Internet traffic unidirectional connections between source-destination nodes are considered. The offered load to the network follows a Poisson process, so that different offered loads are obtained by keeping the mean HT of the connections constant to 200 s, while modifying their mean IAT accordingly (i.e., offered load = HT/IAT). Bit rate demands for each source-destination pair are randomly generated following an exponential distribution over the range from 12.5 Gb/s (1 frequency slot) to 125 Gb/s (10 frequency slots). Hence, we are implicitly considering a signal modulation format with spectral efficiency of 1 b/s/Hz, like Binary Phase Shift Keying (BPSK) [XPDY12]. To start, the defragmentation interval is fixed into 70 in the periodic defragmentation scenario. This means that a network-wide defragmentation is periodically performed every 70 connections established. Nonetheless, also the effect of this parameter on the network blocking probability will be evaluated later on in this section.

As a first study, the focus is put on periodic defragmentation and initially the effect of the number of iterations performed by the IDA algorithm is investigated. The aim of this study is to find such a number of iterations in IDA that effectively reduces the blocking probability in the network, while keeping reasonable the number of re-allocated connections. As mentioned before, more re-allocated connections imply additional network control and management burden, which may not be translated into actual blocking probability reduction.

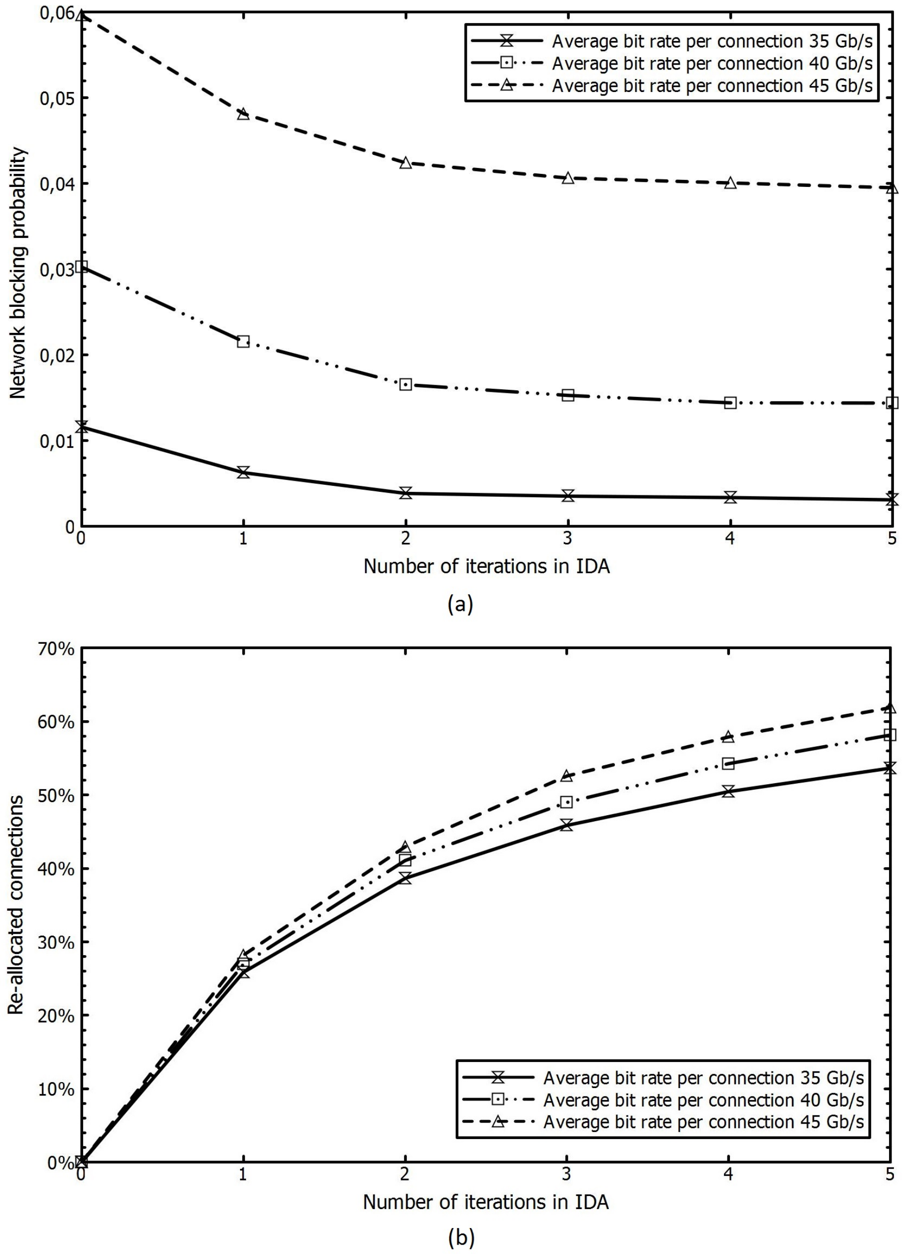


FIGURE 5.3: Effect of the number of iterations on the performance of the proposed IDA algorithm.

Specifically, the load of 14 Erlangs per node (i.e., 14 offered connections per node in average), which makes up a total offered load to the network of 196 is considered. Then, the results for three different average bit-rates per connection, namely, 35 Gb/s, 40 Gb/s and 45 Gb/s, (leading to an average traffic offered per node equal to 490 Gb/s, 560 Gb/s and 630 Gb/s respectively) are extracted. Figure 5.3 (a) shows the blocking probability in the network against the number of iterations in IDA. As seen, by increasing the number of iterations, defragmentation operation is more effective, which helps in decreasing the blocking probability in the network. This is particularly true for 1 and 2 iterations under all average connection bit-rates. From then on, however, blocking probability reduction

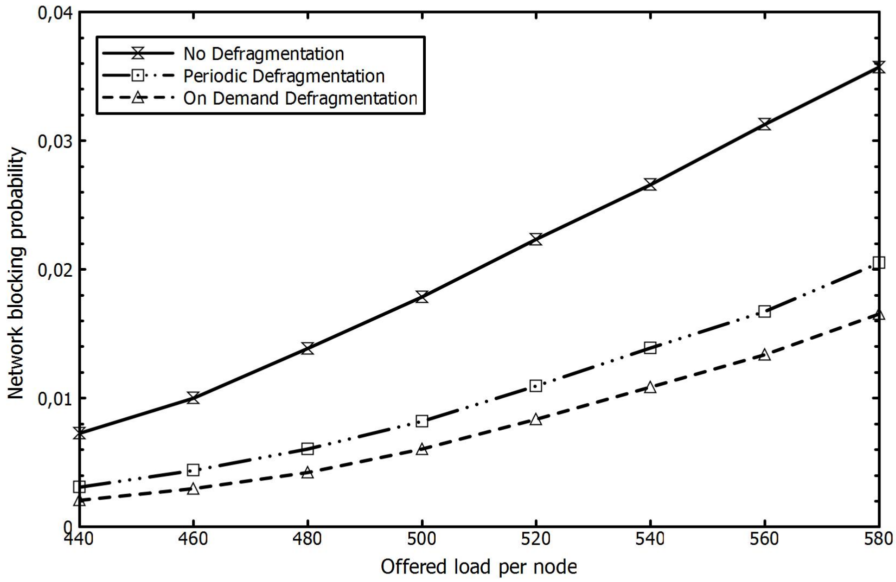


FIGURE 5.4: Network blocking probability for different traffic granularities. The offered load per node varies from 11 to 14.5, with an average bit-rate per connection equal to 40 Gb/s.

becomes marginal with the number of iterations. In Figure 5.3 (b), the percentage of re-allocated connections over the total number of active connections in the entire network is quantified. As shown there, for instance, by changing the number of iterations from 2 to 3, 10% more connections have to be re-allocated, while almost no improvement in terms of blocking probability is experienced. This trend also holds for larger number of iterations. Hence, from now on, we fix the number of iterations in IDA to 2, which allows to significantly reduce the blocking probability in the network with reasonable network control and management overhead.

Figure 5.4 compares periodic defragmentation against no defragmentation and on-demand defragmentation in terms of network blocking probability as a function of the offered load per node. In this study, the offered load per node ranges from 11 to 14.5, with an average bit-rate per connection equal to 40 Gb/s. This is translated into an offered traffic per node ranging from 440 Gb/s to 580 Gb/s. From the results, we observe that on-demand defragmentation outperforms both other cases along the entire offered load range. However, as it is well highlighted in Figure 5.4, there is a slight difference between the results of on-demand and periodic defragmentation. In fact, the observed outcome can be explained by the following two reasons: 1) the network-wide defragmentation versus k^{th} shortest path defragmentation in the periodic and on-demand cases, respectively; 2) the defragmentation interval of 70 in periodic defragmentation. As will be shown later on, this parameter has crucial importance on the performance of the proposed algorithm.

To give further insight into the effects of the offered traffic characteristics on the benefits of network defragmentation, Figure 5.5 compares the network blocking probability achieved by periodic, on-demand and no defragmentation as a function of the average

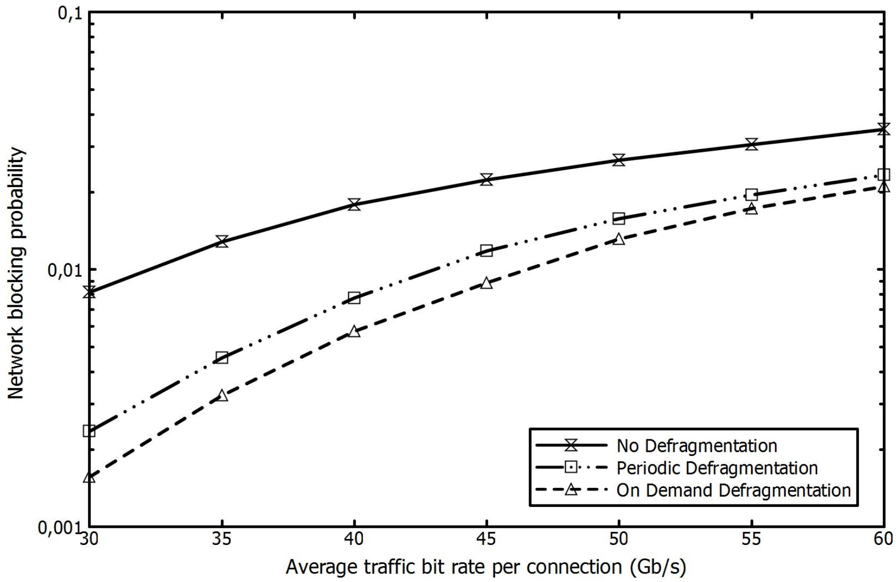


FIGURE 5.5: Network blocking probability for an offered traffic per node equal to 500 Gb/s. The average bit-rate per connection varies from 30 Gb/s to 60 Gb/s, changing the offered load per node accordingly.

bit rate per connection. To produce these results, we have fixed an offered traffic per node of 500 Gb/s in all cases. Hence, higher bit-rates per connection mean lower offered load per node values and vice-versa. As illustrated in the figure, even under the same offered traffic, relative benefits of defragmentation are clearly affected by the actual bit-rates of the connections. For instance, for low bit-rates per connection, almost one order of magnitude blocking probability reduction is achieved by periodic defragmentation against no defragmentation, while such a difference decreases when bit-rates increase. Comparing on-demand versus periodic defragmentation, we can also see that the former slightly outperforms the latter for entire range of study. Again, this is due to the fact that network-wide defragmentation on a periodic basis (every 70 established connections) is almost productive as reactive on-demand defragmentation, especially with low bit-rate connections. Indeed, such differences decrease with the bit-rate per connection, as spectrally wider connections are more difficult to be efficiently re-allocated in general.

As highlighted in previous figure, defragmentation benefits clearly depend on the bit-rate of those connections offered to the elastic optical network. To quantify these benefits, Figure 5.6 illustrates the profitability of defragmentation against no defragmentation for different bit-rates per connection. Only periodic defragmentation is considered here, with 3 different defragmentation intervals, namely, 28, 70 and 280. Furthermore, such a defragmentation profitability is measured as follows: for the evaluated bit-rate per connection we adjust the offered load per node in the network so as to obtain a 2% blocking probability (BP_{ND}) with no defragmentation. Then, we measure the improvement in blocking probability, equal to the steady-state blocking probability with no defragmentation minus the achieved blocking probability with periodic defragmentation (BP_{PD}), all divided by

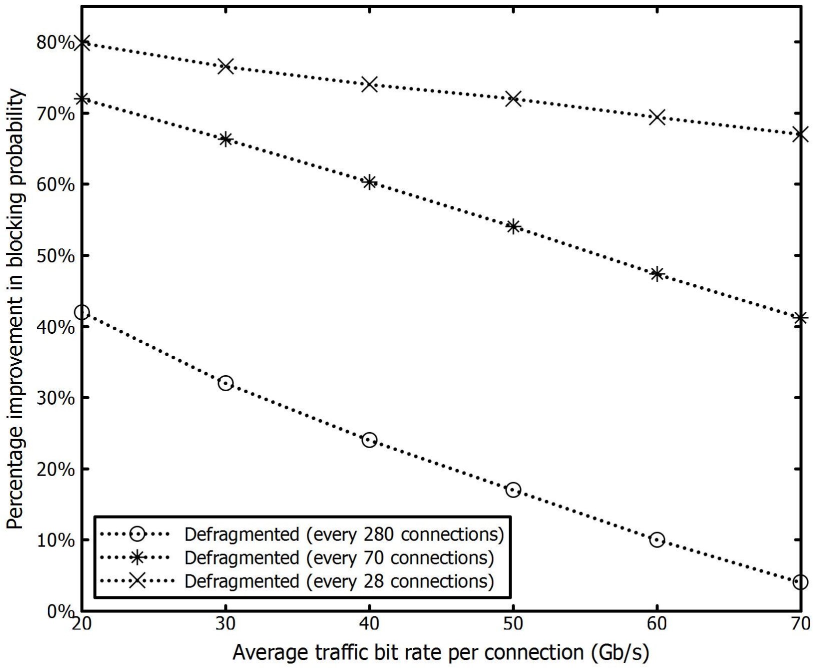


FIGURE 5.6: Percentage improvement in blocking probability for different bit-rates per connection (blocking probability equal to 2% with no defragmentation).

BP_{ND} :

$$Improvement(\%) = [(BP_{ND} - BP_{PD})/BP_{ND}] \times 100 \tag{5.1}$$

Looking at Figure 5.6, the obtained results are very in-line with those in Figure 5.5, showing a periodic defragmentation improvement decreasing as the bit-rate of the connections increase. Moreover, the same behavior is observed no matter the applied defragmentation interval is, although smaller defragmentation intervals (i.e., more frequent defragmentation) seem to moderate this effect. For example, with a defragmentation interval of 280, improvement sharply falls from around 40% in a network scenario with average connection bit-rate of 20 Gb/s, to merely 5% when connection bit-rate increases to 70 Gb/s, even though the offered load in both scenarios is adjusted to equally achieve 2% blocking probability. In contrast, with a defragmentation interval of 28, ten times lower, improvement only decreases from 80% to around 70% when connection bit-rates change from 20 Gb/s to 70 Gb/s, respectively.

Another conclusion that can be extracted from Figure 5.6 is the paramount importance of the defragmentation interval value on the improvements that periodic defragmentation can yield. Indeed, more frequent defragmentation foster improvement in blocking probability, although introducing more control and management burden in the network, as already mentioned. An interesting outcome of this figure, however, is that taking the

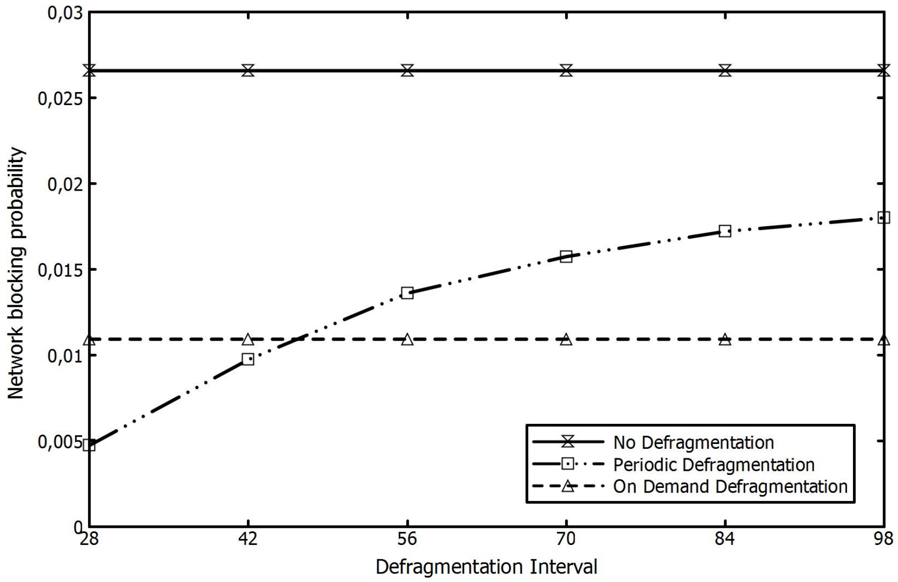


FIGURE 5.7: Network blocking probability against defragmentation interval in periodic defragmentation.

bit-rate of the connections into account, a network operator can intelligently set the periodicity of the defragmentation in the network. For example, to achieve 40% improvement with a bit-rate of 70 Gb/s, a defragmentation interval of 70 is required. Nonetheless, if the bit-rate of the connections appears to be 20 Gb/s, the defragmentation interval can be increased to 280, as only 1/4 of the defragmentation is necessary in this scenario to achieve the same improvement. This could also open the possibility for operators to implement monitoring strategies of the incoming connections bit-rate (e.g., during predefined time periods or a number of connection establishments) to dynamically adjust the defragmentation interval in the network, making a good trade-off between blocking probability and control and management burden.

To round off the discussion, Figure 5.7 shows in more detail the effect of the defragmentation interval on the performance of periodic defragmentation. To this end, a load of 10 per node with average bit-rate per connection of 45 Gb/s has been offered. It leads to blocking probability of 1% with on-demand defragmentation. In such a scenario, the blocking probability versus defragmentation interval for no defragmentation, on-demand and periodic defragmentation is plotted. Of course, the former two behave constant with the defragmentation interval, as their performance does not depend on this parameter. However, they are used in the figure as a benchmark. As shown, when increasing the defragmentation interval, the possibility of successfully re-allocating connections in periodic defragmentation decreases. This could be explained from the fact that the randomness of the connection arrivals and departures creates such a bad network situation during each defragmentation period, that the defragmentation periodically performed cannot re-arrange it in a better way. In any case, periodic defragmentation always stays below no defragmentation for any of the evaluated intervals. Specifically, to get similar performance as on-demand defragmentation (or better), the defragmentation interval has to be set around 50 (or lower). Therefore, provided that defragmentation intervals below 50 are acceptable for a network operator, periodic defragmentation can be a good option against the on-demand one, which has to be forcefully simpler to avoid incoming demands experiencing high establishment delays.

To sum up, while decreasing the defragmentation interval has direct impact on improving the blocking probability in the network, taking into account the bit-rate of the connections can also lead to the same results but with more relaxed defragmentation intervals and, thus, lower network control and management burden. Therefore, it is always crucial to find a tradeoff. In addition, by correlating the defragmentation periodicity to the offered traffic characteristics (offered load and bit-rate per connection), it is possible to trigger the defragmentation process in more intelligent manner. It means that, instead of having blindly selected fixed defragmentation interval for a network during its operation period, it would be possible to dynamically change the defragmentation interval considering the existing offered traffic characteristics. It can be easily translated to cost and energy savings as well as less control plane processing overheads.

5.4 Chapter summary

The recently proposed elastic optical network which provides enhanced flexibility in spectrum allocation and data rate accommodation has opened up a new prospect to serve the future Internet demands more efficiently. However, the inevitable spectral fragmentation problem in such networks significantly degrades their performance. To address the problem, the idea of spectral defragmentation in elastic optical network has been proposed. Assuming a periodic defragmentation scenario, this chapter discussed the effects of the offered traffic characteristics (offered load and bit-rate per connection), as well as the defragmentation periodicity, on the profitability that defragmentation can yield to network operators. Indeed, while decreasing the defragmentation interval has direct impact on improving the blocking probability in the network, taking into account the bit-rate of the connections can also lead to the same results but with more relaxed defragmentation intervals and, thus, lower network control and management burden.

To begin, this chapter has initially reviewed the principles of defragmentation process. There, it has highlighted that the basic idea of defragmentation is to consolidate the occupied portion of spectrum into one side of available optical spectrum in the network. Such a process leads to better spectrum resource utilization as well as better network maintenance, more efficient network restoration and enhances the quality of service for a given spectral capacity. The two commonly used defragmentation approaches have been also discussed. Moreover, famous connection re-allocation mechanisms have been reviewed.

To realize the better defragmentation functionality in the network, a novel algorithm, namely iterative-defragmentation algorithm has been introduced. The proposed algorithm is able to increase the network spectrum utilization, while minimizing the number of re-allocated connections during the defragmentation operation. Considering the iterative-defragmentation algorithm into account and taking both no defragmentation and on-demand defragmentation scenarios as a benchmark, supported by extensive simulation results, it has been shown how spectral defragmentation periodicity can be effectively configured by having knowledge of the offered traffic granularity. Such a study has opened a new horizon for realization of intelligent defragmentation process.

Chapter 6

Efficient time-varying connection allocation

In the previous chapters, we have seen that the RSA problem in elastic optical networks has been widely studied, putting more emphasis on dynamic network scenarios. In a dynamic network scenario connection arrival and departure processes are random and the network has to accommodate incoming traffic in real time. Considering the near future technology advances (e.g., high capacity bandwidth variable transponders) and the exponential increase of network traffic, it is foreseeable to have large intervals between the establishment and the release of connections. Thus, during such relatively long periods, the bit-rate demand of any connection may fluctuate following short- and mid-term traffic variations. Although the EON technology enables flexible adaptation of connections to such time-varying traffic demand changes, the spectrum fragmentation issue prevents high resource utilization in EONs. In light of this, various spectrum defragmentation proposals, requiring the periodic or on-demand re-allocation of connections, have been introduced [GJLY12]. The basic idea behind these proposals is to consolidate fragmented spectrum bands, aiming to increase the probability of finding sufficient contiguous spectrum to accommodate future connection requests over the network. Despite spectrum defragmentation schemes can improve the network efficiency under time-varying traffic, connection re-allocation increases the complexity and cost of the network. Moreover, advanced optical devices like wavelength converters and tunable optical switches are necessary for realizing such proposals, further increasing the complexity and also cost of the network. Finally, it is worth mentioning that a significant amount of control plane signaling messages are required to setup and release lightpaths in the network, which burdens the control plane in the network with additional overhead.

While spectral voids between adjacent connections (due to fragmentation) are traditionally considered as a problem, this statement does not always apply. Indeed, as long as connections required bandwidth may grow over time, free spectral voids are crucial to accommodate additional bandwidth demands without requiring the re-allocation of the already established connections (an existing connection can easily adapt to transmission rate fluctuations if it has free spectral voids around it). In light of this, this chapter focuses on lightpath adaptation under time variable traffic demands in EONs. Specifically, the possibility of utilizing the spectral fragmentation to increase the spectrum allocation capabilities of EONs is explored. In this context, a heuristic spectrum allocation algorithm, which intentionally increases the spectral fragmentation in the network is proposed and validated. In the proposal, the spectrum assigned to each new connection is in the middle of the largest free spectral void over the route, aiming to provide considerable spectral space between adjacent connections. These free spectral spaces are then used to allocate time-varying connections without requiring any lightpath reallocation. The obtained simulation results show a significant improvement in terms of network blocking probability when utilizing the proposed algorithm.

6.1 EONs and time-varying traffic

In this section, initially the problem of serving time-varying connections in EONs is introduced, and then some previous contributions on this topic are reviewed. Next, applicable lightpath adaptation policies are presented.

6.1.1 Time-varying traffic

As previously reviewed, to accommodate traffic in EONs, the total available spectrum is divided into constant spectrum units with a granularity finer than the typical 50-GHz grid used in WDM systems (e.g., 12.5 GHz), referred as frequency slots. For example, 1, 1.5 and 2 THz spectrum correspond to 80, 120 and 160 FSs, respectively. Each FS can carry some bit rate depending on the modulation format used [CTV10b]. For the sake of simplicity, a modulation efficiency of 1b/s/Hz is assumed in this chapter. A connection is served by assigning a route and allocating a set of contiguous FSs on all links along it.

As mentioned in chapter 3, the problem of static RSA received the research community's attention. In this scenario, all the requested connections are given, as a traffic matrix known in advance. Then, connections are served under the constraint that no spectrum overlapping is allowed among them. The solution gives the route and the allocated frequency slots to every connection, while minimizing a given performance metric, such as the total utilized spectrum. Some studies like those in [THS+10, CTV10a, CTV11b] focus on the Routing, Modulation Level and Spectrum Allocation (RMLSA) in EONs. They formulated the problem and proved that it is NP-complete. ILP formulations, as well as heuristic algorithms for solving such a complex planning problem were presented in these studies.

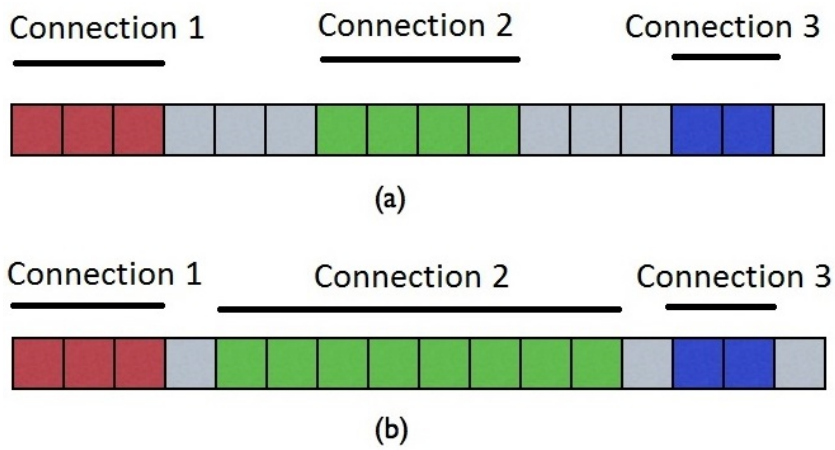


FIGURE 6.1: Spectrum allocation of an exemplary link with time-varying connections. Two different time instances are displayed in (a) and (b). Free frequency slots between adjacent connections are used to accommodate time-varying traffic changes.

While minimizing the total required spectrum for serving a static traffic matrix is important in the planning phase of EONs, there is an increasing need for dynamic lightpath provisioning, as traffic fluctuates over time in current networks. Thus, the community's attention also focused on the dynamic spectrum allocation problem. Authors in [CTV11a] triggered this effort by proposing a general algorithm to assign frequency slots in EONs under dynamic traffic. Meanwhile, they proposed the first distance adaptive dynamic routing and frequency slot assignment in [THS+11b], concluding that the necessary bandwidth for serving connections can be significantly reduced by employing a distance adaptive proposal. In [PJJW11], the dynamic allocation and release of connections ranging from 10 Gb/s to 400 Gb/s were investigated. This study shows that by introducing technologically advanced devices, such as high capacity flexible optical transponders, the holding time of the optical connections in EONs increases significantly. During such a long period, the connection bit rate may vary as a function of the time. Thus, the spectrum allocated to the connection (lightpath) has to flexibly change, so as to adapt to the variation in the requested bit rate. Figure 6.1 presents the spectrum utilization of an exemplary link in an EON with time-varying connections at two different moments. As shown in Figure 6.1(a), connections over the exemplary link carry traffic between different end nodes. A specific set of FS (which are highlighted in the figure) is assigned to each connection. Figure 6.1(b) shows the spectrum utilization of the same link at another instant, where the bandwidth required by connection 2 has doubled. As shown, the number of FS allocated to this connection has changed to adapt to the required transmission rate. It is worth to note that the free frequency slots between adjacent connections are used to accommodate the mentioned traffic change. There exist different policies for such a lightpath adaptation in the literature [CV12, CTV13, PSK+11]. The one used in this chapter is described in the next subsection.

6.1.2 Lightpath adaptation policies

The way how connections adapt their spectrum to the instantaneous required bit rates is called lightpath adaptation policy. Authors in [CV12] and [CTV13] studied for the first time different policies through extensive simulations results. They continued their work in [PSK+11], by introducing some mechanisms to the previously proposed policies, aiming to strike a balance between network blocking probability and the number of re-allocated connections. These policies can be summarized as follows:

- **Constant Spectrum Allocation (CSA):** A fixed number of FS are reserved around each connection. No spectrum sharing is permitted among adjacent connections. No connection re-allocation is permitted.
- **Dynamic Alternate Direction (DAD):** A connection wishing to increase its bit rate alternates between using its higher and lower FS, until it reaches an already occupied slot. If additional slots are needed, the symmetry of the expansion is lost but the connection continues to expand towards the only possible direction. No connection re-allocation is permitted.
- **Avoid Close Neighbors (ACN):** Each connection expands towards the opposite direction of its closest neighboring connection on any of the links along its path. Keeping the same principle, contraction is conducted from the direction of the closest neighboring connection. No connection re-allocation is permitted.
- **Shift-ACN:** This is an enhanced version of ACN that allows connection re-allocation. If there are no available FS in the maximum allowable expansion region, neighboring connections are shifted in a way that maximizes the minimum available FS among all of its neighbors. Note that connection re-allocation is only allowed to direct neighboring connections of the connection requesting a spectrum expansion.
- **Float-ACN:** This is an enhanced version of Shift-ACN. In this version, all connections are free to float in the spectrum as they are pushed by their neighbors. Thus, connection re-allocation is not only restricted to the direct neighboring connections of the connection requesting a spectrum expansion, as it was in the previous case

It is worth to mention that, to avoid traffic interruption during the extension process, hitless techniques such as the push-pull technique in [CSS+12, WM13] are applied.

Considering the aforementioned cases, an enhanced version of the DAD policy, namely Shift-DAD policy is proposed. Note that, since the connections can contract without any extra efforts, here only the extension part of this policy is explained.

Shift-DAD policy:

1. Calculate the necessary number of FSs to satisfy the connection's bandwidth change. Set this number as the required FSs.

2. Count the number of free FSs at both sides of the connection that needs to expand. In case of it less than required FSs go to Step 3, otherwise go to Step 4.

3. Check the spectral status of the path to find the first void with enough FSs to accommodate the connection. If found, re-allocate it. Otherwise, do not extend the connection and add the amount of bandwidth change into the total bandwidth dropped. **Finish**.

4. Check the left side of the connection for a free FS; if it exists, extend the connection by one FS toward the left. Decrease the required FSs by one.

5. If the required FSs are higher than zero, check the right side of connection for a free FS; if it exists, extend the connection by one slot toward the right. Decrease the required FSs by one.

6. If the required FSs are still higher than zero, go back to Step 4. Otherwise, **Finish**.

Similar to the DAD policy, a connection wishing to increase its bit rate alternates between using its higher and lower FSs, until reaching an already occupied slot. If additional slots are needed, the symmetry of the expansion is lost but the connection continues to expand towards the only possible direction. When a connection needs more FSs than those available around it, the connection is re-allocated to the spectrum void with enough bandwidth along the connection's path. Note that, if a void large enough to re-allocate the connection is not found along the path, the entire bandwidth expansion operation is blocked. An alternative to this could have been to permit partial satisfaction of the bandwidth expansion. Nonetheless, this has been left for future study.

In practical cases that use conventional spectrum allocation algorithms such as First Fit, it happens that connections are established very close to each other over the network, aiming to increase the available spectrum for new arriving connections. With these approaches, it is hard to find enough bandwidth around a lightpath to adapt it to its traffic fluctuation. Meanwhile, since the occupied portion of spectrum is compacted in one side of available spectrum (lower side of spectrum), it is possible to have enough FS for serving time varying connections in the upper side of spectrum. Therefore, by re-allocating connections over the network in a hitless fashion, a significant improvement in time-varying traffic allocation can be achieved.

Despite its potential benefits, connection re-allocation increases the complexity and the cost of network. As it was stated before, many advanced photonic devices are needed, as well as a large amount of control plane overhead. In light of this, it is important to find a good trade-off between the successfulness in allocating time-varying connections and network complexity and cost-efficiency.

Moreover, it is worth to highlight that SA algorithms have a great impact on the efficacy of serving time-varying connections in EONs. Indeed, SA algorithms can achieve good arrangement of the connections in the space and frequency domains, thus increasing the possibility of serving and expanding time-varying connections in the network. An appropriate SA algorithm serves the connection requests, by assigning FSs in a way that minimizes the average network blocking probability, taking into account the requirements of the lightpath adaptation policy. To achieve the previously mentioned goals, next section details a novel SA algorithm called Mid Fit.

6.2 Spectrum assignment algorithm

There exist various SA approaches to allocate incoming connections with different bandwidth granularities in EONs [RCC+12]:

- **First Fit:** The connection request is placed in the first spectral gap along its route fitting the requested bandwidth. This algorithm is used for benchmarking purposes in this chapter.
- **Smallest Fit:** The connection request is placed in the smallest available spectral band along its route.
- **Random Fit:** Any available spectrum portion along the route, with enough space to allocate the connection request, can be randomly selected to allocate it.

In contrast, in this chapter a novel heuristic called Mid Fit SA approach is proposed. Its main objective is to maximize the spectral voids between adjacent connections, thus increasing the possibility to successfully serve their potential bandwidth increments. To achieve this goal, after calculating the candidate path between source and destination nodes of the connection request, this one is established in the middle of the largest contiguous spectrum void along the calculated path. Specifically, if multiple same-sized spectral bands exist, the one placed in the lowest part of the spectrum is selected. In this way, the spectral distance between adjacent connections is maximized. The available spectrum left between connections can later on be used to serve connection bandwidth fluctuations. It is worth to mention that lightpath bit rate adaptation can then be realized without any spectrum conversion or re-allocation. This implies a significant reduction in the network cost, complexity and energy consumption. In fact, bit rate fluctuations are allocated by just increasing the bandwidth (number of FSs) assigned to the connection (assuming that the total connection bit rate is lower than the whole capacity of the transmitter).

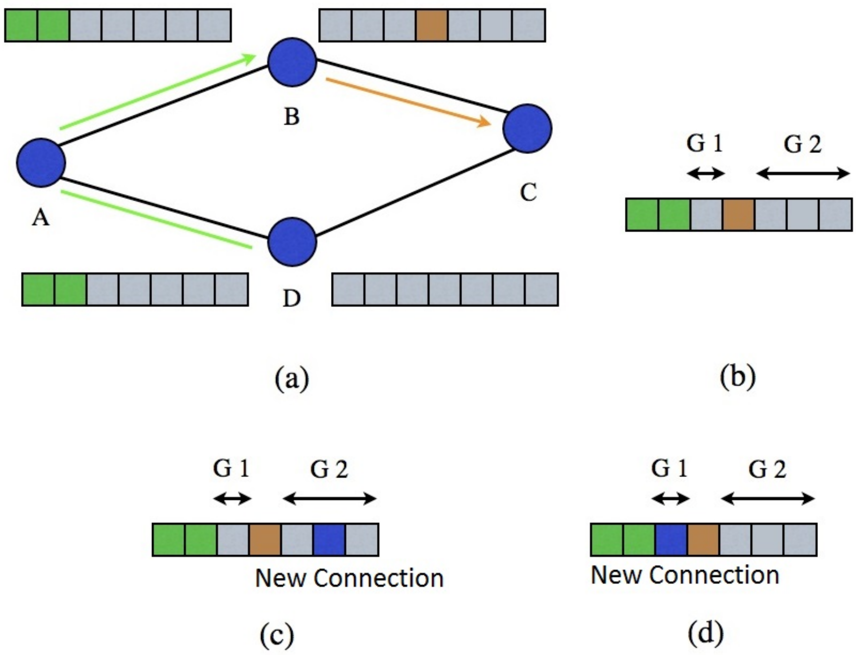


FIGURE 6.2: Illustrative example (a) Simple 4-node network (b) spectral status of the candidate path (c) FS status using the Mid Fit SA approach (d) FS status using conventional First Fit SA.

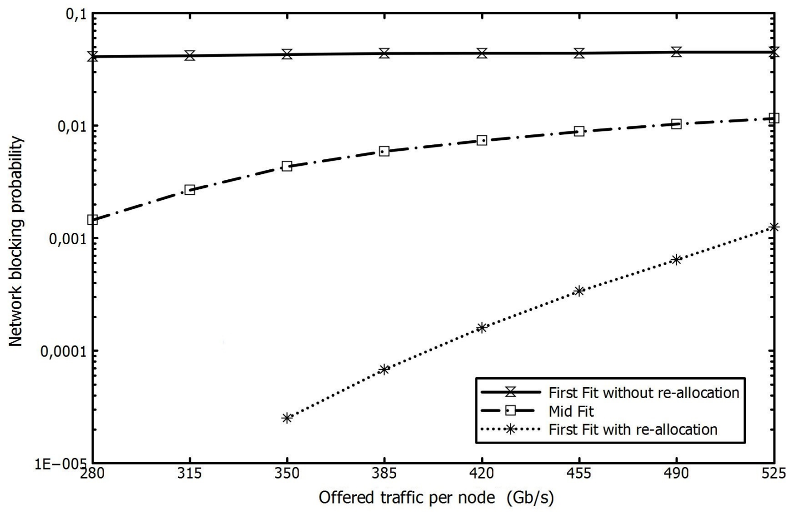
Figure 6.2 illustrates a simple 4-node network, whose current spectral status is shown in Figure 6.2(a). There exist some connections with different path lengths (a 2 FSs connection from D to B and a 1 FS connection from B to C). If a new connection request arrives, for example a 1 FS connection between nodes A and C, the candidate path for establishing the connection is firstly calculated. Let us assume that this path consists of links AB and BC. The spectral status of this candidate path is shown in Figure 6.2(b). As illustrated, there exist two spectral voids in the spectrum of the candidate path, G1 and G2. According to our proposal, the Mid Fit algorithm assigns the central FS of G2 to the connection, as shown in Figure 6.2(c). The free frequency slots between existing connections are used to serve data rate fluctuations. By applying this spectral allocation strategy the bit rate of the connection can be doubled and even triplicated in the future without any need for connection re-allocation. That is, bit rate fluctuations are accommodated in the network by only increasing the bit rate of transmitters (assuming that the final bit rate is less than the whole capacity of the transmitter).

In contrast, let us consider a conventional SA algorithm such as First Fit for spectrum allocation in this example. After calculating the candidate path, the first gap with enough FSs (G1) is selected for establishing the new connection request, as shown in Figure 6.2(d). Hence, since there is no space between adjacent connections, there is no chance for serving the connection data rate fluctuations without re-allocating it. Indeed, it could be possible to accommodate the connection in the network upon expansion (i.e., over spectral void G2). However, re-allocation would have to be unavoidably employed in this case.

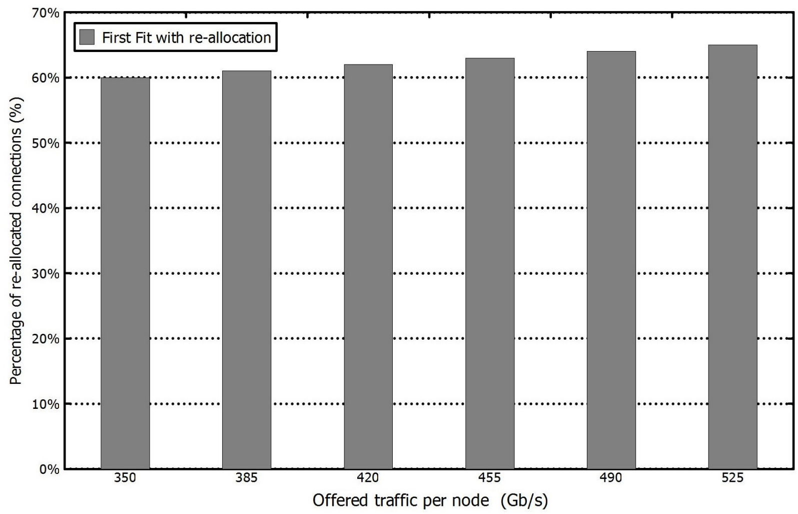
6.3 Simulation results

The performance of the proposed Mid Fit SA approach through extensive discrete event simulation studies is evaluated. As a benchmark the First Fit SA [CTV10b] in a scenario with time-varying elastic connections is assumed. In both cases, a k-Shortest Path routing strategy, with k=3 is used. During the simulations, existing connections are allowed to change their bit rate, so that the spectrum they use can be dynamically expanded and contracted accordingly. Time-varying connection selection starts after an initial transient phase, in which, 10^4 connection requests are simulated (i.e., enough to achieve steady state network operation). Once this initial transient phase ends, a total number of 5×10^6 connection requests are simulated, which allows us to get statistically relevant BP results. Furthermore, a percentage of the established connections are randomly selected and triggered to change their bandwidth. This percentage of time-varying connections with respect to the total of established connections allows observing the relationship between traffic fluctuation frequency and network performance. In particular, it is assumed that 15% of the served connections change their bandwidth during their lifetime. To increase the fairness of the comparison, the Shift-DAD policy proposed in section 6.1.2 is considered along with the First Fit SA scenario for benchmark purposes (i.e., a scenario where connection re-allocation is allowed). That is, if it is not possible to accommodate the traffic growth in the spectrum band originally assigned to a connection, it can be re-allocated to the first spectrum void with enough capacity. It is worth to mention that, since avoiding connection re-allocations is the main purpose of Mid Fit SA, only basic DAD adaptation policy as in [PSK+11] is allowed in this case. In addition, in this chapter, BP is considered as one of the evaluation metrics. It represents the overall failed attempts to setup new connection requests and bandwidth changes of already established connections. The 14-Node with 21 bidirectional links NSFnet reference topology has been selected for the evaluation (Figure 4.4). A total optical spectrum of 1.5 THz per link is assumed, which is discretized in frequency slots of 12.5 GHz. In addition, according to the asymmetric nature of today's Internet traffic, unidirectional connections between source and destination nodes are considered. To appropriately model the offered traffic granularity (i.e., average number of offered connections per node and average bit rate per connection), the traffic generation follows a Poisson distribution process, so that different offered load values (average number of connection requests per node) are obtained by keeping the mean HT of the connections constant to 200s, while modifying their IAT accordingly (i.e., offered load = HT/IAT). Connection bit rates are randomly generated following a log-normal distribution over the range from 12.5 Gb/s (1 FS) to 125 Gb/s (10 FSs) [GJLY12]. As mentioned before, for the sake of simplicity, a spectral efficiency of 1 b/s/Hz has been considered (realizable with a simple BPSK modulation format).

The first results are shown in Figure 6.3, where the average number of offered connections per node ranges from 8 up to 15. As the average bit rate per connection is 35 Gb/s, the total average traffic generated per node ranges from 280 Gb/s to 525 Gb/s. Concerning



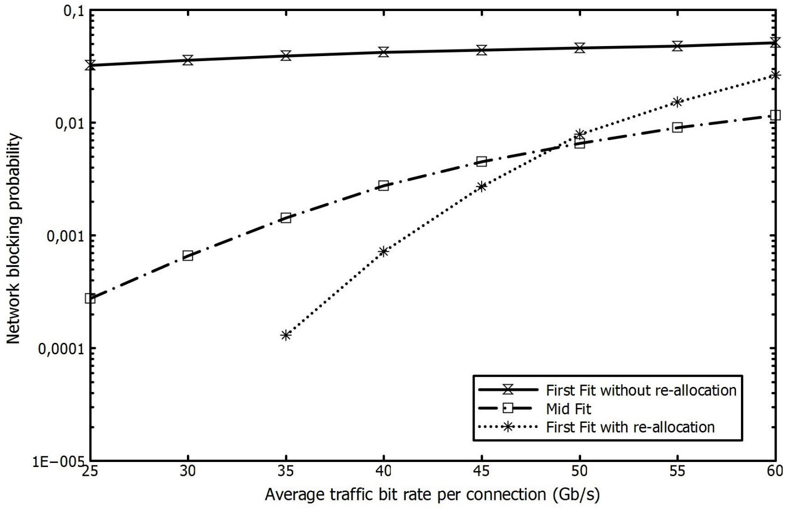
(a)



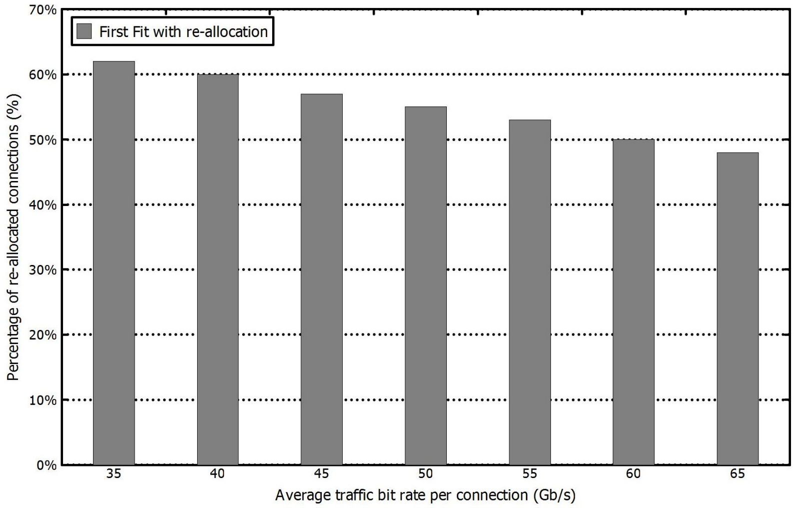
(b)

Figure 6.3: (a) Network blocking probability for different offered traffic per node values. The average number of offered connections per node changes from 8 to 15 while the average bit rate per connection is 35 Gb/s (b) Percentage of re-allocated connections vs. offered traffic per node (only connections requiring expansion are taken into account to compute this percentage).

the bandwidth variation of the selected time-varying connections, it is assumed that their bandwidth can either be doubled or halved with 50% probability (for the sake of simplicity). As shown in Figure 6.3(a), the First Fit SA approach with connection re-allocation outperforms the remainder approaches along the entire offered traffic range. The notable differences between First Fit SA with and without connection re-allocation are due to the fact that with First Fit SA most of the connections need re-allocation upon bandwidth expansion. Indeed, when the First Fit SA approach is used, connections are allocated very close to each other, thus the possibility of finding free spectral resources around them is very low. As a result, many of them have to be moved from their original band. To highlight this, the percentage of re-allocated connections for each offered traffic



(a)



(b)

FIGURE 6.4: (a) Network blocking probability for different average bit rate per connection values. The average number of offered connections per node is fixed to 12, while the average bit rate per connection changes from 25 Gb/s to 60 Gb/s (b) Percentage of re-allocated connections vs. average bit rate per connection (only connections requiring expansion are taken into account to compute this percentage).

value is shown in Figure 6.3(b). As seen, over 60% of the connections experiencing bandwidth expansion must be re-allocated when First Fit SA is used. Therefore, the benefits of First Fit with connection re-allocation on the BP are achieved at expenses of a large number of re-allocations, which are both complex and costly processes. In contrast, an alternative way to achieve significant benefits with low complexity is the proposed Mid Fit SA approach. In this case, around one order of magnitude improvement can even be achieved for low loads with respect to the First Fit SA without re-allocation, while no connection re-allocation is needed. Not so pronounced but still significant benefits are observed for Mid Fit SA against First Fit SA without re-allocation in highly loaded network scenarios.

To investigate more about the benefits of the proposal, similar studies have been done for a fixed offered load of 12 offered connections per node (168 connections offered to the entire network), while changing the average bit rate demand per connection from 25 Gb/s to 60 Gb/s (2 to 5 FSs). According to the mentioned load profile, the average traffic generated per node ranges from 300 Gb/s to 720 Gb/s. Again the percentage of time varying connections in the whole simulation is assumed to be 15%, and the bandwidth of each randomly selected connection can be either doubled or halved with 50% probability. As shown in Figure 6.4(a), a significant reduction in blocking probability can be achieved by allowing time-varying connections to freely shift in the spectrum (First Fit SA approach with connection re-allocation). However, by increasing the average bit rate per connection, the possibility of finding enough spectrum resources for re-allocating active connections is reduced. In fact, for average bit rate values greater than 50 Gb/s the Mid Fit SA approach leads to better BP performance in the network. Moreover, this performance is achieved in a simpler and more cost-effective manner, since no control plane-driven re-allocation is triggered. Figure 6.4(b) shows the percentage of re-allocated connections for each average bit rate value. As shown, by increasing the connection bit rate, the percentage of re-allocated connections decreases, which verifies the abovementioned effect.

In the next study, the impact of the percentage of time-varying connections on the EON performance is evaluated. The offered load is fixed to 12 connections per node and the average bit rate demand per connection equal to 35 Gb/s. As illustrated in Figure 6.5, Mid Fit SA improves the performance of the network in terms of BP in the whole range of the simulation when compared to First Fit SA without re-allocation. Considering First Fit SA with re-allocation, as illustrated, its efficacy in serving time-varying connections decreases as traffic fluctuation occurs more frequently in the network. For percentages greater than 30% the Mid Fit SA approach leads to better BP performance in the network. Indeed, by increasing the number of time-varying connections in the network, the possibility to successfully re-allocate a connection decreases. Therefore, worse BP performance using First Fit SA with re-allocation against Mid Fit SA is observed.

Looking for a way to approach the performance of Mid Fit SA to that of First Fit SA with connection re-allocation, providing some extra spectrum to the Mid Fit SA scenario is targeted. This would allow finding larger voids and, thus, decreasing the BP due to lack of spectrum upon bandwidth expansion. It is noteworthy here that a strategy like this does not necessarily entail higher network CAPEX, as a network operator may be underutilizing the entire 5 THz C-Band bandwidth. Furthermore, if the number of offered connections to the network remains constant, the number of devices that must be equipped in the network nodes (e.g., transponders) also remains unaltered. For this study, an average number of offered connections per node equal to 20, with an average bit rate demand of 35 Gb/s, is considered. Moreover, the percentage of time-varying connections in the whole simulation is assumed to be 15%, and the bandwidth of each selected time-varying connection can either be doubled or halved with 50% probability.

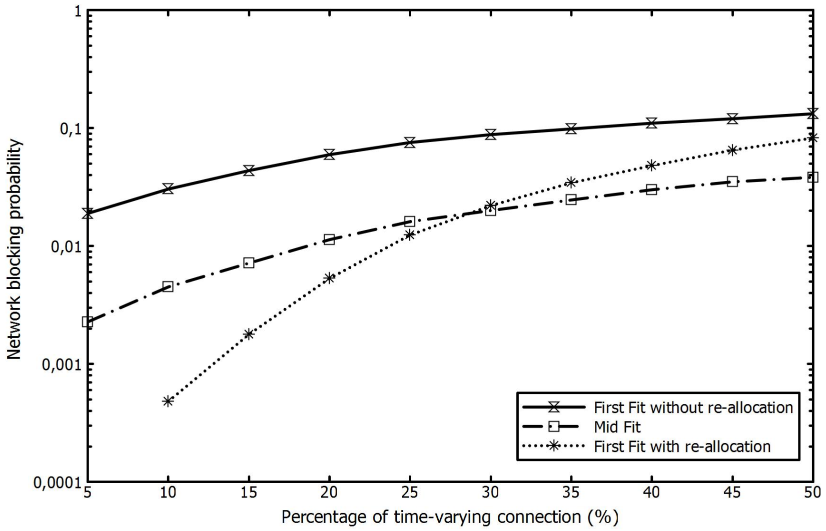


FIGURE 6.5: Network blocking probability vs. percentage of time-varying connections.

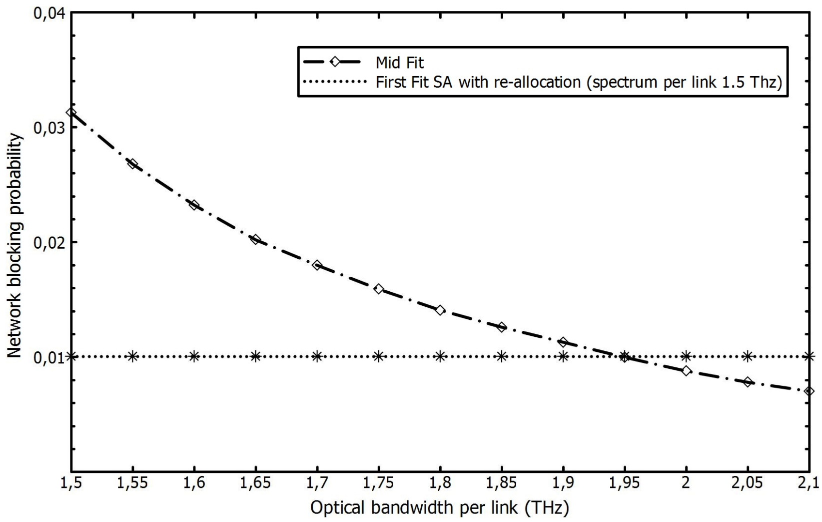


FIGURE 6.6: Network blocking probability vs. total spectrum per link.

As shown in Figure 6.6, such an amount of traffic leads to 1% blocking probability with First Fit SA with re-allocation if the total bandwidth per link is 1.5 THz. In contrast, BP rises up to 3% when Mid Fit SA is applied. Nevertheless, by increasing the spectrum from 1.5 THz to 1.95 THz the performance of Mid Fit SA shows no penalty compared to First Fit SA with re-allocation. Hence, increasing the operational bandwidth of the fiber links by around 25% to 30% allows Mid Fit SA to achieve the same BP performance as First Fit SA, but without any connection re-allocation, which simplifies the network operation to a large extent. In view of this result, Mid Fit SA becomes an interesting option for EON operators that can reduce network complexity by dedicating some extra spectrum in their potentially underutilized fiber links.

6.4 Chapter summary

This chapter focused on lightpath adaptation under time variable traffic demands in EONs. Specifically, the possibility of utilizing the spectral fragmentation to increase the spectrum allocation capabilities has been explored. To do so, initially, the precise definition of time-varying connections has been presented. There, we have seen that considering the near future technology advances (e.g., high capacity bandwidth variable transponders) and the exponential increase of network traffic, it is foreseeable to have large intervals between the establishment and the release of connections. Thus, during such relatively long periods, the bit-rate demand of any connection may fluctuate following short- and mid-term traffic variations. In addition, it has been highlighted that EON technology enabled flexible adaptation of connections to such time-varying traffic demand changes. Furthermore, the role of time-varying traffic fluctuation on increasing the spectral fragmentation in the network has been reviewed. Based on the common belief, spectral voids between adjacent connections (due to fragmentation) are considered as a problem. However, this statement does not always apply. It is shown that as long as connections required bandwidth grows over time, free spectral voids are crucial to accommodate additional bandwidth demands without requiring the re-allocation of the already established connections (an existing connection can easily adapt to transmission rate fluctuations if it has free spectral voids around it). In light of this, a heuristic SA algorithm, called Mid Fit approach, to intentionally increase spectral fragmentation in the network has been proposed.

To begin, this chapter initially has reviewed available solutions for accommodating time-varying traffic demands in EONs. Moreover, this chapter has introduced a novel heuristic algorithm, namely Shift-DAD policy. According to this algorithm, a connection wishing to increase its bit rate alternates between using its higher and lower FSs, until reaching an already occupied slot. If additional slots are needed, the symmetry of the expansion is lost but the connection continues to expand towards the only possible direction. When a connection needs more FSs than those available around it, the connection is re-allocated to the spectrum void with enough bandwidth along the connection's path. Note that, if a void large enough to re-allocate the connection is not found along the path, the entire bandwidth expansion operation is blocked. This proposal is a powerful solution which can be applied in EONs that are using conventional spectrum allocation algorithms such as First Fit. As a matter of fact, by using First Fit SA algorithm, it happens that connections are established very close to each other over the network, aiming to increase the available spectrum for new arriving connections. There, it is hard to find enough bandwidth around a lightpath to adapt it to its traffic fluctuation. Meanwhile, since the occupied portion of spectrum is compacted in one side of available spectrum (lower side of spectrum), it is possible to have enough FS for serving time varying connections in the upper side of spectrum. Therefore, by re-allocating connections over the network in a hitless fashion, a significant improvement in time-varying traffic allocation can be achieved.

In addition, it has been highlighted that SA algorithms have a great impact on the efficacy of serving time-varying connections in EONs. SA algorithms can achieve good arrangement of the connections in the space and frequency domains, thus increasing the possibility of serving and expanding time-varying connections in the network. An appropriate SA algorithm serves the connection requests, by assigning FSs in a way that minimizes the average network blocking probability, taking into account the requirements of the lightpath adaptation policy. To achieve the previously mentioned goals, a novel heuristic SA algorithm, called Mid Fit approach, to intentionally increase spectral fragmentation in the network has been proposed. In the proposal, the spectrum dedicated to a connection is in the middle of largest possible free spectral void over the route, providing greater spectral resource between adjacent connections. These spectral spaces are used for dynamic expansions of lightpaths, so as to adapt them to the time-varying required transmission rate. By means of simulation, it has been demonstrated that such a proposal can serve time-varying connections in a simple and cost efficient manner.

Chapter 7

Conclusions and future work

Elastic optical networks appear as a promising short to mid-term solution to the optical transport panorama. By breaking the fixed-grid spectrum allocation limit of conventional WDM networks, EONs increase the flexibility in the connection provisioning. To do so, depending on the traffic volume, an appropriate-sized optical spectrum is allocated to connections in EON. Furthermore, unlike the rigid optical channels of conventional WDM networks, a lightpath can expand or contract elastically to meet different bandwidth demands in EON. In this way, incoming connection requests can be served in a spectrum-efficient manner.

This technological advance poses additional challenges on the networking level, specifically on the efficient connection establishment. Similar to WDM networks, an elastic optical connection must occupy the same spectrum portion between its end-nodes, that is, ensuring the so called spectrum continuity constraint. In addition, the entire bandwidth of the connections must be contiguously allocated, also referred as the spectrum contiguity constraint. The new contiguity constraint adds a degree of complexity to the conventional RWA problem. As a matter of fact, the available RWA proposals for WDM networks are no longer directly applicable in EON. A new routing and resource allocation scheme has to be developed, namely RSA problem. The RSA problem has grabbed a lot of attention lately, putting more emphasis on dynamic network scenarios. There, connection arrival and departure processes are random and the network has to accommodate incoming traffic in real time. On this basis, the present thesis identifies and addresses some issues in the dynamic RSA problem, namely 1) dynamic source aggregation of sub-wavelength connections, 2) correlation between traffic granularity and defragmentation periodicity and 3) using spectrum fragmentation to better allocate time-varying connections.

In order to provide better understanding for the chapters to come, chapter 2 surveyed the evolution of optical transport networks. Special attention was paid to the architecture, benefits, and enabling technologies of EON. It has been shown that elastic optical networking enables sub- and super-wavelength accommodations in a highly spectrum-effective manner, as well as provides cost-effective fractional bandwidth service. Dynamic bandwidth variation of elastic optical path creates new business opportunities for network operators offering cost-effective and highly-available connectivity service through time-dependent bandwidth sharing, energy efficient network operation, and highly survivable restoration with bandwidth squeezing.

Chapter 3 focused on the problem of routing and spectral resource allocation in optical transport networks. In general, a solution to this problem indicates a route and allocated spectrum resource to incoming connection requests as to optimize a certain performance metric (e.g. network blocking probability). To start with, this chapter reviewed the routing and wavelength allocation problem in conventional WDM networks. Minimizing the amount of connection blocking, or maximizing the number of connections that are established in the network is the main objective of the solutions. The ILP formulation is a powerful tool to obtain a precise answer for the problem. However, this approach is very complex and time-consuming. Alternatively, it is possible to break the problem into two sub-problems, 1) routing and 2) wavelength assignment, and solve them separately. Heuristic algorithms are commonly used to solve the problem in an easier and faster way. With the appearance of the EON technology, the RWA problem has been replaced by RSA problem. In this new problem, an elastic optical connection must occupy the same spectrum portion between its end-nodes, that is, ensuring the spectrum continuity constraint. In addition, the entire bandwidth of the connections must be contiguously allocated, also referred as the spectrum contiguity constraint. In order to solve it, the concept of frequency slot as a strong tool for converting available RWA solutions to RSA algorithms has been introduced and based on this idea the solutions for RSA problem has been reviewed.

Chapter 4 concentrated on the important role of source aggregation in better resource utilization of EONs. Considering the ever-increasing growth of IP traffic, transport networks must be dimensioned with more and more transmitters which is neither spectrum nor cost efficient. To address the problem, the idea of source aggregation in elastic optical network has been introduced. By aggregating same source but different destination sub-wavelength connections, both transmitter and spectrum usage savings can be obtained. A novel dynamic source aggregation algorithm which supports grouping of multiple sub-wavelength connections with the same source into a single transmitter has been detailed. Also the equipment-level requirements to support the proposal in a cost-efficient manner have been discussed. Performance evaluations were made to compare the spectrum usage and transmitter saving benefits of source aggregation and non-aggregating scenarios. The results show that source aggregation achieves significant transmitter savings (10% - 50%), with better or equal spectrum utilization compared to non-aggregating case.

A possibility to extend this idea is to derive analytical models to formally quantify the effect of the number of shared sections in proposed node architecture on the relative cost and blocking probability performance of the elastic optical network. In addition, the comparison of dynamic source aggregation and electrical grooming from energy and cost perspective is another good research topic.

Chapter 5 presented the spectral fragmentation issue in EONs. This inevitable problem significantly degrades the performance of elastic optical networks. In light of this, the idea of spectral defragmentation has been introduced. Assuming a periodic defragmentation scenario, this chapter discussed the effects of the offered traffic characteristics (offered load and bit-rate per connection), as well as the defragmentation periodicity, on the profitability that defragmentation can yield to network operators. Indeed, while decreasing the defragmentation interval has direct impact on improving the blocking probability in the network, taking into account the bit-rate of the connections can also lead to the same results but with more relaxed defragmentation intervals and, thus, lower network control and management burden. All these findings were supported by extensive simulation results, where no defragmentation and on-demand defragmentation scenarios were also contemplated as a benchmark.

Future work could entail the derivation of the analytical model to formally quantify the effect of traffic granularity on the periodicity of defragmentation operation. From there, more investigations to realize intelligent defragmentation process can be a final goal in this research line.

Chapter 6 focused on the lightpath adaptation under time variable traffic demands in EON. Specifically, the possibility of utilizing the spectral fragmentation to increase the spectrum allocation capabilities of EONs has been explored. In this context, a heuristic spectrum allocation algorithm, called Mid Fit, which intentionally increases the spectral fragmentation in the network has been proposed and validated. With this proposal, the spectrum assigned to each new connection is in the middle of the largest free spectral void over the route, aiming to provide considerable spectral space between adjacent connections. These free spectral spaces are then used to allocate time-varying connections without requiring any lightpath reallocation. By means of simulation, it has been demonstrated that such a proposal can serve time-varying connections in a simple and cost efficient manner.

Further examination of lightpath adaptation policies and designing new SA algorithms based upon them could be a nice way to extend this topic.

Appendix A

Hybrid OBS/OCS architecture: alternative solution for future optical networks

Dynamic bandwidth allocation in response to the bandwidth requirements of new emerging applications is an essential demand for future optical networks. As highlighted previously, several proposals including elastic optical network architecture, optical packet switching networks and optical burst switching networks has been proposed. These proposals offer traffic accommodation in a spectral efficient manner. During the chapters of this thesis, we have seen the benefits of utilizing EON architecture. However, alternative solutions are still worth to be investigated. In this appendix, the hybrid OBS/OCS architecture which combines the benefits of OBS and OCS switching technologies in a single node is reviewed. They are key elements to support wavelength and sub-wavelength granularities simultaneously. Here, a novel feedback-based hybrid OBS/OCS node architecture that integrates slow (ms regime) and fast (ns regime) switching elements is introduced. The aim of proposal is to provide flexible bandwidth allocation of connections in a cost effective manner. Such a node utilizes the pre-transmission idle periods of slow elements in order to send those contending fast bursts, thus improving the overall network performance. The obtained simulation results illustrate significant improvement in terms of Burst Loss Rate (BLR), and lower related network costs when compared to previously proposed hybrid OBS/OCS node architectures.

A.1 OBS and OCS

The traffic growth in the Internet is explosive nowadays. Furthermore, this noteworthy growth trend will continue in the foreseeable future [CIS13]. By some estimates, it is expected that the volume of data growth associated to consumer broadband services will grow 60% per year, as a result of the spread and development of the new generation of applications, such as video streaming and new class of Internet services, which couple scientific instruments, distributed data archives, sensors and computing resources via optical networks [NZZ+08]. Each application has its own traffic profile, resource usage pattern and requirements. Meanwhile, technology evolutions such as all optical regeneration, wavelength conversion or dispersion compensation could drive the application bandwidth requirements beyond the current state [RVA+08]. At present, optical networks rely on different switching techniques, such as OCS and OBS.

In OCS schemes, network resources are dedicated to a demand between two end-points by reserving one or more full wavelengths for relatively long holding times [LBD+09]. In fact, OCS networks provide a very coarse bandwidth granularity. OCS networks allow an efficient and QoS compliant data transmission for long-lived flows via ms regime fabrics (e.g., MEMS). Moreover, since high port count OCS elements are available, scalability concerns are solved. However, they offer poor bandwidth usage and reduced adaptation to bursty data traffic patterns.

In contrast, OBS [CQY04, Yoo06b] has recently arisen as a promising technology able to realize a statistical multiplexing directly in the optical domain, thus increasing bandwidth efficiency. In particular, OBS granularity lies between those of OPS and OCS providing better adaptation than OCS to the transmission of on-demand small sets of traffic, and presenting more relaxed technological requirements than OPS. However, absolute QoS guarantees are still an important challenge in OBS networks. Furthermore, from the economical point of view, a pure OBS network needs a high number of expensive switching elements (e.g., SOA-based).

Compared to these pure switching solutions, hybrid optical networks provide a promising trade-off in long-haul networks in terms of cost, capacity and dynamicity using a unified platform in response to the requirements of those applications in higher layers [GKB+06]. As a matter of fact, hybrid optical nodes could support heterogeneous types of applications in both wavelength and sub-wavelength switching granularities. Such functionalities are provided by means of different switching schemes, such as OCS and OBS in one single node, aiming to utilize the advantages of different technologies while avoiding their disadvantages, which improves the overall performance of the network in a flexible and cost effective way [PSCJ09]. The smooth traffic flows with high QoS requirements (hereafter slow traffic) are carried by end-to-end circuits (millisecond switching regime), whereas burst data traffic (hereafter fast traffic) is supported on OBS (nanosecond switching regime).

This appendix proposes a novel and cost-effective hybrid OBS/OCS node architecture, aiming to improve the overall performance of the existent alternatives in the literature. To enhance the performance, Tunable Wavelength Converters (TWC) are used to avoid traffic losses in case of contention by transferring traffic over free resources in the idle period of switching elements. Next, the role of an algorithm for TWC assignment regarding

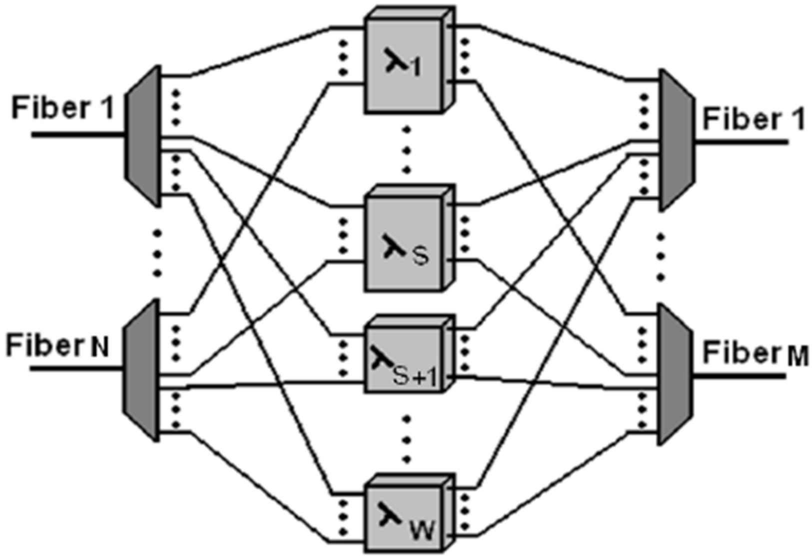


Figure A.1: Parallel hybrid OBS/OCS architecture.

to the nodal degree of node in a network is highlighted. Finally, the performance of the architecture on a reference network is investigated and the relative total cost of the network is evaluated.

A.2 Hybrid node architectures

This section reviews the hybrid nodal architectures previously proposed in the literature. In order to support different traffic granularities, the concept of Multi Granular Optical Cross Connects (MG-OXC) has been proposed. In general, MG-OXC nodes are switching fabrics that integrate two or more switching technologies in a single node. Many efforts have been done to extend the switching granularity through the combination of different switching technologies [CXAQ02, NVD01]. Even though multi granular switching has been obtained in such nodes, design complexity and cost are still important challenges.

The authors in [LDV+08] proposed a generic optical switch that supports wavelength and sub-wavelength granularities. Such an OBS/OCS node architecture consists of two separate slow and fast switching parts. Figure A.1 presents this architecture, which is named parallel as both parts of node work independently. Regarding the requirements of upcoming demands, a scheduling algorithm at the edge nodes of the network is introduced, which maps the incoming traffic into the appropriate parts of the hybrid node. The improvements of the hybrid switch over a wide range of traffic and switching parameters are obtained through simulation results. The work presented in [ZLS+09] can be considered as complementary to the previous study; there the authors highlighted how the wavelength and sub-wavelength granularities can be supported using millisecond and nanosecond switching regimes, respectively, in an experimental hybrid OBS/OCS node

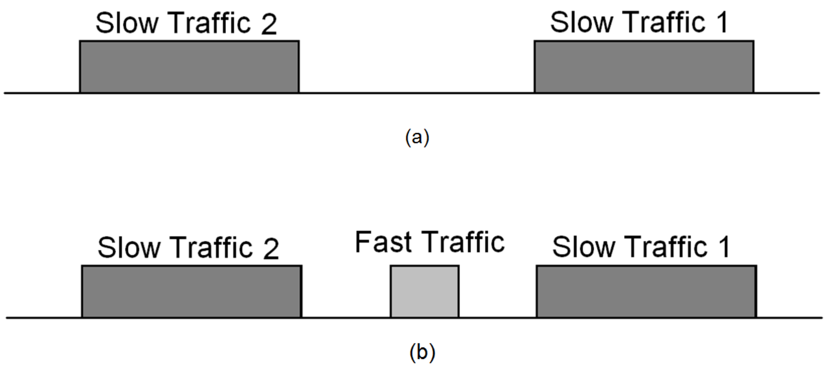


FIGURE A.2: (a) Consecutive slow traffic (b) fast over slow.

prototype. Furthermore, an investigation on the attributes of available slow and fast technologies was done. Given the high port-count optical switches as a mature technology under production, and also their related low cost, optical MEMS have been indicated as the slow switching technology. Conversely, many fast switching technologies are still in the research stage. Thus, there has been no other possible option than SOA-based switches. In summary, the design, analysis, and demonstration of a multi-granular optical cross-connect has been presented and the feasibility of this architecture on an application-aware multi-bit-rate end-to-end OBS test-bed has been shown.

There are two notable characteristics in this basic architecture. First, the slow and fast parts of the architecture are completely isolated and there is no possibility to send traffic from one part to another (parallel hybrid node). The second point is the well-defined concept of wavelength modularity, that is, identical wavelengths from different input fibers are switched in non-blocking switching fabrics. Each node consists of N input and M output fibers with total number of λ_w wavelengths per fiber. Indeed, the total number of wavelengths per fiber includes all the slow (λ_s, those switched by the slow switches), and the fast (λ_f , those switched by the fast switches) ones. After the demultiplexers, there are λ_s slow and λ_f fast switching elements, which are labeled from λ_1 to λ_s in the slow part and from $\lambda_{(s+1)}$ to λ_w in the fast part. The number of input and output ports in each switching element is equal to the number of input and output fibers of the node, respectively. Finally, wavelengths are multiplexed on the output fibers before leaving the node. As it was mentioned, slow switching elements are millisecond switching technologies (e.g., Optical MEMS), while the fast elements are nanosecond fabrics (e.g., SOA-based switches). Two-way reservation mechanisms can be used to reserve the resources over the OCS network, while typical one-way Just In Time (JIT)-based reservation schemes could be used to control the resources in the OBS part [CQY04].

The fundamental problem with the parallel hybrid OBS/OCS architecture is its poor bandwidth efficiency, especially under high traffic loads. In general, the switching resources of both parts are assigned to the traffic demands for the corresponding holding time. However, contentions can occur among bursts in one part of the switch (e.g. the fast one), while on the other part (e.g., the slow one) some idle resources might be found

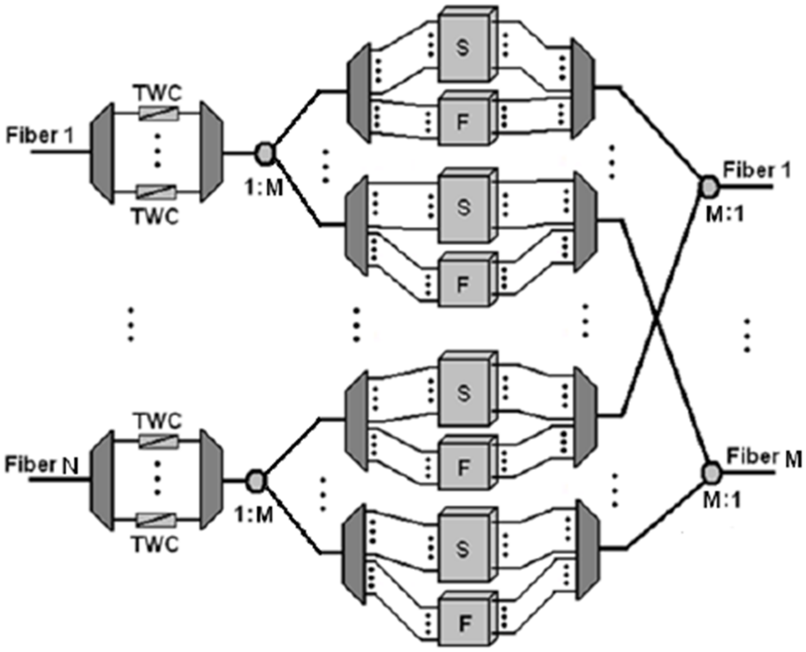


FIGURE A.3: Broadcast and select OBS/OCS hybrid architecture.

(idle period). As an example, Figure A.2 (a) represents the idle period of a slow resource between two transmissions of slow traffic demands. However, due to the lack of flexibility of the parallel architecture, there is no possibility to transfer contending traffic between any elements inside the parallel hybrid architecture. Hence, even if idle resources are available, there is no chance to use such resources to avoid traffic losses.

In order to improve the resource utilization, authors in [SZQ+09] presented a B&S hybrid OBS/OCS architecture, as shown in Figure A.3. Its realization requires equipping each of the N input fibers with λ_w full range TWCs. Looking at the literature, much work has undertaken the study of this kind of architectures [PPP03, SMP07]. Assuming a $N \times M$ node, splitters divide each input signal into M equal parts. Note that amplifiers should be added at the input of each block to ensure the optical power level of the divided signals, which increases the cost of this structure compared to the parallel one. Next, similar to the former architecture, demultiplexed wavelengths are switched by individual devices. As illustrated in Figure A.3, each switching block of the B&S architecture consists of ON/OFF optical gate arrays. It is worth to mention that the B&S architecture is a high port-count architecture due to the splitting of the input signals into the number of outputs. Indeed, it is M times greater than the number of input ports in the parallel architecture which mentioned before.

In addition, in such nodes, TWCs are introduced at all wavelengths. Thus, each element at each block can be used by any traffic demand in that part, by configuring the devices on the fly in case of contention, thanks to the wavelength conversion capability at the inputs. Moreover, it is possible to use the configured slow switching elements during idle periods to transmit fast bursts. Assuming that the slow element will keep its state during

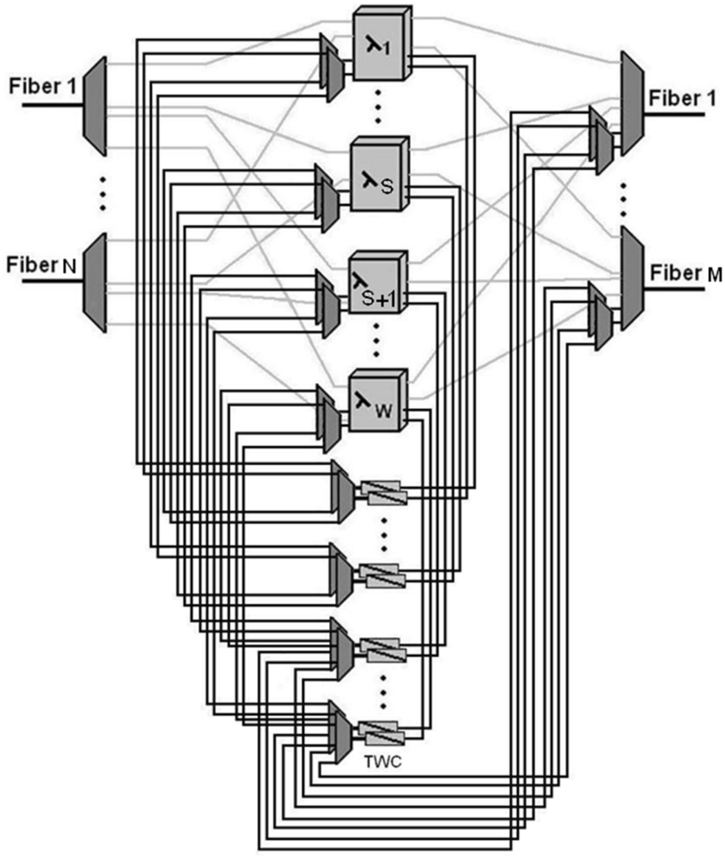


Figure A.4: Proposed feedback-based OBS/OCS hybrid architecture.

the idle time after the transmission of a slow traffic demand, it is possible to transmit fast bursts with the same input port and directed to the same output port in case of contention. The concept of using a slow resource to transmit a fast traffic is referred as fast over slow in the rest of this work, and it is illustrated in Figure A.2 (b).

With the introduction of TWCs at each input of the node, the problem of bandwidth efficiency is solved. However, this architecture is not cost-effective due to the high port-count and the necessity for utilizing expensive devices, such as TWCs and amplifiers, at all input wavelengths. In addition, more energy consumption and worse signal to noise ratio is expected in this architecture, due to the existence of active devices. In this appendix, a more cost-effective hybrid OBS/OCS node describing a feedback-based architecture is proposed.The details of the proposal are described in the following section.

A.3 Feedback hybrid OBS/OCS node architecture

In the design of the Feedback-based (FB) hybrid OBS/OCS node architecture, the main driver was cost reduction, while approaching the B&S architecture performance in terms of BLR. From the overview presented in the previous section, it is concluded that B&S

based architectures are much more expensive than the parallel based architectures due to the high port-count and active devices required. As shown in Figure A.4, the fundamental structure of the FB architecture is similar to the parallel one. However, there are some additional ports in each switching element. These extra ports provide configurable routes to the conversion section of the architecture. In contrast to the B&S architecture, no TWC is placed per input wavelength. In fact, to reduce the number of required TWCs, they are moved from the input to the feedback section. Thus, TWCs are shared between the same wavelengths arriving from different inputs. In this way, it is possible to reduce the related cost of the node while keeping the BLR in a reasonable level as will be demonstrated in next section. Furthermore, switching elements are non-blocking slow and fast fabrics as those used in the parallel architecture. Note, however, that there are some extra configurable routes to avoid burst drops. Hence, all free resources at one part are considered as a potential path to solve contention, due to the wavelength conversion capability at the feedback section. In addition, like to the B&S hybrid nodes, the slow resources could be used to perform fast over slow during their idle periods. However, this approach is quite different from the B&S one, as explained in the following subsection.

A.3.1 Fast over slow capability

As mentioned previously, the fast over slow concept is referred to transferring some fast traffic over slow resources during its idle time. In order to provide this capability, in B&S hybrid architectures full range TWCs are inserted for all wavelengths in each input; otherwise, there is no possibility to deal with contention at the input without TWC. In the FB architecture, the conversion range of shared TWCs for slow wavelengths is $\lambda_s - 1$, which is used to find a free resource in the slow part. Meanwhile, this range for fast part is $\lambda_w - 1$, (i.e., $(\lambda_f - 1)$ is needed to find out a free resource at the fast part and the remaining are utilized to send fast traffic demands over slow idle resources). As shown in Figure A.4, resources are partitioned according to the number of outputs to make fast over slow connections. Therefore, the slow wavelengths could be used to transfer a traffic demand to a given destination. In fact, the reduced flexible number of TWCs due to their shared nature is the main advantage of the proposed FB architecture in front of the B&S one. This approach has a good potential to reduce the number of required TWCs significantly.

In case of contention, the first option for both types of traffic is to get a resource inside the corresponding part. For the fast traffic, if no available fast resource is found, an idle slow switching fabric, already configured to the desired output port, is searched. If there is a wavelength which is not in use for slow transmission, the TWC performs the wavelength conversion to the available wavelength and sends it to the appropriate slow switching element. In contrast to B&S architecture, there is no need to search for an already set-up connection in slow part to perform fast over slow. It is worth to mention that the resources in each part are dedicated to the offered traffic to that part. However,

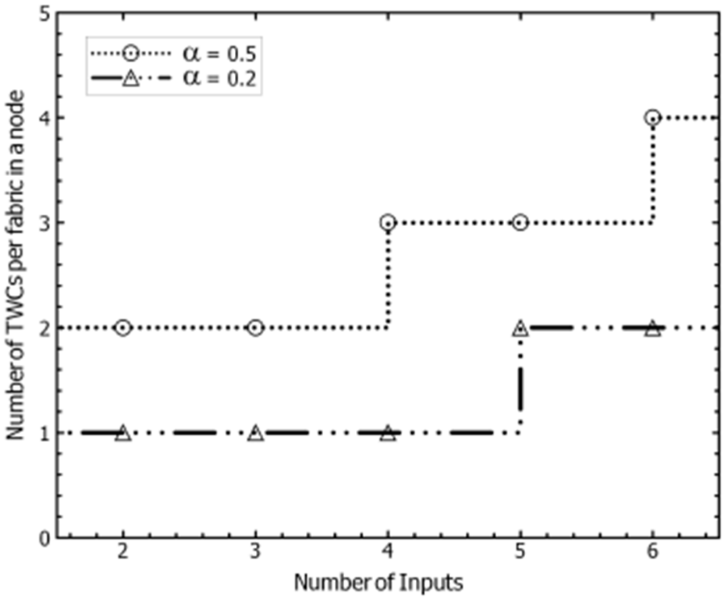


FIGURE A.5: Number of TWCs per fabric in a node for two given shared factors.

it is possible to have some collision between slow and fast over slow traffics. In such a case, pre-emption is applied for slow traffic to guarantee the resource availability. As a result, a requested slow resource carrying fast traffic will be released for the incoming slow traffic.

A.3.2 Algorithm for TWC assignment

As mentioned, wavelength partitioning related to the number of outputs is one of the important factors to perform fast over slow. For instance, assuming a node with M outputs and λ_s slow resources, there are λ_s/M slow resources dedicated to fast over slow to a given output port. If there are special QoS requirements for all the traffic departing from a specific output port, extra resources could be added.

Note that the slow switching fabrics in all intermediate B&S or FB nodes receive two different kinds of traffic. First, the slow traffic carried by the slow resources and, second, the fast traffic moved over slow wavelengths. The time gap between header and payload is not generally enough to configure the slow switching elements in latter kind of traffic. Hence, if a slow switching fabric is not already configured from the input to the desired output port, an incoming fast burst must be dropped. It shall be mentioned, though, that in the B&S architecture, the TWCs at the input ports to give the contenting burst the possibility to be moved again to any available resource in any part of the switch (even be moved again to the fast part of the switch). In contrast, in the FB nodes there is no direct access to the conversion section of architecture for the fast over slow bursts due to the required configuration time of slow fabrics and the place of TWCs at the architecture. However, to solve this it would be possible to find some already set connection at extra

FIGURE A.6: 16 node EuON core topology.

ports of slow fabrics to TWCs. In this case, the fast burst could be moved to any available resource in any part of the switch.

Based on the discussion above, selecting the number of extra ports which are connected to the shared TWCs is an important issue. A node with higher offered load at a network needs more TWCs to solve contention efficiently, which means a greater sharing factor. The number of input links at a node is a good candidate to reflect the role of offered load in the equation. In fact, higher number of input links at a node generally means higher traffic offered to it. Considering $\alpha \leq 1$ as the sharing factor that shows how many inputs share a TWC at each element inside a node and N as the number of inputs, $f(\alpha, N)$ indicates the number of shared TWCs at each element inside the switch as follows:

$$f(\alpha, N) = \begin{cases} 1 & \text{if } \alpha = 0 \\ \lfloor \alpha \times N + 1 \rfloor & \text{if } 0 < \alpha < 1 \\ N & \text{if } \alpha > 1 \end{cases} \tag{A.1}$$

As seen in A.1, if $\alpha = 1$ each switching fabric will have N TWCs. In contrast, the number of shared TWC at each fabric for $\alpha = 0$ is 1 to keep the feedback nature of architecture. Figure A.5 illustrates $f(\alpha, N)$ for two given shared factors as a function of number of input ports. For example, assuming a 3×3 FB node, with 10 wavelengths per incoming fiber, 2 TWCs would be equipped per switching element inside the node if a sharing factor equal to 0.5 would have been applied. This would finally result in 20 TWCs in the node.

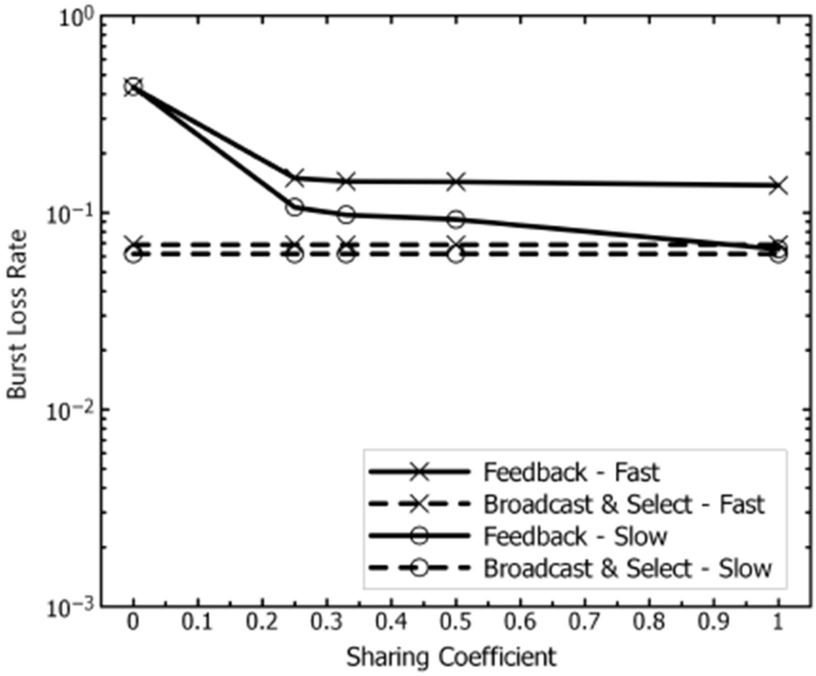


FIGURE A.7: Burst loss rate vs. sharing coefficient.

A.4 Simulation results

The performance of the proposed FB architecture has been evaluated through extensive discrete event simulation studies. To this goal, the European Optical Network (EuON) core topology composed of 16 nodes (Figure A.6) is used [MCL+03]. In addition, 10 wavelengths per fiber is assumed. Specifically, the burst loss rate performance and cost evaluation have been considered. The offered traffic is distributed at network uniformly, 70% of generated traffic is assumed to be slow traffic while the other 30% is fast traffic. 7 wavelengths per fiber are dedicated to slow traffic demands while the other 3 are used to carry fast traffic. The offset times between a control packet and the respective data are assumed to be controlled by source nodes, sufficiently provisioned to allow the configuration of appropriate switching fabric. The traffic generation implements a Poisson distribution with a varying average inter-arrival time to establish different loads. Data size follows an exponential distribution with average 5 ms for slow bursts and 250 μs for fast bursts. Un-weighted shortest path routing is used for finding routes in the network. In addition, a one way JIT-like reservation mechanism is used to support burst traffic in both parts. Pre-emption is applied for slow traffic. As a consequence, if a slow request arrives, the resource with fast traffic demand at slow part is unallocated and switch element configured for the upcoming slow demand. The confidence interval of 95% is applied at all runs.

The effect of the sharing factor on the BLR in the FB nodes is firstly investigated and compared to the BLR figures obtained by the B&S architecture. A fixed offered load of

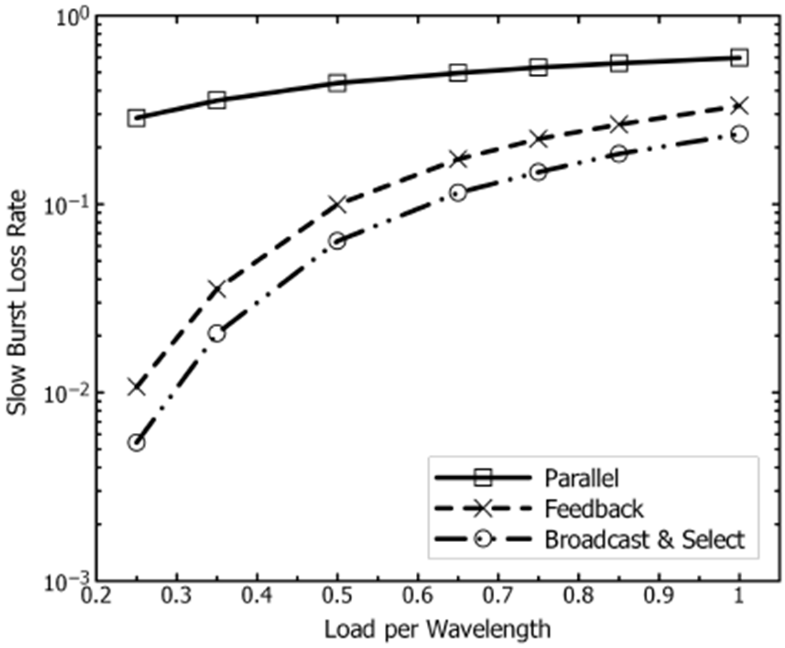


FIGURE A.8: Slow burst loss rate vs. load per wavelength.

0.5 Erlang per wavelength is used. The results for five different sharing coefficient values are shown in Figure A.7. Dash lines show the results of the network built of B&S nodes, which are quite equal due to the appropriate mapping of offered load and resources. By increasing the sharing factor, TWCs would be shared among fewer numbers of inputs. Therefore, the solid line will converge to the dash lines, which means total drops reduction. For $\alpha = 1$, slow burst loss rate reaches the boundary of the B&S. Conversely, the fast burst loss rate is affected by the occupancy of slow resources in high loads. It is worth to mention that the BLR experienced by the slow traffic is always lower than in the case of the fast one. Indeed, this is related to the higher number of resources in the slow part, as any slow traffic burst has 6 possibilities to avoid a drop while this number is less than half in the fast part. In addition, the preemption guarantees the resource availability in the slow part, being the slow traffic insensible to the fast packets transmitted on slow resources. From now on, a $\alpha = 1/3$ is chosen for the subsequent simulation studies, which makes a good trade-off between performance and cost in the proposed FB architecture.

In the next experiment, simulations are performed to evaluate the BLR in all architectures for different offered loads per wavelength using the α value previously selected. The slow and fast BLR figures are shown in Figure A.8 and Figure A.9, respectively. As illustrated in Figure A.8, the BLR of the slow traffic in B&S and FB architectures is almost similar. Moreover, the BLR of the slow traffic when the FB architecture is used is reduced by almost one order of magnitude for low an medium loads compared to the parallel architecture. The same results for the fast traffic are depicted in Figure A.9. Indeed, the fast drop rate of parallel based-network is same as its slow curve. In addition, the BLR reduction for both FB and B&S architectures is quite similar to the previous

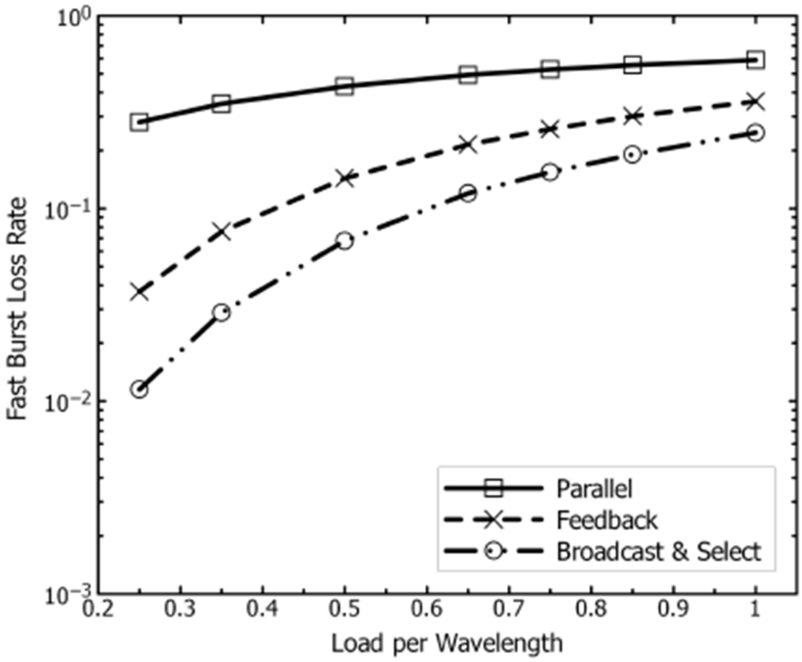


Figure A.9: Fast burst loss rate vs. load per wavelength.

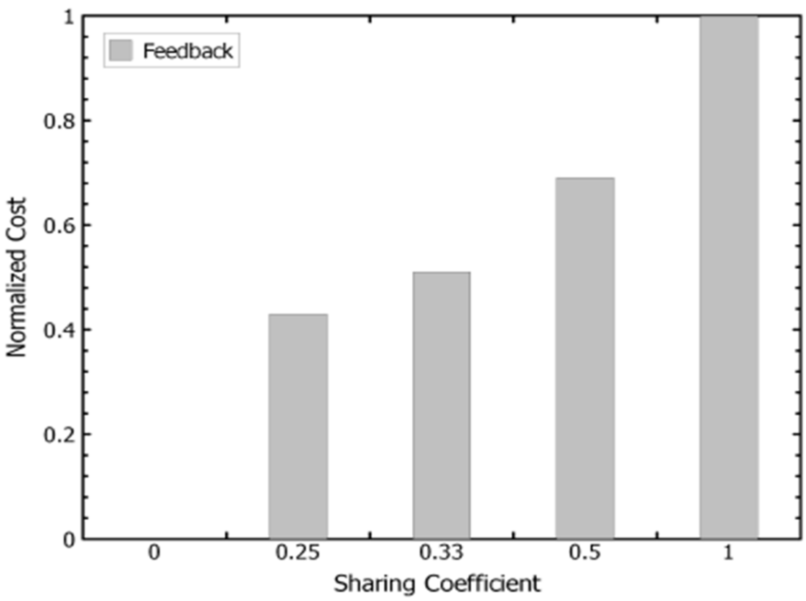


Figure A.10: Total cost of network.

results. However, this reduction is lower than the obtained one in the slow case. As mentioned, the return of fast traffic from a slow resource to the fast part of node in B&S is quite easy due to the place of TWCs, while it is almost impossible in the FB case. This effect leads to such a larger gap between curves.

Furthermore, the overall network cost (depending on whether the B&S or the proposed FB architecture is deployed in the 16-node network under study) is evaluated. Based

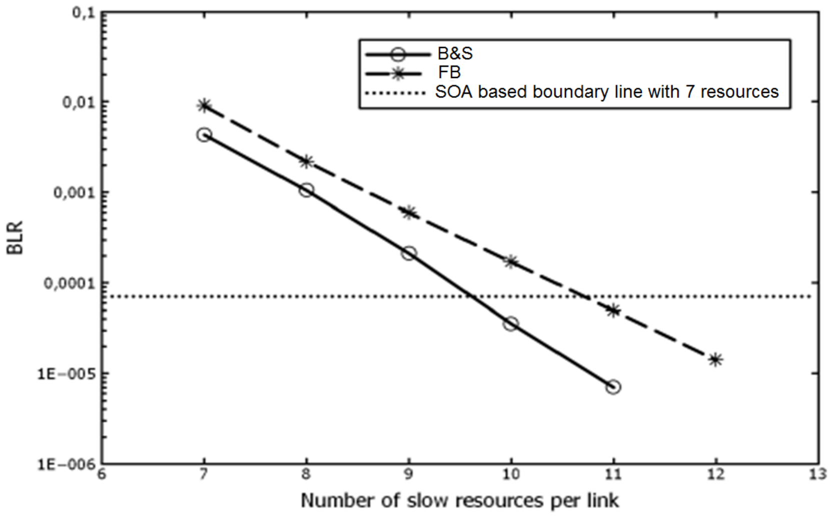


FIGURE A.11: Fast BLR performance.

on the sharing capability of the TWCs, the proposed FB architecture leads to lower overall costs with respect to the B&S architecture. In general, introducing TWCs in both architectures makes them more expensive than the parallel one. However, this additional cost drastically improves the QoS in the network. It is worth to mention that the port-count number and number of active elements are two other important parameters in cost increment. In contrast to the B&S, there is no need for signal amplification in the FB nodes which reduces the overall cost. Moreover, port-count number is lower in case of FB nodes. A parametric cost-benefit analysis for the B&S and FB nodes in the network under study shows a notable costs reduction using shared TWCs in the FB architecture, as shown in Figure A.10. Such presented results are normalized to the total cost of the network provided that all nodes are B&S-like. As seen, the total network cost in terms of the required number of TWC is reduced by 50% when $\alpha = 1/3$ is applied. However, as obtained before in Figure A.8 and Figure A.9, BLR performance of network remain in a reasonable range. Furthermore, the proposed FB architecture allows a cost-effective node design by tuning the α parameter appropriately, so that the network QoS are meet at the lowest network cost. Indeed, such a cost-effective design is not allowed in the B&S architecture. Otherwise the B&S performance would be prevented in certain incoming wavelengths.

Since power consumption of nodes is one of the major cost factors in the networks, in the next step, the energy consumption of pure SOA based and two hybrid architectures, B&S and FB, have been evaluated through discrete event simulation studies. To this goal, the energy consumption of mentioned nodes with same BLR performance has been compared. Firstly, the BLR performance of pure SOA based node within a scenario with two sources and one destination and 10 wavelengths per fiber is evaluated as a boundary of analyses. As mentioned above, the traffic generation follows a Poisson distribution with the same portion of total offered load as before. However, to meet the BLR performance in acceptable range of OBS networks, the total offered load per source node is assumed

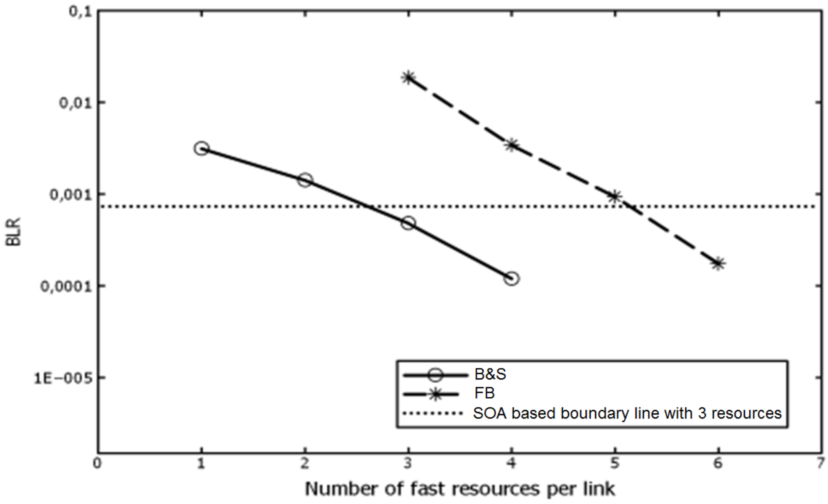


FIGURE A.12: Slow BLR performance.

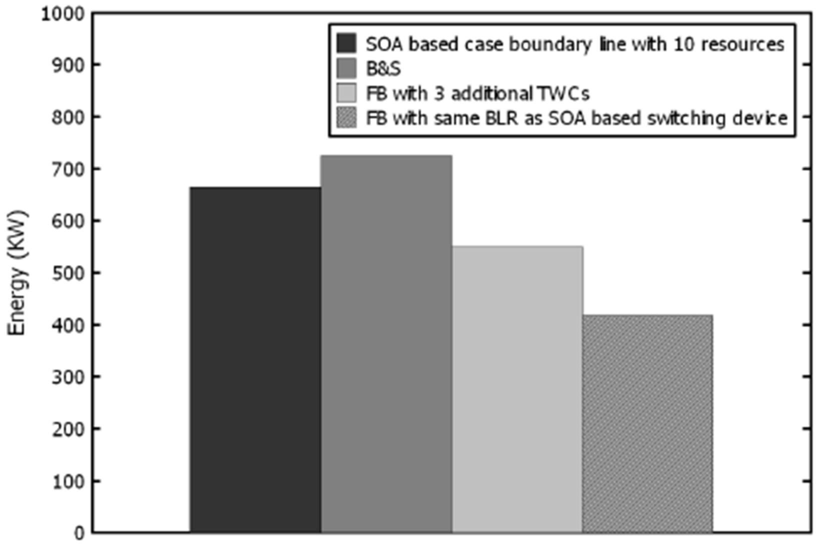


FIGURE A.13: Energy consumption evaluation.

0.15 Erlangs per wavelength. Data size follows an exponential distribution with average 40 ms for slow bursts and 500 μs for fast bursts, that meets the resource utilization of more than 70% for link speed of 10 Gb/s in all simulations, considering few ns and 10 ms as the switching configuration time of fast and slow switching elements, respectively. Preemption is applied for slow traffic like previous study. Figure A.11 and Figure A.12 show the slow and fast BLR performance of B&S and FB hybrid architectures with different number of slow and fast wavelengths. As it is illustrated in the figures, the SOA switching device boundary could be met using 10 slow resources in hybrid architectures. Meanwhile, the required fast resources at B&S and FB hybrid architecture to get almost same BLR performance as boundary is 3 and 5, respectively.

Finally, the energy consumption of all architectures with same BLR performance, considering mentioned sharing factor for FB case, is evaluated. The energy consumption of all active SOA connections assumed 230 mW, while MEMS connections consume 107 mW [Ale09]. In addition, each TWC comprising two SOAs and one Distributed Feedback (DFB) laser, consumes 1.65 W in case of conversion [Ale09]. Figure A.13 illustrated the results. The power consumption reduced around 20% using the proposed FB architecture. Therefore, in long term cost evaluations the novel FB node will save more energy.

In summary, these simulation results illustrated that the proposed feedback-based architecture outperforms the parallel architecture. Moreover, it provides similar BLR performance compared to the B&S architecture, while leading to a significant overall network cost reduction. In point of fact, as the FB architecture requires a lower number of active devices respect to the B&S architecture, it is expected to require lower energy consumption.

Appendix B

Publication List

B.1 Publications in Journals

1. **P. S. Khodashenas**, J. Comellas, S. Spadaro, and Jordi Perelló. Dynamic Source Aggregation of Sub-wavelength Connections in Elastic Optical Networks. *Photonic Network Communications*, 26(2-3): 131-139, December 2013.

2. **P. S. Khodashenas**, J. Comellas, Jordi Perelló, and S. Spadaro. Correlation Between Traffic Granularity and Defragmentation Periodicity in Elastic Optical Networks. Accepted for publication in *Transactions on Emerging Telecommunications Technologies*, Article first published online: 27 January 2014, DOI: 10.1002/ett.2795.

3. **P. S. Khodashenas**, J. Comellas, S. Spadaro, Jordi Perelló, and Gabriel Junyent. Using Spectrum Fragmentation to Better Allocate Time-Varying Connections in Elastic Optical Networks. Accepted for publication in *Journal of Optical Communications and Networking*, scheduled to June 2014.

B.2 Publications in Conferences

1. **P. S. Khodashenas**, Jordi Perelló, S. Spadaro, J. Comellas, and G. Junyent. A Feedback-based Hybrid OBS/OCS Architecture with Fast-Over-Slow Capability. In *Proceedings of 15th International Conference on Optical Network Design and Modeling (ONDM 2011)*, Bologna (Italy), February 2011.

2. **P. S. Khodashenas**, Jordi Perelló, S. Spadaro, J. Comellas, and G. Junyent. Cost and Energy Analysis of Feedback-based Hybrid Node Architecture. In *Proceedings of Future Internet: Efficiency in high-speed networks (W-FIERRO 2011)*, Cartagena (Spain), July 2011.

B.3 Publications under review

1. **P. S. Khodashenas**, J. Comellas, Jordi Perelló, and S. Spadaro. On the Performance of Dynamic Source Aggregation of Sub-wavelength Connections in EONs. Submitted for publication in *18th International Conference on Optical Network Design and Modeling (ONDM 2014)*, Stockholm (Sweden), May 2014.

2. D. Pomares, **P. S. Khodashenas**, Jordi Perelló, S. Spadaro, and J. Comellas. Spectrum Management Strategies to Improve Elastic and Multi-Rate Optical Networks Performance. Submitted for publication in *16th International Conference on Transparent Optical Networks (ICTON 2014)*, Graz (Austria), July, 2014.

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