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Resource allocation and scalability in dynamic wavelength-routed optical networks

Alejandra Liliana Zapata Beghelli

A thesis submitted to the University of London for the degree
of Doctor of Philosophy (Ph.D.)



Department of Electronic and Electrical Engineering

University College London

August 2006

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Abstract

This thesis investigates the potential benefits of dynamic operation of wavelength-routed optical networks (WRONs) compared to the static approach.

It is widely believed that dynamic operation of WRONs would overcome the inefficiencies of the static allocation in improving resource use. By rapidly allocating resources only when and where required, dynamic networks could potentially provide the same service that static networks but at decreased cost, very attractive to network operators.

This hypothesis, however, has not been verified. It is therefore the focus of this thesis to investigate whether dynamic operation of WRONs can save significant number of wavelengths compared to the static approach whilst maintaining acceptable levels of delay and scalability.

Firstly, the wavelength-routed optical-burst-switching (WR-OBS) network architecture is selected as the dynamic architecture to be studied, due to its feasibility of implementation and its improved network performance. Then, the wavelength requirements of dynamic WR-OBS are evaluated by means of novel analysis and simulation and compared to that of static networks for uniform and non-uniform traffic demand. It is shown that dynamic WR-OBS saves wavelengths with respect to the static approach only at low loads and especially for sparsely connected networks and that wavelength conversion is a key capability to significantly increase the benefits of dynamic operation.

The mean delay introduced by dynamic operation of WR-OBS is then assessed. The results show that the extra delay is not significant as to violate end-to-end limits of time-sensitive applications.

Finally, the limiting scalability of WR-OBS as a function of the lightpath allocation algorithm computational complexity is studied. The trade-off between the request processing time and blocking probability is investigated and a new low-blocking and scalable lightpath allocation algorithm which improves the mentioned trade-off is proposed.

The presented algorithms and results can be used in the analysis and design of dynamic WRONs.

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*Alejandra Zapata
Department of Electronic and Electrical Engineering
University College London
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List of Abbreviations

ACK	Acknowledgement
ALU	Arithmetic Logic Unit
AR-LEH	Adaptive Routing with Limited Extra Hops
AUR-E	Adaptive Unconstrained Routing - Exhaustive
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CoS	Class of Service
DRAM	Dynamic Random Access Memory
EDF	Earliest Deadline First
FAT	Fixed Aggregation Time
FBS	Fixed Burst Size
FDL	Fibre Delay Line
FF	First Fit
FIFO	First In First Out
FWC	Full Wavelength Conversion
ILP	Integer Lineal Programming
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
JET	Just-Enough-Time
JIT	Just-In-Time
LAN	Local Area Networks
LAUC-VF	Latest Available Unscheduled Channel with Void Filling

LBS	Limited Burst Size
LI	Least Influence
LU	Least Used
MU	Most Used
NACK	No-Acknowledgement
NP	Non Polinomial
OPS	Optical Packet Switching
OBS	Optical Burst Switching
QoS	Quality of Service
RA	Route Allocation
RAM	Random Access Memory
RCL	Relative Capacity Loss
RF	Random Fit
RM	Rate Monotonic
RR	Reconfigurable Routing
RTT	Round-Trip Time
RUF	Re-Utilisation Factor
RWA	Routing and Wavelength Allocation
SDH	Synchronous Digital Hierarchy
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Network
SP-FF	Shortest Path - First Fit
SRAM	Static Random Access Memory
TCP	Transport Control Protocol
TDM	Time Division Multiplexing

UBS	Unlimited Burst Size
WA	Wavelength Allocation
WAN	Wide Area Networks
WDM	Wavelength Division Multiplexing
WRON	Wavelength-Routed Optical Network
WR-OBS	Wavelength-Routed Optical Burst Switching

List of Symbols

a_l	Number of active connections in link l
$b_{i,j}$	Maximum bit rate at which node i transmits information to node j
e	Number of extra hops of a route with respect to the shortest path
k	Number of alternative routes between a node pair
p	Probability that a packet source is in ON state
r_i	Lightpath request with Class of Service i
$r_{i,k}$	Lightpath request with priority i from source node k
$t_{A/L}$	Time required to perform an arithmetic or logical operation in a processor
t_{tx}	Packet transmission time
$t_{i,k}$	Time between consecutive arrivals of lightpath requests from source node k with Class of Service i
t_{mem}	Memory access time
w_l	Number of wavelength in link l
A	Set of active connections in a network
\hat{A}	Set of active connections A with the longest routes
B	Network-wide blocking probability
B_l	Blocking probability of link l
B_r	Blocking probability of route r
C	Processing time per lightpath request
C_w	Bandwidth (bit rate) of a wavelength channel
D	Diameter of the network (number of hops of the longest route in the network)

D_i	Mean delay experienced by packets accumulated during the interval I_i in the UBS aggregation scheme
G_i	Graph associated to wavelength i
H	Average path length (in number of hops) of the shortest paths of all node pairs in a network
H_A	Average path length (in number of hops) of connections in set A
$H_{\hat{A}}$	Average path length (in number of hops) of connections in set \hat{A}
H_r	Number of hops of route r
I_i	i -th interval in the aggregation process of a burst in the UBS aggregation scheme
L	Number of uni-directional links in a network
\mathcal{L}	Set of uni-directional links in a network
\mathcal{L}_i	Set of uni-directional links where wavelength i is not used
M	Traffic matrix
$M[i,j]$	Element located in the i -th row and the j -th column in matrix T
N	Number of network nodes
\mathcal{N}	Set of network nodes
N_{Cos}	Number of classes of services
N_i	Mean number of packets received during interval I_i in the UBS aggregation scheme
N_l	Maximum number of lightpaths transmitted over link l
N_{max}	Maximum number of nodes for which the latencies are not violated in a network
N_{tot}	Total number of sources generating requests in the network
P	Burst size, in number of packets

R	Fraction of connections required to be accommodated in the network in the dynamic case compared to the static case
RTT	Mean Round-trip time: time for the lightpath request to be propagated from the source node to the control node and back
$RTT_{i,k}$	Time to propagate the request $r_{i,k}$ to the central node and return the acknowledgement to the source node
R_W	Ratio between the wavelength requirements in the dynamic case and those of the static case
S	Number of slots in a aggregation period of length T for the FAT scheme
T	Length of aggregation period in the FAT scheme
T_{aggr}	Time a packet must wait in the buffer due to the aggregation process
T_{buffer}	Time a packet spends in the source transmission buffer before being transmitted
$T_{buffer\ i,k}$	Time a packet with CoS i spends in the source transmission buffer of node k before being transmitted
T_{ee}	End-to-end delay experienced by a packet in an optical network without processing in the optical core
T_i	Duration of interval I_i in the UBS aggregation scheme
T_{pkt}	Time required to fully receive a packet in the aggregation buffer (packet length divided by input bit rate)
T_{prop}	Propagation time from the source to the destination node
T_{rqst_prop}	Time for the lightpath request to be propagated to the control node and back to the edge node
T_{tx}	Packet transmission time

T_{CN}	Time the request remains in the control node to be allocated a lightpath
T_{OFF}	Mean duration of OFF period for any connection in a network under uniform traffic demands
$T_{OFF}^{i,j}$	Mean duration of OFF period for connection between node i and j
T_{ON}	Mean duration of ON period for any connection in a network under uniform traffic demands
$T_{ON}^{i,j}$	Mean duration of ON period for connection between node i and j
U	Level of utilisation for a processor
W	Number of wavelengths per link
\mathcal{W}	Set of wavelengths in a network
W_{LB}	Lower bound for wavelength requirements in adaptive routing
W_{LB}^{fixed}	Lower bound for wavelength requirements in adaptive routing
α	Physical connectivity
β	Parameter such that the area under the normal distribution in the range $(-\infty, \beta]$ equal $(1-B)$
δ	Average nodal degree
δ_n	Nodal degree of node n
$\phi(x)$	Area under the normal distribution curve in the range $(-\infty, x]$
γ	Mean rate at which packets arrive to the edge node buffer
η	Degree of non-uniformity
λ_i	Wavelength number i
ρ	Offered traffic load in a network under uniform traffic demands
$\rho_{i,j}$	Offered traffic load by connection between node i and j

σ_H	Standard deviation of the number of hops of the shortest paths
Δ	Average number of slots between the last packet arrival and the end of the aggregation period in the FAT scheme

Chapter 1

Introduction

1.1. Research topic

The ever increasing amount of data traffic, growing at a rate of about 60-100% per year [Des05, Tel04, Yin04, Ros02, Cof02], and the emergence of demanding network applications as interactive TV, computing grid, data storage, video-on-demand, online gaming or multimedia-conferencing [Czy06, Cav05, San04, Wei03, Tog98] impose high bandwidth demands on transport networks. For example, recent studies have predicted that for 2006 worldwide traffic would be about 2,800 Petabits per second (Pb/s) [Tel04, Tel03]. Whilst this bandwidth requirement cannot be provided by electronic time division multiplexed (TDM) based systems used in SONET/SDH networks without significant investment in new fibre infrastructure, it is easily met by migrating from TDM to Wavelength Division Multiplexing (WDM) systems [Agr02]. Unlike TDM-based SONET/SDH networks (with current transmission rates of 10 Gb/s in commercial systems), where data is transmitted using only one channel per fibre, a WDM-based system simultaneously transmits data at multiple carrier wavelengths (channels) over a fibre – currently allowing bandwidths in excess of 10 Tb/s per fibre [Ofc06, Eco05]. As a result of this huge bandwidth provision, WDM systems are now successfully used in transport networks as high-speed transmission channels throughout the world, see for example [Siv04, Fal02, Muk00, Shi00, Wau99, Wei99, Mar96].

At the moment, however, the full potential of WDM could not be utilised because conventional electronic processing, buffering and routing of information (traditional router tasks) cannot match the high speed of optical transmission [Nei05]. Carrying out these tasks fully in the optical domain would overcome the processing speed mismatch and provide an all-optical network. All-optical WDM networks have the additional advantages of not requiring costly EOE (electronic-optical-electronic) conversions and being transparent to bit rate, modulation format and protocol, allowing for easy upgrading. However, optical processing and buffering technology is not yet mature [Nei05, Baw02, Mah01, Hun00] and thus, cannot offer the same functionalities as its electronic counterpart. Therefore, it is desirable to avoid the processing and buffering functions in the optical core as long as these technological constraints are not overcome.

Additionally, to offer the same flexibility of conventional networks, WDM networks must allow the use of different wavelengths along the path transmission if required (otherwise, data would be blocked when the required wavelength is used in the output link, even though other wavelengths may be available). This is possible only if wavelength conversion capability is provided in the nodes, another technical challenge. On one hand, electronic wavelength conversion inherits the same problems of electronic processing described above. That is, it requires EOE conversions and it cannot match the speed of optical transmission [Cam00]. On the other hand, optical wavelength conversion is still technically immature and expensive [Cam00, Elm00] and may not be a feasible solution in the short term.

The discussed current technological constraints hamper the implementation of already successful networking approaches, such as packet-switching. Currently, implementing packet-switching is problematic in WDM networks because its operation principle of “store-and-forward” [Kes97] is based on the availability of buffers and processors at the intermediate nodes of the transmission path whilst the packet-by-packet allocation scheme assumes that a packet can be sent through any available channel in the output link. As a result, in the last decade research has focused in designing new networking approaches that allow the implementation of a WDM-based network (also called optical network throughout this thesis). To do so, it is desirable that optical buffering is avoided, the network architecture used ensures that data remains in the optical domain as much as possible and wavelength conversion is provided only if strictly necessary to achieve an acceptable performance from the resource allocation algorithm.

Many optical network architectures proposed so far comply with the above requirements [Düs02, Ara99, Tur99, Qia99, Bar97]; in these approaches electronic data is buffered and processed at the ingress of the network (also called the network edge) and then transmitted in the optical domain, through a bufferless optical core where data does not undergo further electronic processing. Among these proposals, it is possible to distinguish between WDM networks which operate under static or dynamic models for the traffic demand (called static and dynamic networks in the remainder of this thesis).

In static networks (see, for example [Sir03, Ye00, Bar97]), termed static Wavelength-Routed Optical Network (WRON) [Bar97], lightpaths (i.e. a route and a

unique wavelength on that route) between network node pairs must be allocated according to a traffic matrix M whose element $[i,j]$ represents the number of wavelengths (lightpaths) required to transmit information from node i to node j at any time. Each element of matrix M is calculated according to the following expression:

$$M[i, j] = \left\lceil \frac{b_{i,j}}{C_w} \right\rceil$$

where $\lceil x \rceil$ represents the lowest integer greater or equal to x , $b_{i,j}$ the maximum bit rate at which node i transmits information to node j at any time and C_w is the bandwidth per wavelength channel.

Because the maximum bit rate at which a node can transmit information is usually determined by the transmission capacity of line cards (which remain unchanged for long periods of time), it is expected that the traffic matrix does not change frequently and thus, it is considered *static* or *quasi-static*.

Once the traffic matrix is determined, lightpath allocation is performed off-line and optical switches/wavelength routers as well as transmitters/receivers are configured accordingly. Lightpath allocation is done with the aim of minimising the number of wavelengths required per link, whilst accommodating all traffic demands and avoiding wavelength collisions in the same fibre in the core. Minimising the number of wavelengths per link is key for network feasibility as the wavelength requirement determines device and network parameters, such as wavelength stability, channel spacing, EDFA bandwidth and switches size [Bar97].

Optimal lightpath allocation (i.e., the allocation which minimises the number of wavelengths per link) could be carried out by trying all the possible solutions and choosing the best, but this technique is not practical given its exponential computational cost. Instead, the optimal solution is found by using Integer Linear Programming (ILP) solvers, for example as in [Bar98], or by efficient heuristic algorithms which, whilst do not necessarily yield the optimal solution, can reach a good one in much shorter time than ILP solvers. Once the lightpath allocation is performed, data arriving to the electrical interface of an end node (which emit and terminate the lightpaths) is classified per destination, converted into an optical signal and sent into the corresponding assigned lightpath, as shown in Figure 1.1. In the optical core, switches route the lightpaths according to the configuration of the switching matrix (which has been configured according to the lightpath allocation).

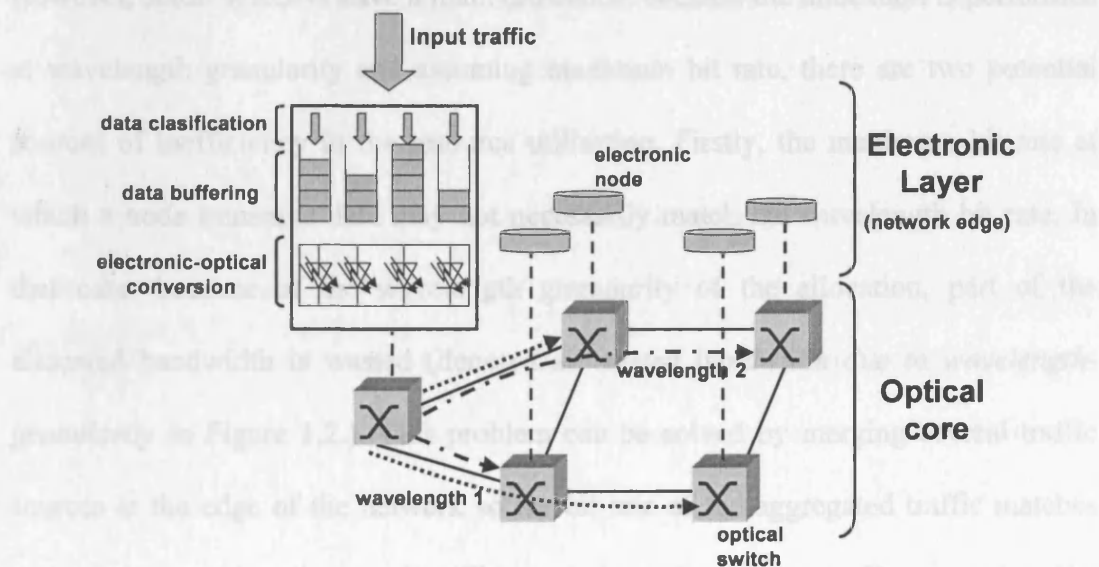


Figure 1.1. Schematic of a static WRON architecture

Static WRONs are attractive for several reasons. Firstly, they are simple to operate and manage. Since lightpaths are fixed, there is no need for tunable lasers in the edge nodes or on-line lightpath schedulers. Secondly, it is possible to find the optimal (or near optimal) solution because there is no restriction on the processing time due to the off-line nature of the lightpath allocation. Thirdly, it has been found that the number of wavelengths required by the optimal allocation (assuming no wavelength conversion capability) cannot be significantly further reduced using wavelength converters [She04, Ass02, Bar97, Wau96, Chl92] hence, wavelength conversion is not required in static WRONs. This simplifies the required network infrastructure and decreases network deployment and upgrade costs. Finally, static WRONs are designed to have zero delay in the head of the transmission buffer and zero blocking, which offers the best possible service to users.

However, static WRONs have a main drawback: because the allocation is performed at wavelength granularity and assuming maximum bit rate, there are two potential sources of inefficiency in the resource utilisation. Firstly, the maximum bit rate at which a node transmits data may not necessarily match the wavelength bit rate. In that case, because of the wavelength granularity of the allocation, part of the allocated bandwidth is wasted (denoted as *wasted bandwidth due to wavelength-granularity* in Figure 1.2.). This problem can be solved by merging several traffic sources at the edge of the network so the bit rate of the aggregated traffic matches that of the wavelength capacity. This technique, known as *traffic grooming* (for surveys see, for example, [Cer05, Dut02]), is beyond the scope of this thesis. In the remainder it is assumed that the maximum bit rate at which a node transmits information is equal to the wavelength capacity.

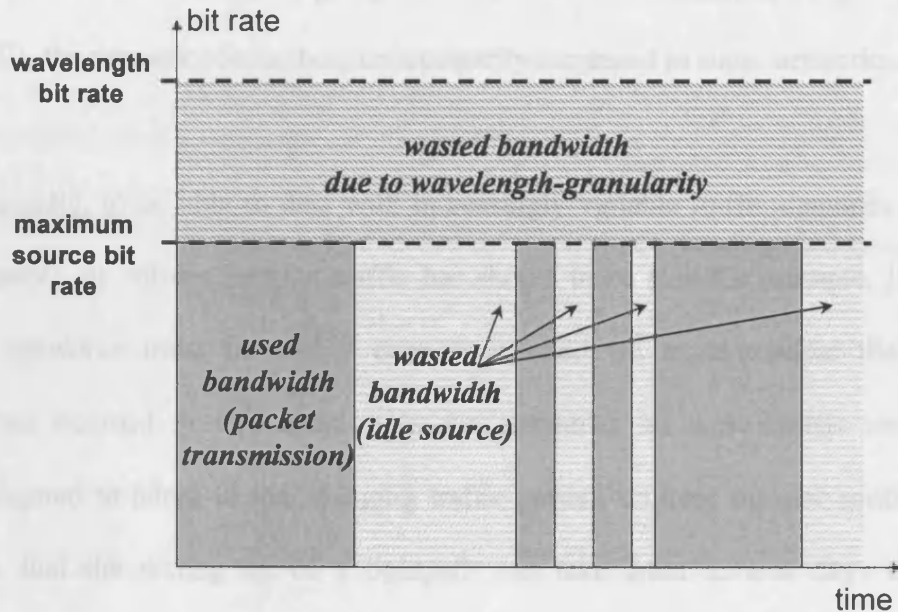


Figure 1.2. Inefficiency in bandwidth usage due to the mismatch between the maximum source bit rate and the wavelength bit rate (wavelength-granularity wasted bandwidth) and due to the maximum bit rate allocation (lower rate wasted bandwidth)

Secondly, it may happen that the source remains idle for some periods of time, which again results in allocated bandwidth not being used (denoted as *wasted bandwidth due to idle source* in Figure 1.2). Additionally, during the periods the source remains idle, the transmitter and the receiver allocated to the connection are not used either.

Given that recent studies have shown that most of networks currently operate at most at 30% of their maximum capacity [Odz03, Bha01], under static operation a significant number of wavelengths and transmitters/receivers would be inefficiently used. With the number of wavelengths mainly determining the cost of switches and

physical impairment-compensating equipment and the number of transmitters/receivers affecting significantly the cost of terminating equipment [Ban00], the network cost is thus, unnecessarily increased in static networks.

Additionally, to be able to deal with increasingly variable traffic demands (in time and space) -as current Internet traffic has shown to be (see for example, [Bha01]), static networks must be highly over-provisioned (to accommodate the highest expected demand at any location in the network), as they cannot be quickly reconfigured to adapt to the changing traffic pattern (current manual configuration means that the setting up of a lightpath can take from several days to weeks [Düs05]).

Although there are no conclusive results to date, it is widely believed that the dynamic allocation of resources in optical networks would overcome the inefficiencies of the static allocation in improving resource use, see for example [Lel06, Düs05, Ger03, Sen03, Ass01, Mah01, Zan01, Hun00, Spa00]. As a result, significant research has been carried out in the field of dynamic WDM networks in the last decade. By rapidly allocating resources only when and where required, dynamic networks could potentially provide the same service that static networks but at decreased cost, very attractive to network operators. This view has been further supported by previous results in conventional circuit-switched networks [Che90, Ash04] and in many other resource allocation systems (for example, service overlay networks [Dua03], Code Division Multiple Access (CDMA) networks [Par02], load balancing in mainframes [Kam00], Variable Bit Rate (VBR) video transmission [Zha97], manufacturing systems [Dan96] and virtual memory allocation systems

[Bud81]), reporting significant resource savings by applying dynamic allocation. In the case of WDM optical networks the resource savings would come from decreased number of wavelengths per link (affecting switching and physical impairment-compensating equipment cost) and transmitters/receivers (affecting terminating equipment cost).

However, the demand in dynamic systems is inherently uncertain and the allocation may be needed to be performed at very short timescales (for example, to support a highly loaded network with ~ 100 nodes, every lightpath request must be processed in the order of μs , as shown in Chapter 6). This necessarily leads to sub-optimal resource allocation because the entire set of traffic demands is not known and there is not enough time for optimisation algorithms to be executed. In addition, as all-optical wavelength conversion is currently problematic, the same wavelength must be used in all the links composing a path, a condition known as *wavelength-continuity constraint*. Although networks operating under the wavelength-continuity constraint are attractive due to their simplicity and the fact that routing functionality remains in the optical domain, they may experience poor resource re-utilisation as a lightpath request may be blocked even if there is available capacity in the network (as different available wavelengths in the links of a path cannot be used). As a result, the potential benefits of introducing dynamic operation in WDM networks may not prove to be as significant as expected.

Other drawbacks of dynamic allocation are in the additional delay and the eventual blocking of lightpath requests. The extra delay comes from data buffering at the

edge of the network as well as the time required to perform the lightpath allocation. Requests may be blocked due to wavelength contention.

Finally, although dynamic lightpath allocation can be implemented in a centralised (e.g. [Dus02, Soh03]) or distributed way (e.g. [Liu04, Ara99]), centralised provisioning is more attractive because the central control node maintains global information on the network state (topology and wavelengths utilization) [Cas94]. This achieves a more efficient allocation of resources and, therefore, a lower blocking probability than distributed lightpath assignment algorithms [Liu04, Ram01]. However, centralised systems have the potential risk of poor survivability and scalability, which may render them impractical. Survivability (i.e. the ability of the network to survive failures) is improved by redundancy of the control information in one (or more) back-up control nodes [Tri97]. Scalability (i.e. the maximum number of nodes that can be supported by such dynamic optical network architectures), however, remains a fundamental drawback of centralised allocation as a single node must maintain all the information on the network state and perform the processing of all the lightpath requests generated by the network nodes. With the number of increasing network nodes (or edge routers) all generating requests, scalability might be the one of the weakest point of centralised dynamic lightpath allocation.

Despite the mentioned drawbacks, dynamic WDM networks may prove to be attractive if it can be shown that, compared to the static networks, significant resource savings can be achieved whilst maintaining acceptable levels of blocking, delay and scalability. This might be a significant challenge as networks of practical

interest can reach hundred nodes and currently accepted levels of blocking and delay for a connection may be as low as 10^{-3} (at packet level) and 100 ms for data and time-critical applications, respectively, as defined by the International Telecommunication Union – Telecommunication Standardization Sector (ITU-T) [Sei03]. Additionally, even if these conditions on resource savings, blocking delay and scalability are met, dynamic WDM networks should ensure that the cost reduction achieved by the decrease in resource requirements is high enough to compensate for the extra cost introduced by the new components.

Table 1.1 summarises the main characteristics defining the performance of static and dynamic WDM networks discussed in this chapter, namely: resource utilisation (bandwidth/number of wavelengths and number of transmitters/receivers), blocking, delay, scalability, network complexity and lightpath provision speed.

	Static allocation		Dynamic allocation	
Resource utilisation	✗	Low when not transmitting at maximum bit rate	?	Higher than static
Blocking	✓	Zero	✗	Higher than static
Delay	✓	Propagation and edge buffer queueing	?	Higher than static
Scalability	✓	High	?	Much lower than static
Network complexity	✓	Low (wavelength conversion and on-line schedulers not required)	✗	Higher than static
Lightpath provision speed	✗	Low	✓	Higher than static

Table 1.1. Qualitative comparison of static and dynamic operation in optical networks. Boxes with a question mark indicate a lack of quantitative results at the moment of starting the research described in this thesis.

Absence of quantitative results comparing static and dynamic WDM networks in terms of resource utilisation, delay and scalability, makes it difficult to answer the question of whether the widely expected migration from the (current) static WDM networks to dynamic ones is justified.

This thesis aims to answer this question by investigating the potential benefits of dynamic WDM networks with respect to static architectures in terms of resource (wavelengths) savings, delay and scalability, a question of fundamental importance for the design of future optical networks. The structure of this thesis is as follows.

Chapter 2 presents a review of dynamic WDM network architectures and dynamic lightpath allocation algorithms proposed to date. Architectures are discussed in terms of their short-term feasibility of implementation, complexity, resource utilization efficiency and delay. Algorithms are studied in terms of blocking performance and computational complexity. Open research questions in the field of dynamic vs. static WDM networks are identified and discussed.

Chapter 3 investigates the resource requirements of dynamic WDM networks – defined in terms of the number of wavelengths per link required to achieve a target blocking probability, and compares them to that of static networks under uniform traffic demand. New analytical and heuristic lower bounds for the wavelength requirements are derived. The heuristic lower bound corresponds to a new lightpath allocation algorithm which implements a near-optimal lightpath allocation by rearranging active lightpaths every time a new lightpath request is received. Different dynamic algorithms are implemented in a centralized wavelength-routed optical burst

switched network and their wavelength requirements are quantified under uniform traffic demand and compared to the requirements of an equivalent static network. The effect of equipping the network with wavelength conversion is also analysed. A second new and practical lightpath allocation algorithm is also presented. This new algorithm achieves lower wavelength requirements than the best reported to date (AUR-E [Mok98]) and has similar computational complexity. The performance of the algorithms in terms of wavelength requirements is investigated by applying them to 7 real physical network topologies. This allows to study the impact that the network topology has in the wavelength requirements of the algorithms. The results show the impact of the network topology, the dynamic lightpath algorithm and wavelength conversion in the potential benefits of dynamic optical networks with respect to static ones.

In Chapter 4, as in Chapter 3, a comparison between dynamic and static wavelength-routed optical networks is carried out, but in this case by considering non-uniform traffic demands. The results allow to study the effect of the degree of traffic demand concentration in the potential benefits of dynamic optical networks.

Chapter 5 focuses on the analysis of the delay parameter. In this Chapter the average delay under dynamic operation (mainly due to aggregation and propagation) is quantified by means of analysis and simulation. Novel analytical expressions to quantify the extra delay introduced by five different aggregation mechanisms at the edge of the network are derived and validated through simulation.

Chapter 6 focuses on the consideration of scalability. In this Chapter the limiting scalability of a dynamic wavelength-routed optical network is studied as a function of the lightpath allocation algorithm computational complexity is studied. The maximum lightpath request processing time for the network to be able to process the lightpath requests generated by all network nodes is derived for different scheduling policies. The complexity and execution time of different lightpath allocation algorithms were investigated and compared to the limiting processing time to quantify the maximum number of nodes supported by the network. Scheduling theory and static performance prediction techniques are applied to define the bounds on the electronic processing time of requests, and hence the maximum number of nodes supported by a centralised dynamic optical network for given blocking probability, latency, and network diameter. Sensitivity analysis in terms of memory access time and processor speed is described. The trade-off between the request processing time and blocking probability is investigated and a new low-blocking and scalable lightpath allocation algorithm is proposed which improves the mentioned trade-off.

Finally, Chapter 7 presents a summary of the main conclusions of the research and provides suggestions for future work.

1.2. Contribution of this work

The novel contributions of this thesis are the following:

- i. A new performance metric to allow a direct comparison between dynamic and static networks, namely the resources required to achieve a specific blocking probability [Zap05]

- ii. New analytical formulation to obtain a lower bound for the wavelength requirements of dynamic WDM networks [Zap06, Zap05]
- iii. A near-optimal dynamic lightpath allocation algorithm based on the execution of near-optimal heuristics for the static case. Although the algorithm is not practical, it provides an algorithmic lower bound for the resource requirements of dynamic WDM networks [Zap06, Zap05]
- iv. The evaluation of the performance of dynamic lightpath allocation algorithms in terms of the new performance metric (i) and their comparison with the wavelength requirements of static networks [Zap06, Zap05, Zap05a, Zap04]
- v. A novel (and practical) dynamic lightpath allocation algorithm with lower resource requirements than the best to date
- vi. The evaluation of the effect of physical connectivity and wavelength conversion in the benefit of dynamic operation [Zap06, Zap05]
- vii. The evaluation of the effect of non-uniform traffic demand on the potential benefits of dynamic operation compared to static wavelength-routed optical networks
- viii. The analytical formulation for the evaluation of the extra mean delay introduced by dynamic operation of optical networks [Zap03a]
- ix. The quantification of the scalability of dynamic lightpath allocation algorithms [Zap05b, Düs04, Zap03]
- x. A new dynamic lightpath allocation algorithm which performs as good as the best to date but with significantly increased scalability [Zap05b]

1.3. Publications and conference presentations

3 Journal papers

- **A. Zapata**, P. Bayvel, “Do we really need dynamic wavelength-routed optical networks?”, Lecture Notes in Computer Science, 4208, 477-486, 2006
- **A. Zapata**, I. de Miguel, M. Dueser, J. Spencer, P. Bayvel, D. Breuer, N. Hanik, A. Gladish, “Next generation 100-Gigabit Metro Ethernet (100GbME) using multi-wavelength optical rings”, IEEE/OSA Journal of Lightwave Technology 22 (11), 2420-2434, special issue on “Metro & Access Networks”, November 2004
- M. Dueser, **A. Zapata**, P. Bayvel, “Investigation of the scalability of dynamic wavelength-routed optical networks”, OSA Journal of Optical Networking (JON) 6, 667-686, special issue on “Optical Interconnection Networks”, September 2004, **Invited paper**.

13 International conference papers

- **A. Zapata**, P. Bayvel, “Do we really need dynamic wavelength-routed optical networks?”, International Conference on High Performance Computing and Communications, Munich, Germany, September 2006
- **A. Zapata**, P. Bayvel, “Improving the scalability of lightpath assignment algorithms in dynamic networks”, 31st European Conference on Optical Communications, Glasgow, Scotland, vol.1, 35-36, September 2005
- **A. Zapata**, P. Bayvel, “Dynamic vs. static lightpath allocation in WDM networks”, 31st European Conference on Optical Communications, Glasgow, Scotland, vol.2, 273-274, September 2005

- **A. Zapata**, P. Bayvel, "Optimality of dynamic resource allocation in WDM networks", 10th European Conference on Networks and Optical Communications (NOC 2005), 131-138, July 2005, London, UK. **Invited paper.**
- **A. Zapata**, P. Bayvel, "Optimisation of scheduling delay in wavelength-routed optical burst switched networks with re-attempt capability", Optical Fiber Communications Conference 2004 (OFC 2004), Los Angeles, USA, February 2004. Described as "**a significant advancement in the field**" by the OFC subcommittees and OFC media team.
- **A. Zapata**, P. Bayvel, "Impact of burst aggregation schemes on delay in optical burst switched networks", IEEE LEOS Annual Meeting, Arizona, USA, October 2003
- **A. Zapata**, I. de Miguel, M. Dueser, J. Spencer, P. Bayvel, D. Breuer, N. Hanik, A. Gladish, "Impact of non-uniform traffic on performance and resource requirements in optical ring networks", 29th European Conference on Optical Communications (ECOC 2003), September 2003, Rimini, Italy.
- **A. Zapata**, I. de Miguel, M. Dueser, J. Spencer, P. Bayvel, D. Breuer, N. Hanik, A. Gladish, "Performance comparison of static and dynamic optical metro ring network architectures", 29th European Conference on Optical Communications (ECOC 2003), September 2003, Rimini, Italy.
- M. Dueser, **A. Zapata**, P. Bayvel, "Scalability analysis for QoS-aware optical networks with dynamic wavelength allocation", 29th European Conference on Optical Communications (ECOC 2003), September 2003, Rimini, Italy.
- J. Spencer, M. Dueser, **A. Zapata**, I. de Miguel, P. Bayvel, D. Breuer, N. Hanik, A. Gladish, "Design considerations for 100-Gigabit Metro Ethernet

(100GbME)" , 29th European Conference on Optical Communications (ECOC 2003), September 2003, Rimini, Italy.

- **A. Zapata**, J. Spencer, I. de Miguel, M. Düser, P. Bayvel, D. Breuer, N. Hanik, and A. Gladisch, "Investigation of Future Optical Metro Ring Networks based on 100-Gigabit Ethernet", ITG-Fachtagung "Photonische Netze", 5-6 May 2003, Leipzig, Germany.
- **A. Zapata**, P. Bayvel, "Dynamic Wavelength-Routed Optical Burst Switched Networks: Scalability Analysis and Comparison with Static Wavelength-Routed Optical Networks", Optical Fiber Communications Conference 2003 (OFC2003), 23-28 March 2003, Atlanta, USA.
- E. Kozlovski, M. Dueser, **A. Zapata**, P. Bayvel, "Service Differentiation in Wavelength-Routed Optical Burst-Switched Networks", Optical Fiber Communications Conference 2002 (OFC2002), March 17-22, Anaheim Convention Center, Anaheim, California. USA. pp.774-776

Other presentations

A. Zapata, P. Bayvel, "Wavelength-Routed Optical Burst Switched Networks: Scalability Analysis and Comparison with Static Wavelength-Routed Optical Networks", Grasmere, ESPRC, September 2002

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Chapter 2

Dynamic wavelength-routed optical networks

As discussed in Chapter 1, as long as significant wavelength savings as well as acceptable levels of delay and blocking can be achieved, the introduction of dynamic operation in wavelength-routed optical networks is potentially very attractive for network operators. To explore the feasibility of this, research in the field of dynamic optical network architectures and lightpath allocation algorithms has been extremely active in the last 10 years, although many questions still remain unanswered.

In this chapter, different proposed dynamic architectures and algorithms for wavelength-routed optical networks proposed to date are reviewed. Architectures are discussed in terms of feasibility of implementation, complexity, efficiency in the resource utilisation and delay. Different lightpath allocation algorithms are discussed in terms of computational complexity and blocking. The open issues in the area of dynamic vs. static wavelength-routed networks are identified to set the context for the work described in the rest of this thesis.

2.1. Dynamic optical network architectures

Considering the technological constraints discussed in Chapter 1, namely: the lack of optical buffering/processing and the difficulty of implementing wavelength conversion, the proposed approaches to achieving dynamic optical network architectures can be grouped as three main architectures. They are, in decreasing order of technological complexity, as follows:

- ***Optical Packet Switching*** (OPS) [Dev04, Bat03, Hun00, Mah01] is the architecture with the highest technological requirements: it cannot operate without wavelength conversion and optical buffering/processing. For this reason it would be feasible for implementation only in the long-term, although several small-scale demonstrators with limited capabilities have been built in the last years, see for example [Ran06, Wol06, Gau05, Car04, Xue04, Dit03, Jeo03, Gui00, Hun99, Car98, Shr00, Tol98].
- ***Optical Burst Switching*** (OBS) [Qia99, Tur99] does not require optical buffering/processing (although performance can be significantly improved by providing optical buffering). However, wavelength conversion is mandatory for this architecture to achieve an acceptable performance. Given that wavelength conversion is not a commercial technology yet, this type of architecture is still some years away.
- ***Wavelength-Routed Optical Burst Switching*** (WR-OBS) [Düs02], amenable to be implemented in the short-term with current components as it does not require wavelength conversion or optical buffering/processing to achieve an acceptable performance.

The different technological requirements of these optical architectures result in data units of different sizes: OPS can deal with very small packets (in the order of 400-1500 bytes) whilst OBS/WR-OBS architectures are designed to operate with data unit sizes of a few kBytes/Mbytes (typically, 1kB - 40 kB in OBS [Dol01, Xio00, Yoo00, Tur99, Wei99] and about 2-25 MB in WR-OBS [Düs02]). This is summarised in Figure 2.1, which shows the technological requirements and the data unit size for each dynamic architecture. The case of static WRON is included for comparison.

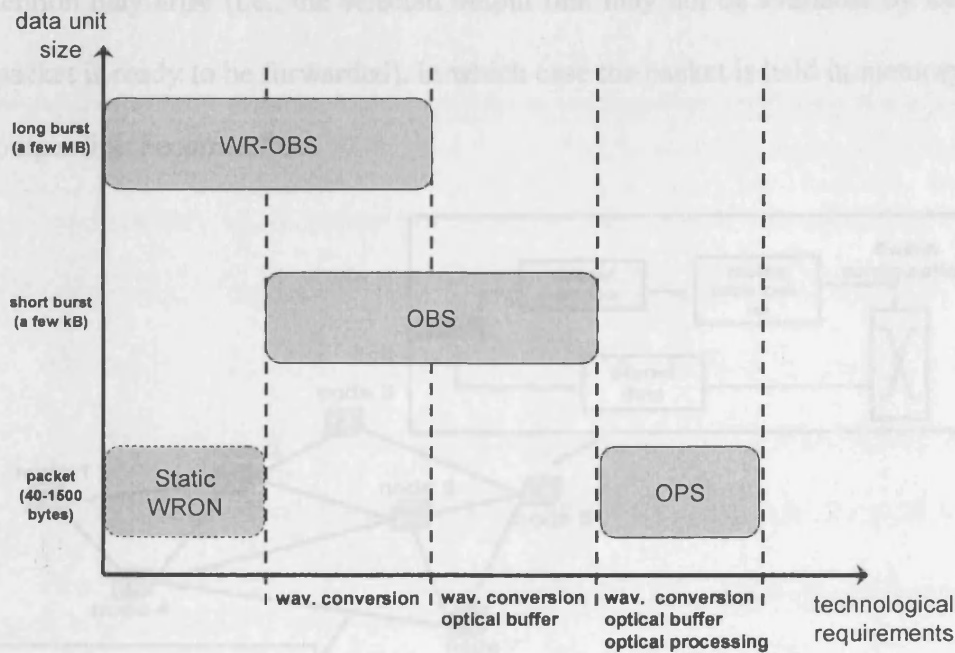


Figure 2.1. Technological requirements and data unit size of optical architectures

WR-OBS, OBS, OPS and static WRON.

These dynamic architectures are discussed in detail in the following sections in terms of feasibility of implementation, complexity, efficiency in the resource utilisation and delay.

2.1.1. Optical Packet Switching (OPS)

In OPS networks, optical packets are sent through the optical network using the store-and-forward technique of conventional packet-switching networks [Kes97]. That is, packets are routed on a hop-by-hop basis. As shown in Figure 2.2, at every node, the control information (header) of the packet is read to extract its destination and the packet payload (data) is held in memory, while a routing table is inspected to identify the output link for transmission. Due to the random nature of packet arrivals, contention may arise (i.e., the selected output link may not be available by the time the packet is ready to be forwarded), in which case the packet is held in memory until the output link becomes free.

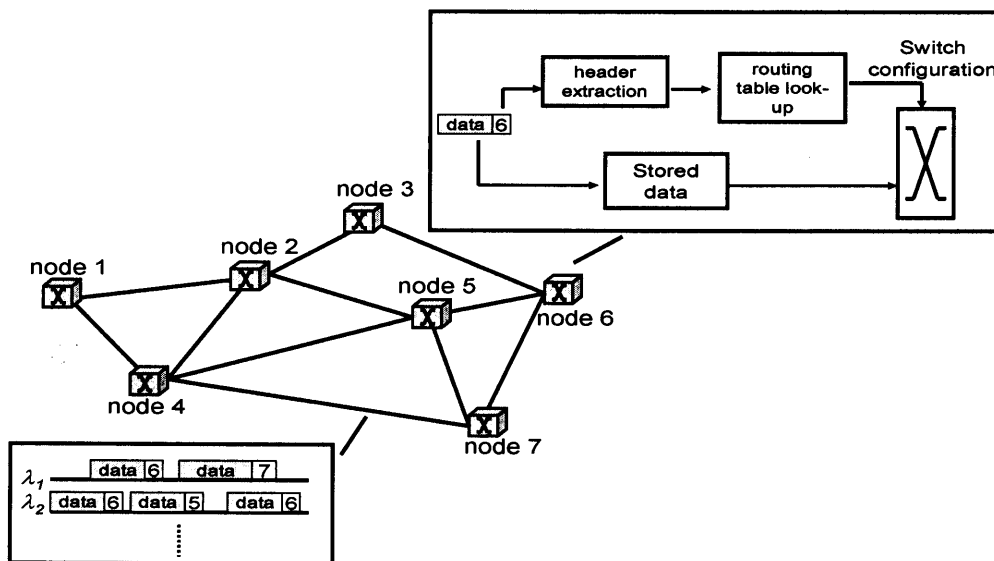


Figure 2.2. Schematic of OPS network architecture operation

Packet-switching is thought to be the most bandwidth-efficient technique [Dev04, Bat03, Blu03, Jou01, Hun00, Mah01, Chl89], as resources are allocated only when required at the finest (packet) granularity. This feature may be particularly attractive

under bursty traffic, as data traffic has been shown to be [Gon05, Gon05a, Cro97]. Envisaged as the ultimate all-optical network, it has fuelled great interest as demonstrated by the significant amount of experimental small-scale OPS switches and network demonstrators, see for example [Ran06, Wol06, Gau05, Car04, Xue04, Dit03, Je003, Gui00, Hun99, Car98, Shr00, Tol98].

However, several technological constraints hamper the implementation of a pure large-scale optical packet-switching network in the short/medium-term:

- **Lack of optical buffers.** The use of random access memories lies at the core of the electronic store-and-forward technique. With typical packet sizes of 389.5 bytes [Xio00] at link rates of 40 Gb/s it would be necessary to process each packet in 78 ns, which would be reduced to 8ns for 40-byte TCP acknowledgement. Only static RAM (SRAM) can provide this access speed (10 ns [Cha02], <1ns [Nam00]) but they are limited in size (1 Mbit for access times lower than 1 ns [Nam00]) which makes the storage of lookup tables and packets difficult. Since scalable optical random access memories are not yet available, buffering can only be partially mimicked by transmitting packets through optical fibre delay lines (FDLs). FDLs operate by delaying the packets for a fixed amount of time, given by the length of the fibre line divided by the speed of light in fibre. Given that packet length can vary over a wide range (40 – 12000 B [Xio00]), the availability of a discrete number of delays to solve contention results in gaps between packets (because the delayed packet may still have to travel through the FDL when the contending packet has released the resource), which degrades network

performance [Cal00]. In addition, FDLs may be bulky when deep buffers are required [Hun98] (which limits integration), difficult to stabilise with respect to temperature and may need to include amplification due to excessive recirculations [Mah01, Baw02]. Wavelength conversion and deflection routing [Pat06, Cal04, Era04, Ove04, Dit03, Yao03, Hun99, Dan98] have been proposed as means to decrease the memory requirements by partially solving the problem of contention in the wavelength and space domain, respectively. However, research showing that wavelength conversion alone could compensate for the absence of buffers [Dan98] also indicates that a wavelength converter per output port would be required, increasing significantly the network cost. Additionally, all-optical wavelength conversion is not a mature technology yet [Elm00]. Deflection routing instead does not require extra hardware to be implemented, but it is only effective in highly connected networks at low/moderate loads [Pat06, Yao03, Cas99]. In addition, it causes mis-ordering of packets at the receiving end (which affects the performance of higher layers, as TCP) and packets may be indefinitely deflected in the network. Recently, the hypothesis of TCP being able to operate with small buffers (~20 packets) at the expense of lower channel utilisation has been investigated in [Beh06, Wis05]. In this case, optical buffering of packets could be easily implemented with FDLs. This hypothesis, however, is still to be proven effective in real networks.

- **Lack of all-optical processing.** The packet processing speed requirement (in the timescales of nanoseconds) is well beyond the electronic processor capabilities predicted by Moore's Law for the next future and the expected achievable electronic memory access times (only improving at the rate of

about 5% per year [Blu03]). Adding the fact that optoelectronic interfaces dominate the power dissipation and cost [Ell04, Pap03], as well as not scaling well with the port count and bit rate, it can be seen that electronic packet processing will not be suitable for the increasing WDM transmission speeds. All-optical processing would overcome these drawbacks. However, although header processing research started in the 1990's, it is not yet a mature enough technology [Baw02]. Currently, only some basic header processing functions can be achieved all-optically: header recovery, packet compression, reading, erasure and re-write [Ran06, Blu04, Blu03, Nor03, Cot99]. But, packet scheduling, routing table look-up and identification of new-formatted headers are more complex functions which must be performed electronically.

- **Requirement for high-speed switching.** Operation in a packet-by-packet basis requires that switching time is in the nanosecond scale range (for example, typical 400-byte packets transmitted at 40Gb/s require 78ns each to be processed). Currently, these switching speeds can only be provided by a limited number of electro-optical switches [Gri03, Ma03, Pap03, Ben01] such as Ti:LiNbO₃ switches (~5 ns) [Kra02], PLZT switches (~20 ns) [Nas01], MMI-based semiconductor space switches (~120 ps) [Ear02], SOA-based switches (~200 ps) [Gal02] and electro-holographic optical switches (~10 ns) [Agr02]. However, to date, they have failed to achieve acceptable levels of scalability (switch size). For instance, LiNbO₃ and SOA-based switches of only up to 32x32 and 8x8 ports, respectively, are available to date [Gri03], which cannot be cascaded further due to the high losses experienced.

Given the discussed technological drawbacks, the practical implementation of OPS networks is still not possible in the short-term. This has prompted the proposal of alternative dynamic architectures which trade granularity by feasibility in the short term, as discussed in the following.

2.1.2. Optical Burst Switching (OBS)

OBS networks, originally proposed in [Qia99, Tur99], aim to decrease the speed requirements imposed by the packet-by-packet operation of OPS networks by electronically aggregating packets at the edge of the network. The aggregation of packets is into a container, called a burst (typically of a few kBytes [Dol01, Xio00, Yoo00, Tur99, Wei99]), which is optically transmitted through the network just after a control packet has configured switches on a hop-by-hop basis. By operating on a burst-by-burst basis (as opposed to a packet-by-packet basis), the demanding switching and processing speed requirements of OPS networks are relaxed. Use of a control packet to reserve the transmission resources in advance, while the burst is electronically held at the edge of the network, eliminates the need for optical memory to store the burst while the routing table look-up takes place. Figure 2.3 shows schematically the operation of an OBS network.

Input packets arriving to an edge node are classified according to their destination. In each buffer the packets are aggregated into a burst until a pre-defined event occurs (for example, until the burst reaches a determined size [Hu03] or until a timer expires [Ge00]). This event triggers the release of a control packet whose role is to reserve

transmission resources for the burst on a hop-by-hop basis. To avoid the need to store the burst in each node whilst an appropriate output wavelength is being looked for

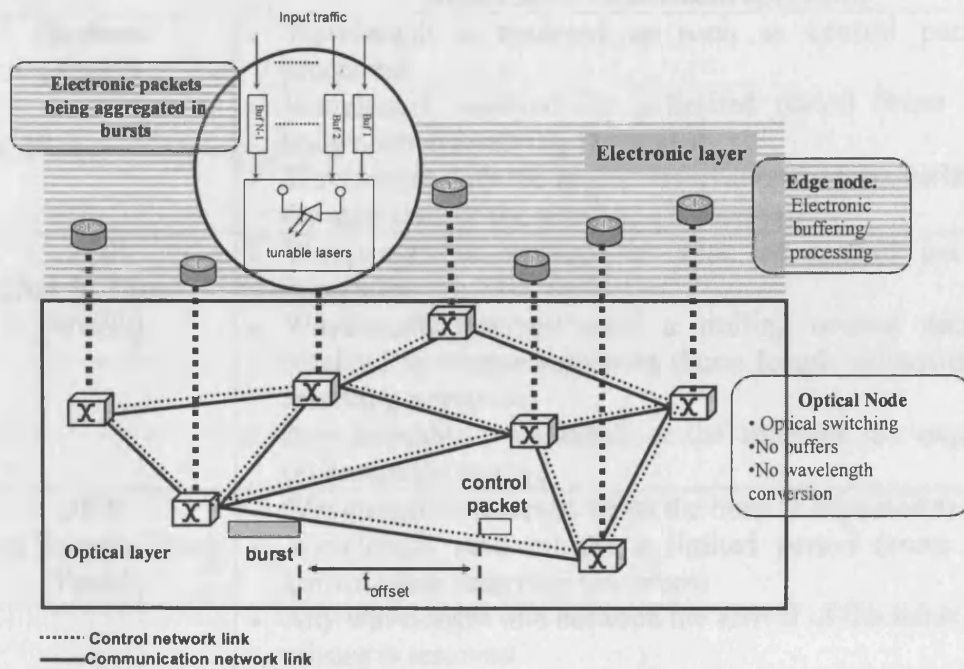


Figure 2.3. Schematic of OBS network architecture operation

and the switch configured accordingly, the burst is held in the edge node for a short period of time (called *offset time*) in the electronic buffer of the edge node. The *offset time* must be long enough to ensure that every switch in the path is already configured when the burst arrives. With the aim of keeping the delay as short as possible, once the offset time expires, the burst is released into the optical core without waiting for confirmation of the reserved resources.

Different resource reservation mechanisms for the OBS architecture have been proposed. They are summarised in Table 2.1 in chronological order. All of them assume full wavelength conversion and no optical processing in the core.

	<i>Reservation mechanism operation</i>
Horizon [Tur99]	<ul style="list-style-type: none"> • Wavelength is reserved as soon as control packet is processed • Wavelength reserved for a limited period (burst length known when reserving resources) • Wavelength with the largest reservation horizon earlier than the start time of the new burst is reserved
JIT (Just in Time) [Wei99]	<ul style="list-style-type: none"> • Wavelength is reserved as soon as control packet is processed • Wavelength reserved until a trailing control packet is received to release resources (burst length unknown when reserving resources) • Any available wavelength at the moment the request is processed is reserved
JET (Just Enough Time) [Yoo00]	<ul style="list-style-type: none"> • Wavelength is reserved when the burst is expected to arrive • Wavelength reserved for a limited period (burst length known when reserving resources) • Any wavelength idle between the arrival of the burst and its release is reserved
LAUC-VF (Latest Available Unscheduled Channel with Void Filling) [Xio00]	<ul style="list-style-type: none"> • Wavelength is reserved when the burst is expected to arrive • Wavelength reserved for a limited period (burst length known when reserving resources) • The wavelength which most tightly fills the gap between the arrival of the burst and its release is reserved
JIT+ (Just in Time Plus) [Ten05]	<ul style="list-style-type: none"> • Wavelength is reserved as soon as control packet is processed • Wavelength reserved for a limited period (burst length known when reserving resources) • Any wavelength with the a reservation horizon earlier than the start time of the new burst is reserved only if at most one other reservation exists in such wavelength

Table 2.1. Reservation mechanisms for the OBS architecture

The reservation mechanisms can be sorted from the best to the worst performing (in terms of burst loss rate) in the following order: LAUC-VF, JET, JIT+, JIT, Horizon [Ten05, Gau01]. LAUC-VF is the best performing algorithm because uses all possible voids in the wavelengths to allocate the burst as well as reserving the wavelengths only for the duration of the burst. In this way, wavelengths are highly

used only when burst transmission takes place. Remaining algorithms either do not use all available voids or reserve the wavelength for longer than required for burst transmission, which makes them to exhibit higher burst loss rates.

The main drawback of the OBS architecture is the significant burst loss rate due to wavelength contention. For example, in ring topologies, the throughput of OBS-JET can be up to one third of that of static WRON [Zap04] whilst in [Bay01, Mye01] it was shown that, equipping an OBS-JET network with the same capacity of static WRON, even at low loads the burst loss probability rapidly becomes unacceptable (higher than 10^{-3} for loads in exceed of 0.4). Recently the impact of OBS on higher network layers as TCP has been evaluated in [Cam05] and it has been found that, for OBS to be able to efficiently carry TCP traffic, a large number of wavelengths must be provisioned. Since there is no end-to-end acknowledgement prior to burst transmission (bursts are assumed to be in the range of tens of kilobytes, at 40 Gb/s this means that a burst is ready to be sent in a few microseconds and therefore, there is no time to end-to-end path reservation) and nodes are bufferless, bursts can be dropped at any point along the path to destination due to channel contention. Therefore, not only the already reserved/used resources are wasted in case the burst is dropped, but also critical data is not guaranteed to be delivered. Moreover, because bursts from an application may not follow the same path, jitter sensitive applications may also be affected.

Several proposals have been made to decrease the burst loss of OBS networks: the compulsory use of full wavelength conversion in every node, especially to efficiently carry TCP traffic [Cam05], fibre delay lines to provide limited buffering capabilities

at the core nodes [Yoo00], deflection routing [Hsu02], partial discard of contending bursts [Det02] and delaying bursts originating at a node in the case they contend with passing-through bursts [Li04] or a combination of them [Gau04].

However, all these proposals significantly increase the complexity of the network architecture. In addition, some of them are not yet available (all-optical wavelength conversion [Elm00]), suffer from side effects as bulky set-ups (buffering using FDLs), out-of-order packets (deflection routing, partial discarding) or are inefficient in decreasing significantly the burst loss rate. For example, in [Zap03] it was shown that operating with full wavelength conversion, an OBS network still requires more wavelengths than a simpler centralised two-way reservation wavelength-routed optical burst switched network to achieve the same blocking probability. This centralised wavelength-routed optical burst switched network with end-to-end reservation is described in the following.

2.1.3. Wavelength-Routed Optical Burst Switching (WR-OBS)

To overcome the inefficiencies of conventional OBS networks, the Wavelength-Routed Optical Burst Switching (WR-OBS) architecture was proposed in [Düs00]. As already described in the previous section, burst loss (and consequently reduced throughput) in OBS networks comes mainly from two facts:

- wavelengths are allocated in a hop-by-hop basis without global knowledge of the wavelength utilisation in the network
- significant resources are wasted by transmitting bursts that may be later dropped

WR-OBS overcomes these shortcomings by using end-to-end reservation with acknowledgement, relying on global information about the state of the network resources. Therefore, the reserved resources are actually used for transmission.

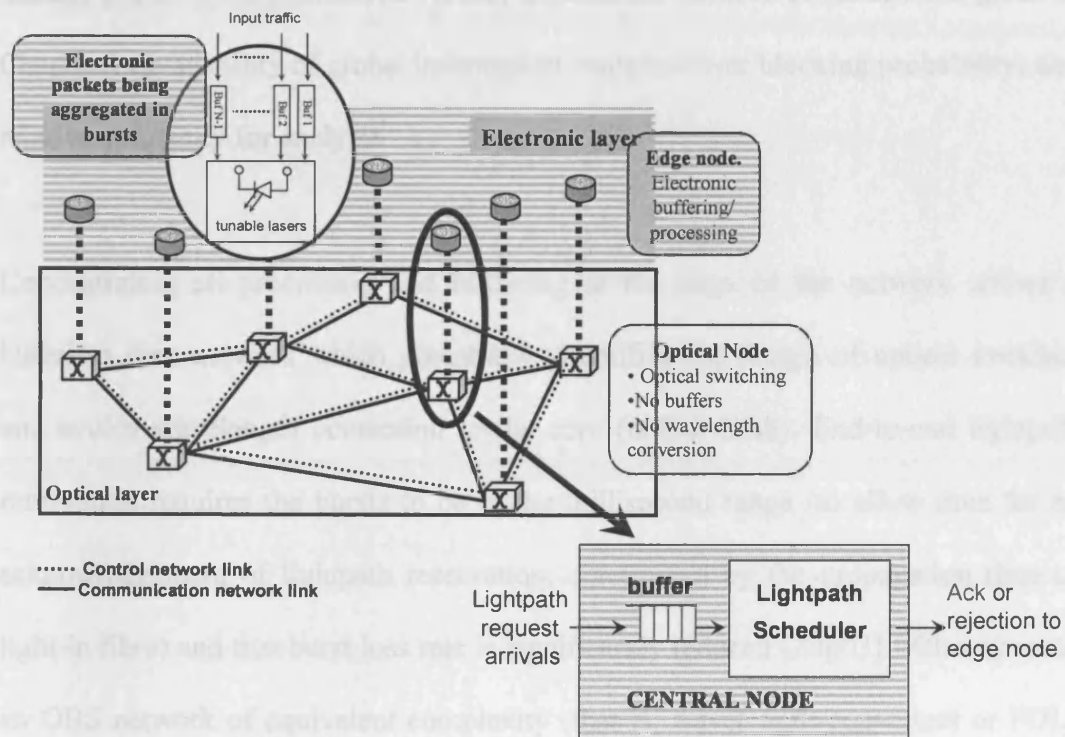


Figure 2.4. Schematic of WROBS network architecture operation.

The operation of a WR-OBS network is shown schematically in Figure 2.4. As in OBS, packets are electronically aggregated into bursts at the edge of the network according to their destination and at some point of the aggregation process a request is sent to the core network to find and reserve resources for the burst. But unlike OBS, end-to-end lightpath reservation is required prior transmission of a burst through the optical core. Once the lightpath has been reserved in the core, an acknowledgement with the information on the selected lightpath is sent to the edge

node, and the burst can be transmitted. In case a lightpath is not found, a negative acknowledgement is sent to the edge node and the burst is dropped.

Although WR-OBS can be implemented in a centralised [Düs02] or distributed manner [Ara99], the centralised version is preferred because of the reasons given in Chapter 1 (availability of global information leads to lower blocking probability) and relative simplicity for analysis.

Concentrating all processing and buffering at the edge of the network allows a bufferless core network which potentially simplifies the design of optical switches and avoids wavelength contention in the core (unlike OBS). End-to-end lightpath reservation requires the bursts to be in the millisecond range (to allow time for an acknowledgement of lightpath reservation, determined by the propagation time of light in fibre) and that burst loss rate is significantly reduced [Zap03] with respect to an OBS network of equivalent complexity (that is, wavelength-converters or FDLs are not used).

Compared to the static WRON, WR-OBS has the potential to require a lower number of wavelengths as the preliminary analysis in [Düs02] has shown. In [Düs02] the wavelength re-utilisation factor, RUF, defined as the ratio between the time a wavelength is not being used by a particular connection and the time this connection maintains the reserved wavelength (whether it uses it or not), is introduced. RUF allows to quantify how many different connections could use the same wavelength, assuming an ideal lightpath allocation algorithm (that is, a wavelength is always available when requested). For values of RUF equal to 1, WR-OBS brings no

benefits with respect to the static WRON. Only for values of RUF higher than 1 WR-OBS would be attractive with reference to the static WRON of lower wavelength requirements. In [Düs02] it was found that for potential wavelength savings (that is, $RUF > 1$) the burst transmission time must be much larger than the time the wavelength is reserved but not in use (this time is given by the ACK propagation time plus the propagation time for the first bit of the burst to arrive at the destination edge node). In this thesis, this condition is denoted as *efficiency criterion*.

Contrary to expectations, WR-OBS operates well with current-size buffers [Düs02] and, as shown in [Zap03, Koz02, Mig01] and later in this thesis (Chapter 5), the extra delay introduced by the burst aggregation process is not high enough to exceed the end-to-end delay beyond the critical threshold of 100 ms, established for time-sensitive applications [Sei03]. Therefore, whilst WR-OBS increases the end-to-end delay, the increase is not significant as to affect the quality of the service offered to the most demanding applications.

Given that WR-OBS have been shown to have the potential to achieve a much lower blocking probability than the other only feasible dynamic optical network to date (OBS), the introduced extra delay is not high enough as to affect the performance of time-critical applications and it has the potential of achieving significant wavelength savings with respect to the static approach (as shown by the RUF parameter introduced in [Düs02]), the work described in this thesis focused on centralised WR-OBS as the dynamic network architecture to be compared to the static WRON.

2.2. Dynamic lightpath allocation algorithms

An optical network architecture alone cannot guarantee acceptable levels of service if it is not supported by an efficient routing and wavelength allocation algorithm. This section focuses on those lightpath assignment algorithms amenable to be implemented in a centralised WR-OBS architecture.

The target of a dynamic routing and wavelength allocation algorithm is to find a lightpath in real time (in practical terms, this means on μs timescales as shown in Chapter 6) whilst minimising the resources used and maximising the probability to accommodate future requests. These are conflicting requirements, as typically good allocation algorithms require significant execution time to be computed (see Chapter 6), highlighting a trade-off between the quality of the allocation algorithm and its processing speed (computational complexity) [Düs04].

As shown in Figure 2.5, lightpath allocation algorithms proposed to date either 1) try to achieve a good trade-off between speed and complexity by solving the problem of routing (R) and wavelength assignment (WA) separately or 2) try to achieve the best possible allocation by jointly solving the routing and wavelength assignment problem (joint RWA), at the expense of high processing time. In both cases, most proposals correspond to conventional algorithms, although recently a few papers have applied some techniques from the soft computing area (such as genetic algorithms [Bis04, Mig04, Le04], ant colony algorithms [Na06, Ngo06, Pav06, Ngo04, Gar02] or learning automata techniques [Aly04]) to solve the lightpath allocation problem.

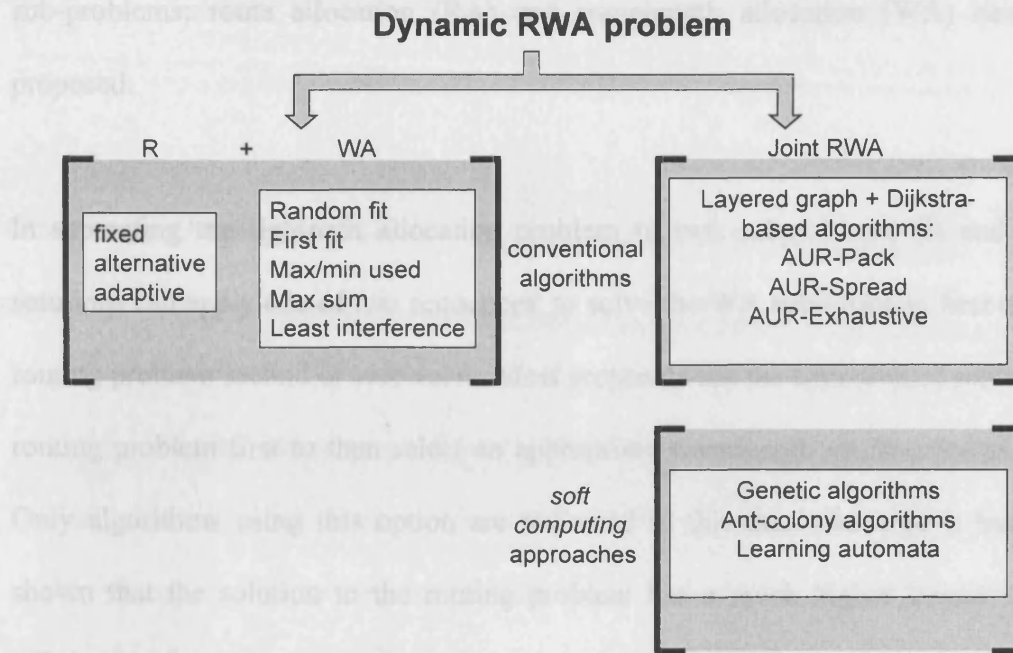


Figure 2.5 Algorithmic approaches used to solve the dynamic RWA problem

In the following, algorithms in both classifications (separated and joint routing and wavelength assignment) are described.

2.2.1. Separated routing and wavelength assignment

The dynamic lightpath allocation problem consists on finding a route and a unique wavelength on that route for each of the incoming lightpath requests whilst minimising the number of wavelengths used in the network. Such problem is NP-hard [Zan01, Chl89], which means that the time to find an optimal solution grows exponentially with the problem size (number of nodes, links and wavelengths in the case of optical networks). Given that dynamic networks need to find a lightpath on microsecond timescales (as shown in Chapter 6), algorithms with low execution time ($\sim \mu\text{s}$) are of fundamental importance. Therefore, to simplify (and speed up) the lightpath allocation task, the separation of the lightpath allocation problem into two

sub-problems: route allocation (RA) and wavelength allocation (WA) has been proposed.

In separating the lightpath allocation problem in two subproblems (R and WA), solutions can apply one of two sequences: to solve the WA sub-problem first and the routing problem second or vice versa. Most proposals use the approach of solving the routing problem first to then select an appropriate wavelength on the chosen route. Only algorithms using this option are reviewed in this thesis because it has been shown that the solution to the routing problem has a much higher impact on the efficiency of the allocation than the wavelength allocation algorithm used [Zan01, Bir95]. Thus, constraining the routing space solution by first selecting an available wavelength does not seem to be a sensible approach.

The main algorithms proposed to solve the RA and the WA sub-problems are discussed in the following sections.

2.2.1.1. Route allocation (RA) algorithms

Three methods to find a route can be distinguished: fixed, alternate and adaptive routing.

When using ***fixed routing***, a unique route between every pair of nodes is computed off-line (thus, the network state at the moment the lightpath is requested is not considered). Usually, the shortest route is selected, as it minimises the resources

used. Every time a lightpath is requested between a node pair, the same pre-computed route is used.

Fixed routing is simple and fast, with a worst-case time complexity of just $O(N)$, N number of network nodes, to retrieve a route. However, it fails to use alternative available capacity in the network when the selected route is not available, which results in increased blocking of requests. In addition, under link failure, it is not able to find alternate routes. However, because of its simplicity, fixed routing has been widely used in the literature; see for example [Shi06, Mai04, Fen04, Wan03, Li99, Xu00, Xu99, Sub97, Bir95, Chl92, Chl89].

Alternate routing overcomes the drawback of fixed routing by pre-computing a set of k different routes (usually disjoint to ensure fault-tolerance capability in the network) for every pair of nodes. The routes are sorted according to some criterion (typically, length in number of hops) and on lightpath request, the list of routes is attempted, in order, until an available route is found. Because alternative paths are searched when the first path fails, alternate routing decreases blocking significantly with respect to the fixed approach [Ngo06, Ass01, Lan01, Spa00, Xu00, Li99, Har97, Bir95, Bal91]. This is achieved at the expense of little extra computation (worst-case complexity $O(kN)$), which makes alternate routing a much better alternative than fixed routing. Alternate routing for optical networks has been very much used in the literature; see for example [Mew06, Mar06, Sue05, Aly04, Lee04, Gon03, Wan03, Kim02, Ram02, Ho02, Zho02, Kum01, Hyy00, Spa00, Li99, Xu00, Kar98, Ram98, Bir95, Ram94, Cha94, Bal91]. The main drawback of alternate routing is that, by pre-computing the set of k routes in an off-line manner, the state of

the network (wavelength utilisation) is not taken into account when the lightpath request is processed. This may lead to bad allocation decisions. For example, the sector of the network used by the alternate routes could be heavily loaded (which may result in future blocked requests) whilst other parts remain slightly used.

When applying ***adaptive routing*** a route is chosen from a pre-determined set of routes considering the state of the network in the instant the lightpath request is generated. To do so, a cost function is defined for each route and the route which minimises such function is selected. Typically, the cost function considers one or more of the following aspects: the number of free wavelengths in the route [Lee04, HoQ03, Ho02, Ass01, Hsu01, Li99, Kar98, Har97, Ban96, Cha94] or in the whole network [Har97], the number of hops [Hsu01, Har97], the length of route [HoQ03], the probability of blocking future requests [Gon03], the probability of finding a free wavelength [Zha03] and the traffic load in the path [Lee04]. By adapting to the changing network conditions, adaptive routing achieves lower blocking than alternate routing [Hsu03, Yoo03, Ass01, Hsu01, Lan01, Jue00, Xu00, Li99]. However, its computational complexity is higher (typically, $O(LW)$, where L and W denote the number of network links and the number of wavelengths per link, respectively) due to the extra computations required to select a route.

Among the three routing schemes, adaptive routing achieves the lowest blocking but at the expense of higher computational complexity. Additionally, to achieve global network knowledge, either a link-state propagation protocol or a centralised control node must be implemented. The former case increases the network control plane complexity whilst the latter might affect the network scalability and survivability.

Table 2.2. summarises (in chronological order) the main adaptive routing algorithms proposed to date.

Algorithm	Selected route
Least Congested Path (LCP) [Cha94, Ban96]	Route with the highest number of available wavelengths on the most congested link
[Har97]	Route (and wavelength) which minimises the weighted sum $\delta_{ij} = \alpha\beta_i + (1 - \alpha)\theta_j(\gamma_j, h_j)$ β_i : number of links on which wavelength i is idle γ_j : number of free wavelengths in route j h_j : number of hops of route j
Least Loaded Route (LLR)/First Path Least Congested (FPLC) [Kar98, Li99, Hsu01]	Route with the highest number of available wavelengths in all the links of the route
Weighted-Shortest Path (WSP) [Hsu01]	Route which minimises a function of the number of hops and wavelength utilisation
Asynchronous Critically Avoidance (ACA) [Ho02]	Route with more than L available wavelengths and that minimises a function of the number of available wavelengths in each link of the path.
[Zha03]	Route which maximises the probability of finding a free wavelength
Less Influence Path First (LIPF) [Gon03]	Route which minimises the probability of blocking future requests
[HoQ03]	Route which minimises a function of distance and wavelength availability
Min-Sum [Lee04]	Route which minimises a function of the potential traffic load on the path and the wavelength availability

Table 2.2. Adaptive routing algorithms proposed for WDM networks.

The performance of the above described algorithms depends on the network topology, the network nodes capability and traffic parameters. The published papers on adaptive routing algorithms have only carried out partial comparisons under different conditions for network topology, node capability and traffic, which makes difficult to rank the performance of the different proposals. The algorithms Min-

Sum, ACA and LIPF have been reported to achieve a lower blocking performance than FPLC (no more than one order of magnitude) in [Lee04, Gon03, Ho02] whilst the remaining algorithms have only been compared to fixed or alternate routing schemes.

2.2.1.2. Wavelength allocation (WA) algorithms

The impact that the wavelength allocation algorithm has in the performance of lightpath allocation algorithms has been proved to be low compared to the impact of the routing algorithm [Zan00, Zhu00, Sub97]. Hence, although this section presents a review of performance of the different described WA algorithms, it should be noticed that the difference in performance between them is not significant (less than one order of magnitude, see for example [Zan00, Xu99, Kar98, Sub97]). The most used algorithms to select the wavelength for a given route are described in the following.

Random Fit (RF) algorithm [Yoo03, Zan00, Mok98, Kar98, Har97, Bir95] selects a wavelength randomly (uniform probability distribution) from the set of available wavelengths. Random fit aims to use the wavelength space uniformly but in doing so, generates a high level of fragmentation of the wavelength space which normally leads to a higher blocking probability than other methods [Zan00, Zhu00, Sub97].

First Fit (FF) algorithm [Yoo03, Xu00, Kar98, Mok98, Har97, Ban96, Bir95, Ram95, Ram94, Chl92, Chl89] indexes wavelengths in an arbitrary order. It checks the lowest-indexed wavelength first, if this is not available, it checks the second lowest-indexed and so on. This strategy aims to keep fragmentation of the wavelength space low and results in FF being one of the WA algorithms with the

lowest blocking probability [Zan00, Zhu00]. The Min Product algorithm, proposed in [Jeo96] for multi-fibre networks, corresponds to the FF algorithm in a single-fibre network.

In ***Least/Most Used*** (LU/MU) algorithm [Yoo03, Mok98, Kar98, Har97, Sub97, Bal91, Chl89] wavelengths are sorted according to their level of utilisation in the network (a control node has this information in a centralised scheme or link-state protocols for dissemination of link utilisation should be used in a distributed scheme). The least/most used wavelength is attempted first. Upon failure, the second least/most used wavelength is tried, and so on. MU achieves a performance slightly better than FF whilst LU is one of the algorithms achieving the worst performance [Zan00] because it increases the wavelength space fragmentation. The algorithms Least Loaded (LL) and Minimum Sum (MS) proposed in [Kar98] for multifibre networks reduce to MU in single-fibre networks. A combination of LU and MU algorithms was proposed in [Bir95] where the least used wavelength is chosen for single-hop connections and the most used for multi-hop connections. No significant difference in terms of blocking were found between this algorithm and FF.

Least Influence (LI) algorithm [Xu99] selects the least used wavelength in all the paths sharing links with the selected route (as opposed to the least used in the whole network). In this way it is expected that the wavelength with the lowest chance of collision with other routes is selected. The performance of LI is close to that of MU.

Max Sum algorithm [Sub97], originally proposed for multi-fibre networks. In a single-fibre network the algorithm selects the wavelength which minimises the decreasing in capacity in the network after establishing the connection.

Relative Capacity Loss (RCL) algorithm [Zan00, Zha98] improves the performance of Max Sum by selecting the wavelength which minimises the decrease in the *relative capacity* of the network. The *relative capacity* is the ratio between the decrease in the capacity in the network due to selecting route p and the number of alternative wavelengths on which the connection could be established. RCL has a slightly better performance than Max-Sum.

The described wavelength allocation algorithms are sorted in increased order of blocking, according to the results in [Yoo03, Zan00, Zhu00, Xu00, Xu99, Kar98, Har97, Sub97], in Table 2.3.

<i>Wavelength allocation algorithm</i>	<i>Worst-case computational complexity</i>
MU	$O(WL)$
RCL	$O(WN^3)$
LI	$O(WN^3)$
Max-Sum	$O(WN^3)$
FF	$O(W)$
LU	$O(WL)$
RF	$O(W)$

Table 2.3. Wavelength allocation algorithms sorted in decreasing order of blocking probability and their corresponding worst-case computational complexity.

It should be noticed that the algorithms perform similarly (same order of magnitude) and may appear in different order depending on the traffic load and evaluated topology. The worst-case computational complexity of each algorithm is also shown

in the table, where W is the number of wavelengths per link, L in the number of links and N the number of nodes.

In practice, FF is the preferred algorithm to be implemented because of its similar performance to the best performing algorithm (MU) and its low computational complexity.

2.2.2. Joint routing and wavelength assignment algorithms

All conventional dynamic algorithms which jointly solve the routing and the wavelength assignment implement variants of the following generic algorithm:

1. Implement one graph per wavelength, defined as $G_i = \{\mathcal{N}, \mathcal{Z}_i\}$, $i=1,2,\dots,W$;
where $\mathcal{W} = \{\lambda_1, \lambda_2, \dots, \lambda_W\}$ is the set of wavelengths, \mathcal{N} the set of network nodes and \mathcal{Z}_i the set of links where λ_i is not used.
2. Assign a cost to each edge in each set \mathcal{Z}_i .
3. When a request to establish a lightpath between source (s) and destination (d) is received, find the lowest cost path in each graph G_i . Select the path with the lowest cost among all the found paths. If several paths have the same cost, apply a tie-break rule. If no path is found, then block the request.
4. Update the graph where the lowest cost path was selected from by deleting the edges corresponding to the links used in the path.
5. On lightpath release, add the links making up the path to the corresponding graph again

The set of graphs G_i generated in step 1 is known as a “layered graph”.

The lowest cost path in step 3 is found by applying the Dijkstra algorithm [Sed98]. For cases of practical interest (i.e. networks with less than 100 nodes) this algorithm has a worst-case complexity of $O(N^2)$ where N is the number of nodes. Thus, this type of lightpath algorithms have a overall worst-case computational complexity of $O(WN^2)$, which makes them slow (as it is shown in Chapter 6). However, to date, they have been shown to achieve the lowest blocking [Yoo03, She01, Xu00, Hyy00].

Different proposed algorithms differ in the manner they implement the step 2 and the tie-break rule used in step 3. To date, the variant known as Adaptive Unconstrained Routing – Exhaustive (AUR-E) algorithm [Mok98] achieves the lowest blocking [Yoo03, She01, Xu00, Hyy00]. AUR-E assigns a value equal to 1 to each link cost in the step 2 (thus, in step 3 the algorithm finds the shortest available path in each graph G_i), but it does not specify a tie-break rule in case two or more paths have the same cost. In [Hul03] it was reported that applying a tie-break rule that chooses the path in the graph with most used links decreased the blocking probability. However, this conclusion was based on the simulation results obtained for only 2 topologies.

Other variants of the generic algorithm include different cost functions for the links such as physical length [Chen96], wavelength availability [Yoo03, Bhi01] or a function of wavelength availability and number of hops [Mai04], presence of wavelength converters [Sah00], time that links are on service [Pon03] and a combination of present and past occupancy of links [Mai04].

2.3. Research open issues

Although the previous sections have described a large amount of research work in the area of dynamic optical networks, the key issue of whether dynamic operation of wavelength-routed networks is preferable to the static approach remains unanswered. This is so mainly because most research to date has analysed static and dynamic optical networks separately, focusing on different performance metrics (usually, capacity requirements for static networks and blocking for dynamic ones), which makes any comparison hard. The few initial investigations which have focused on direct comparison of static and dynamic operation of optical networks [Ban96, Mae03, Hua03, Ger99, Zap04, Düs04, Kam04] have studied very particular cases, not allowing for general conclusions.

In [Ban96, Hua03] the connections of a static traffic matrix were offered sequentially (randomly ordered) to a dynamic network. Once setup, lightpaths were never released (i.e. incremental dynamic traffic). Results showed that under incremental traffic dynamic networks require a higher number of wavelengths than the static approach because, by knowing the demand sequentially, lightpath allocation cannot be optimised as in the static case. However, this type of traffic does not represent fully dynamic scenarios (where lightpaths are set up and released) which would benefit from wavelength savings due to the statistical multiplexing of traffic demands. In [Ger99] worst-case theoretical analysis on the number of wavelengths required in the case of simple topologies (rings, trees and lines) was carried out under incremental and fully dynamic traffic. It was found that, under both types of traffic, dynamic networks require as much as twice the number of wavelengths than static ones. However, given the worst-case nature of the analysis, the results might not be

representative of real average-case situations where the worst possible sequence of lightpath requests is unlikely to happen. In [Mae03] a dynamic slotted optical network was compared to a static one in terms of wavelength requirements. However, the analysis was simulation-based only, only one topology was studied and full wavelength conversion was assumed. In addition, the lightpath allocation algorithm used is not described, in spite of the huge effect that such algorithm has in the network performance. In [Zap04] the author of this thesis compared the capacity requirements of static and 3 different dynamic optical rings under fully dynamic traffic and it was found that dynamic operation could save significant resources when lightpath requests are allowed to reattempt allocation for a limited time when they are blocked. Because the simulation-based results focused on only one particular topology and one sub-optimal lightpath allocation algorithm, this analysis lacked of general conclusions and predictions for other scenarios. Finally, in [Düs04] the author of this thesis evaluated the wavelength-requirements of 7 mesh networks for a uniform traffic load of 0.1. Results showed that dynamic allocation saves significant resources with respect to the static allocation, especially in sparsely connected networks. However, wavelength-requirements for higher loads were not presented neither analytical bounds were derived. Only recently, in [Zap06, Zap05, Zap05a], the author of this thesis investigated the wavelength requirements of dynamic networks for a wide range of traffic loads and analytical bounds for the wavelength requirements of dynamic networks were derived.

In this thesis the performance of dynamic centralised WR-OBS architecture operating with a number of selected dynamic lightpath allocation algorithms is compared to the performance of a static WRON in terms of wavelength

requirements, end-to-end delay and scalability by means of analysis and simulation for a wide range of topologies.

To do so, the following issues –which constitute the contribution of this thesis-, must be addressed:

1. The ***definition of a new metric*** for fair comparison of the performance of static and dynamic networks. To date, static networks have been typically evaluated in terms of wavelength requirements whilst dynamic networks performance has been evaluated in terms of blocking, which makes any comparison difficult. This new metric, the ***number of wavelengths required to achieve an acceptable level of blocking***, is introduced in Chapter 3.
2. ***Evaluation of the optimality*** of dynamic lightpath allocation algorithms. At the beginning of the work described in this thesis it was unknown whether current dynamic proposals are close to optimal whilst the algorithms used for the static case are known to be near-optimal, which makes the comparison unfair. The optimality of 3 current lightpath allocation algorithms under uniform traffic demand is carried out in Chapter 3 by comparing their performance against new analytical and heuristic lower bounds, derived in this thesis.
3. ***Proposal of a new lightpath allocation algorithm***. If the optimality test shows that the performance of current lightpath allocation algorithms is not close enough to that of the lower bounds, the research must then focus on the proposal of a better lightpath allocation algorithm. This issue is addressed in Chapter 3.

4. ***Evaluation of wavelength requirements of static and dynamic networks under uniform demand.*** This is carried out in Chapter 3, where the performance of different lightpath allocation algorithms is evaluated against the number of wavelengths required by the static case for 7 different real networks. The results determine the conditions for which dynamic operation bring benefits compared to the static approach.
5. ***Evaluation of wavelength requirements of static and dynamic networks under non-uniform demand.*** Whilst uniform traffic demand is easily modelled, it does not represent real-world traffic distribution. To date, none of the published comparisons between dynamic and static optical networks have considered non-uniform traffic demand. To validate the results in a realistic environment, non-uniform demand must be considered. This is carried out in Chapter 4.
6. ***Evaluation of mean extra delay introduced by dynamic operation.*** Dynamic optical networks are attractive not only if significant wavelength savings are achieved at expenses of acceptable blocking, but also if a maximum end-to-end delay is guaranteed to preserve the quality of the transmitted information. To date, only the maximum extra delay introduced by the aggregation process of dynamic WR-OBS has been studied. A mean value analysis, carried out to differentiate different schemes for WR-OBS is described in Chapter 5.
7. ***Evaluation of scalability*** (maximum number of nodes supported by a given architecture) of centralised WR-OBS. Scalability is of fundamental importance as it establishes the feasibility of the architecture. Scalability might become the weakest point of the centralised WR-OBS architecture, as a control node must process all the node pairs lightpath requests. A worst-case

analysis to find out how practical this architecture is in terms of the size of the networks that can be implemented as centralised WR-OBS is needed. This is carried out in Chapter 6.

8. ***Proposal of a new lightpath allocation algorithm with high scalability.*** If the scalability analysis shows that the best performing algorithm cannot scale to networks of practical interest (~100 nodes), a new algorithm overcoming this drawback should be proposed. This issue is addressed in Chapter 6.

2.4 Summary

This chapter reviewed the different architectures proposed to date to implement dynamic optical networks in the medium/long term. The current technological constraints which hamper the implementation of some proposals (OPS, OBS) have been discussed as well as their performance drawbacks (e.g. high loss probability for OBS networks). Based on its feasibility of implementation in the short-term and its good performance, centralised WR-OBS architecture was selected as the dynamic optical architecture forming the reference architecture investigated in this thesis.

Because the performance of a dynamic optical architecture depends strongly on the dynamic resource allocation algorithm used, main proposals for lightpath assignment algorithms were reviewed. These can be classified in two main categories: those which solve the routing problem first to then solve the wavelength allocation problem and those which solve jointly the routing and the wavelength allocation problem. The former is simpler to implement, but it has been shown that it performs worse (up to two orders of magnitude higher blocking, depending on the traffic load and the topology [Mok98]) than those algorithms in the latter classification. In fact,

the best performing algorithm to date (AUR-E) belongs to the second category, where the Dijkstra algorithm is executed every time a new request arrives. The drawback of these algorithms is however, their high computational complexity (Dijkstra algorithm alone has a computational complexity of $O(N^2)$, where N is the number of nodes) which makes them slow. This feature might be relevant when the algorithm is implemented in a centralised architecture like WR-OBS, where a control node must process the requests from all the node pairs.

Finally, the open research-issues in the area of static vs dynamic optical networks were identified and as well as the tasks required to address them.

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Chapter 3

Wavelength requirements in dynamic WDM optical networks under uniform demand

As discussed in Chapter 1, one of the main motivations for the network operators to migrate from the (current) static WDM optical networks to dynamic operation lies in the potential wavelength savings achieved when bandwidth is allocated only when and where required. This potential saving can have a significant impact on the network cost as the wavelength requirements determine the size of switching nodes, the number and complexity of physical impairment-compensating devices and the required tunability range of transmitters (tunable lasers) [Som04, Gil99, Gil96].

However, whilst providing opportunity for resource savings, dynamic operation requires new functionalities as well: online lightpath scheduling and the corresponding control plane. The key question is whether the cost reduction achieved by the potential decrease in the number of wavelengths is high enough to compensate for the extra cost introduced by the new components so the application of dynamic

allocation in WDM networks bring benefits in terms of resource requirements compared to the static approach.

In this chapter the wavelength requirements of dynamic WDM networks are evaluated by means of novel analysis and simulation and compared to that of static networks for uniform traffic demand. The traffic is defined as uniform where the traffic demand is the same for all node pairs. Although most of real-world traffic is highly non-uniform [Bro04, Sen04, Fra03, Wil01, Taf01, Bha01, Cla99, Fan99], uniform traffic demand was assumed in the work described in this chapter (as well as in many published works evaluating the performance of dynamic optical networks, see for example [And06, Ye05, Sab04, Soh03, Wal03, Xio03, Tri00, Mok98]) to simplify the analytical treatment (the effect of non-uniform demand is studied in Chapter 4). The aim is to determine the conditions for the dynamic allocation to yield a lower network cost than the static one in terms of the wavelength requirements.

3.1. Network model and traffic characterisation

Unless stated otherwise, results of all the following chapters are based on the network and traffic model assumptions described in this section.

3.1.1. Network model

The network is assumed to consist of N nodes arbitrarily connected by L unidirectional links (two adjacent nodes are connected with one pair of unidirectional link (fibre), one per direction). The nodal degree of node n , denoted δ_n , is the number

of links incoming and outgoing such node. The average nodal degree, denoted δ , is given by L/N . The physical connectivity of the network, α , given by $L/[N(N-1)] = \delta/(N-1)$, is the normalised number of uni-directional links with respect to a physically fully-connected network of the same size (this expression for α differs from the definition given in [Bar97] by a factor of 2 because this thesis considers uni-directional links instead of bi-directional links). A value of α equal to 1 defines a fully connected network. The concept of physical connectivity was first introduced in [Bar96a], where its impact on the wavelength requirements of static networks was shown and quantified: sparsely connected networks require more wavelengths than strongly connected ones. In this thesis the physical connectivity parameter is used to investigate whether it affects the wavelength requirements of dynamic networks and ultimately, the potential resource savings.

3.1.2. Static and dynamic network architectures

The static network architecture considered in this thesis is the same as in [Bar97] and described in Chapter 1 (Figure 1.1). In it, each node consists of an *end-node* (or electronic terminal) and an optical switch. The end-nodes emit and terminate the lightpaths (pre-computed off-line according to the traffic matrix), whilst the optical switches route the lightpaths from sources to destinations. The optical switches have no wavelength conversion capabilities, as it has been shown that the benefit of introducing wavelength-conversion in static networks is not significant [Ass02, Bar97, Wau96, Chl92].

The architecture chosen for the analysis of the dynamic allocation of lightpaths corresponds to a centralised dynamic architecture with end-to-end resource reservation (WR-OBS) for the reasons given in Chapter 2 (short-term feasibility of implementation compared to OPS, higher efficiency in resource allocation compared to one-way reservation alternatives (OBS) or distributed two-way schemes, and significant potential wavelength savings with respect to the static approach). As described in the previous chapter, in a centralised WR-OBS architecture input packets are aggregated into bursts. Every time a node has a burst to transmit, it sends a lightpath request to the control node, which sends back an acknowledgement (ACK) and configures the network switches if it has been successful in finding a lightpath (otherwise, a no-ACK message is sent).

In this chapter, lightpath request propagation times and the time the requests spend in the control node of a centralised WR-OBS architecture are not considered in the analysis because the effect of the propagation time in the level of wavelength reutilization has been already studied in [Düs02] (see discussion in Chapter 2) whilst the time spent in the control node is negligible (in the order of microseconds, see Chapter 6) compared to the propagation times (in the order of milliseconds). The study described in this chapter focuses on the impact that the lightpath allocation algorithm and topology have in the dynamic network performance.

3.1.3. Traffic demand

In the static case the traffic demand between every pair of nodes is transformed into the number of wavelengths required to satisfy the maximum possible bit rate from source to destination. In this work the generic case of one wavelength between every

node pair is considered, as in [Bar97]. This means that a total of $N(N-1)$ connections must be allocated one uni-directional lightpath each (uni-directional demand) or that a total of $N(N-1)/2$ connections must be allocated one bi-directional lightpath each (bi-directional demand). By assuming bi-directional demand (as in [Bar97]) the lightpath connecting nodes A and B must follow exactly the same route and wavelength as the lightpath connecting B to A. This assumption reduces to half the execution time of the lightpath allocation task, without affecting the total wavelength requirements. Therefore, in the rest of this thesis, the static allocation considers bi-directional lightpaths, one per node-pair as in [Bar97].

The characterisation of the traffic demand in static networks is simple: the maximum bit-rate between every pair of nodes is converted to a wavelength-granularity demand. This peak rate allocation, suitable for constant bit rate (CBR) traffic [Add98], guarantees that the nodes will be provided with enough bandwidth, whenever required, with minimum delay. But, for other types of traffic (different from CBR), by allocating bandwidth at wavelength-granularity -irrespective of their actual bandwidth requirement at distinct times, may lead to bandwidth being inefficiently used, as shown in Figure 1.2.

In the dynamic case instead, a more accurate characterisation of the demand between node pairs is used. Instead of simply using the maximum bit rate to model the demand at any time, a set of parameters (e.g., the maximum and mean bit rate, the mean duration of periods at maximum bit rate, the mean duration of idle periods) is used to define a probabilistic model which represents the evolution of the traffic between nodes [Add98, Ada97]. By better defining the traffic it is expected that

resources can be more efficiently allocated. In the work described in this thesis the demand between every pair of nodes is dynamically modelled at the burst level. That is, it is assumed that packets arriving at an edge node are aggregated according to some burst aggregation method, as carried out in the WR-OBS architecture. The aggregation process transforms the original packet traffic into burst-level traffic which can be described by a source which switches its level of activity between two states: ON (burst transmission) and OFF (time between the transmission of consecutive bursts), as shown in Figure 3.1. During the ON period, the source transmits at the maximum bit rate (i.e., wavelength capacity). During the OFF period, the source transmits no data. The traffic model corresponding to this type of behaviour is known as the ON-OFF model and it is used throughout this thesis to model the burst traffic generated at the edge nodes. Previous work applying the ON-OFF model to the burst-level traffic can be found in [Cho04, Zuk04, Tan99].

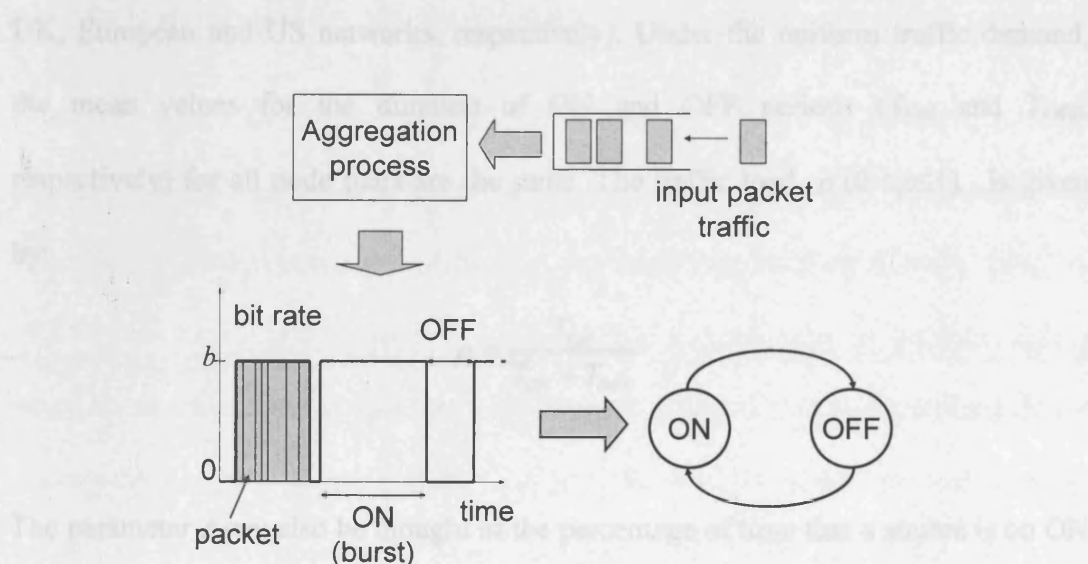


Figure 3.1. Aggregation of input packet traffic into bursts, leading to ON-OFF operation mode

Depending on the burst aggregation mechanism used, different probability distributions are used to characterise the duration of the ON and OFF periods, see for example [Cho05, Yu04, Luo03, Yu02]. The analysis carried out in the following sections is insensitive to the distribution of the ON and OFF periods (except through the ratio of their means), thus making unnecessary to specify any particular distribution.

Lightpath requests are assumed to be generated at the start of each ON period (propagation times of requests and time spent in the control node are assumed negligible, for the reasons discussed in the previous section). To comply with the *efficiency criterion* defined in [Düs02] and discussed in Chapter 2 (i.e., that the overhead time should be shorter than burst transmission time), the mean duration of the ON period (T_{ON}) is set to the round-trip time (equal to 5, 10 and 25 ms for the UK, European and US networks, respectively). Under the uniform traffic demand, the mean values for the duration of ON and OFF periods (T_{ON} and T_{OFF} , respectively) for all node pairs are the same. The traffic load, ρ ($0 \leq \rho \leq 1$), is given by:

$$\rho = \frac{T_{ON}}{T_{ON} + T_{OFF}}$$

The parameter ρ can also be thought as the percentage of time that a source is on ON state or the probability of a source being in ON state [Ros96]. It should be noticed that the static case is equivalent to considering $\rho=1$ for all node pairs.

3.2. Analytical lower bounds for wavelength requirements

Depending on whether an adaptive routing (i.e. routes are allocated taken into account the current network state) or a fixed routing (i.e. routes are pre-computed) scheme is used, different analytical lower bounds for the wavelength requirements can be obtained. As discussed in Chapter 2, fixed routing is attractive because routes are pre-computed and do not need to be updated as the network state changes, which leads to a simple and fast routing-decision-making. Conversely, adaptive routing is slow, but it can lead to better allocation decisions by considering the current state of the network. In the following, analytical lower bounds for the wavelength requirements of adaptive and fixed routing algorithms are derived and compared.

3.2.1. Adaptive routing

The lower bound for the wavelength requirements is obtained by assuming an ideal allocation of the lightpaths. That is, the set A of active connections (connections in ON state) is routed using the paths with the minimum number of hops, fully re-utilising the wavelength space (it should be noticed that this could be unachievable in practice: by taking the network state into account, adaptive routing algorithms do not necessarily use the shortest paths and the wavelength constraint may lead to inefficient wavelength usage). This would lead to lower bound for the mean wavelength requirements per link equal to:

$$W_A = \left\lceil \frac{|A| \cdot H_A}{L} \right\rceil \quad (3.1)$$

where $|A|$ represents the cardinality of the set A and H_A the average path length (in number of hops) of the connections in the set A . Eq. (3.1) is similar to the lower bounds proposed in [Bar97, Pan95] in the context of static wavelength-routed optical networks. However, in [Bar97, Pan95] the set A corresponds to the total traffic demand, completely known *a priori*.

Different sets of active connections with cardinality $|A|$ have different values for H_A , which results in different values of W_A . For a strict lower bound, the set A with the lowest value for H_A should be selected. However, for a given traffic load, the network must be dimensioned to accommodate any possible set A . Hence, for a tighter lower bound, the set A with the highest value for H_A determines the lower bound W_{LB} for the total wavelength requirement:

$$W_{LB} = \max_{\forall A} W_A = \left\lceil \frac{|\hat{A}| \cdot H_{\hat{A}}}{L} \right\rceil \quad (3.2)$$

where \hat{A} corresponds to the set A of active connections with the longest routes and $H_{\hat{A}}$ corresponds to the average path length of the connections in the set \hat{A} .

By sorting all the possible $N(N-1)$ connections in decreasing path length (the path length of a connection corresponds to the number of hops of its shortest path) and letting h_i be the length of the i -th longest connection (thus, h_1 and $h_{N(N-1)}$ are the number of hops of the connections with the longest and the shortest paths, respectively), Eq. (3.2) can be re-written as follows:

$$W_{LB} = \left\lceil \frac{\sum_{i=1}^{|\hat{A}|} h_i}{L} \right\rceil \quad (3.3)$$

Although Eq. (3.3) represents a simple closed analytical expression for a lower bound on the wavelength requirement, it is difficult to evaluate because the maximum number of active connections $|\hat{A}|$ depends, in a non-trivial manner, on the acceptable level of blocking and the traffic load. In the following section an analytical approximation to evaluate $|\hat{A}|$ is given.

The value of $|\hat{A}|$ depends on the acceptable blocking level and the traffic load. If the goal is to achieve absolute zero blocking, $|\hat{A}|$ must be equal to $N(N-1)$, irrespective of the traffic load. This is because even at very low loads it can happen –although with extremely low probability– that all the connections are in the ON state simultaneously, that is $|\hat{A}|=N(N-1)$. Instead, if some level of blocking is acceptable, those sets occurring with significantly low probability can be neglected in the process of dimensioning the network. The probability with which every possible set occurs depends on the traffic load. At low loads there is a higher probability of having sets with a low number of active connections. Conversely, at high loads sets with a number of active connections close to $N(N-1)$ are more probable.

Let B be the acceptable network-wide blocking probability. Given that the network is dimensioned to accommodate a maximum of $|\hat{A}|$ connections, the blocking

probability corresponds to the probability of having more than $\left\lceil \hat{A} \right\rceil$ simultaneous active connections. That is:

$$B = \Pr\{n > \left\lceil \hat{A} \right\rceil\} \quad (3.4)$$

where n is the number of simultaneous active connections.

Given that the state of an individual connection is a binary random variable (a connection is in ON state with probability ρ , and in OFF state with probability $(1-\rho)$), by definition it can be described using the Bernoulli distribution. Thus, the probability of having n simultaneous active connections, $\Pr\{n\}$, is given by the binomial distribution:

$$\Pr\{n = a\} = Bi(N(N-1), \rho) = \binom{N(N-1)}{a} \rho^a (1-\rho)^{N(N-1)-a} \quad (3.5)$$

Combining equations (3.4) and (3.5), the following expression for B is obtained:

$$B = \sum_{n=\left\lceil \hat{A} \right\rceil+1}^{N(N-1)} Bi(N(N-1), \rho) \quad (3.6)$$

Given the target acceptable blocking B , the traffic load ρ and the number of nodes N , the maximum number of active connections $\left\lceil \hat{A} \right\rceil$ can be numerically obtained from Eq. (3.6). However, there is a simpler way to obtain $\left\lceil \hat{A} \right\rceil$, given by the normal approximation of the binomial probability distribution [Ros02] which provides a closed analytical expression for $\left\lceil \hat{A} \right\rceil$, as follows:

$$\left\lceil \hat{A} \right\rceil \approx \min \left\{ N(N-1) \cdot \rho, N(N-1) \cdot \rho + \beta \sqrt{N(N-1) \cdot \rho \cdot (1-\rho)} \right\} \quad (3.7)$$

where β is such that the area under the normal distribution curve in the range $(-\infty, \beta]$ is equal to $(1-B)$ and it can be obtained from standard tables for the normal distribution, for example in [Yat99].

Eq. (3.7) is known to be accurate for $N(N-1)\rho(1-\rho) \geq 10$ [Ros02], which means that N must be greater or equal to 11 for $\rho \in [0.1, 0.9]$. Given that most real networks have a number of nodes higher than 11, the approximation is applicable to cases of practical interest.

From Eq. (3.7) it can be seen that the maximum number of active connections $|\hat{A}|$ in the dynamic case is always lower than $N(N-1)$ (the number of active connections considered in the static case), except when $\rho=1$. This means that the dynamic network would require less capacity than the static one due to the (statistically computed) lower number of simultaneous active connections. This is also known as *statistical multiplexing gain* [Kes97].

To investigate which parameters have the greatest impact in decreasing the number of active connections in the dynamic case, with respect to the static case, the ratio $R \in [0,1]$ is defined as follows:

$$R = \frac{|\hat{A}|}{N \cdot (N-1)} = \min \left\{ \rho, \rho + \beta \sqrt{\frac{\rho(1-\rho)}{N(N-1)}} \right\} \quad (3.8)$$

R represents the fraction of connections required to be accommodated in the network in the dynamic case compared to the static case. Thus, the closer R gets to 0 the highest the potential wavelength savings obtained by dynamically operating the network. From Eq. (3.8) it can be seen that R decreases with ρ , β and $1/N$, as shown

in Figure 3.2, where R is plotted as a function of the number of network nodes N , for the case of 3 different traffic loads ρ and for values of blocking probability, B , equal to 10^{-6} ($\beta=4.755$) and 0.1 ($\beta=1.285$).

From the figure it can be seen that for large networks ($N>40$), the parameter which determines the value of R is the traffic load, ρ , irrespective of the value of the accepted blocking probability.

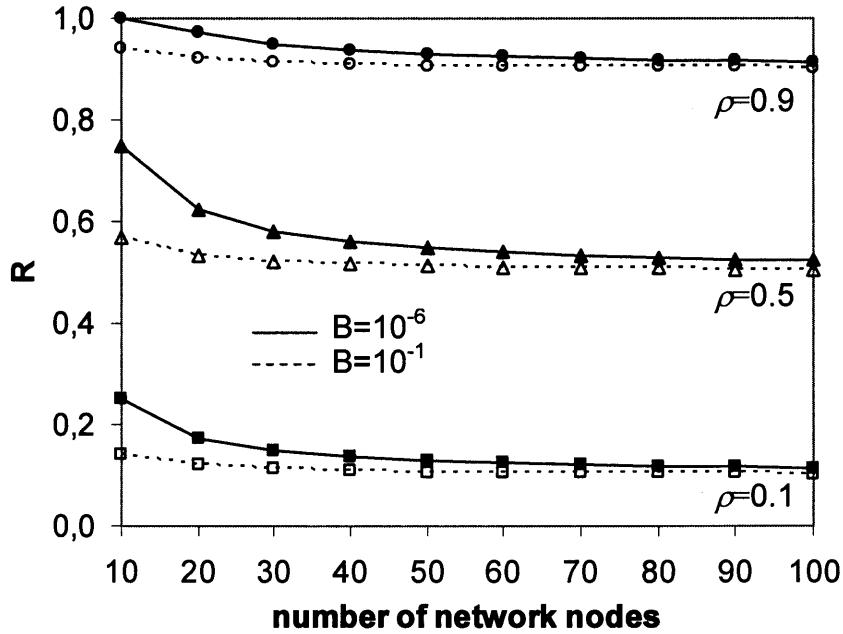


Figure 3.2. Fraction of active connections in the dynamic case with respect to the static case as a function of the number of network nodes N for values of traffic loads $\rho = 0.1, 0.5, 0.9$ and for acceptable levels of blocking of 10^{-6} ($\beta=4.755$) and 10^{-1} ($\beta=1.285$).

This behaviour can also be observed when evaluating $\lim_{N \rightarrow \infty} R$, which equals ρ . That is, in large networks the number of connections that need to be allocated lightpaths is approximately a factor of ρ times lower than in the static case. For networks with

less than 40 nodes, R depends on ρ , N and B . In that case, the number of active connections increase with ρ , B and $1/N$, as established by Eq. (3.8).

These results show that, in principle, large networks ($N > 40$) would benefit most from dynamic operation because they need to provide resources for roughly a fraction ρ of the connections considered in the static case. This should lead to a lower wavelength requirement, determined by the Eq. (3.3). Smaller networks instead, must accommodate a higher fraction of the connections considered in the static case, which would decrease the benefit of dynamic operation. In both cases, the most determining factor in the potential benefit of dynamic operation is the traffic load.

To investigate the potential wavelength savings achieved by dynamically operating the network, the ratio R_w , defined as the ratio between the lower bound for the wavelength requirements in the dynamic case and those of the static case, is given in the following:

$$R_w = \frac{\left\lceil \frac{\hat{A} H_{\hat{A}}}{L} \right\rceil}{\frac{N(N-1)H}{L}} = \frac{\left\lceil \frac{RH_{\hat{A}}}{\alpha} \right\rceil}{\frac{H}{\alpha}} \quad (3.9)$$

On the extreme case of $\alpha=1$ (i.e., fully connected topology), $H = H_{\hat{A}} = 1$. Thus, $R_w = \lceil R \rceil = 1$ which means that fully connected networks do not benefit from dynamic operation, irrespective of the value of N , B and ρ . This is reasonable, as fully connected networks require the minimum number of wavelengths per link (1) in the static case - making impossible for dynamic operation to further decrease this requirement.

For other values of α the analytical evaluation of Eq. (3.9) is problematic because of the lack of an expression for $H_{\hat{A}}$. However, the following equation is proposed to numerically estimate $H_{\hat{A}}$:

$$\phi\left(\frac{H_{\hat{A}} - H}{\sigma_H}\right) \approx 1 - \frac{|\hat{A}|}{N(N-1)} \quad (3.10)$$

where $\phi(z)$ corresponds to the value of the cumulative distribution function of the standard normal curve evaluated in z (obtained from tables, see for example [Yat99]), H is the mean number of hops of the shortest paths which can be estimated using the formula $\sqrt{(N-2)/(\delta-1)}$ (derived in [Kor04] by fitting the curves for the minimum-hop-number paths of 14 physical topologies with different values of physical connectivity) and σ_H is the standard deviation of the number of hops of the shortest paths (estimated from $\sqrt{\ln N}$ [Dor02]).

Eq. (3.10) is based on the assumption that the path length of the shortest paths in a network can be approximated by a Gaussian random variable with mean equal to H (as shown, for example, in [Dor02]). This approximation is supported by the Central Limit Theorem [Yat99], given that the number of shortest paths in any practical network easily exceeds the hundred.

The ratio between number of active connections $|\hat{A}|$ and the total number of possible connections ($N(N-1)$) corresponds to area under the curve between H_A^* and ∞ (see Figure 3.3).

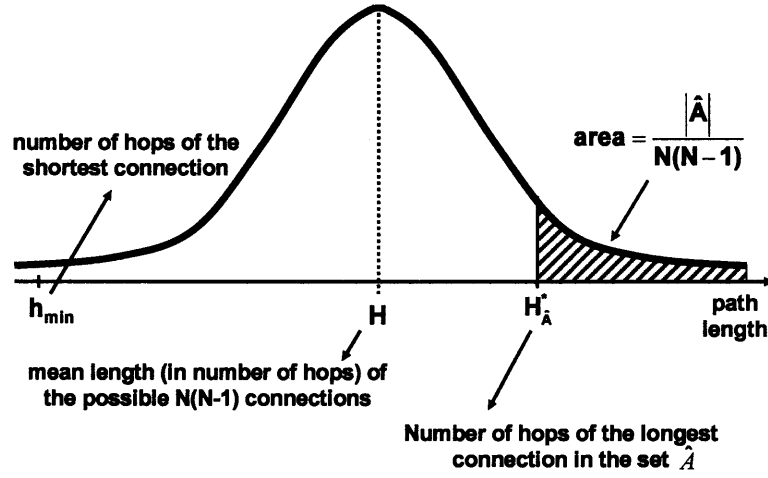
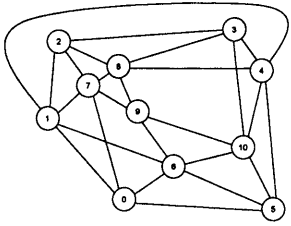
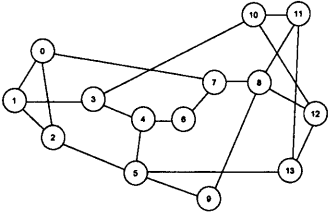
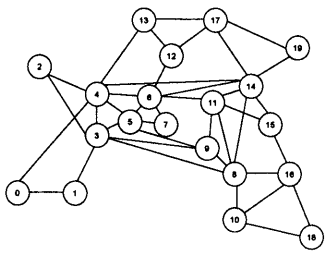
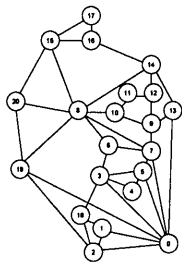


Figure 3.3. Gaussian approximation for the shortest path length distribution

H_A^* corresponds to the number of hops of the connection with the shortest path among the $|\hat{A}|$ active connections. Thus, by knowing the mean and the standard deviation of the shortest paths, it is possible to know the value of H_A^* from the standard tables for $\phi(z)$ and use it as a under-estimation of H_A .

To study the effect that the number of nodes N , the physical connectivity α and the traffic load ρ have on the potential wavelength savings achieved by the dynamic operation, R_W was plotted for a target blocking value of $B=10^{-6}$ and different values of N , α and ρ using the approximation of Eq. (3.10) for H_A . In addition, R_W was calculated for the same 7 real-world mesh topologies used in [Bar98] (for which the exact values of H_A can be calculated), which have now become the standard analysis topologies. The set comprises three US networks, three European networks

and one UK topology. Those networks and their main topological parameters are described in Table 3.1.

<i>Network</i>	N	L	$(\delta, \delta_{min}, \delta_{max})$	α	H
Eurocore 	11	50	(4.5, 4, 5)	0.45	1.58
NSFNet 	14	42	(3, 2, 4)	0.23	2.14
EON 	20	78	(3.9, 2, 7)	0.2	2.38
UKNet 	21	78	(3.7, 2, 7)	0.19	2.51

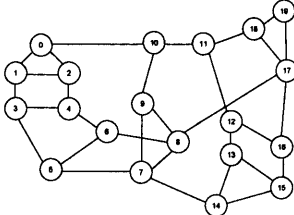
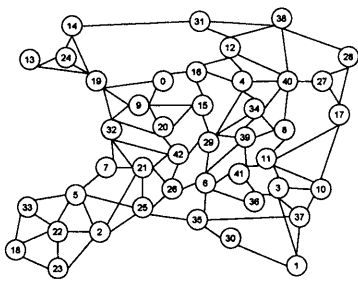
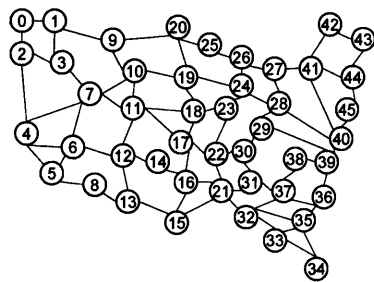
ARPANet 	20	62	(3.1, 2, 4)	0.16	2.81
Eurolarge 	43	180	(4.2, 2, 6)	0.1	3.6
USNet 	46	152	(3.3, 2, 5)	0.07	4.4

Table 3.1. Topological parameters of real-world topologies. N denotes the number of nodes; L the number of uni-directional links; δ , δ_{\min} and δ_{\max} the average, minimum and maximum nodal degree, respectively; α the physical connectivity and H the average path length in number of hops.

Figure 3.4 shows the results of R_W as a function of the number of nodes for different values of ρ and α . It can be seen that the Gaussian approximation used to estimate H_A yields good results, as the curves are close to the results obtained for the topologies of Table 3.1. The ratio R_W is not significantly affected by the number of nodes but decreases with ρ and α . That is, the highest savings are expected for low

loads ($\rho \leq 0.5$) and sparsely connected networks ($\alpha \leq 0.2$). This is reasonable, as static networks are most inefficiently used at low loads and highly-connected networks already require very low number of wavelengths per link (for example, 4 in Eurocore) making it difficult for dynamic operation to further decrease this requirement.

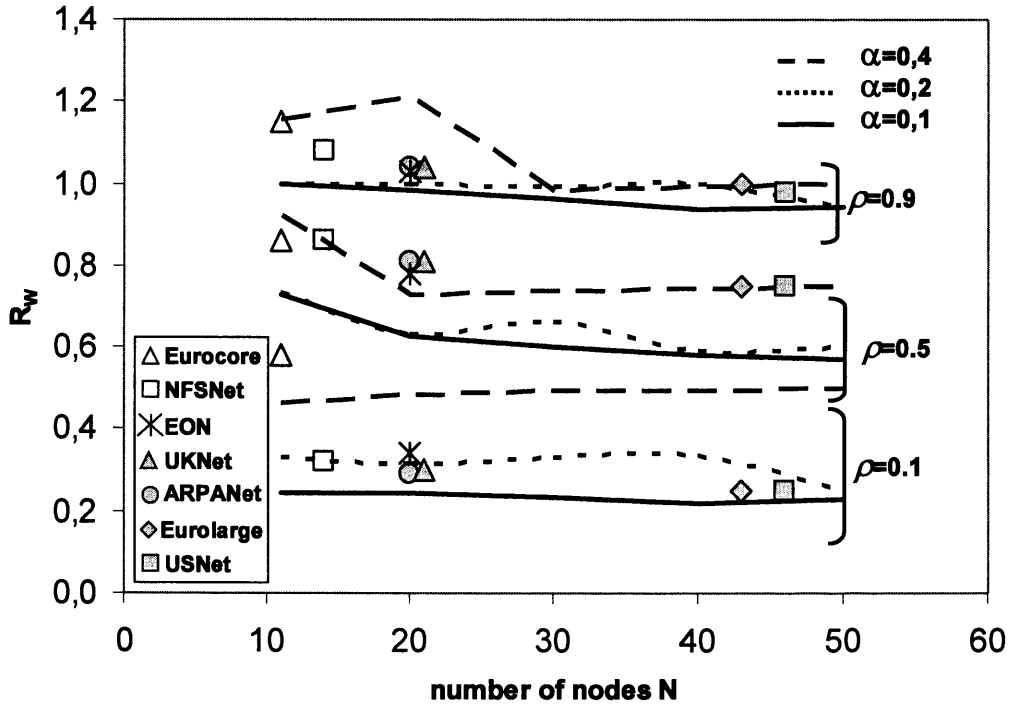


Figure 3.4. Ratio R_w between the lower bund for the wavelength requirements in the dynamic case to achieve a maximum blocking of 10^{-6} and the wavelength requirements in the static case as a function of the number of nodes N and for values of physical connectivity $\alpha = 0.1, 0.2$ and 0.4 and values of traffic load $\rho = 0.1, 0.5$ and 0.9 .

The above results indicate that, for most values of the traffic load, dynamic operation has the potential of achieving significant savings in networks with a low physical

connectivity ($\alpha \leq 0.2$). Increasing the levels of acceptable blocking slightly increases the percentage of savings as well, but the accepted blocking is usually determined by the applications rather than the network design process. Similar conclusions concerning the level of connectivity and traffic load were drawn in a simulation-based study [Mae03] of a slotted optical network equipped with full wavelength conversion capability.

Although the derived lower bound for adaptive routing makes dynamic allocation attractive in terms of wavelength requirements for a wide range of traffic loads in sparsely connected networks, a practical implementation of an adaptive routing algorithm may be very slow (as it must consider the current network state to allocate lightpaths), hampering network scalability as will be shown in Chapter 6 [Düs04]. A much faster fixed routing algorithm would be thus desirable. To investigate whether fixed routing can provide as good a lower bound as adaptive routing, in the following lower bounds for the case of fixed routing are derived and compared to the lower bound derived for adaptive routing.

3.2.2. Fixed routing

Unlike in the case of adaptive routing, fixed routing allocates the same and unique path (pre-computed off-line) to each connection each time is requested. Hence, the maximum number of connections transmitted over each link is known in advance. In this case, the lower bound for the mean wavelength requirement per link is given by:

$$W_{LB}^{fixed} = \frac{\sum_{l=0}^L a_l}{L} \quad (3.11)$$

where a_l is the number of active connections in link l at any time; $a_l \leq N_l$, where N_l is the maximum number of lightpaths transmitted over link l (determined by the fixed routing algorithm).

Analogously to the case of the set A in the previous section, a_l depends on the level of acceptable blocking and the traffic load. In the following, an expression for a_l is derived.

Assuming that blocking occurs independently from link to link (this assumption is more accurate for highly-connected networks and exact when the network physical connectivity, α , is equal to 1 [Beb02]), the blocking probability B_r for the node pair connected by the route r , is given by:

$$B_r = 1 - \prod_{\forall l \in r} (1 - B_l) \quad (3.12)$$

where B_l is the blocking probability of the link l .

For simplicity, the same value for the blocking of links is assumed. It should be noticed that this assumption does not affect the final goal (guaranteeing a maximum value for B_r). Thus, from Eq. (3.12) the following expression for B_l is obtained:

$$B_l = 1 - \sqrt[H_r]{1 - B_r} \quad (3.13)$$

where H_r corresponds to the number of hops of the route r .

To ensure a maximum value of B_r for the blocking probability per node pair, the highest value for H_r , known as the diameter of the network $D = \max_{v_r} \{H_r\}$, must be considered in Eq. (3.13). Hence:

$$B_l = 1 - \sqrt[D]{1 - B_r} \quad (3.14)$$

Applying the same reasoning used to derive Eq. (3.6), a_l can be numerically obtained from the following equation:

$$1 - \sqrt[D]{1 - B_r} = \sum_{n=a_l+1}^{N_l} \binom{N_l}{n} \rho^n (1 - \rho)^{N_l-n} \quad (3.15)$$

The normal approximation to the binomial distribution (to obtain a closed analytical formula for a_l), however, cannot be applied here for the cases of practical interest, as the following condition must apply: $N_l \rho(1-\rho) \geq 10$ [Ros02]. This means that N_l must be higher than 111 for the approximation to be valid in the range for ρ of [0.1, 0.9].

Using the formula $N_l \approx \frac{(N-1)H}{\delta}$ [Kor04, Bar97] (which is the average number of wavelengths required per link in a static network) this condition leads to a high requirement in the number of nodes: higher than 38 and 108 nodes, for extreme values of δ equal to 2 (a ring topology) and 5, respectively. Thus, a_l must be numerically obtained from Eq. (3.15) in the case of fixed routing.

To investigate the potential benefit of using fixed routing compared to the adaptive routing, Eqs. (3.11) and (3.15) were used to evaluate the lower bound for the wavelength requirements of networks of different sizes ($N=20, 50, 80, 100$) to achieve a maximum blocking, B , of 10^{-6} (under uniform demand and for the same value of B_r for all the routes, the value of the network-wide blocking probability B is equal to the value of B_r). Three values for the physical connectivity, α , were

considered: 0.1, 0.2 and 0.4. Results for R_W as a function of the number of nodes are shown in Figure 3.5, where the results obtained for the adaptive routing in the section 3.2.1 have been included for comparison.

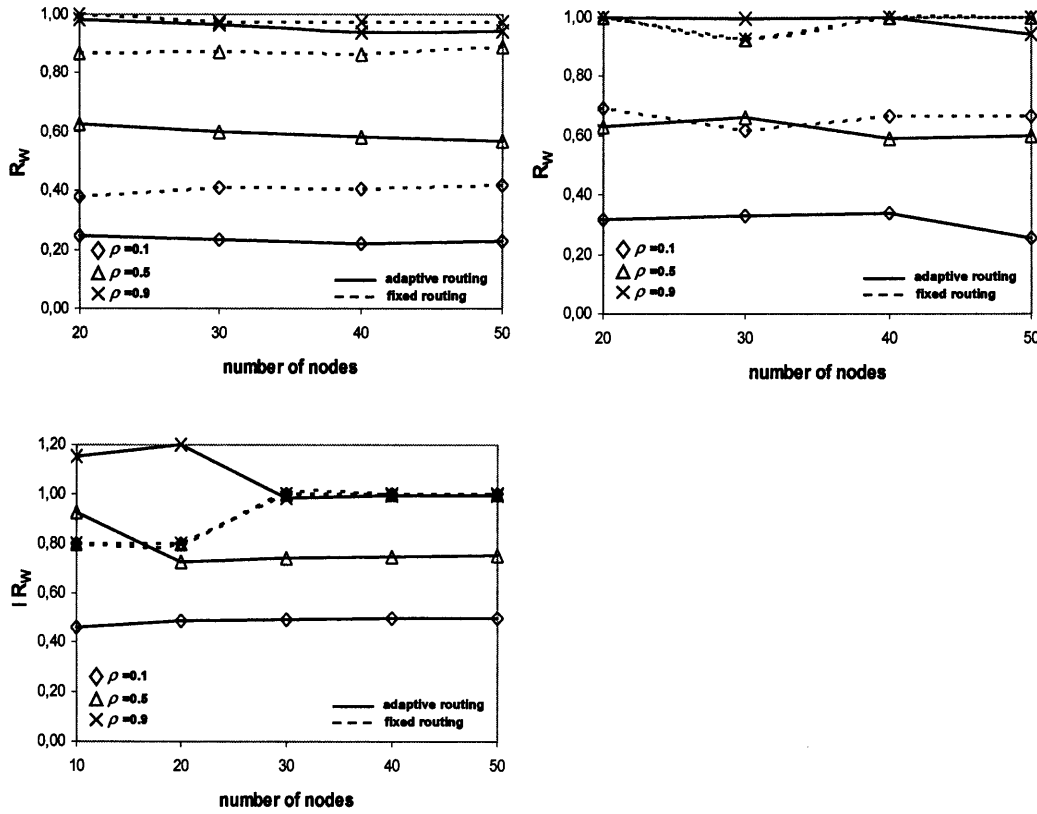


Figure 3.5. Ratio R_W between the average number of wavelengths per link required to achieve a blocking of 10^{-6} for dynamic networks with fixed and adaptive routing and static networks for network sizes of 10, 20, 30, 40 and 50 nodes, for physical connectivity α equal to 0.1 (upper left), 0.2 (upper right) and 0.4 (lower left).

The values of the number of nodes (N), mean path length (H), maximum number of lightpaths (connections) passing through a link (N_l), longest shortest path (D , approximated by the expression $D \approx \sqrt{2H}$ [Kor04]), acceptable blocking probability in any link (B_l), and the maximum number of simultaneous lightpaths carried over

any link as a function of the traffic load and acceptable blocking (a_l) are shown in Table 3.2 for the considered values of α .

N	$\alpha=0.1$								$\alpha=0.2$								$\alpha=0.4$							
	H	N_l	D	B_l	a_l				H	N_l	D	B_l	a_l				H	N_l	D	B_l	a_l			
					ρ	ρ	ρ						ρ	ρ	ρ						ρ	ρ	ρ	
					0.1	0.5	0.9						0.1	0.5	0.9						0.1	0.5	0.9	
10	---	---	---	---	---	---	---		3.16	16	4.47	$2.24 \cdot 10^{-7}$	10	16	16		1.75	4	2.48	$4.03 \cdot 10^{-7}$	4	4	4	
20	4.47	45	6.32	$1.58 \cdot 10^{-7}$	17	39	45		2.54	13	3.59	$2.79 \cdot 10^{-7}$	9	13	13		1.65	4	2.34	$4.28 \cdot 10^{-7}$	4	4	4	
30	3.84	38	5.43	$1.84 \cdot 10^{-7}$	16	34	38		2.42	12	3.42	$2.93 \cdot 10^{-7}$	8	12	12		1.63	4	2.30	$4.35 \cdot 10^{-7}$	4	4	4	
40	3.62	36	5.12	$1.95 \cdot 10^{-7}$	15	32	36		2.36	12	3.34	$2.99 \cdot 10^{-7}$	8	12	12		1.61	4	2.28	$4.38 \cdot 10^{-7}$	4	4	4	
50	3.51	35	4.96	$2.02 \cdot 10^{-7}$	15	32	35		2.34	12	3.30	$3.03 \cdot 10^{-7}$	8	12	12		1.61	4	2.27	$4.40 \cdot 10^{-7}$	4	4	4	

Table 3.2. Values of the parameters H , N_l , D and B_l to calculate the maximum number of simultaneous connections going through any link a_b as a function of the traffic load for $N=10, 20, 30, 40, 50$

A difference in the relative performance of the lower bounds can be seen depending on the value of the physical connectivity, α . For $\alpha \leq 0.2$, the wavelength requirements for a dynamic network using fixed-routing is much higher (up to double) than that of adaptive routing, except for very high loads (close to 0.9) when the difference between both schemes is very small due to the low statistical multiplexing gain (in fact, Table 3.1. shows that a_l is exactly equal to the value of wavelengths required in the static case (N_l) for high loads). At low loads (about 0.1) the fixed scheme requires about twice the capacity of the adaptive scheme whilst at moderated loads (close to 0.5) the amount of extra capacity required by the fixed scheme can be up to 1.5 times that of the adaptive scheme. For $\alpha=0.4$, because a lower number of connections share the same link, the gain due to statistical multiplexing decreases leading to lower

savings for the adaptive routing and practically no savings in the case of fixed routing.

In summary:

- in both routing schemes the determining factor in the wavelength savings is the traffic load because the statistical multiplexing gain is strongly dependant on this parameter (as defined by equations 3.7 and 3.13)
- the ratio R_w decreases with the physical connectivity, as highly connected networks already require a low number of wavelengths in the static case. The impact of the physical connectivity is higher in the fixed scheme because in this case the statistical multiplexing gain is based on the number of connections per link, which is very low in highly connected networks.
- the lower bound for fixed routing is higher than the adaptive routing lower bound because of its lower statistical multiplexing gain

The results of this section show that the use of a dynamic adaptive routing algorithm (instead of a fixed routing scheme) is preferable to achieve the highest savings with respect to a static network, especially at low and moderated loads (<0.8) where the capacity requirements of the adaptive scheme can be the half of that required by the fixed routing algorithm (similar conclusions were obtained in [Nar02] in the context of reconfigurable wavelength-routed optical networks). In analysing the adaptive routing scheme by means of a lower bound for the wavelength requirements for a target blocking, it was found that the benefits of dynamic operation are expected in sparsely connected networks ($\alpha \leq 0.2$) operating at low/moderated traffic loads

($\rho \leq 0.8$). The size of the network (number of nodes) does not significantly affect the benefits of dynamic operation.

These theoretical results are further supported by the simulation results presented in section 3.5.

3.3. Heuristic lower bound for wavelength requirements

The analytical lower bound derived in the previous section for the wavelength requirements of an adaptive lightpath allocation algorithm might be unachievable in practice, because under real operation adaptive routing does not necessarily use the shortest paths nor fully utilises the wavelength space. To have a more realistic lower bound (due to the difficulty of modelling the length of paths and the wavelength usage obtained by adaptive routing), a heuristic (algorithmic) lower bound is proposed in this section.

The heuristic lower bound tackles the adverse effects of demand uncertainty by re-allocating lightpaths (according to a close-to-optimal heuristic based in the one proposed in [Bar98]) every time a new lightpath request arrives. In this way, a close to optimal allocation (i.e. minimum wavelength requirements) could be achieved given the wavelength continuity constraint (i.e. a unique wavelength must be used along the route). However, this algorithm would be impractical because the re-allocation process would disrupt active connections and increase the lightpath request processing beyond the limits allowed by scalability considerations [Düs04]. Nevertheless, by assuming such an algorithm a heuristic lower bound could be achieved. For this reason a lightpath allocation algorithm, called **Reconfigurable Routing** (RR), is proposed in this work to be included in the investigation of

wavelength requirements. RR rearranges active lightpaths every time a new lightpath request arrives as follows:

1. Represent the network with as many graphs as the maximum number of wavelengths in any link (layered graph)
2. Sort the active connections (including the new arrival) according to the number of hops of their shortest (in number of hops) paths (longest first)
3. Allocate lightpaths one by one, choosing connections according to the order established in step 2. To do so, apply the following lightpath allocation algorithm:
 - i. Execute Dijkstra to find the shortest available path in every graph (one per wavelength)
 - ii. Allocate the first path found which is at most e hops longer than the shortest path of step 2. If no such path is found on any of the graphs, block the request.

The parameter e in step 3.ii was varied between 0 and 3 depending on the traffic load, as higher values did not reduce the wavelength requirements in the studied networks.

Notice that RR is very similar to the heuristic proposed in [Bar98] to accommodate static traffic in a near-optimal way. Thus, RR it can be thought as running the heuristic to accommodate static traffic every time a new lightpath must be established. The only difference with the heuristic proposed in [Bar98] is that instead of pre-computing a random list of routes between every pair of nodes (as done in

[Bar98]), RR calculates the routes on-line every time is required by using the Dijkstra algorithm. By doing so it is expected that shorter available routes are used (as the heuristic proposed in [Bar98] does not necessarily computes all possible routes between every node pair).

3.4. Simulation results for wavelength requirements

In this section, the initial conclusions regarding the wavelength requirements of dynamic networks, obtained by applying the proposed lower bounds to different networks, are investigated by means of simulation. To do so, the wavelength requirements of dynamic networks are evaluated for the same 7 mesh topologies of previous sections and 3 different lightpath allocation algorithms.

3.4.1. Dynamic lightpath allocation algorithms

Among the many dynamic lightpath allocation algorithms proposed to date (see Chapter 2), the following extreme ones (in terms of speed and performance) have been chosen to study their wavelength requirements in this thesis:

- ***Adaptive Unconstrained Routing – Exhaustive*** (AUR-E). This algorithm has been shown to yield the lowest blocking to date, due to the online execution of the Dijkstra algorithm per request [Mok98]. The Dijkstra algorithm is an optimal solution to find the paths with the minimum cost (if the cost of each link is equal for all the links of the network, the Dijkstra algorithm finds the paths with the minimum number of hops). By executing the Dijkstra

algorithm online every time a lightpath request arrives, AUR-E minimises the number of links used in establishing the lightpath whilst considering the current state of the network. Thus, available resources are efficiently used which results in low blocking. By comparing this algorithm to the lower bounds presented in sections 3.3.1 and 3.4 the optimality of the best solution to date can be evaluated. It should be noticed, however, that the on-line execution of Dijkstra algorithm per lightpath request makes AUR-E computationally intensive and thus, slow (see Chapter 6).

- ***Shortest Path – First Fit*** (SP-FF). This has been shown to be the fastest algorithm available to date. Its high speed comes mainly from the use of pre-computed routes (only one per node pair) and the simplicity of the wavelength allocation algorithm. It has been selected in this study because of its simplicity (and speed) and because it is widely cited in the literature. However, because it uses fixed routing, this algorithm does not utilise resources efficiently (see discussion in Chapter 2 and section 3.3.2) leading to higher blocking values than AUR-E.

Ideally, an algorithm combining the good performance of AUR-E and the speed of SP-FF would be the better alternative to implement. For this reason, a third algorithm is included in this comparison:

- ***k Alternate Paths using Shortest Path First Fit*** (*k*-SP-FF). This algorithm tries to achieve a good compromise between computational complexity and performance by applying alternate routing. Thus, the performance of fixed

routing is improved without incurring in the high computational cost of Dijkstra-based AUR-E.

3.4.2. Topologies

The wavelength requirements for the seven topologies described in Table 3.1 are investigated.

3.4.3. Wavelength requirements

The wavelength requirements resulting from the application of the algorithms presented in the previous section were evaluated by means of simulation. Simulation details are as follows.

The target blocking was set to a maximum value of 10^{-3} per node pair. In this way, all node pairs are fairly treated. By requiring the same blocking per node pair and assuming uniform demand, the network-wide blocking (denoted by B in previous sections) is also 10^{-3} [Siv00].

ON and OFF periods were assumed identically and exponentially distributed for all node pairs and lightpath requests were generated at the start of each ON period. To comply with the efficiency criteria [Düs02] (that is, the transmission time of a burst should be at least as long as the overhead time, see section 3.3.3) the mean ON period (μ_{ON}) was set to 5, 10 and 25 ms for the UK, European and US networks, respectively.

After eliminating transient simulation behaviour (first 10^3 lightpath requests per node pair), 10^3 lightpath requests per node pair were generated. To quantify the wavelength requirements, the original number of wavelengths in each link, W , was varied until no more than 1 request generated per node pair was rejected (in this way, a maximum blocking of 10^{-3} is ensured). The number of wavelengths required per link for the different lightpath allocation algorithms was calculated as follows:

For each arrival:

1. find a lightpath according to the dynamic lightpath allocation algorithm used
2. increment w_l -the number of wavelengths used the link l belonging to the path, by one. If w_l is higher than the previously recorded maximum w_{l_max} , update w_{l_max} with the value of w_l
3. record i_l , the index of the highest wavelength used in the link l of the path. If i_l is higher than the previously recorded maximum i_{l_max} , update i_{l_max} with the value of i_l

For each departure:

1. decrease the number of wavelengths used in all the links of the path by one

At the end of the simulation:

1. average all the w_l values (one per link)
2. average all the i_l values (one per link)

In the case of the SP-FF algorithm, the original number of wavelengths per link, W , was set to *infinity* (in practice, this number was 128 as none of the studied networks required such a high number of wavelengths per link). In the case of the remaining algorithms, the number of wavelengths per link was originally set to a predetermined

number, W . If, after running the simulation, 0 requests were rejected, W was decreased and the simulation was run again. If, after running the simulation, more than 1 request was rejected, W was increased and the simulation was repeated. The final value of W was determined after obtaining 1 or 0 rejections in a simulation.

The average wavelength requirement per link is then given by the average of all i_l values. The average of all the w_l values corresponds to the wavelength requirements in the case of full wavelength conversion.

The described simulation experiment was executed several times to obtain a confidence interval of 95% for the wavelength requirements of each link. For the SP-FF and k-SP-FF algorithms, 100 simulations were executed (for each network, for a specific value for the traffic load) and the confidence interval was in average 0.3% and 3.1% of the mean value for SP-FF and 3-SP-FF, respectively. For AUR-E and RR instead, only 15 simulations were executed, due to their high simulation time (as a way of illustration, the evaluation of the wavelength requirements of RR for the USNet topology for a unique value of the traffic load took more than 1 week in a Pentium 4 of 2.5 GHz and 256 MB RAM). The confidence interval was in average 3.5% and 3.4% of the mean value for AUR-E and RR, respectively.

To investigate the potential benefit in terms of wavelength savings of the dynamic networks compared to the static networks, the ratio R_w between the wavelength requirements per link in the dynamic case and the static case is plotted as a function of the traffic load in Figure 3.6 a)-g) for the SP-FF, 3-SP-FF (that is, up to 3 disjoint routes per node pair were used as higher values of k did not achieve better results in

terms of wavelength requirements) and AUR-E algorithms. The ratio R_W obtained for the analytical and the heuristic lower bounds is also included for comparison.

Eurocore, $\alpha=0.45$
mean wavelength requirements per link
(static case: 3,5)

traffic load ρ	Static	SP-FF	3-SP-FF	AUR-E	Anal. lower bound	Heur. lower bound
0,1	1	1,14	0,86	0,78	0,26	0,58
0,2	1	1,31	1,14	0,86	0,43	0,86
0,3	1	1,42	1,14	1,14	0,58	0,87
0,4	1	1,50	1,32	1,14	0,71	1,14
0,5	1	1,61	1,43	1,20	0,78	1,14
0,6	1	1,66	1,43	1,43	0,84	1,18
0,7	1	1,70	1,43	1,43	0,90	1,43
0,8	1	1,71	1,43	1,43	0,95	1,43
0,9	1	1,69	1,43	1,43	1,00	1,43

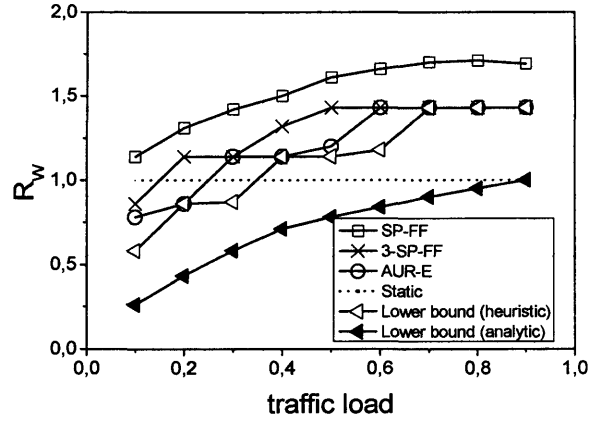


Figure 3.6.a. Ratio between static and dynamic wavelength requirements for Eurocore

NSFNet, $\alpha=0.23$
mean wavelength requirements per link
(static case: 9,27)

traffic load ρ	Static	SP-FF	3-SP-FF	AUR-E	Anal. lower bound	Heur. lower bound
0,1	1	0,82	0,66	0,57	0,24	0,50
0,2	1	1,06	0,90	0,80	0,42	0,70
0,3	1	1,23	1,08	0,97	0,55	0,85
0,4	1	1,36	1,23	1,08	0,66	1,00
0,5	1	1,48	1,39	1,29	0,75	1,12
0,6	1	1,58	1,51	1,40	0,84	1,23
0,7	1	1,67	1,60	1,43	0,91	1,34
0,8	1	1,74	1,62	1,62	0,95	1,43
0,9	1	1,78	1,70	1,62	1,00	1,52

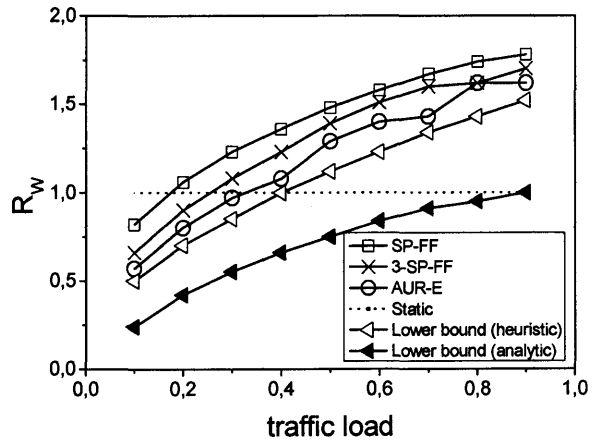


Figure 3.6.b. Ratio between static and dynamic wavelength requirements for NSFNet

EON, $\alpha=0.2$

mean wavelength requirements per link
(static case: 11,6)

traffic load ρ	Static	SP-FF	3-SP-FF	AUR-E	Anal. lower bound	Heur. lower bound
0,1	1	0,78	0,66	0,62	0,25	0,49
0,2	1	1,03	0,93	0,80	0,39	0,69
0,3	1	1,23	1,15	1,00	0,53	0,85
0,4	1	1,40	1,34	1,20	0,64	1,00
0,5	1	1,55	1,47	1,37	0,73	1,13
0,6	1	1,68	1,64	1,46	0,81	1,25
0,7	1	1,81	1,73	1,63	0,89	1,34
0,8	1	1,91	1,85	1,72	0,94	1,41
0,9	1	1,96	1,90	1,81	0,97	1,47

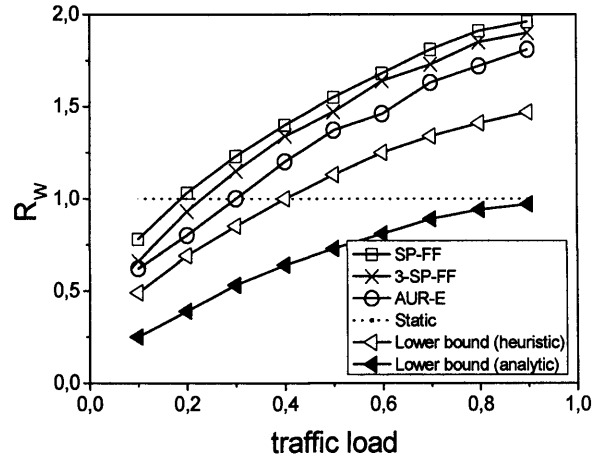


Figure 3.6.c. Ratio between static and dynamic wavelength requirements for EON

UKNet, $\alpha=0.19$

mean wavelength requirements per link
(static case: 13,5)

traffic load ρ	Static	SP-FF	3-SP-FF	AUR-E	Anal. lower bound	Heur. lower bound
0,1	1	0,73	0,59	0,49	0,25	0,40
0,2	1	0,99	0,85	0,66	0,40	0,58
0,3	1	1,19	1,06	0,81	0,53	0,74
0,4	1	1,35	1,25	1,03	0,65	0,89
0,5	1	1,50	1,42	1,18	0,73	1,04
0,6	1	1,63	1,55	1,29	0,81	1,17
0,7	1	1,75	1,70	1,41	0,89	1,29
0,8	1	1,85	1,78	1,55	0,94	1,40
0,9	1	1,92	1,85	1,70	0,98	1,51

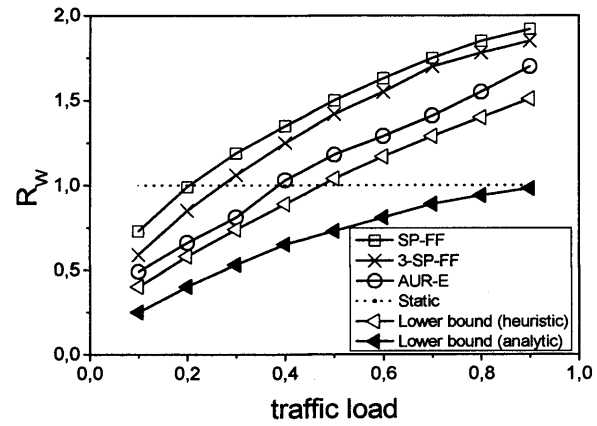


Figure 3.6.d Ratio between static and dynamic wavelength requirements for UKNet

ARPANet, $\alpha=0.16$

mean wavelength requirements per link
(static case: 17,2)

traffic load ρ	Static	SP-FF	3-SP-FF	AUR-E	Anal. lower bound	Heur. lower bound
0,1	1	0,74	0,61	0,52	0,25	0,48
0,2	1	1,04	0,90	0,77	0,41	0,71
0,3	1	1,29	1,14	1,01	0,53	0,92
0,4	1	1,50	1,35	1,26	0,65	1,10
0,5	1	1,68	1,55	1,43	0,76	1,27
0,6	1	1,84	1,73	1,60	0,83	1,43
0,7	1	1,98	1,87	1,80	0,90	1,58
0,8	1	2,10	2,01	1,92	0,95	1,71
0,9	1	2,19	2,09	2,03	0,98	1,82

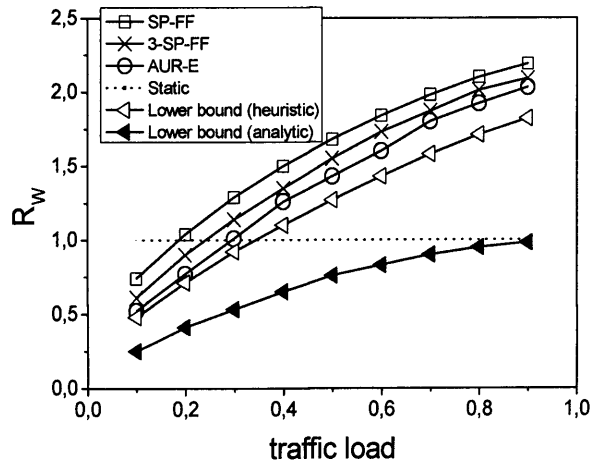


Figure 3.6.e Ratio between static and dynamic wavelength requirements for ARPANet

Eurolarge, $\alpha=0.1$

mean wavelength requirements per link
(static case: 36,2)

traffic load ρ	Static	SP-FF	3-SP-FF	AUR-E	Anal. lower bound	Heur. lower bound
0,1	1	0,60	0,54	0,34	0,21	0,31
0,2	1	0,90	0,84	0,59	0,36	0,52
0,3	1	1,17	1,10	0,80	0,50	0,71
0,4	1	1,41	1,35	1,01	0,61	0,88
0,5	1	1,63	1,58	1,19	0,71	1,06
0,6	1	1,84	1,79	1,39	0,80	1,23
0,7	1	2,03	1,99	1,58	0,88	1,39
0,8	1	2,20	2,18	1,74	0,93	1,54
0,9	1	2,34	2,33	1,90	0,98	1,70

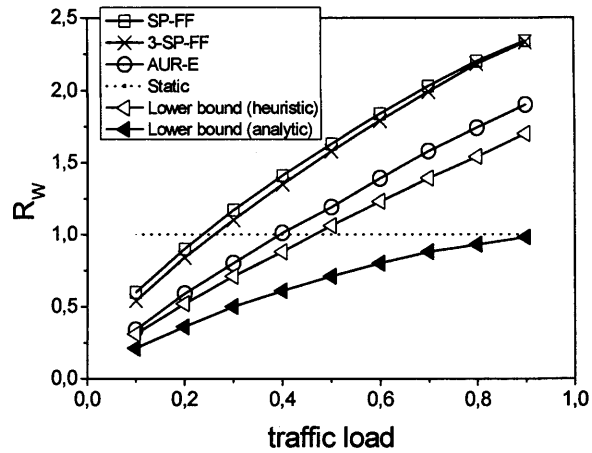


Figure 3.6.f Ratio between static and dynamic wavelength requirements for Eurolarge

USNet, $\alpha=0.07$

mean wavelength requirements per link
(static case: 59,9)

traffic load ρ	Static	SP-FF	3-SP-FF	AUR-E	Anal. lower bound	Heur. lower bound
0,1	1	0,47	0,43	0,32	0,22	0,27
0,2	1	0,72	0,68	0,55	0,38	0,45
0,3	1	0,95	0,91	0,74	0,51	0,63
0,4	1	1,16	1,12	0,94	0,63	0,79
0,5	1	1,35	1,32	1,12	0,72	0,95
0,6	1	1,53	1,50	1,30	0,81	1,10
0,7	1	1,70	1,67	1,47	0,88	1,25
0,8	1	1,86	1,84	1,62	0,94	1,40
0,9	1	1,99	1,97	1,78	0,98	1,55

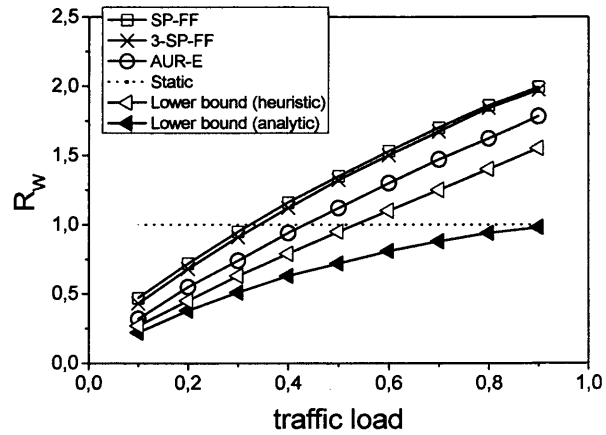


Figure 3.6.g Ratio between static and dynamic wavelength requirements for USNet

From Figures 3.6 a-g four main conclusions can be drawn:

- The heuristic lower bound is still significantly higher than the analytical one: 46% on average. This difference is due to the assumption of full re-utilisation of the wavelength space to obtain the analytical lower bound whilst the heuristic lower bound operates assuming no wavelength conversion. The heuristic lower bound predicts that potential wavelength savings can be

achieved only at low/moderated traffic loads (0.3-0.5) and that sparsely connected networks experience the highest wavelength savings.

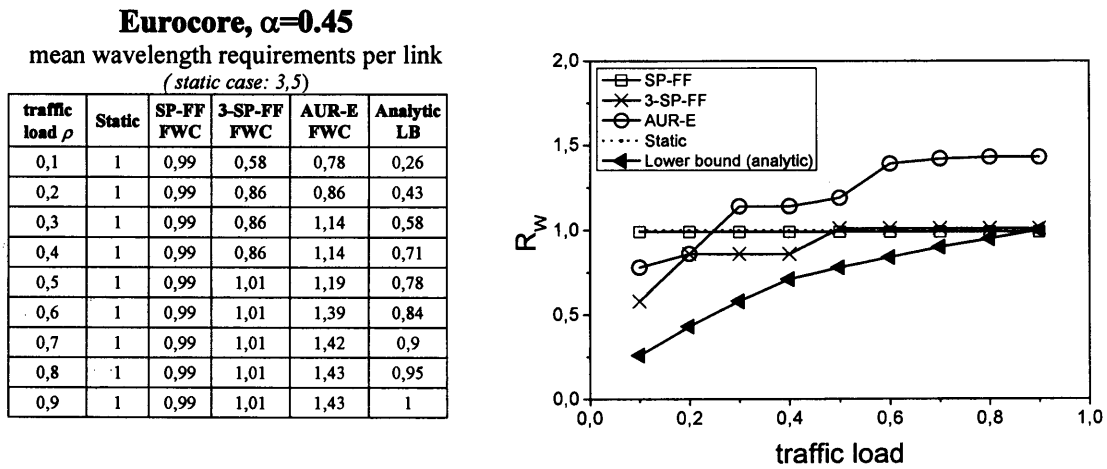
- SP-FF and 3-SP-FF require a much higher number of wavelengths than AUR-E to achieve the same blocking: 24% and 18% higher wavelength requirements on average, respectively. In large networks such as USNet, for example, this difference might require a few thousand extra wavelengths to offer the same service. Thus, in terms of resource utilisation efficiency, SP-FF and k-SP-FF should not be considered for implementation in wavelength-routed networks (i.e., optical networks without full wavelength conversion).
- Although AUR-E corresponds to the best performing algorithm, its performance is still far from that of the analytical lower bound: 67% higher wavelength requirements in average. Given that the analytical lower bound assumed full wavelength conversion, this comparison might be unfair (AUR-E is simulated without wavelength conversion capability). The performance of AUR-E is much better when compared to that of the heuristic lower bound (which, as AUR-E, does not consider full wavelength conversion): in that case AUR-E requires, in average, 14% higher number of wavelengths to achieve the same blocking performance. This percentage still represents a high number of additional wavelengths in networks of large size (about 2000 extra wavelength in USNet) thus, the design of a lightpath allocation algorithm which improves the performance of AUR-E is still desirable. It should be noticed, however, that this is expected to be a very difficult task (since the proposal of AUR-E in 1996 there have been no better algorithms in spite of the active research in the field) as the heuristic lower bound achieves

its good performance by re-allocating the active connections, something not possible in real optical networks.

- Considering the best practical algorithm proposed to date (AUR-E), the advantages of dynamic operation with respect to the static approach are observed only at low/moderated loads (< 0.4) and the wavelength savings are higher for sparsely connected networks (as predicted by the analytical lower bound): networks with physical connectivity, α , lower than 0.2 experience wavelength savings for traffic loads up to 0.4 whilst more connected networks (as Eurocore or NSFNet) experience savings only for loads up to 0.3. For loads in exceed of 0.4 all the studied dynamic networks require more wavelengths than their corresponding static networks and thus, in that range of operation dynamic operation uses network resources more inefficiently than the static scheme.

In summary, in wavelength-routed optical networks the best algorithm to date (AUR-E) still needs improvement and fails to achieve significant wavelength savings in a wide range of traffic loads: only for traffic loads lower than 0.4 dynamic operation in wavelength-routed networks saves wavelengths, with respect to the static networks. The best performance under dynamic operation is observed in sparsely connected networks ($\alpha < 0.2$). This result is contradictory to the widely expected savings in dynamic networks and should encourage the research community to review the idea that dynamic operation of wavelength-routed optical networks is always the best choice.

Although the work described in this thesis focused on wavelength-routed optical networks, the evaluation of the impact of wavelength conversion in the wavelength requirements of optical networks is a key aspect to consider since it has been shown that wavelength-convertible networks could offer a significantly improved performance in terms of blocking, see for example [Chu05, Yat99a, Bar96, Kov96]. To investigate the impact of equipping the networks with wavelength conversion capability on the wavelength requirements of dynamic networks, the wavelength requirements of the same algorithms (SP-FF, 3-SP-FF and AUR-E) were evaluated assuming full wavelength conversion. Results for R_W between the wavelength requirements of the different algorithms and the wavelength requirements in the static case are plotted in Figure 3.7 along with the analytical lower bound.



NSFNet, $\alpha=0.23$

mean wavelength requirements per link
(static case: 9,3)

traffic load ρ	Static	SP-FF FWC	3-SP-FF FWC	AUR-E FWC	Analytic LB
0,1	1	0,69	0,56	0,55	0,24
0,2	1	0,85	0,76	0,74	0,42
0,3	1	0,94	0,86	0,88	0,55
0,4	1	0,99	0,93	0,98	0,66
0,5	1	1	0,97	1,09	0,75
0,6	1	1	0,97	1,17	0,84
0,7	1	1	0,97	1,25	0,91
0,8	1	1	1	1,29	0,95
0,9	1	1	1,07	1,32	1

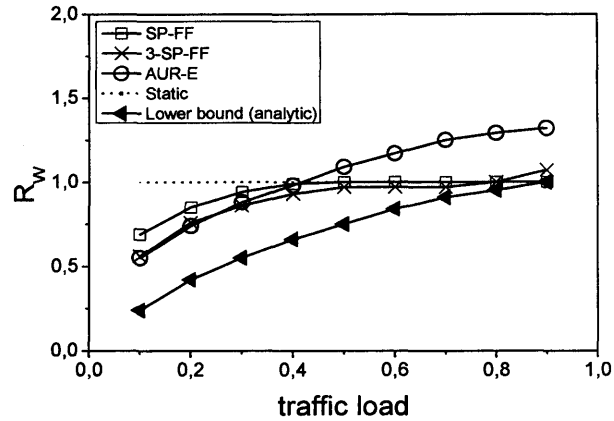


Figure 3.7.b. Ratio between static and dynamic wavelength requirements in wavelength-convertible NSFNet

EON, $\alpha=0.2$

mean wavelength requirements per link
(static case: 11,6)

traffic load ρ	Static	SP-FF FWC	3-SP-FF FWC	AUR-E FWC	Analytic LB
0,1	1	0,61	0,54	0,51	0,25
0,2	1	0,76	0,69	0,67	0,39
0,3	1	0,87	0,84	0,8	0,53
0,4	1	0,93	0,86	0,93	0,64
0,5	1	0,98	0,95	1,04	0,73
0,6	1	0,99	0,95	1,12	0,81
0,7	1	0,99	0,95	1,21	0,89
0,8	1	0,99	0,95	1,28	0,94
0,9	1	0,99	1,03	1,33	0,97

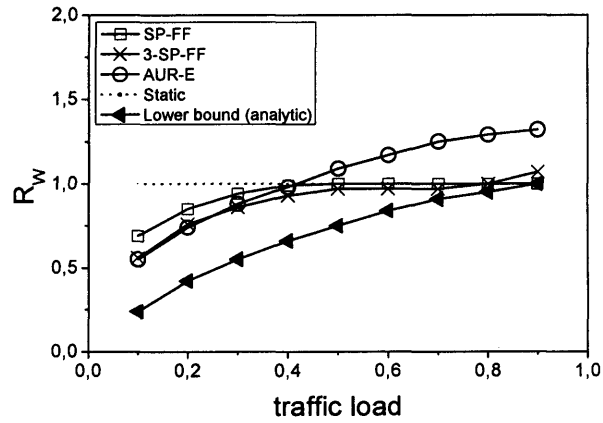


Figure 3.7.c. Ratio between static and dynamic wavelength requirements in wavelength-convertible EON

UKNet, $\alpha=0.19$

mean wavelength requirements per link
(static case: 13,5)

traffic load ρ	Static	SP-FF FWC	3-SP-FF FWC	AUR-E FWC	Analytic LB
0,1	1	0,57	0,52	0,45	0,25
0,2	1	0,73	0,67	0,61	0,4
0,3	1	0,84	0,81	0,74	0,53
0,4	1	0,92	0,89	0,88	0,65
0,5	1	0,97	0,96	0,99	0,73
0,6	1	1	0,96	1,08	0,81
0,7	1	1	0,96	1,18	0,89
0,8	1	1	0,98	1,26	0,94
0,9	1	1	1,04	1,32	0,98

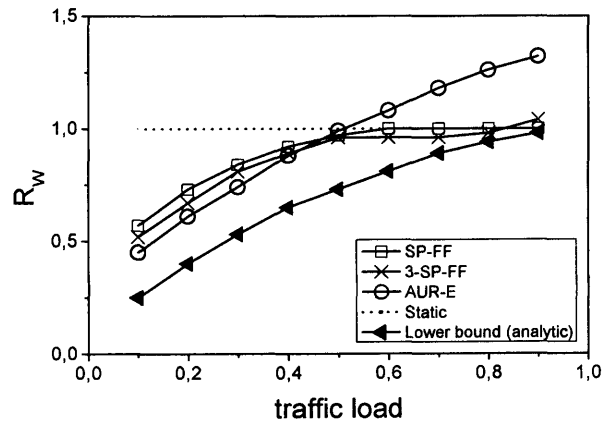


Figure 3.7.d. Ratio between static and dynamic wavelength requirements in wavelength-convertible UKNet

ARPANet, $\alpha=0.16$

mean wavelength requirements per link
(static case: 17,2)

traffic load ρ	Static	SP-FF FWC	3-SP-FF FWC	AUR-E FWC	Analytic LB
0,1	1	0,51	0,47	0,44	0,29
0,2	1	0,67	0,62	0,61	0,46
0,3	1	0,78	0,75	0,74	0,58
0,4	1	0,87	0,81	0,86	0,7
0,5	1	0,94	0,89	0,96	0,81
0,6	1	0,97	0,93	1,05	0,87
0,7	1	1	0,99	1,13	0,93
0,8	1	1	1	1,2	0,99
0,9	1	1	1,04	1,26	0,99

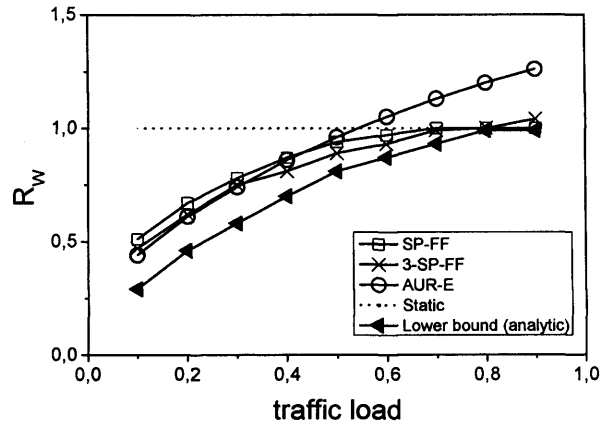


Figure 3.7.e. Ratio between static and dynamic wavelength requirements in wavelength-convertible ARPANet

Eurolarge, $\alpha=0.1$

mean wavelength requirements per link
(static case: 36,2)

traffic load ρ	Static	SP-FF FWC	3-SP-FF FWC	AUR-E FWC	Analytic LB
0,1	1	0,37	0,36	0,3	0,22
0,2	1	0,52	0,5	0,46	0,39
0,3	1	0,63	0,61	0,61	0,5
0,4	1	0,74	0,72	0,74	0,64
0,5	1	0,82	0,8	0,87	0,72
0,6	1	0,9	0,88	0,99	0,8
0,7	1	0,96	0,94	1,1	0,89
0,8	1	0,99	0,98	1,21	0,94
0,9	1	1	1	1,31	1

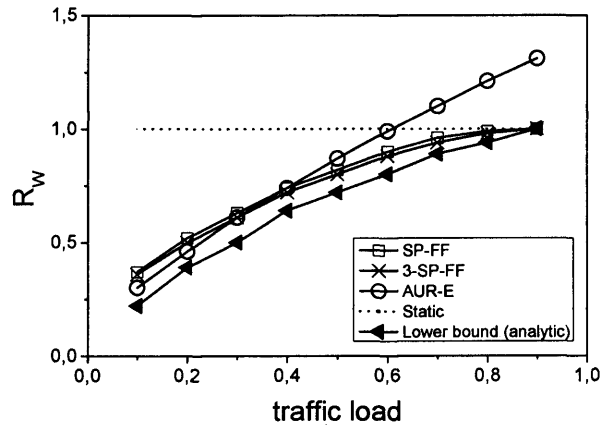


Figure 3.7.f. Ratio between static and dynamic wavelength requirements in wavelength-convertible Eurolarge

USNet, $\alpha=0.07$

mean wavelength requirements per link
(static case: 59,9)

traffic load ρ	Static	SP-FF FWC	3-SP-FF FWC	AUR-E FWC	Analytic LB
0,1	1	0,31	0,3	0,26	0,23
0,2	1	0,45	0,43	0,41	0,38
0,3	1	0,57	0,55	0,53	0,52
0,4	1	0,67	0,67	0,65	0,63
0,5	1	0,77	0,75	0,76	0,73
0,6	1	0,85	0,84	0,87	0,82
0,7	1	0,92	0,92	0,97	0,88
0,8	1	0,97	0,97	1,07	0,95
0,9	1	1	1	1,16	0,98

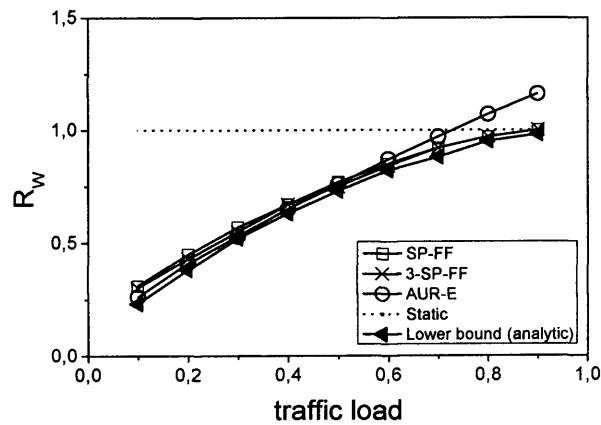


Figure 3.7.g. Ratio between static and dynamic wavelength requirements in wavelength-convertible USNet

From Figures 3.7 a-g, the following main conclusions can be drawn:

- Wavelength conversion capability greatly impacts the relative performance of the lightpath allocation algorithms: AUR-E is no longer the best performing algorithm over the complete traffic load range. In fact, at high traffic loads (>0.5) AUR-E requires the highest number of wavelengths because of the longer routes utilised. The 3-SP-FF algorithm achieves the best performance.
- Wavelength conversion capability improves the performance of the three studied algorithms. The improvement is significant in sparsely connected networks. For example, for Eurocore ($\alpha=0.45$) the maximum traffic load at which 3-SP-FF obtains wavelength savings increased from 0.2 to 0.4 whilst for Eurolarge ($\alpha=0.1$) the same value increased from 0.3 to 0.8.
- Wavelength conversion capability increases significantly the load at which dynamic operation achieves wavelength savings compared to the static scheme: wavelength savings are observed for traffic loads from 0.5 to 0.8. Similarly to the wavelength-routed networks, the highest benefits of dynamic operation are observed in sparsely connected networks (Eurolarge and USNet) where wavelength savings are achieved for loads up to 0.8.

As a way of summary of the results presented in this section, the maximum traffic load at which wavelength savings are achieved for the different studied topologies is plotted in Figure 3.8 for AUR-E

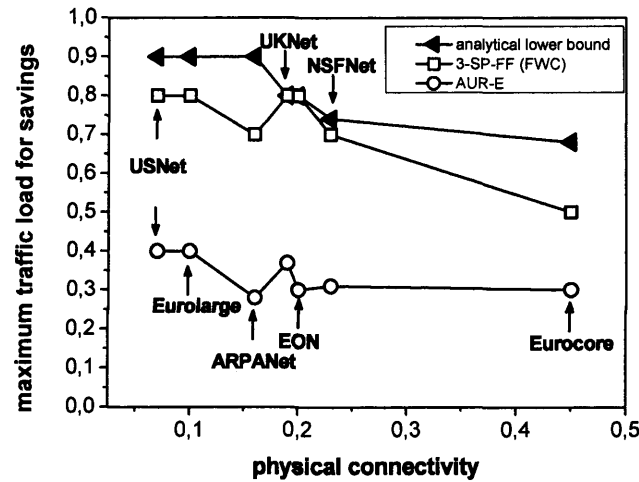


Figure 3.8. Maximum loads at which wavelength savings are obtained with respect to the static operation

(best performing algorithm for wavelength-routed networks), 3-SP-FF FWC (with full wavelength conversion, best performing algorithm for wavelength-convertible networks) and the analytical lower bound.

From the figure it can be seen that the potential wavelength savings achieved by real dynamic lightpath algorithms with respect to their static counterparts is significantly affected by the network physical connectivity and the wavelength conversion capability:

- **Physical connectivity (α).** Strongly connected networks (such as Eurocore) do not benefit significantly from dynamic operation since their requirements in the static case are already low, as shown in [Bar97].
- **Wavelength conversion.** Dynamic algorithms in sparsely connected networks ($\alpha < 0.2$) can achieve savings close to that of the lower bound only if wavelength conversion is provided. In this case, networks with $\alpha < 0.2$ can

achieve savings for loads in the range 0.7-0.8. Without wavelength conversion, savings are achieved at much lower loads (in the range 0.3-0.4).

The results show that research should focus on the improvement of dynamic lightpath allocation algorithms for networks without wavelength conversion, particularly in sparsely connected networks as strongly connected networks are better served with static operation. In the following section, a new lightpath allocation algorithm is presented. The aim of this new algorithm is to improve the performance of AUR-E in wavelength-routed optical networks.

3.5. A novel lightpath allocation algorithm

AUR-E corresponds to a type of algorithm known in Computer Science as a *greedy* algorithm, widely used in optimisation problems. A greedy algorithm always takes the optimal immediate, or local, solution. By choosing a local optimum it is expected that a global optimum can be achieved, although this is not guaranteed.

AUR-E is classified as *greedy* because it always selects the wavelength which has an available shortest path, no matter whether this choice re-uses wavelengths or not. By doing so, the wavelength space is quickly used-up. Instead, if a non-greedy approach was used where a slightly longer path in an already used wavelength was chosen, it is expected that a lower number of wavelengths would be required.

In this section a new, non-greedy, DRWA algorithm, named Adaptive Routing with Limited Extra Hops (AR-LEH), is described. AR-LEH is based on AUR-E, but by

forcing the selection of slightly longer routes (than the shortest) on already used wavelengths it is expected that it achieves wavelength requirements reduction compared to AUR-E in wavelength-routed optical networks.

In this section, AR-LEH is described and its wavelength requirements quantified.

As AUR-E, AR-LEH is a Dijkstra-based algorithm which uses the concept of layered graph (see Chapter 2). But, unlike AUR-E, AR-LEH prefers to allocate the lowest indexed wavelength available as long as the length of the lightpath in that wavelength does not exceed the length of the shortest path by a maximum of e hops. In this way, by using slightly longer paths (typically, $e < 4$), the wavelength requirements might be decreased, especially at low loads where unused capacity in the lowest-indexed wavelengths can be re-utilised.

Let W be the maximum number of wavelengths and G_i be the topology graph corresponding to the wavelength i , $i=1,2,\dots, W$. For every lightpath request between nodes *source* and *destination*, ARLEH executes the following steps:

Pseudo-code	Comments
$i=1;$	Lightpath search starts with the lowest-indexed wavelength
while($i \leq W$) { $route = \text{Dijkstra}(source,$ $destination, G_i)$ if ($\text{hops}(route) \leq SP+e$)	The shortest available path between <i>source</i> and <i>destination</i> in the layered graph G_i is obtained and stored in the variable <i>route</i> If the shortest path found in G_i does not exceed the

<pre> { allocate(<i>i</i>, <i>route</i>); end request processing; } else <i>i</i>++; } if (<i>i</i> > <i>W</i>) reject request ; </pre>	<p>length of shortest path (SP, pre-computed off-line) by e hops,</p> <p>the lightpath defined by route and wavelength i is allocated to the request</p> <p>If the shortest path found in G_i exceeds the length of shortest path by e hops, the next wavelength is attempted</p> <p>If all the wavelengths have been searched and not lightpath has been found, the request is rejected</p>
---	--

Table 3.3. Pseudocode for AR-LEH algorithm

Note that when the number of allowed extra hops, e , is set to 0, ARLEH does not necessarily reduces to AUR-E because eventually AUR-E would select a path longer than the shortest one if no other is available. Instead, AR-LEH is forced to block the request if the shortest path is not available.

To investigate the potential advantage of AR-LEH compared to AUR-E in wavelength-routed networks under uniform traffic, the wavelength requirements of AR-LEH were evaluated by means of simulation using the same settings and topologies used in the section 3.5. The results for R_w are plotted in Figure 3.9 for the range of values of the traffic load where AR-LEH achieves wavelength savings with respect to the static case.

Eurocore, $\alpha=0.45$

mean wavelength
requirements per link
(static case: 3,5)

traffic load ρ	Static	AUR-E	AR-LEH (e)
0,1	1	0,78	0,61 (2)
0,2	1	0,86	0,86 (2)
0,3	1	1,14	1,12 (0)
0,4	1	1,14	1,14 (0)
0,5	1	1,20	1,31 (0)
0,6	1	1,43	1,43 (0)
0,7	1	1,43	1,43 (0)
0,8	1	1,43	1,45 (0)
0,9	1	1,43	1,55 (0)

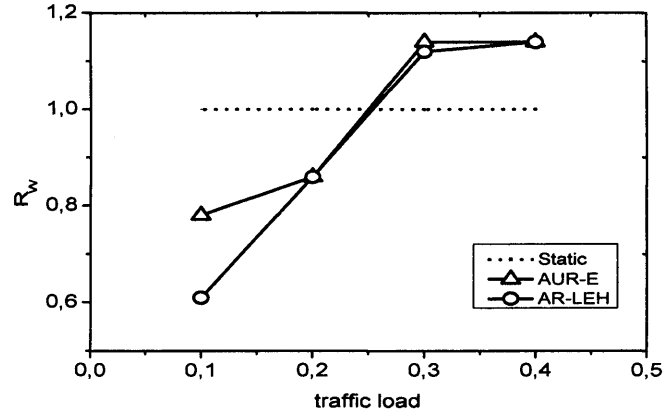


Figure 3.9.a. Ratio between static and dynamic wavelength requirements for AUR-E and AR-LEH algorithms in Eurocore. (e) corresponds to the number of extra hops.

NSFNet, $\alpha=0.23$

mean wavelength
requirements per link
(static case: 9,3)

traffic load ρ	Static	AUR-E	AR-LEH (e)
0,1	1	0,57	0,54 (3)
0,2	1	0,80	0,78 (3)
0,3	1	0,97	0,97 (2)
0,4	1	1,08	1,14 (0)
0,5	1	1,29	1,29 (0)
0,6	1	1,40	1,41 (0)
0,7	1	1,43	1,51 (0)
0,8	1	1,62	1,62 (0)
0,9	1	1,62	1,67 (0)

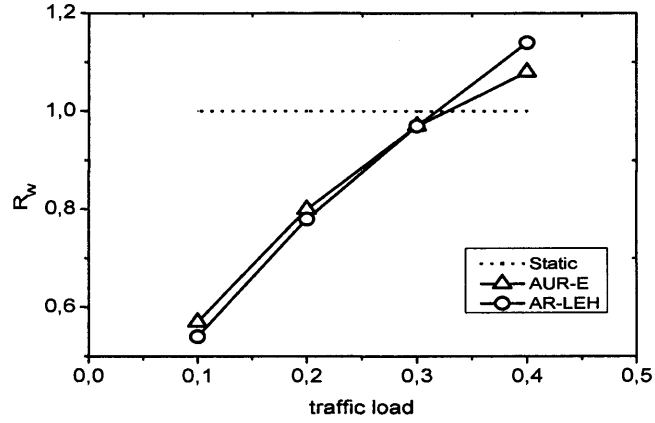


Figure 3.9.b. Ratio between static and dynamic wavelength requirements for AUR-E and AR-LEH algorithms in NFSNet. (e) corresponds to the number of extra hops.

EON, $\alpha=0.2$

mean wavelength
requirements per link
(static case: 11,6)

traffic load ρ	Static	AUR-E	AR-LEH (e)
0,1	1	0,62	0,54 (2)
0,2	1	0,80	0,78 (2)
0,3	1	1,00	0,98 (2)
0,4	1	1,20	1,16 (2)
0,5	1	1,37	1,32 (2)
0,6	1	1,46	1,46 (1)
0,7	1	1,63	1,59 (1)
0,8	1	1,72	1,70 (1)
0,9	1	1,81	1,79 (1)

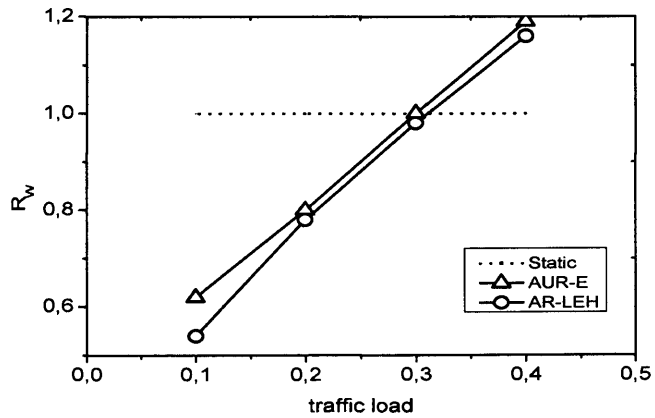


Figure 3.9.c. Ratio between static and dynamic wavelength requirements for AUR-E and AR-LEH algorithms in EON. (e) corresponds to the number of extra hops.

UKNet, $\alpha=0.19$

mean wavelength
requirements per link
(static case: 13,5)

traffic load ρ	Static	AUR- E	AR- LEH (e)
0,1	1	0,49	0,46 (3)
0,2	1	0,66	0,69 (2)
0,3	1	0,81	0,88 (2)
0,4	1	1,03	1,04 (1)
0,5	1	1,18	1,20 (0)
0,6	1	1,29	1,34 (0)
0,7	1	1,41	1,48 (0)
0,8	1	1,55	1,62 (0)
0,9	1	1,70	1,70 (0)

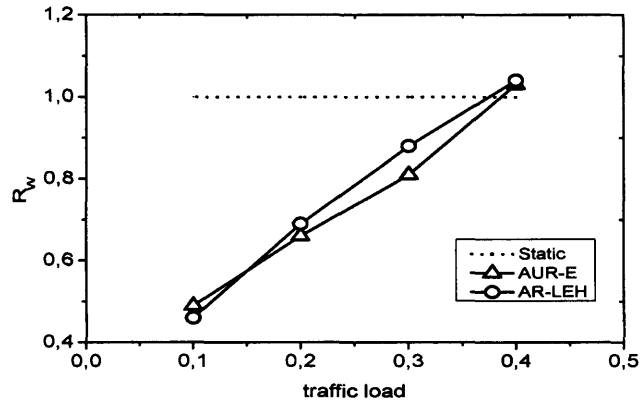


Figure 3.9.d. Ratio between static and dynamic wavelength requirements for AUR-E and AR-LEH algorithms in UKNet. (e) corresponds to the number of extra hops.

ARPANet, $\alpha=0.16$

mean wavelength
requirements per link
(static case: 17,2)

traffic load ρ	Static	AUR- E	AR- LEH (e)
0,1	1	0,52	0,52 (3)
0,2	1	0,77	0,79 (3)
0,3	1	1,01	1,03 (3)
0,4	1	1,26	1,24 (3)
0,5	1	1,43	1,44 (3)
0,6	1	1,60	1,62 (2)
0,7	1	1,80	1,79 (2)
0,8	1	1,92	1,94 (1)
0,9	1	2,03	2,04 (0)

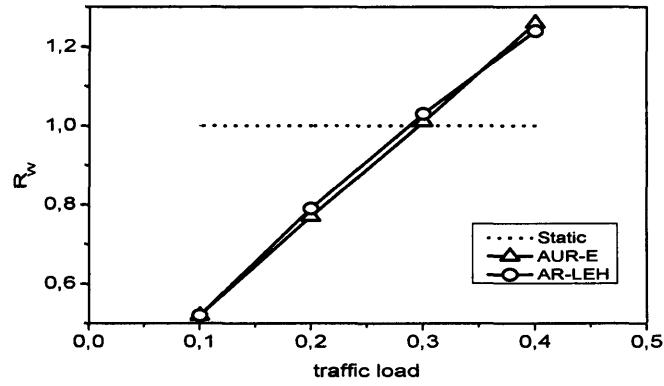


Figure 3.9.e. Ratio between static and dynamic wavelength requirements for AUR-E and AR-LEH algorithms in ARPANet. (e) corresponds to the number of extra hops.

Eurolarge, $\alpha=0.1$

mean wavelength requirements
per link
(static case: 36,2)

traffic load ρ	Static	AUR- E	AR- LEH (e)
0,1	1	0,34	0,36 (3)
0,2	1	0,59	0,59 (3)
0,3	1	0,80	0,81 (3)
0,4	1	1,01	1,01 (1)
0,5	1	1,19	1,21 (0)
0,6	1	1,39	1,40 (0)
0,7	1	1,58	1,58 (0)
0,8	1	1,74	1,75 (0)
0,9	1	1,90	1,90 (0)

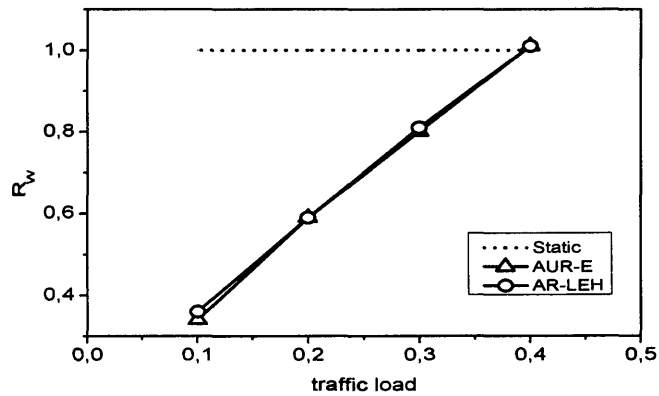


Figure 3.9.f. Ratio between static and dynamic wavelength requirements for AUR-E and AR-LEH algorithms in Eurolarge. (e) corresponds to the number of extra hops.

USNet, $\alpha=0.07$
mean wavelength
requirements per link
(static case: 59,9)

traffic load ρ	Static	AUR-E	AR-LEH (e)
0,1	1	0,32	0,33 (3)
0,2	1	0,55	0,55 (3)
0,3	1	0,74	0,75 (2)
0,4	1	0,94	0,94 (1)
0,5	1	1,12	1,13 (1)
0,6	1	1,30	1,30 (1)
0,7	1	1,47	1,47 (1)
0,8	1	1,62	1,62 (0)
0,9	1	1,78	1,78 (0)

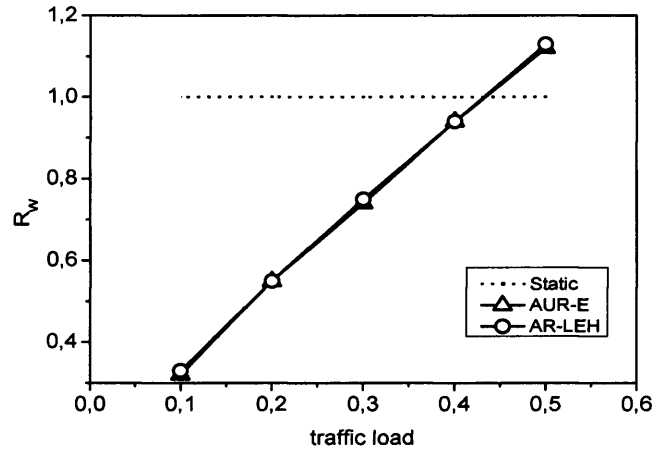


Figure 3.9.g. Ratio between static and dynamic wavelength requirements for AUR-E and AR-LEH algorithms in USNet. (e) corresponds to the number of extra hops.

It can be seen that the main benefit of AR-LEH can be found in well connected networks operating at low loads (about 0.1), where a reduction in the wavelength requirements is observed. However, this saving is not high enough to increase significantly the maximum load at which dynamic operation in wavelength-routed optical networks can bring benefits compared to the static approach.

3.6. Summary

In this chapter the question of whether dynamic operation in optical networks brings benefits in terms of wavelength requirements with respect to the static operation was addressed, assuming uniform traffic distribution.

Through the derivation of an analytical lower bound for the wavelength requirements it was found that resource allocation schemes utilising adaptive routing achieved higher wavelength savings than those schemes using fixed routing and that dynamic operation had the potential of offering significant wavelength savings for a wide range of traffic loads (about 0.9) when compared to the static approach.

Because the derivation of the analytical lower bound made some assumptions that could be unachievable in practice (shortest paths and full utilisation of the wavelength space), a more realistic lower bound was proposed. This lower bound was based on the successive application of a near-optimal heuristic for the static case every time a new lightpath request was generated. The heuristic lower bound showed that dynamic operation could achieve wavelength savings only at low/moderated traffic loads (0.3-0.5) and that the highest savings were experienced by sparsely connected networks ($\alpha < 0.2$).

The lower bounds were used as a benchmark for the wavelength requirements of three dynamic lightpath allocation algorithms: SP-FF, 3-SP-FF and AUR-E. By means of simulation it was found that SP-FF and 3-SP-FF required a much higher number of wavelengths than AUR-E to achieve the same blocking (24% and 18%% higher, respectively) and that AUR-E required, in average, 14% higher number of wavelengths than the heuristic lower bound.

These results showed that, considering the best dynamic lightpath allocation proposed to date (AUR-E), dynamic wavelength-routed optical networks achieved wavelength savings with respect to the static approach only at low/moderated traffic loads (0.3-0.4) and that the highest savings were achieved in sparsely connected networks.

To investigate whether the wavelength conversion capability could impact significantly the potential benefits of dynamic operation compared to the static networks, the wavelength requirements of the studied algorithms was evaluated for the case of full wavelength conversion capability. It was found that in wavelength-convertible networks dynamic operation can achieve significant wavelength savings for traffic loads up to 0.9. In this case the best dynamic algorithm is alternate routing

(3-SP-FF). AUR-E did not achieve such a good performance as in the case of wavelength-routed networks due to its selection of longer routes to set-up the lightpaths.

Finally, with the aim of finding a better dynamic algorithm for wavelength-routed optical networks, a new algorithm, AR-LEH, was proposed. It was shown that AR-LEH decreased the wavelength requirements of well connected networks at low loads (<0.2) but this advantage was not high enough as to increase the maximum load at which dynamic networks save wavelengths with respect to static networks.

In summary, dynamic wavelength-routed optical networks bring benefits in terms of wavelength requirements compared to the static approach only at low/moderated loads (<0.4) and mainly in sparsely connected networks. Wavelength-routed optical networks operating at higher traffic loads do not benefit from dynamic operation. Wavelength-convertible networks instead benefit significantly from dynamic operation over a wide range of traffic load value (about 0.9), however the additional cost of implementing such a network should be lower than the savings achieved due to the wavelength requirement decrease for this alternative to be feasible. Given that wavelength converters remain expensive, it is not likely that the wavelength savings are enough to make dynamic operation attractive with respect to the static approach in the short-term.

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Chapter 4

Wavelength requirements in dynamic wavelength-routed optical networks under non-uniform traffic demand

It was shown in Chapter 3 that, under uniform traffic, dynamic operation of wavelength-routed optical networks (i.e. nodes are not equipped with wavelength conversion) brings benefits in terms of wavelength requirements with respect to the static approach, only at low traffic loads (up to 0.3-0.4). In this case, sparsely connected networks (physical connectivity $\alpha < 0.2$) achieve the highest wavelength savings. If wavelength conversion capability is provided, the wavelength savings are observed at much higher values for the traffic loads: up to 0.7-0.8. Given that wavelength converters are expensive devices and that wavelength-routed networks would achieve wavelength savings only at low traffic loads, the widely accepted hypothesis that dynamic operation of WDM networks would always bring benefits compared to the static operation is not valid.

However, these conclusions were drawn from analysis and simulations carried out under the assumption of uniform traffic demand. In fact, real traffic demand

distributions are generally non-uniform [Bro04, Sen04, Fra03, Wil01, Taf01, Bha01, Cla99, Fan99], which may significantly affect the network wavelength requirements.

In this chapter the wavelength requirements of dynamic optical networks under non-uniform traffic demand are quantified by means of analysis (lower bounds) and simulation and compared to the wavelength requirements of static optical networks. The network model as well as the network architectures considered (dynamic and static) are the same as in Chapter 3.

4.1. Traffic characterisation

In the static case the traffic demand between every pair of nodes is transformed into the number of wavelengths required to satisfy the maximum possible bit rate from source to destination (and it is assumed that the maximum possible bit rate is always lower or equal to the wavelength bit rate). Thus, in the case of non-uniform traffic demand (where the maximum possible bit rate from node i to j , b_{ij} , can be different for different node pairs) the elements $M[i, j]$, $i \neq j$, of the static traffic matrix can take values 0 or 1 (in the uniform case these elements are all equal to 1). That is, every element $M[i, j]$ of the traffic matrix is defined by the following expression:

$$M[i, j] = \begin{cases} 0 & b_{ij} = 0 \\ 1 & b_{ij} > 0 \end{cases} \quad (4.1)$$

Therefore, for all the cases of non-uniform demand where the elements $M[i, j]$, $i \neq j$, are equal to 1, the wavelength requirements would be the same as in the uniform traffic demand case. For those cases where one or more elements $M[i, j]$, $i \neq j$, are equal to 0 the wavelength requirements are lower than that of the uniform traffic demand case.

In the dynamic case, as in Chapter 3, an ON-OFF model for the burst input traffic is considered. But, unlike Chapter 3, the mean duration of the ON and OFF periods can be different for different connections (and thus, the traffic load ρ). Therefore, in this chapter the ON-OFF traffic demand from node i to node j is characterised by the mean ON and OFF period durations: $T_{ON}^{i,j}$ and $T_{OFF}^{i,j}$, respectively. As a result, the traffic load offered by the connection between node i and j , $\rho_{i,j}$, is given by $T_{ON}^{i,j} / (T_{ON}^{i,j} + T_{OFF}^{i,j})$. The element $M[i,j]$ of the dynamic traffic matrix corresponds to the value of $\rho_{i,j}$.

A key aspect when analysing networks under non-uniform traffic is how to generate (and characterise) non-uniform traffic matrices representative of real-world situations. The methods proposed to date for non-uniform traffic matrix generation can be classified in two main categories:

- **Probabilistic method.** Each element of the traffic matrix ($\rho_{i,j}$ for the dynamic case or $b_{i,j}$ for the static case) is a random variable in $[0,t]$ (following a certain distribution -typically, the uniform distribution is used, as in [Kom02, Lee04]), with t equal to the wavelength bit rate in the static case and equal to 1 in the dynamic case. This non-uniform traffic matrix generation method is simple, but it does not allow control of the total traffic load value. This makes network performance comparison (between uniform and non-uniform traffic matrices) problematic, as the same total traffic load should be used in both cases.
- **Load transfer method.** This approach requires a uniform traffic matrix as a starting point. This initial traffic matrix is completely characterised by its

total traffic load (equal to $N(N-1)\rho$, where ρ corresponds to the traffic load of a node pair and N is the number of network nodes). The original traffic matrix is then modified by transferring a fraction of traffic load from a node pair (or a set of node pairs) to another. In this way, the total traffic load remains unchanged which allows a fair performance comparison between networks under uniform and non-uniform traffic demand. A commonly used load transfer method is known as the *Hot Spot* method [Mis00, Kom02]. In the *Hot Spot* method a $Y\%$ of the total traffic load in the network is uniformly distributed among the $X\%$ of the node pairs (randomly selected) which form the “hot spot” of the network. The remaining $(1-Y)\%$ of the traffic load is uniformly distributed among the remainder of the node pairs. Usually, $Y > 60$ and $X < 25$. Although this method is widely used to study the performance of networks under non-uniform traffic demand, the distribution of the traffic load remains uniform within every set (the set of node pairs belonging to the “hot spot” and the remaining node pairs) which is unlikely in real situations. Another load transfer method was proposed in [Gib93], where a parameter $\eta \in [0,1]$ was introduced to define the level of non-uniformity of the generated traffic matrix. The method randomly selects two elements from the traffic matrix and an amount of traffic load uniformly distributed between $[0, \eta\rho]$ is transferred from one element to the another. The same procedure is repeated until all elements of the traffic matrix have been modified. This method improves on the main shortcoming of the *Hot Spot* method: because the amount of transferred traffic from is a random variable, uniform traffic load distributions in sets of node pairs are very unlikely. In addition, the non-uniformity is characterised by a unique parameter: η . This method is very

unlikely to generate extreme traffic matrices (for example, all the traffic load concentrated in one element of the traffic matrix) which are of theoretical interest but very unlikely to occur in real cases. Due to its advantages (control of the total traffic load and use of a unique parameter to define the level of non-uniformity) this transfer load method was used in the work described in this chapter to generate non-uniform traffic matrices.

4.2. Analytical lower bounds

4.2.1. Adaptive routing

Analogously to the case of uniform traffic (see Eq. (3.3) and its derivation), the total wavelength requirement is given by:

$$W_{LB} = \left\lceil \frac{\sum_{i=1}^{|\hat{A}|} h_i}{L} \right\rceil \quad (4.2)$$

where \hat{A} corresponds to the set A of active connections with the longest routes and h_i to the length of the i -th longest connection (thus, h_1 and $h_{N(N-1)}$ are the number of hops of the connections with the longest and the shortest paths, respectively).

Following the same reasoning used to obtain Eq. (3.6), $|\hat{A}|$ can be evaluated as follows:

$$B = \sum_{a=|\hat{A}|+1}^{N(N-1)} \Pr\{n = a\} = \sum_{a=|\hat{A}|+1}^{N(N-1)} \left(\sum_{\substack{\vec{v} \in \mathcal{V} \\ |\vec{v}|=a}} \prod_{\forall v_{i,j}=1} \rho_{ij} \prod_{\forall v_{i,j}=0} (1 - \rho_{ij}) \right) \quad (4.3)$$

where $\vec{v} = (v_{0,1}, v_{0,2}, \dots, v_{N-1,N})$ corresponds to a vector indicating the state of the different $N(N-1)$ connections: if the connection from node i to j is in ON state, then

$v_{i,j} = 1$ (otherwise, $v_{i,j} = 0$); $|\vec{v}|$ corresponds to the number of elements equal to 1 in \vec{v} . The symbol \neg in the second sum means “such that”.

From Eq. (4.3) $|\hat{A}|$ can be numerically evaluated.

4.2.2. Fixed routing

Similarly to the case of uniform traffic, the total capacity requirement for the case of fixed routing is given by:

$$W_{LB}^{fixed} = \frac{\sum_{l=0}^L a_l}{L} \quad (4.4)$$

Where a_l is obtained from the following expression (see Eq. (3.11)):

$$\Pr\{n > a_l\} = 1 - \sqrt[l]{1 - B_r} \quad (4.5)$$

However, unlike the case of uniform traffic, the expression for $\Pr\{n > a_l\}$ must take into account that every node pair may have a different value for $\rho_{i,j}$:

$$\Pr\{n > a_l\} = \sum_{n=a_l+1}^{N_l} \left(\sum_{\substack{\forall \vec{v} \neg \\ |\vec{v}|=n}} \prod_{\forall v_{ji}=1} \rho_{i,j} \prod_{\forall v_{ji}=0} (1 - \rho_{i,j}) \right) \quad (4.6)$$

Thus, a_l must be numerically derived from the following expression:

$$1 - \sqrt[l]{1 - B_r} = \sum_{n=a_l+1}^{N_l} \left(\sum_{\substack{\forall \vec{v} \neg \\ |\vec{v}|=n}} \prod_{\forall v_{ji}=1} \rho_{i,j} \prod_{\forall v_{ji}=0} (1 - \rho_{i,j}) \right) \quad (4.7)$$

Unlike the uniform case, to draw general conclusions from equations (4.3) or (4.7) is problematic as there is an infinite number of different traffic matrices for the same value of η . Thus, this chapter focuses in simulation results for some specific topologies.

4.3. Numerical results for wavelength requirements

In this section, the wavelength requirements of dynamic centralised WR-OBS under non-uniform traffic matrices are quantified by means of simulation. To do so, the same 4 lightpath allocation algorithms studied in the previous chapter (SP-FF, 3-SP-FF, AUR-E and AR-LEH) are were simulated with 5 out of the 7 topologies studied in the previous chapter (Eurolarge and USNet were not included due to their extremely high simulation time resulting from their large number of nodes). The results allow to evaluate whether dynamic networks can save wavelength resources with respect to the static networks under non-uniform traffic demand.

To investigate the impact of the level of no-uniformity (η) on R_w , the wavelength requirements resulting from the application of the SP-FF, 3-SP-FF, AUR-E and AR-LEH algorithms were evaluated by means of simulation. Simulation details are the same as in Chapter 3, except that in this case, 100 traffic matrices with the same degree of non-uniformity (i.e., the same value for η) were generated for each different topology and value of traffic load. The traffic matrices were generated using the method proposed in [Gib93], as described in the section 4.2. For each topology and traffic load, the wavelength requirements obtained from the different traffic matrices were averaged.

The ratio R_w for the SP-FF, 3-SP-FF, AUR-E and RR algorithms as well as for the analytical lower bound (LB) was plotted as a function of the level of no-uniformity for values of the traffic load such that $R_w < 1$ (i.e. the operating range where dynamic

operation bring benefits compared to the static approach) and the results are shown in Figure 4.1 a)-e).

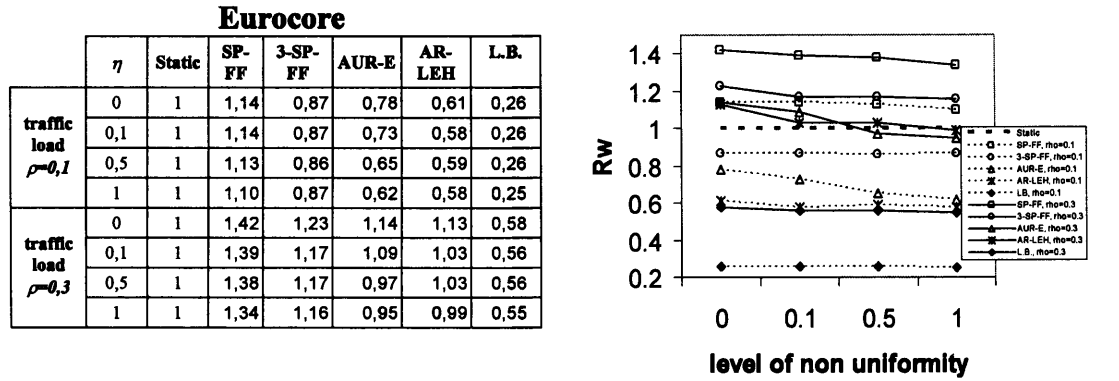


Figure 4.1.a. Ratio R_w for the Eurocore topology as a function of the degree of non-uniformity η

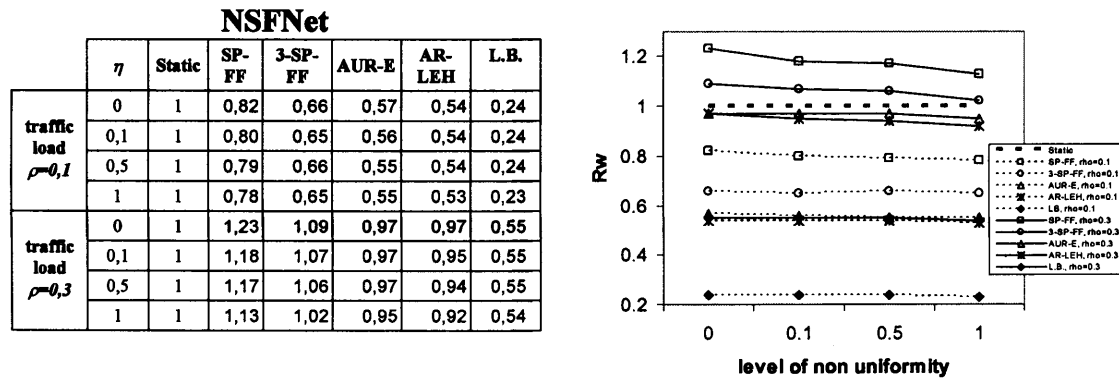


Figure 4.1.b. Ratio R_w for the NSFNet topology as a function of the degree of non-uniformity η

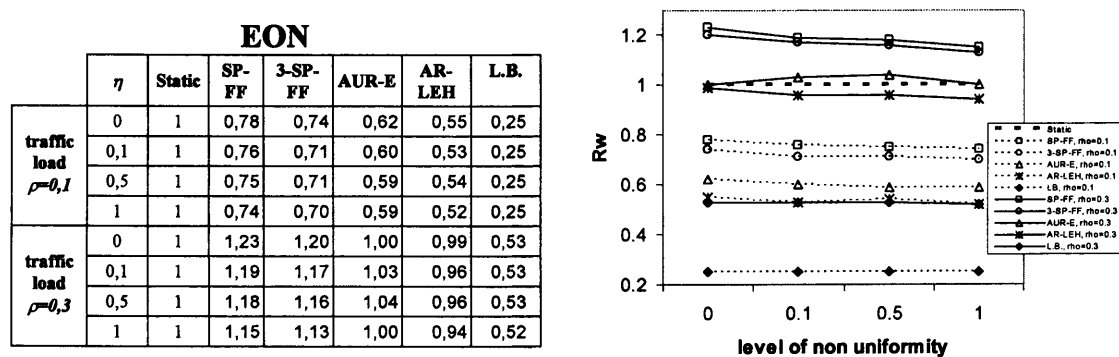


Figure 4.1.c. Ratio R_w for the EON topology as a function of the degree of non-uniformity η

UKNet							
	η	Static	SP-FF	3-SP-FF	AUR-E	AR-LEH	L.B.
traffic load $\rho=0,1$	0	1	0,73	0,66	0,49	0,46	0,25
	0,1	1	0,72	0,64	0,49	0,45	0,25
	0,5	1	0,71	0,64	0,49	0,45	0,25
	1	1	0,70	0,63	0,48	0,45	0,25
traffic load $\rho=0,3$	0	1	1,19	1,12	0,81	0,88	0,53
	0,1	1	1,16	1,09	0,88	0,86	0,53
	0,5	1	1,14	1,08	0,87	0,86	0,53
	1	1	1,11	1,06	0,86	0,84	0,52

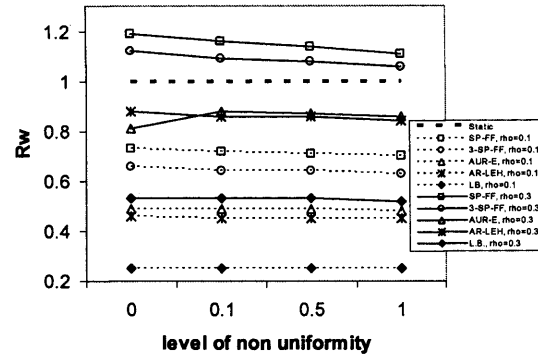


Figure 4.1.d. Ratio R_w for the UKNet topology as a function of the degree of non-uniformity η

ARPANet							
	η	Static	SP-FF	3-SP-FF	AUR-E	AR-LEH	L.B.
traffic load $\rho=0,1$	0	1	0,74	0,62	0,52	0,52	0,25
	0,1	1	0,71	0,60	0,52	0,50	0,23
	0,5	1	0,71	0,59	0,52	0,50	0,23
	1	1	0,69	0,58	0,51	0,49	0,23
traffic load $\rho=0,3$	0	1	1,29	1,16	1,01	1,03	0,53
	0,1	1	1,22	1,10	1,01	0,99	0,52
	0,5	1	1,21	1,09	1,01	0,98	0,52
	1	1	1,18	1,07	0,97	0,96	0,52

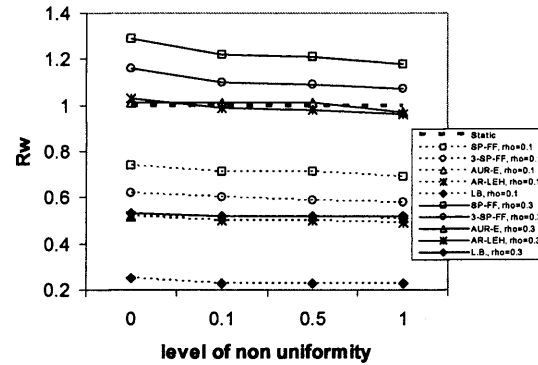


Figure 4.1.e. Ratio R_w for the ARPANet topology as a function of the degree of non-uniformity η

It can be seen that, as in the uniform traffic case, the traffic load is the most significant factor in the achievable wavelength savings. In the studied cases, the maximum traffic load for which savings are obtained is approximately 0.3-0.4. The relative performance of the algorithms remains the same as in the uniform case: SP-FF is the algorithm requiring the highest wavelength savings and AUR-E and AR-LEH the algorithms requiring the lowest number of wavelengths, with AR-LEH performing slightly better than AUR-E.

The effect of the physical connectivity also remains the same as in the uniform case: more connected networks (as Eurocore) achieve lower wavelength savings than sparsely connected networks.

In terms of the impact of the level of non-uniformity, η , it can be seen that as the value of η increases, the wavelength requirements are reduced for all the algorithms. For example, in average, the wavelength requirements of AR-LEH for the studied networks under non uniform traffic with $\eta=1$ experience a decrease of 3,6% with respect to the uniform case for $\rho=0.1$; for traffic loads of 0.3 and 0.5 this percentage increases to 6,7% and 8,7%, respectively. The decrease in the wavelength requirements with η results from the concentration of the traffic load in some sectors of the network leading to a higher statistical multiplexing gain due to the higher number of connections sharing the same resources. These results allow for the assumption that the uniform-traffic case –which is much simpler to analyse, can be used as a measure of worst-case performance in terms of wavelength requirements.

4.4 Summary

In this chapter wavelength requirements of dynamic wavelength-routed networks were quantified under the non-uniform traffic conditions. To do so, a transfer load method for non-uniform traffic matrix generation was used. The method allowed the use of a single parameter to characterise the degree of non-uniformity, η . Simulations results in 5 different mesh topologies showed that, as in the case of uniform traffic, the traffic load is the most determining factor in the wavelength savings achieved and that these savings are observed only at low loads (<0.3) and mostly in sparsely connected networks. The degree of non-uniformity, η , decreased the wavelength requirements due to the higher statistical gain of connections using

the same network resources but the decrease in wavelength requirements was not enough as to modify significantly the maximum traffic load at which wavelength savings are observed. Given that the analysis of networks under uniform traffic conditions is much simpler and represents a worst case scenario for the wavelength requirements, it can be used as an upper bound on the wavelength requirements in dynamic wavelength-routed optical networks.

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Chapter 5

Delay in dynamic WDM networks

The studies described in chapters 3 and 4 showed that dynamic operation of wavelength-routed optical networks can bring benefits in terms of wavelength requirements in sparsely connected networks operating at low loads (<0.4). If the traffic load condition proves to be practical, dynamic operation of WDM networks would become attractive for networks operators.

However, dynamic operation necessarily introduces delay. Because the delay impacts the ability of the network to serve time-critical applications, its quantification is a key aspect of the understanding of the overall network performance. In the case of WR-OBS networks, the aggregation of large bursts may introduce significant additional delay which might lead to the violation of end-to-end delay limits.

The maximum delay introduced by different aggregation mechanisms has been already studied in [Wan03, Mig01]. This has allowed to establish the limiting conditions under which a WR-OBS network can guarantee a given maximum delay. However, different aggregation mechanisms might experience similar levels of maximum delay. This situation hampers the differentiation of aggregation

mechanisms which –whilst having similar maximum delay, can lead to significantly different delay performance in terms of mean values or distribution probability.

In this chapter the mean delay introduced by a centralised wavelength-routed optical burst switched (WR-OBS) network is quantified. To do so, new analytical expressions are derived for different input packet traffic models and validated by means of simulation.

5.1. Mean delay in dynamic WDM networks

The end-to-end delay experienced by a packet in a network is the time elapsed since the packet arrives at the source transmission buffer until it is successfully delivered to the destination node. In any optical network where optical information does not undergo any further processing in the optical core, the end-to-end delay, T_{ee} , is given by:

$$T_{ee} = T_{buffer} + T_{tx} + T_{prop} \quad (5.1)$$

where T_{buffer} is the time a packet spends in the source transmission buffer before being transmitted, T_{tx} is the packet transmission time and T_{prop} is the propagation time from the source to the destination node. T_{tx} and T_{prop} are inherent to any network whilst T_{buffer} depends on the network architecture.

By linearity of the expectation operator [Ros97], the mean value of T_{ee} is given by:

$$E[T_{ee}] = E[T_{buffer}] + E[T_{tx}] + E[T_{prop}] \quad (5.2)$$

where $E[T_{tx}]$ is given by the mean packet length in bits divided by the lightpath bit rate and $E[T_{prop}]$ corresponds to the mean physical length of the path a packet must travel to arrive to destination divided by the speed of light in fibre. Typically, $E[T_{tx}] \ll E[T_{prop}]$. Thus, $E[T_{tx}]$ can be neglected in Eq. (5.2) leading to:

$$E[T_{ee}] = E[T_{buffer}] + E[T_{prop}] \quad (5.3)$$

The term $E[T_{buffer}]$, however, depends on the burst aggregation scheme used. In a centralised WR-OBS network, $E[T_{buffer}]$ is given by:

$$E[T_{buffer}] = \max(E[T_{aggr}], E[T_{rqst_prop}] + E[T_{CN}]) \quad (5.4)$$

where $E[T_{aggr}]$ is the mean time the packet must wait in the buffer due to the aggregation process, $E[T_{rqst_prop}]$ the mean time for the lightpath request to be propagated to the control node and back to the edge node and $E[T_{CN}]$ the mean time the request remains in the control node to be allocated a lightpath. As shown in Chapter 6, the maximum value for T_{CN} is in the timescales of μs . Since $E[T_{rqst_prop}]$ is in the order of ms for any network with a diameter longer than 200km, $E[T_{CN}]$ can be neglected in the expression for $E[T_{buffer}]$. A well-dimensioned aggregation mechanism must comply with the condition that $E[T_{aggr}] \geq E[T_{rqst_prop}] + E[T_{CN}]$.

Thus, typically $E[T_{buffer}] = E[T_{aggr}]$ and, for WR-OBS networks, Eq. (5.3) can be reduced to:

$$E[T_{ee}] = E[T_{aggr}] + E[T_{prop}] \quad (5.5)$$

It should be noticed that Eq. (5.5) gives an expression for the mean end-to-end delay for a dynamic WR-OBS network whilst Eq. (5.3) corresponds to the mean end-to-end delay of any optical network which does not perform processing in the optical core (in particular, it can be applied to the static network case). Thus, both networks (dynamic WR-OBS and static) have the inherent delay associated with the propagation of the information (typically, in the order of ms). The difference in terms of delay between dynamic and static operation lies in the mean time the packets must spend in the buffer before transmission. In the case of a static optical network, this time is usually very short as the packet is immediately transmitted if there are no more packets in the buffer when it arrives to the transmission buffer. Otherwise, it must wait for the transmission of the packets already in the buffer. But, as usually transmission time is in the order of μs , $E[T_{buffer}]$ corresponds to a value which can be neglected in the Eq. (5.3).

In the case of dynamic WR-OBS instead, the time in the buffer is expected to be much higher due to the aggregation process. In the following section, analytical expressions for $E[T_{agg}]$ are obtained for different aggregation mechanisms.

5.2. Mean aggregation delay

In this chapter, the mean packet delay introduced by the most common aggregation schemes is studied. They can be listed, as follows:

- **Fixed Aggregation Time (FAT)** [Ge00] builds a burst with the packets arriving during T units of time after the arrival of the first packet.
- **Fixed Burst Size (FBS)** [Hu03] collects a fixed number of packets, $P-1$, following the arrival of the first packet.
- **FAT/FBS** [Yu02], after the arrival of the first packet, the burst is aggregated until T units of time have elapsed or until $P-1$ packets have been collected, whichever occurs first.
- **Limited Burst Size (LBS)** [Mig01] sends a lightpath request to a control node X units of time after the first packet arrival. After the receipt of the lightpath acknowledgement, the burst aggregation is completed and burst transmission starts (packets arriving during burst transmission are allocated to the next burst).
- **Unlimited Burst Size (UBS)** [Mig01] operates similarly to LBS, but packets arriving during burst transmission are treated as part of the current burst, and are transmitted immediately.

FAT, FBS and FAT/FBS were originally proposed for conventional (one-way reservation) OBS networks (although they can be easily adapted for WR-OBS networks) whilst LBS and UBS were designed specifically for WR-OBS networks.

Two classical traffic models for the arriving packets at the buffer are considered:

- packets arrive as a Poisson process to the buffer at mean rate γ
- packets arrive as a ON-OFF process to the buffer, with p the probability of being in state ON (it should be noticed that, as this is a mean value analysis, the distribution of the duration of ON and OFF periods is not required)

For simplicity, in both cases packets of fixed size are assumed. However, as shown by simulation results at the end of this section, this assumption does not affect the results for the mean delay introduced by the aggregation process, $E[T_{agg}]$.

An analytical expression for $E[T_{agg}]$ is derived in the following, for the different burst aggregation schemes and the two considered traffic models.

5.2.1. FAT aggregation scheme

Poisson packet arrival model

By conditioning in n (as defined in [Ros97]), the number of packets arrived at the buffer during T units of time (after the arrival of the first packet of the burst), the value for $E[T_{agg}]$ when applying the FAT aggregation scheme under Poisson packet arrivals, $E[T_{agg}]_{FAT}^{Poisson}$, is obtained:

$$E[T_{agg}]_{FAT}^{Poisson} = \sum_{n=0}^{\infty} (E[T_{b_tx} / n] + E[T_{a_tx} / n]) \cdot P(n) \quad (5.6)$$

Where T_{b_tx} corresponds to the time a packet must wait in the buffer prior to the burst transmission, T_{a_tx} the time a packet must wait in the buffer after the transmission of the burst has begun and $P(n)$ the probability of receiving n packets during the aggregation time T .

It is well known that if an interval of length T contains exactly n arrivals from a Poisson process, then the instants when these arrivals occurred are uniformly distributed over the same interval [Kle75]. Although this is not exactly the case here because the first arrival determines the start of the interval T , it will be used as an approximation. Thus, $E[T_{b_tx}/n]$ and $E[T_{a_tx}/n]$ are given by:

$$E[T_{b_tx}/n] = \frac{\sum_{i=1}^{n+1} \left(T - \frac{T}{n}(i-1) \right)}{n+1} = \frac{T}{2} \quad (5.7)$$

$$E[T_{a_tx}/n] = \frac{1}{n+1} \sum_{i=1}^{n+1} (i-1)t_{tx} = \frac{nt_{tx}}{2} \quad (5.8)$$

Where t_{tx} is the transmission time of a packet (its length in bits divided by the wavelength bit rate).

Finally, $P(n)$ is given by the Poisson distribution:

$$P(n) = e^{-\gamma T} \frac{(\gamma T)^n}{n!} \quad (5.9)$$

Substituting the equations (5.7-5.9) in (5.6), the following equation is obtained for the mean delay experienced by packets (arriving as a Poisson process) assembled using the FAT mechanism:

$$E[T_{agg}]_{FAT}^{Poisson} = \frac{T}{2}(1 + \gamma_{tx}) \quad (5.10)$$

ON-OFF packet arrival model

To simplify the mathematical treatment without affecting significantly the numerical results, the following approximation is used.

The aggregation interval, T , is divided into as many slots as packets could fit in. Thus, there are $S = T/T_{pkt}$ slots, where T_{pkt} is the time required to fully receive a packet in the aggregation buffer (the packet length divided by the input bit rate). It is assumed that at the beginning of every slot, a packet arrives with probability p (that is, an ON period of fixed duration T_{pkt} is started with probability p).

This approximation allows to model the arrival of a packet in any slot as a Bernoulli random variable of parameter p . Thus, the evaluation of the mean number of arrivals and the mean number of slots between consecutive arrivals is then straightforward:

- the mean number of arrivals during the interval T is equal to $1 + (S - 1) \cdot p$: the first packet which starts the aggregation process plus the mean number of packets received during the remaining $(S-1)$ slots (corresponding to the expectation of a Binomial distribution with parameters $(S-1)$ and p).

- the number of slots between consecutive packet arrivals corresponds to a Geometric random variable with parameter p . Thus, the mean number of slots between consecutive packet arrivals is equal to $1/p$.
- the average number of slots between the last packet arrival and the end of the aggregation period, Δ , is equal to 1. This is obtained as follows:

$$S = \sum_{i=1}^{n-1} s_{i-1,i} + \Delta \quad (5.11)$$

where n is the random variable corresponding to the number of arrivals during the aggregation interval and $s_{i-1,i}$ corresponds to the number of slots between the $(i-1)$ -th and the i -th packet arrivals. The random variables n and $s_{i-1,i}$ follow a binomial distribution with parameters S and p and a geometric distribution with parameter p , respectively.

Applying the expectation operator to Eq. (5.11):

$$E[S] = E\left[\sum_{i=1}^{n-1} s_{i-1,i}\right] + E[\Delta] \quad (5.12)$$

Applying the theorem of the expectation of random sums of independent and identically distributed random variables [Yat99] to the first term in the right-hand sum of Eq. (5.12) the following expression is obtained:

$$E[S] = E[n-1]E[s] + E[\Delta] \quad (5.13)$$

Thus,

$$E[\Delta] = S - (E[n] - E[1])E[s] = S - ((S-1)p)\frac{1}{p} = 1 \quad (5.14)$$

The schematic of Figure 5.1, where slots are numbered from 1 to S , illustrates an average situation which summarises the above points.

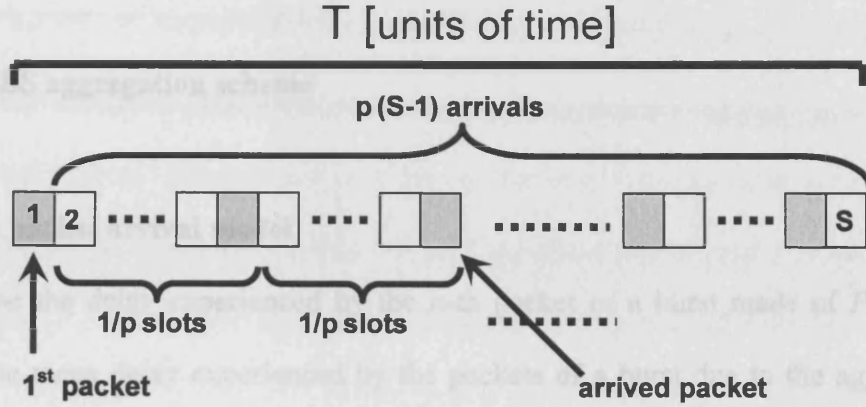


Figure 5.1. Schematic of an average situation for the FAT aggregation scheme under ON-OFF input packet arrivals

The i -th arrived packet must wait in the buffer for the remaining aggregation time (equal to $[S - (i - 1) / p] \cdot T_{pkt}$ plus the transmission time of the $(i - 1)$ previously arrived packets. Thus, the mean packet waiting time in the buffer due to the aggregation process is given by:

$$\begin{aligned}
 E[T_{agg}]_{FAT}^{ON-OFF} &= \frac{\sum_{i=1}^{1+(S-1)p} [S - (i - 1) / p] \cdot T_{pkt} + \sum_{i=1}^{1+(S-1)p} [(i - 1) \cdot t_{tx}]}{1 + (S - 1)p} \\
 &= \frac{(S + 1)}{2} T_{pkt} + \frac{t_{tx}}{2} (S - 1)p
 \end{aligned} \tag{5.15}$$

It should be noticed that for both traffic models, the analytical expressions obtained (Eqs. (5.10) and (5.15)) are very close: the mean aggregation time corresponds to about the half of the aggregation period plus the half of the packet transmission time multiplied by the number of expected arrived packets during the aggregation period.

The difference between both is down to the approximation made in the Poisson case. However, in numerical terms the difference is negligible - in the order of 10^{-4} , (because typically $S \gg 1$) as shown in the simulation results of section 5.3.

5.2.2. FBS aggregation scheme

Poisson packet arrival model

Let d_n be the delay experienced by the n -th packet of a burst made of P packets. Thus, the mean delay experienced by the packets of a burst due to the aggregation process is given by:

$$E[T_{agg}]_{FBS}^{Poisson} = \frac{1}{P} \sum_{n=1}^P d_n \quad (5.16)$$

where d_n corresponds to the remaining time to construct the burst when the packet n arrives plus the time to transmit the previous $(n-1)$ packets, that is:

$$d_n = \frac{P-n}{\gamma} + t_{tx}(n-1) \quad (5.17)$$

Replacing (5.17) in (5.16), the following expression for $E[T_{agg}]_{FBS}$ is found:

$$E[T_{agg}]_{FBS}^{Poisson} = \frac{(P-1)}{2} \left(\frac{1}{\gamma} + t_{tx} \right) \quad (5.18)$$

ON-OFF packet arrival model

As in the FAT case, the aggregation interval is divided in as many slots as packets could fit in and a packet arrives at the beginning of each slot with probability p (that is, an ON period of fixed duration T_{pkt} is started with probability p). Thus:

- the number of slots required to accumulate $(P-1)$ packets after the first packet has arrived corresponds to a Pascal random variable (also known as the Negative Binomial distribution) with parameters $(P-1)$ and p . This is to say that the mean number of slots required to build a burst of P packets (once the first packet has arrived) corresponds to the expectation of a Pascal random variable with parameters $(P-1)$ and p , equal to $(P-1)/p$ plus 1 (the slot used by the first arrived packet).
- the number of slots between consecutive packet arrivals corresponds to a Geometric random variable with parameter p . Thus, the mean number of slots between consecutive packet arrivals is equal to $1/p$.
- The number of slots between the last arrival and the end of the aggregation period is 0, as the burst aggregation finishes when the P -th packet has arrived.

The schematic of Figure 5.2 illustrates an average situation which summarises the above points.

The i -th arrived packet must wait in the buffer the remaining time until the aggregation process is finished (equal to $[(P-1)/p - (i-1)/p] \cdot T_{pkt}$) plus the transmission time of the $(i-1)$ previously arrived packets. Thus, the mean packet waiting time in the buffer due to the aggregation process is given by:

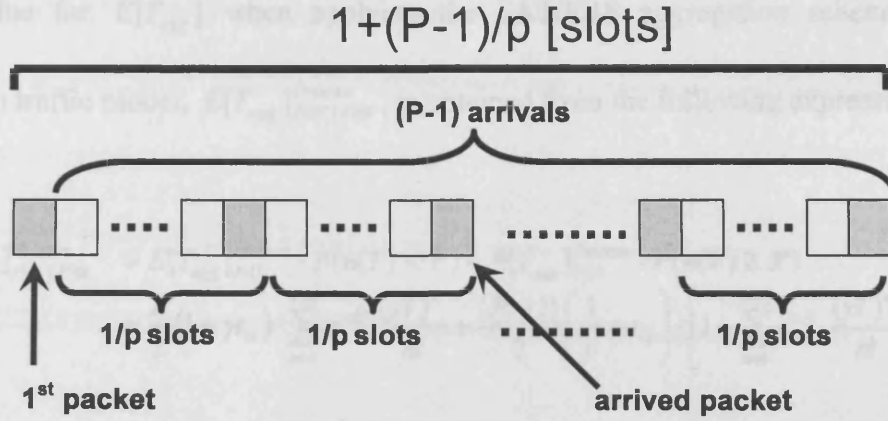


Figure 5.2. Schematic of an average situation for the FBS aggregation scheme under ON-OFF input packet arrivals

$$\begin{aligned}
 E[T_{agg}]_{FBS}^{ON-OFF} &= \frac{\sum_{i=1}^P \left[\frac{P-1}{p} - \frac{i-1}{p} \right] \cdot T_{pkt} + \sum_{i=1}^P (i-1) \cdot t_{tx}}{P} \\
 &= \frac{P-1}{2} \left(\frac{T_{pkt}}{p} + t_{tx} \right)
 \end{aligned} \tag{5.19}$$

The analytical expressions obtained for the mean delay introduced by the FBS aggregation mechanism (Eqs. (5.18) and (5.19)) are equivalent for both traffic models: the mean aggregation time corresponds to the half of the aggregation period plus the time it takes to transmit half of the arrived packets after the first arrival.

5.2.3. FAT/FBS aggregation scheme

Poisson packet arrival model

By conditioning on $n(T)$, the number of packets arrived at the buffer during the interval $[0, T]$ (the instant $t=0$ corresponds to the instant when the first packet arrives),

the value for $E[T_{agg}]$ when applying the FAT/FBS aggregation scheme under Poisson traffic model, $E[T_{agg}]_{FAT/FBS}^{Poisson}$, is obtained from the following expression:

$$\begin{aligned} E[T_{agg}]_{FAT/FBS}^{Poisson} &= E[T_{agg}]_{FAT}^{Poisson} \cdot P(n(T) < P) + E[T_{agg}]_{FBS}^{Poisson} \cdot P(n(T) \geq P) \\ &= \frac{T}{2}(1 + \gamma t_{tx}) \cdot \sum_{n=0}^{P-1} e^{-\gamma T} \frac{(\gamma T)^n}{n!} + \frac{(P-1)}{2} \left(\frac{1}{\gamma} + t_{tx} \right) \cdot \left[1 - \sum_{n=0}^{P-1} e^{-\gamma T} \frac{(\gamma T)^n}{n!} \right] \end{aligned} \quad (5.20)$$

ON-OFF packet arrival model

Analogously to the case of Poisson traffic, the value for $E[T_{agg}]$ when applying the FAT/FBS aggregation scheme under the ON-OFF traffic model is obtained by conditioning on $n(S)$, the number of packets arrived at the buffer during S slots (the first slot corresponds to the slot where the first packet arrives):

$$\begin{aligned} E[T_{agg}]_{FAT/FBS}^{ON-OFF} &= E[T_{agg}]_{FAT}^{ON-OFF} \cdot P(n(S) < P) + E[T_{agg}]_{FBS}^{ON-OFF} \cdot P(n(S) \geq P) \\ &= \left[\frac{(S+1)}{2} T_{pkt} + \frac{t_{tx}}{2} (S-1)p \right] \cdot \sum_{n=0}^{P-1} \binom{S}{n} p^n (1-p)^{S-n} \\ &\quad + \frac{(P-1)}{2} \left(\frac{T}{p} + t_{tx} \right) \cdot \left[1 - \sum_{n=0}^{P-1} \binom{S}{n} p^n (1-p)^{S-n} \right] \end{aligned} \quad (5.21)$$

Because the Poisson distribution can be used as an approximation of the binomial distribution [Ros97], both expressions (Eqs. (5.20) and (5.21)) can be thought as equivalent.

5.2.4. LBS aggregation scheme

This scheme is equivalent to the FAT mechanism making $T=RTT$, where RTT is the time for the lighpath request to be propagated from the source to the control node and back. Therefore,

$$E[T_{agg}]_{LBS}^{Poisson} = \frac{RTT}{2}(1 + \gamma_{tx}) \quad (5.22)$$

$$E[T_{agg}]_{LBS}^{ON-OFF} = \frac{(S+1)}{2}T_{pkt} + \frac{t_{tx}}{2}(S-1)p \quad (5.23)$$

with $S=RTT/T_{pkt}$.

5.2.5. UBS aggregation scheme

Poisson packet arrival model

Consider the Figure 5.3, where the burst aggregation process is divided into intervals. In each interval, arriving packets are accumulated.

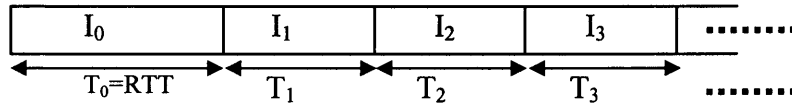


Figure 5.3. Burst assembly process using the UBS aggregation mechanism

The first interval (I_0 in the figure) starts with the arrival of the first packet of the burst and finishes when an ACK for the lighpath request is received (that is, the interval I_0 lasts for RTT units of time – where RTT is the time required for the lighpath request to propagate to the control node and back to the source node). When an ACK is received, the transmission of the packets accumulated during the interval I_0 starts.

The ACK arrival also triggers the start of the following interval, I_1 . Packets arriving during I_1 are accumulated until the interval I_1 finishes; which occurs when the last packet received during I_0 is transmitted. In that instant, the accumulation of packets during interval I_2 and the transmission of the packets accumulated during I_1 start. In general:

- the interval I_i starts simultaneously with the transmission of the packets accumulated during the interval I_{i-1}
- the interval I_i ends when the last packet received during the interval I_{i-1} is transmitted

Thus, the mean duration of the interval I_i ($i > 0$), denoted by T_i , corresponds to the mean time required to transmit the packets of the interval I_{i-1} . That is, T_i is equal to the number of packets received during the interval I_{i-1} multiplied by the transmission time of a packet and is given by the following recurrent expression:

$$T_i = (\gamma \cdot T_{i-1}) \cdot t_{tx} \quad (5.24)$$

With the initial condition:

$$T_0 = RTT \quad (5.25)$$

Eqs. (5.24) and (5.25) can be summarised in the following expression:

$$T_i = RTT(\gamma \cdot t_{tx})^i \quad (5.26)$$

If D_i is the mean delay experienced by the packets accumulated during the interval I_i and N_i the mean number of packets received during the duration of such interval I_i , then:

$$E[T_{agg}]_{UBS}^{Poisson} = \frac{\sum_{i=0}^{\infty} D_i N_i}{\sum_{i=0}^{\infty} N_i} \quad (5.27)$$

where D_i is obtained using equation (5.10) for the FAT aggregation scheme with $T=T_i$:

$$D_i = \frac{T_i}{2}(1 + \gamma_{tx}) = \frac{RTT \cdot (\gamma_{tx})^i}{2}(1 + \gamma_{tx}) \quad (5.28)$$

and N_i is given by

$$N_i = \gamma T_i = \gamma RTT (\gamma_{tx})^i \quad (5.29)$$

Thus,

$$D_i = \frac{T_i}{2} + \frac{N_i}{2} t_{tx} \quad (5.30)$$

Substituting Eqs. (5.28-5.29) in (5.27), the following expression for the mean packet delay for the UBS aggregation mechanism is obtained:

$$E[T_{agg}]_{UBS}^{Poisson} = \frac{RTT}{2} \quad (5.31)$$

ON-OFF packet arrival model

In the case of ON-OFF traffic model the expressions for T_i , N_i and D_i are as follows:

$$T_i = RTT \left(\frac{p \cdot t_{tx}}{T_{pkt}} \right)^i \quad (5.32)$$

$$N_i = \frac{T_i}{T_{pkt}} p = \frac{RTT \cdot p}{T_{pkt}} \left(\frac{p \cdot t_{tx}}{T_{pkt}} \right)^i \quad (5.33)$$

$$\begin{aligned} D_i &= \frac{(S_i + 1)}{2} T_{pkt} + \frac{t_{tx}}{2} (S_i - 1) = \frac{\frac{T_i}{T_{pkt}} + 1}{2} \cdot T_{pkt} + \frac{t_{tx}}{2} \left(\frac{T_i}{T_{pkt}} - 1 \right) p \\ &= \frac{T_{pkt}}{2} \left(\frac{RTT}{T_{pkt}} \left(\frac{p \cdot t_{tx}}{T_{pkt}} \right)^i + 1 \right) + \frac{t_{tx}}{2} \left(\frac{RTT}{T_{pkt}} \left(\frac{p \cdot t_{tx}}{T_{pkt}} \right)^i - 1 \right) p \end{aligned} \quad (5.34)$$

Replacing equations (5.32)-(5.34) in (5.27) the following expression for $E[T_{agg}]$ is

obtained:

$$E[T_{agg}]_{UBS}^{ON-OFF} = \frac{RTT}{2} + \frac{T_{pkt} - p \cdot t_{tx}}{2} \quad (5.35)$$

Given that RTT is in the order of magnitude of a few milliseconds whilst T_{pkt} and t_{tx} are in the order of microseconds (with $T_{pkt} \geq t_{tx}$), the second term of the right side of Eq. (5.28) can be neglected. Thus,

$$E[T_{agg}]_{UBS}^{ON-OFF} \approx \frac{RTT}{2} \quad (5.36)$$

Table 5.1 summarises the main results obtained for the mean delay of the different studied burst aggregation mechanisms:

Aggregation mechanism	Input traffic model	
	Poisson	ON-OFF
FAT	$\frac{T}{2}(1 + \gamma_{tx})$	$\frac{(S+1)}{2}T_{pkt} + \frac{t_{tx}}{2}(S-1)p_{ON}$
FBS	$\frac{(P-1)}{2}\left(\frac{1}{\gamma} + t_{tx}\right)$	$\frac{P-1}{2}\left(\frac{T_{pkt}}{p_{ON}} + t_{tx}\right)$
FAT/FBS	$\frac{T}{2}(1 + \gamma_{tx}) \cdot \xi + \frac{(P-1)}{2}\left(\frac{1}{\gamma} + t_{tx}\right)(1 - \xi)$ with $\xi = \sum_{n=0}^{B-1} e^{-\gamma T} \frac{(\gamma T)^n}{n!}$	$\left[\frac{(S+1)}{2}T_{pkt} + \frac{t_{tx}}{2}(S-1)p_{ON}\right] \cdot \zeta + \frac{(P-1)}{2}\left(\frac{T}{p} + t_{tx}\right)(1 - \zeta)$ with $\zeta = \sum_{n=0}^{B-1} \binom{S}{n} p_{ON}^n (1 - p_{ON})^{S-n}$
LBS	$\frac{RTT}{2}(1 + \gamma_{tx})$	$\frac{(S+1)}{2}T_{pkt} + \frac{t_{tx}}{2}(S-1)p_{ON}$
UBS	$\frac{RTT}{2}$	$\frac{RTT}{2}$

Table 5.1. Analytical expressions for the mean aggregation delay of FAT, FBS, FAT/FBS, LBS and UBS aggregations schemes for Poisson and ON-OFF input traffic models

5.3. Simulation results for the mean aggregation delay

To validate the equations derived in sections 5.2.1-5.2.5 for the mean delay experienced by packets due to the aggregation process, simulation experiments were conducted for the Poisson and the ON-OFF input packet traffic. By way of an example, Figure 5.4 shows the simulation results (95% confidence interval) for the five studied aggregation mechanisms for (a) Poisson arrivals of fixed-size packets (400 bytes, typical average size of Internet packets [Xio00]), (b) ON-OFF input packet arrival, ON period of fixed size (0.32 μ s, the time required to transmit a 400-byte packet at 10 Gb/s) and OFF period distributed according to a Pareto distribution with parameter $\alpha=1.5$ and (c) ON-OFF input packet arrival, ON and OFF periods

Pareto distributed with parameter $\alpha=1.5$, mean ON period equal to $0.32 \mu s$. Analytical results of table 5.1 are also included for comparison.

In all the cases a bit rate of $10 Gb/s$ and a network with a diameter of $1000 km$ (typical of a European country) were considered. As a result, RTT - the mean round-trip time required for a lightpath request to be propagated to the control node and back to the source node, equals $5ms$ (the time required for the light to be propagated $1000 km$ in the fibre). Hence, the maximum aggregation time for FAT and FAT/FBS aggregation mechanisms, T , is set to be equal to RTT (a lower value for T makes no sense as the source node has no information about the allocated lightpath yet). For FBS, the burst size in number of packets, P , is set to 15625 which corresponds to the number of packets accumulated during $5 ms$ if the input packet traffic was of the CBR (Constant Bit Rate) type. This choice guarantees that the *efficiency criterion* - discussed in Chapter 2, is met. For the FAT/FBS method the limit for the aggregation time and the maximum burst size were set to $10 ms$ and 15625 , respectively. Finally, the LBS and the UBS aggregation mechanisms do not require a parameter, as they synchronise their operation to the ACK reception instant. Table 5.2 summarises the parameters used for the different aggregation mechanisms.

	Aggregation mechanism				
	FAT	FBS	FAT/FBS	LBS	UBS
<i>T (ms)</i>	5	---	10	---	---
<i>P (packets)</i>	---	15625	15625	---	---
<i>RTT (ms)</i>	5	5	5	5	5

Table 5.2. Parameters T, P and RTT for the burst aggregation mechanisms FAT, FBS, FAT/FBS, LBS and UBS.

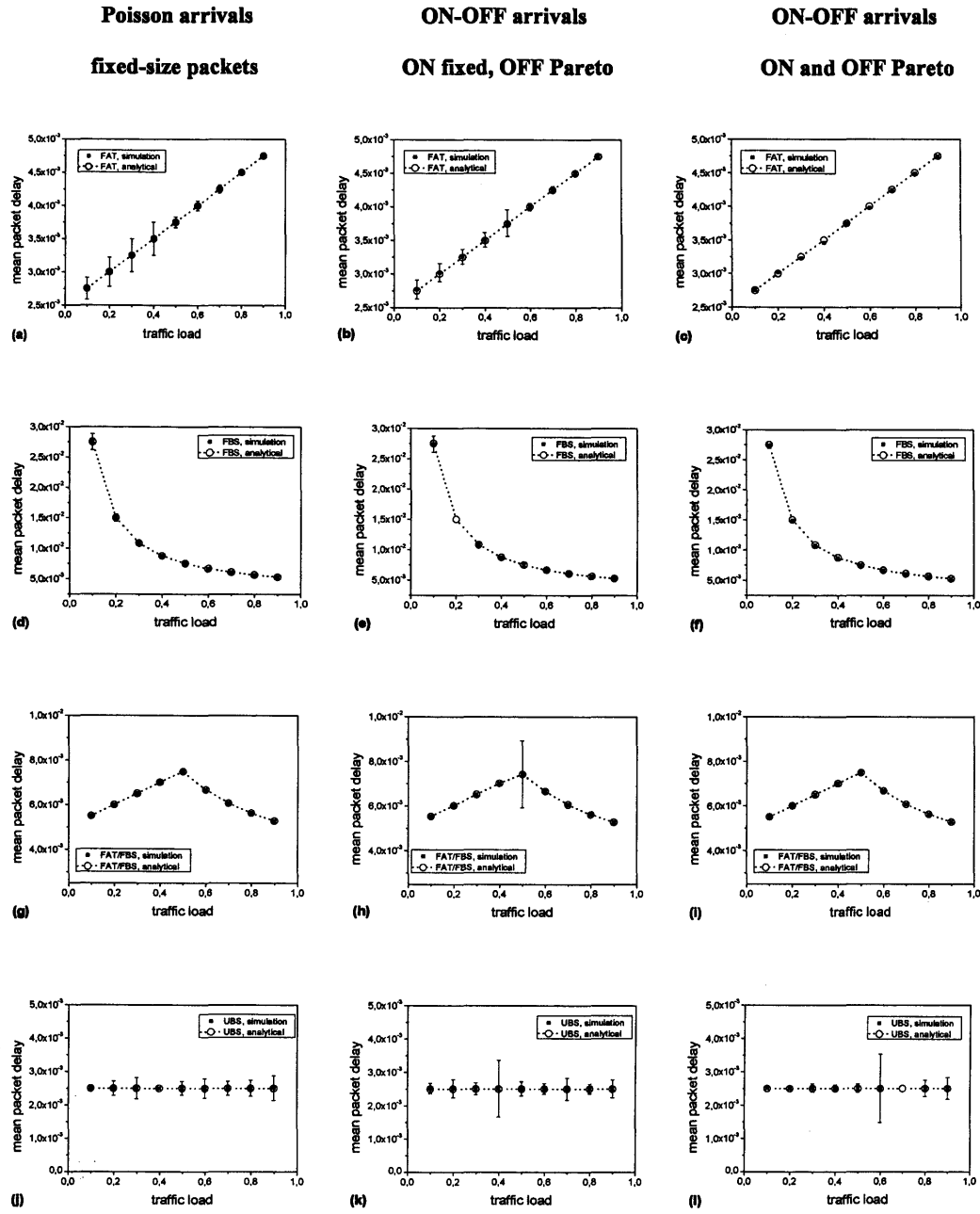


Figure 5.4. Analytical vs. simulation results for the mean packet delay due to the aggregation process for Poisson arrivals of fixed-size packets (left), ON-OFF input packet arrival, fixed size for ON periods, OFF period Pareto distributed (middle) and ON-OFF input packet arrival, ON and OFF periods Pareto distributed (right)

It can be seen that the agreement between the curves obtained by means of simulation and the curves obtained using the analytical expressions is very close.

Thus, in the remainder of this chapter only the analytical expressions have been used in the evaluation of the end-to-end delay. Figure 5.4 also shows that UBS is the aggregation mechanism which results in the lowest mean aggregation delay because the lightpath remains active as long as there are packets to transmit. Thus, packets arriving during the burst transmission do not experience aggregation delay. Conversely, FBS presents the worse performance in terms of delay as at low loads there is no limit to the aggregation time. Thus, FBS is not recommended for use. The mean aggregation delay results also allow the differentiation between UBS and LBS, FAT (configured as LBS) and FAT/FBS as all of them have the same maximum delay (equal to RTT), as shown in [Wan03, Mig01] and easily derived by evaluating the mean delay for the worst scenario (that is, $\gamma_{tx} \rightarrow 1$). Thus, whilst in terms of delay guarantees all of them can meet a maximum delay equal to RTT , only UBS can decrease the mean aggregation delay for all the possible values of the traffic load because packets arriving during burst transmission are immediately transmitted and do not need to wait for a new burst to be built.

Thus, considering that the time spent in the buffer in the case of static operation is negligible compared to the propagation time, if the UBS aggregation mechanism is used, the extra delay introduced due to the aggregation process of dynamic WR-OBS is $RTT/2$. That is, dynamic operation introduces $RTT/2$ extra time in the mean end-to-end delay in the best case and RTT extra time in the worst case. Whether this is acceptable or not, depends on the real time deadlines imposed by the different applications and the size of the network (which determines the value of RTT). However, for typical real-time applications (deadline of 100 ms, [Sei03]) and networks as large as US continental network (5000 km diameter, thus $RTT \approx 25$ ms)

the introduction of extra 12,5 *ms* or even 25 *ms* does not reach the maximum allowed delay. Therefore, in terms of delay, dynamic WR-OBS are feasible for current real-time applications as the extra delay incurred by the aggregation process is not significant as to violate current end-to-end delay constraints.

5.4. Summary

In this chapter dynamic centralised WR-OBS and static optical networks were compared in terms of delay. To do so, new analytical expressions for the mean delay introduced by the aggregation process of the WR-OBS architecture were derived for 5 different aggregation mechanisms and for two different input packet traffic models. The analytical expressions were validated by means of simulation and the match between both set of results was excellent. The analytical expressions showed that the maximum extra delay introduced by the aggregation process was equal to RTT (the round-trip time required to propagate the lightpath request from the source node to the control node and back) and that the aggregation mechanism which introduced the lowest delay was UBS, with a mean delay due to the aggregation process equal to $RTT/2$. Given that end-to-end delay limitations have been recently set to 100 *ms* by the ITU-T [Sei03] and that even in the largest networks RTT does not exceed the 25 *ms*, the utilization of dynamic centralised WR-OBS does not impact delay guarantees.

5.5. References

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Chapter 6

Scalability of centralised dynamic wavelength-routed optical networks

In earlier chapters it was assumed that the dynamic network architecture was centralised because it has been shown that by maintaining global information on the network state (topology and wavelengths utilization) in a central control node [Cas94] a more efficient allocation of resources and, therefore, a lower blocking probability than distributed lightpath allocation algorithms is achieved (see, for example, [Ram01]). However, centralised systems have the potential risk of poor survivability and scalability, which might render them impractical. Survivability (i.e. the ability of the network to survive failures) can be improved by redundancy of the control information in one (or more) back-up control nodes. For an example of a real long-haul centralized optical network utilizing control node redundancy, see [Tri97]. Scalability (i.e. the maximum number of nodes that can be supported by such dynamic optical network architectures), however, remains a fundamental drawback of centralised networks as a single node must maintain all the information on the network state and perform the processing of all the lightpath requests generated by the network nodes. With the number of increasing network nodes (or edge routers)

all generating requests, the key question is – ‘how scalable is a centralised implementation?’.

Earlier analysis of lightpath allocation algorithms in the context of optical burst switched (OBS) networks has provided only partial understanding of the scalability problem in dynamic wavelength-routed optical networks. In [Zap03] the author of this thesis quantified the maximum number of nodes supported by a centralized network for different lightpath allocation algorithms for generic topologies, but *QoS* requirements were not taken into account. In [Düs02] the impact of *QoS* requirements on scalability was analyzed, but the processing times of specific lightpath allocation algorithms were not considered, nor were the results applied to practical topologies which introduce differential delays, potentially impacting the fairness of the lightpath processing. Although in [Düs03] *QoS* requirements and practical topologies were taken into account only asymptotic complexity analysis was carried out to estimate the processing time of a single class of lightpath allocation algorithms, which did not include the investigation of the best- and worst-case scenarios.

In this chapter the scalability of dynamic wavelength-routed optical networks considering different types of lightpath allocation algorithms applied to practical physical network topologies is investigated. A key parameter included in the calculations is the propagation (round-trip) time between the edge and control node which, along with *QoS* constraints such as latency and blocking probability, limits the network scalability.

6.1. Control node architecture and lightpath request scheduling

Figure 6.1 shows the schematic for the control node of a centralised dynamic wavelength-routed optical network architecture. It consists of an optical core of switches, each connected locally to an edge router where, as before, incoming packets are classified according to destination and *QoS* requirements. Every edge router is equipped with a buffer for burst aggregation per destination/*QoS* pair.

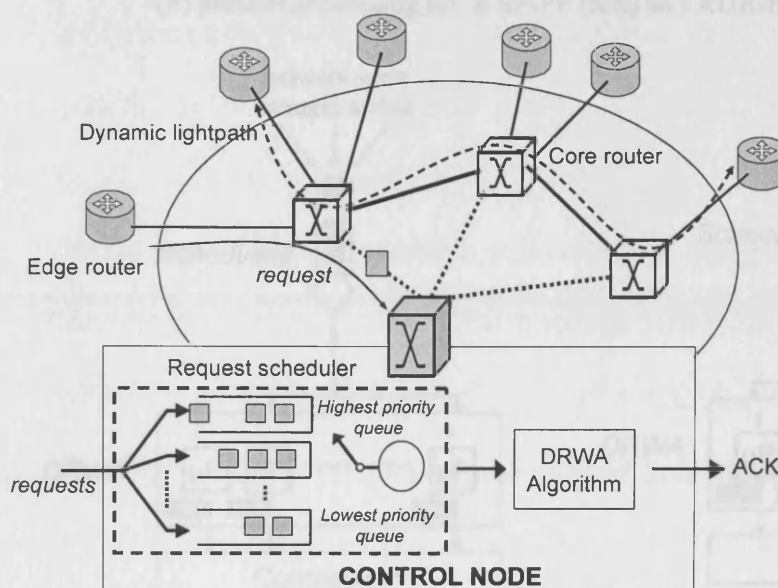


Figure 6.1. Dynamic optical network with centralised lightpath allocation
(ACK, acknowledgement of lightpath request)

The processing of lightpath requests in the control node is divided into two tasks (see Figure 6.2a):

- 1) *Scheduling* of requests according to their assigned class of service (CoS), and the propagation delay between edge routers and control node. The algorithms used and their applicability to calculate the network scalability are discussed in the next section.

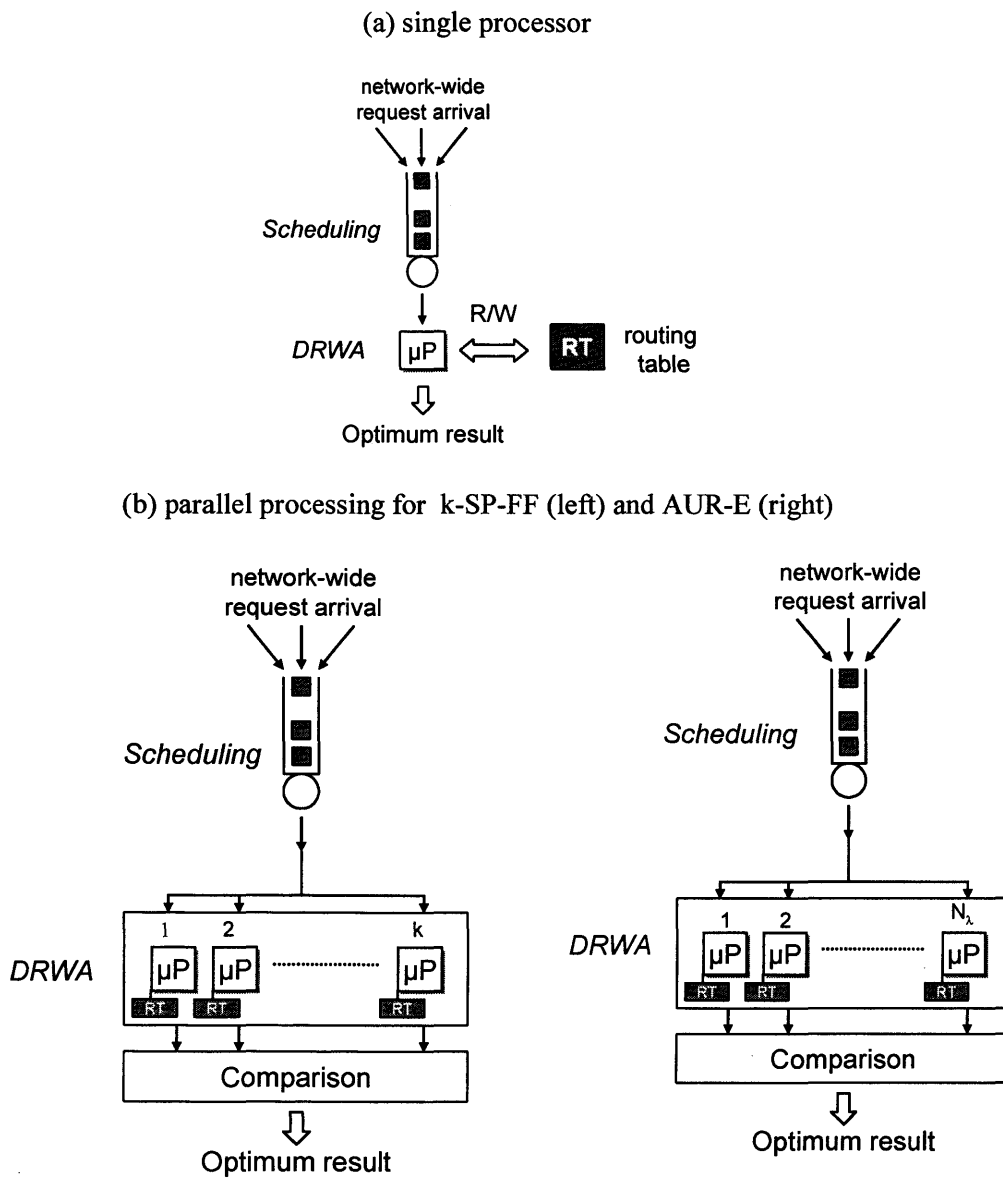


Figure 6.2. Scheduling and request processing (a) for single processor architecture (b) for multi-processor architecture with (left) parallel processing of k pre-computed shortest paths for the k -SP-FF algorithm and (right) parallel processing for all wavelengths for the AUR-E algorithm

- 2) *Processing of lightpath requests using one of a variety of lightpath allocation algorithms. To speed up the serial processing of lightpath requests, parallel electronic processing can be used to carry out some parts of the lightpath*

assignment process (Figures 6.2b). The achievable speed-up is investigated in section 6.2.4. In this chapter, the Shortest-Path First-Fit (SP-FF) and the Adaptive Unconstrained Routing – Exhaustive (AUR-E) algorithms were used, since the first represents the case of fast processing with high blocking, whilst the latter achieves low blocking but suffers from long processing times. In addition, an intermediate solution (namely, k -SP-FF which explores the first k disjoint shortest paths) was considered to verify if similar performance to the AUR-E algorithm can be achieved at lower computational complexity.

At the control node, requests are assigned priorities according to criteria such as QoS and distance from the control node. Then, a request *scheduling* algorithm selects the next request to be processed by the lightpath allocation algorithm applying fairness rules by taking into account the non-negligible propagation delay of requests between the edge and the control node. These propagation delays can reach significant values of several milliseconds for wide-area networks (WANs), resulting in the unfair treatment of nodes furthest away from the central node. If the lightpath allocation algorithm is successful in finding a lightpath, an acknowledgement is sent to the corresponding source node and the network is configured to establish the lightpath. Otherwise, the request is dropped with a no-ACK message sent to the source node. The following scheduling algorithms were investigated:

- **First-In/First-Out (FIFO).** In the simplest case there is no scheduling, with requests processed in the same order as they arrive at the control node.

- **Rate Monotonic (RM).** The RM algorithm was originally designed for the scheduling of several, periodic and time-critical events by a single microprocessor, e.g. in control engineering [Leh89]. Priority for a request r_i is assigned according to the period t_i (the time between successive arrivals of request r_i). Requests with shortest t_i have the highest priority. As shown below, the RM algorithm is less efficient than the Earliest Deadline First (EDF) algorithm described next, but unlike the EDF, the RM algorithm can provide service guarantees even in transient overload situations [Leh89].
- **Earliest Deadline First (EDF).** Every request has a field specifying a deadline by when it must be processed [Fer90]. The request with the earliest deadline is assigned the highest priority; hence it also works for non-periodic request arrivals, i.e. provides the highest flexibility, and also has the highest scheduling efficiency.

FIFO scheduling is suitable for best-effort networks (without *QoS* constraints). RM and EDF are best suited for networks with strict delay requirements, since they guarantee an incoming lightpath request $r_{i,k}$ (i : CoS, k : source node) to be processed within a given deadline, providing that the processor utilization is below a bound U [Bin03], where U ($0 \leq U \leq 1$) is the (dimensionless) processor utilization per request $\rho_{i,k}$, and depends only on:

- The processing time per request, C . A detailed description of how to calculate C for different lightpath allocation algorithms is given in Appendix A.
- The periodicity of request arrivals at the processor in the central control node, $t_{i,k}$. For FIFO scheduling $t_{i,k} \equiv T_{buffer\ i,k}$, where $T_{buffer\ i,k}$ is the maximum time that data with CoS i at the source edge node k is held before transmission

through the optical core. For EDF and RM scheduling, t_{ik} should be set to $T_{buffer\ i,k}$ only for short distances between the edge and control nodes, e.g. in a local area network (LAN). For wide-area networks, however, it is vital to modify t_{ik} , to consider the round-trip time delay ($RTT_{i,k}$, the time to propagate the request $r_{i,k}$ to the central node and return the acknowledgement to the source node). In conventional scheduling $t_{i,k}$ represents the processor time available for a particular request since the round-trip time between the processor and the originator of the request is negligible. This is not true, however, in wide-area networks, where a request needs to propagate to the control node, is processed, and an acknowledgement returned. The total time $t_{i,k}$ between two consecutive requests must, hence, be reduced by $RTT_{i,k}$, so that for the scheduler the periodicity of requests appears to be reduced. This will ensure that requests from furthest nodes from the control node have higher priority than requests from the nearest nodes, so the delay experienced by the different network nodes is equalized. For non-negligible RTT the time available for processing decreases, and hence the periodicity, $t_{i,k}$ becomes:

$$t_{i,k} = T_{buffer\ i,k} - RTT_{i,k} \quad (6.1)$$

For a network to be able to process all the requests in finite time (FIFO case) or before a given deadline (RM and EDF), the following condition must be satisfied:

$$\sum_{i=1}^{N_{Cos}} \sum_{k=1}^N (N-1) \cdot \frac{C_{i,k}}{t_{i,k}} \leq U \quad (6.2)$$

where N_{Cos} is the number of classes of services (1 in the case of FIFO scheduler), N the number of nodes and $C_{i,k}$ the processing time of lightpath request $r_{i,k}$ in the control node. Note that, by using the modified value for $t_{i,k}$ of Eq. (6.1), a worst-case scenario is considered for the scalability evaluation of Eq. (6.2) as the real inter-arrival time of requests is higher than predicted by Eq. (6.1).

The limits for the three different scheduling algorithms under consideration are as follows [Bin03]:

$$\sum_{i=1}^{N_{Cos}} \sum_{k=1}^N (N-1) \cdot \frac{C_{i,k}}{t_{i,k}} = U \leq \begin{cases} N_{tot} \cdot (2^{1/N_{tot}} - 1) \leq 1, & \text{for RM} \\ 1, & \text{for EDF and FIFO} \end{cases} \quad (6.3)$$

where N_{tot} is defined as $N_{tot} = N_{Cos} \cdot N \cdot (N-1)$ and it is the total number of sources generating requests in the network. Further for the limit of the RM algorithm:

$$\lim_{N_{tot} \rightarrow \infty} U_{RM} = \ln 2 \approx 0.69 \quad (6.4)$$

which is the lower bound for U_{RM} , and can be used as a conservative estimate of the limit for the RM algorithm. With these limits on U , all requests can always be scheduled.

The physical network topology will also have an impact on the scalability. In an idealised, star-like network architecture (Figure 6.3), all edge nodes are located the same distance away from the central control node, which allows to simplify equation (6.3).

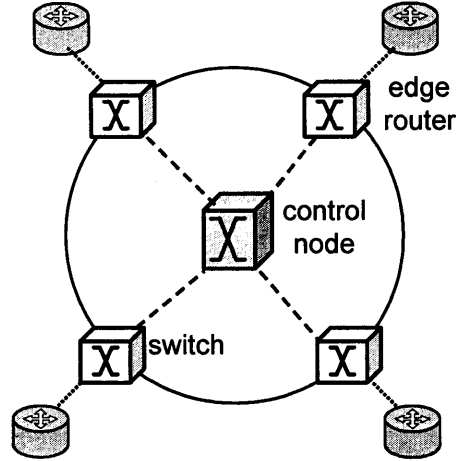


Figure 6.3. Optical network architecture in star topology, with edge nodes being equidistant from the control node

For the same CoS, the propagation delay to the control node is the same for all nodes, hence $t_{ik} = t_i$ and $RTT_{i,k} = RTT$. N_{max} is the maximum number of nodes for which the system is stable (no violation of latencies) for a given number of CoS, N_{CoS} . It is further assumed that the round-trip times of all connections are identical (equidistant node spacing), and that the edge delay for every CoS is unique, leading to $T_{buffer,i,k} = T_{buffer,i}$. Solving the quadratic equation given by Eq. (6.3), N_{max} is given as:

$$N_{max} = \left\lceil \frac{1}{2} + \left(\frac{1}{4} + U \cdot \left(C \cdot \sum_{i=1}^{N_{CoS}} \frac{1}{t_i} \right)^{-1} \right)^{1/2} \right\rceil \quad (6.5)$$

For large N , $N \cdot (N-1) \cong N^2$, so that equation (6.5) can be simplified to:

$$N_{max} \approx \left\lceil \sqrt{U \cdot \left(C \cdot \sum_{i=1}^{N_{CoS}} \frac{1}{t_i} \right)^{-1}} \right\rceil \propto \frac{1}{\sqrt{C}} \quad (6.6)$$

Figure 6.4 shows the maximum number of edge routers, N_{max} , as a function of processing time C assumed to be in the range 0.1-10 μs (quantification details in the

next section), for the case of 3 CoS under RM and EDF schedulers, and 1 CoS (lowest latency t_1 only) with the EDF and FIFO schedulers.

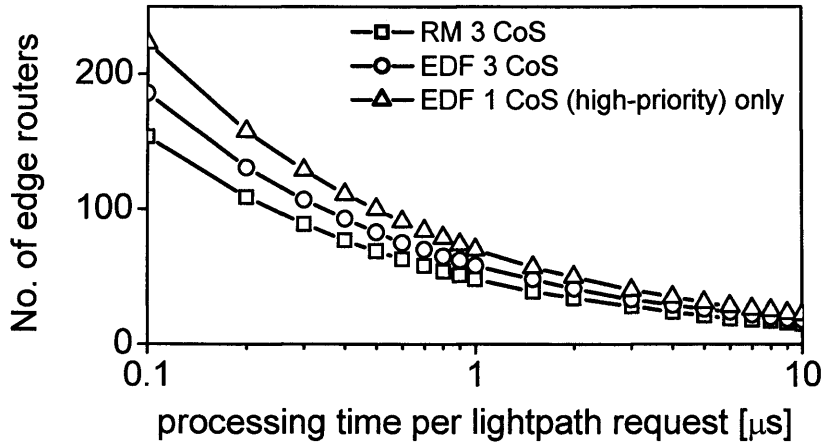


Figure 6.4. Number of edge routers as a function of the processing time C and for 3 CoS using the RM or EDF scheduling algorithm ($t_1=5\text{ms}$, $t_2=15\text{ms}$, $t_3=45\text{ms}$), as well as 1 CoS ($t_1=5\text{ms}$) only for the EDF and FIFO algorithms. All calculations assumed a network diameter of 1000 km ($\text{RTT}=5\text{ms}$)

To ensure that network resources are used efficiently, the data transmission time must be at least as long as the time required to set the lightpath (mainly determined by the round-trip-time, RTT). This means that data should be aggregated at the edge node at least for RTT, which determines the minimum period between consecutive lightpath requests. The following values were used in plotting Fig. 6.4.: $\text{RTT} = 5\text{ ms}$, and request periods $t_1 = 5\text{ ms}$, $t_2 = 15\text{ ms}$, and $t_3 = 45\text{ ms}$. It can be seen that the number of allowable edge routers decreases as $C^{-1/2}$. For $C = 0.1\text{ }\mu\text{s}$ (equivalent to 100 cycles of a 1-GHz processor) and 3 CoS, the network can support requests from up to 186 edge routers without missing a deadline. When only one CoS with $t_1 = 5\text{ ms}$ implemented, this increases to 223. This implies, as expected, that the most time-sensitive requests (highest CoS) determine the overall network performance;

additional CoS with less stringent delay requirements can co-exist with a minimal reduction in the allowable number of edge routers. Given that the scalability reduces as $C^{-1/2}$, it is important to quantify its value accurately (not possible with asymptotic computational complexity analysis). In the next section we investigate the processing time C as function of the network topology, necessary for the scalability analysis presented in section 6.3.

6.2. Lightpath requests processing times

As the time required for request processing is mainly determined by the speed of the lightpath allocation task, fast algorithms must be used for maximum scalability (as shown in Figure 6.4). This can be achieved by minimizing on-line processing, which is usually done using pre-computed routes without checking the network status (topology and wavelength availability) for each request. However, this leads to a higher blocking probability than in more computationally complex lightpath allocation algorithms which take into account the network status to find a lightpath. This highlights an inevitable trade-off between scalability and blocking probability, which is a problem which has not been investigated previously, but it is key for the practical implementation of dynamic networks.

Amongst the large number of lightpath allocation algorithms proposed to date (see Chapter 2), this chapter focuses on three, namely: The *Shortest-Path First-Fit* (SP-FF), *k-Shortest Path First-Fit* (*k*-SP-FF) and *Adaptive Unconstrained Routing-Exhaustive* (AUR-E) algorithms (described in Chapter 2 and analysed in terms of wavelength requirements in Chapters 3 and 4). As before, in Chapters 3 and 4, SP-FF and AUR-E have been selected because they represent two extreme (in terms of

computational complexity) lightpath allocation algorithms, so best and worst-case scalability can be evaluated. The k -SP-FF algorithm has been selected to verify whether the good performance of AUR-E can be achieved by means of a much simpler (low computational complexity) algorithm.

6.2.1. SP-FF algorithm

As discussed in Chapter 2, the SP-FF algorithm was first introduced in [Chl89]. It arbitrarily assigns integer numbers (indices) to wavelengths, and it selects the wavelength with the lowest index available in all the links of the shortest path between the source and destination. The implementation considered in this work is as follows. Let $SP_{sd} = \{l_{sd1}, l_{sd2}, \dots, l_{sd|SP_{sd}|}\}$ be the set of links comprising the shortest path between source (s) and destination (d) nodes, computed off-line and stored for subsequent use. Let $W = (W_1, W_2, \dots, W_L)$ be a vector of L elements (L : number of links), where every element comprises $|W|$ bits. The j -th bit of element W_i represents the availability of wavelength j in link i (0 if it is idle and 1 otherwise). Upon receiving a request for a lightpath between nodes s and d , the SP-FF algorithm executes the following operations:

```

set_available_wavelengths=0
wavelength=-1
for  $l \in SP_{sd}$ 
    set_available_wavelengths=(set_available_wavelengths) BITWISE OR
    ( $W[l]$ )
for  $i=1, 2, \dots, |W|$ 
    if ((set_available_wavelengths BITWISE AND  $2^i$ ) ==0) then
        {
            wavelength=i
            set_available_wavelengths=set_available_wavelengths
            BITWISE OR  $2^i$ 
        }

```

```

        break
    }
ACK(wavelength, SPsd) sent to source node

```

In the pseudo-code above, a *bitwise* logical operation is a standard function of high-level programming languages which performs a logical operation (**AND**, **OR**, etc.) between two numbers by applying the logical operation to the corresponding bits of each number in a single ALU operation (thus, bits are processed in parallel). Thus, all the wavelengths of the links of the path are processed simultaneously, leading to an asymptotic time complexity for the lightpath search task of $O(L+W)$, where L is the number of links and W the number of wavelengths. Given that L scales as $O(N^2)$ – N number of network nodes – and W does as $O(N^2)$, the overall complexity results in $O(N^2)$.

The scaling of L was estimated considering that a fully connected network has $N(N-1)$ uni-directional links. Therefore, $L \sim O(N^2)$. The scaling of W was obtained assuming that, in the worst-case, a different wavelength should be provided for each possible connections. As the maximum number of connections corresponds to $N(N-1)$, W scales with N^2 .

A complexity of $O(N^2)$ is a significant reduction with respect to the previously published implementations of the SP-FF algorithm which achieve a computational complexity of $O(LW)$ [Chl92], i.e. $O(N^4)$. The decrease in the time complexity is made possible by checking for wavelength availability in a parallel manner (rather than sequentially for every wavelength in every link of the path), as a result of the bitwise operations (since each bit represents an individual wavelength and all bits are

processed simultaneously during a single ALU operation). Hence, there is no benefit implementing this algorithm in a multi-processor environment as the bitwise parallel processing has already exploited the speed-up of parallelism.

The linear increase in processing time with W and L makes the SP-FF algorithm computationally simple and fast. However, the SP-FF algorithm results in poor blocking probability performance and higher wavelength requirements compared to other more complex algorithms (see [Mok98] and Chapters 3 and 4). A technique to overcome this limitation of the SP-FF algorithm, whilst maintaining its low computational complexity, is through the search of more than one path using the k -SP-FF lightpath allocation algorithm.

6.2.2. k -SP-FF algorithm

As described in Chapter 3, k -SP-FF searches up to k disjoint shortest paths between source and destination. In a single processor environment, the pseudo-code of SP-FF must be repeated k times, resulting in a increased computational complexity of $O(kL + kW)$; however in a multiprocessor environment (k processors, one processor per path), the computational complexity of the k -SP-FF algorithm would remain the same as that of the SP-FF algorithm, whilst reducing the blocking probability. Hence, the blocking probability can be lowered at the expense of using more electronic hardware.

6.2.3. AUR-E algorithm

The AUR-E algorithm, as described in Chapter 3, implements one undirected graph per wavelength, defined as $G_i = \{V, E_i\}$ $i=1,2,\dots,|W|$ where $W = \{\lambda_1, \lambda_2, \dots, \lambda_{|W|}\}$ is the set of wavelengths, V the set of nodes and E_i the set of links where λ_i is not used. When a request to establish a lightpath between source (s) and destination (d) is received, the *Dijkstra* algorithm is executed in each G_i . As a result a set of shortest paths $SP_{sd} = \{SP_{sd_{\lambda_1}}, SP_{sd_{\lambda_2}}, \dots, SP_{sd_{\lambda_{|W|}}}\}$ is generated, where $SP_{sd_{\lambda_i}} = \{l_{sd_{\lambda_i}_1}, l_{sd_{\lambda_i}_2}, \dots, l_{sd_{\lambda_i}_{|SP_{sd}|}}\}$ corresponds to the set of links comprising the shortest path between source (s) and destination (d) in graph G_i . From the set SP_{sd} , the path with the minimum number of links (hops) is chosen and the correspondent graph is updated, deleting the edges corresponding to the links used in the path. On lightpath release, these links are again added to the graph. The implementation of the AUR-E algorithm used in this work is as follows:

```

for  $i=1,2,\dots,|W|$ 
    shortest_path[i]=Dijkstra( $G_i, s, d$ )
j=minimum_hop(shortest_path)
ACK(shortest_path[j]) sent to source node

```

From the pseudo-code above it can be seen that the asymptotic time complexity of the lightpath search task is $O(WN^2+W)$, with the execution of the *Dijkstra* algorithm dominating the computational complexity ($O(N^2)$, See Appendix A). Other implementations of the *Dijkstra* algorithm may yield a lower computational complexity (for example, using *Fibonacci* heaps instead of static arrays [Kin90], leading to $O(N\log N+L)$). However, this only applies to networks with a high number of nodes ($\gg 100$), not applicable to practical networks (typically

less than 100 nodes). Assuming a multi-processor environment (one processor per wavelength) the computational complexity of the AUR-E algorithm can be reduced to $O(N^2 + W)$.

Although the *Dijkstra* algorithm makes the AUR-E algorithm computationally expensive with respect to the SP-FF algorithm and its variant k -SP-FF, the AUR-E algorithm has been shown to achieve significantly better performance [Mok98, Xu00, Che96, Hyy00, She01] as it searches all possible routes (instead of a reduced set) for every request. In the remainder of this section, the trade-off between the maximum number of supported nodes and the resulting processing time for the just described algorithms is investigated.

For the scalability analysis of practical network architectures it is not sufficient to only know the asymptotic complexity $O(f(N))$ of algorithms. This is because asymptotic complexity analysis assumes that the variables of interest (e.g. N , L and W used in the SP-FF and AUR-E algorithms) take very high values. Therefore, operations not involving those variables are considered to be executed in negligible time and are not taken into account in the complexity analysis. In practical cases, however, the neglected operations may contribute significantly to the execution time. This renders asymptotic complexity analysis ineffective in accurately estimating execution times or providing tight bounds. In this chapter analytically tractable upper bounds were obtained for the execution time of the studied algorithms using a technique known as *static performance prediction* [Gau00, Ber00]. This technique considers all operations performed by an algorithm at the source code level. The

execution time of every operation is then estimated from the number of memory accesses and arithmetic/logical operations carried out during each operation. Because the total processing time of an algorithm depends on the type of operations executed (dynamically chosen according to the input data), this technique provides an upper bound by analysing the longest possible execution time. Hardware- or software-dependent optimizations for speed-ups (e.g. pipelining, parallel execution of instructions or compiler optimizations) have not been considered since they are specific to each implementation. As a result, the application of the static performance prediction leads to an over-estimation of the execution time (worst case).

6.2.4. Processing times

Using the static performance prediction technique, the expressions below (second column in Table 6.1) for the execution time of the different lightpath allocation algorithms under investigation were obtained. The asymptotic computational complexity is also given. The following notation was used throughout for the formulae in the tables (detailed derivation in Appendix A):

N : number of nodes

L : number of links

W : number of wavelengths per link

D : longest path (in number of hops)

H : mean length of paths (in number of hops)

k : number of different paths explored during the execution of the k -SP-FF algorithm

$f()$: a function where the coefficients are linear with memory access time (t_{mem}) and the time required to perform an arithmetic or logical operation ($t_{A/L}$).

Please refer to the Appendix A for a detailed derivation and description of the formulae for the processing times of the individual algorithms, obtained using the static performance prediction technique.

Algorithm	Execution time	Complexity
SP-FF single/multi proc.	$f(D, W)$	$O(L+W) \sim O(N^2)$
k-SP-FF single proc.	$f(k, D, W)$	$O(kL+kW) \sim O(N^2)$
k-SP-FF multi proc.	$f(D, W)$	$O(L+W) \sim O(N^2)$
AUR-E single proc.	$W f(N^2, N, L) + f(W, H)$	$O(N^2 W) \sim O(N^4)$
AUR-E multi proc.	$f(N^2, N, L, W, H)$	$O(N^2)$

Table 6.1. Processing time and computational complexity of the different lightpath allocation algorithms (SP-FF, k-SP-FF, AUR-E)

The results obtained with the static performance prediction technique were validated by comparing the estimated times (obtained with formulae of second column of Table 1) with the measured execution times of the SP-FF and AUR-E algorithms for the Eurocore and NSFNet topologies (these topologies can be found in Table 3.1 of Chapter 3). Execution times were measured in a 1.8 GHz Pentium 4 processor using the technique described in [Int98]. The results showed that the estimation is a good indication of the actual running times: whereas tight bounds are provided for the AUR-E algorithm, a decrease in the real execution time of up to 3 times can be expected for the SP-FF algorithm.

The formulae given in the second column of Table 6.1 were applied to the 7 real, arbitrarily meshed optical network topologies of Table 3.1 to obtain the values of the maximum lightpath allocation processing time C for the SP-FF, 3-SP-FF (i.e. k -SP-FF with $k = 3$ since a higher number of disjoint paths did not lead to significantly increased performance) and AUR-E algorithms. The maximum lightpath allocation processing time C was evaluated for both single and multiprocessor environments (Table 6.2). As a worst case assumption, the number of wavelengths considered was equivalent to that required in the case of static lightpath assignment, whilst a lower count would be expected in dynamic networks due to the potential capacity savings. The processing times were calculated assuming a Pentium 4 processor operating with an ALU (arithmetic logical unit) processing time of 0.83 ns, and SRAM at 1.8 GHz access speed of 1 ns [Hin01].

Network	N	L	D	W	C SP-FF	Processing time C 3-SP-FF		Processing time C AUR-E	
					(single/ multi- proc.)	(single- proc.)	(multi- proc.)	(single- proc.)	(multi- proc.)
USNet	46	76	11	108	1.70 μ s	3.17 μ s	1.70 μ s	4.48 ms	43.20 μ s
Eurolarge	43	90	8	88	1.31 μ s	2.48 μ s	1.31 μ s	3.24 ms	38.30 μ s
ARPANet	20	31	6	33	0.56 μ s	1.03 μ s	0.56 μ s	0.28 ms	9.09 μ s
UKNet	21	39	5	21	0.42 μ s	0.76 μ s	0.42 μ s	0.20 ms	9.87 μ s
EON	20	39	5	18	0.40 μ s	0.71 μ s	0.40 μ s	0.16 ms	9.06 μ s
NSFNet	14	21	3	13	0.27 μ s	0.49 μ s	0.27 μ s	0.06 ms	4.64 μ s
EuroCore	11	25	3	4	0.20 μ s	0.34 μ s	0.20 μ s	0.01 ms	3.20 μ s

Table 6.2. Processing time of SP-FF, k -SP-FF and AUR-E algorithms for seven arbitrarily meshed networks

By inspection of the equations for the estimate of the processing times (Appendix A), it can be seen that the memory access time has a significant impact on the processing

times. Therefore, the use of SRAM instead of DRAM is paramount due to the significantly lower memory access times (1ns vs. 50ns, respectively). The total storage space available in SRAM, however, is significantly lower (Mbit regime) and it is necessary to confirm that the data structures used by the algorithms are within the SRAM capacity. For the k -SP-FF algorithm the memory requirement is $O(N^3)$, mostly given by the size of the routing table ($k \cdot N^2 \cdot D$ bytes) whilst for AUR-E the required size of memory is $O(N^4)$ mostly determined by the structures to store the network state ($W \cdot N^2$ bytes). The analysis to calculate memory requirements for both algorithms (details in Appendix A) led to the values shown in Table 6.3, and it can be seen that memory requirements are well below the limits of current SRAM designs [Amr00].

Network	3-SP-FF (Kbyte)	AUR-E (Kbyte)
USNet	76.8	228.3
Euro large	51.6	162.9
ARPA Net	8.7	13.7
UKNet	8.4	9.6
EON	7.7	7.5
NSFNet	2.6	2.7
Euro Core	1.8	0.6

Table 6.3. Memory requirements for k -SP-FF and AUR-E algorithms for the same seven topologies as used in Table 6.2

Using the formulae in the second column of Table 6.1, the maximum processing time per request, C , is plotted against the number of nodes in Figure 6.5 for (a) the SP-FF algorithm in a single and multi-processor environment, as well as the case of multi-processor implementation of the 3-SP-FF algorithm, (b) the 3-SP-FF algorithm in a single-processor machine, (c) the AUR-E algorithm in a single-processor computer and (d) the case of multi-processor implementation of the AUR-E algorithm. All

graphs contain the results for a constant number of wavelengths (the number required in the static case, used as a worst-case scenario), as well as the results for the seven network architectures listed in Table 6.2. Using the least-squares fit method, a straight line was fitted to the processing times of the seven network architectures. Its slope (exponent of N) defines the complexity of the processing time as a function of the number of nodes.

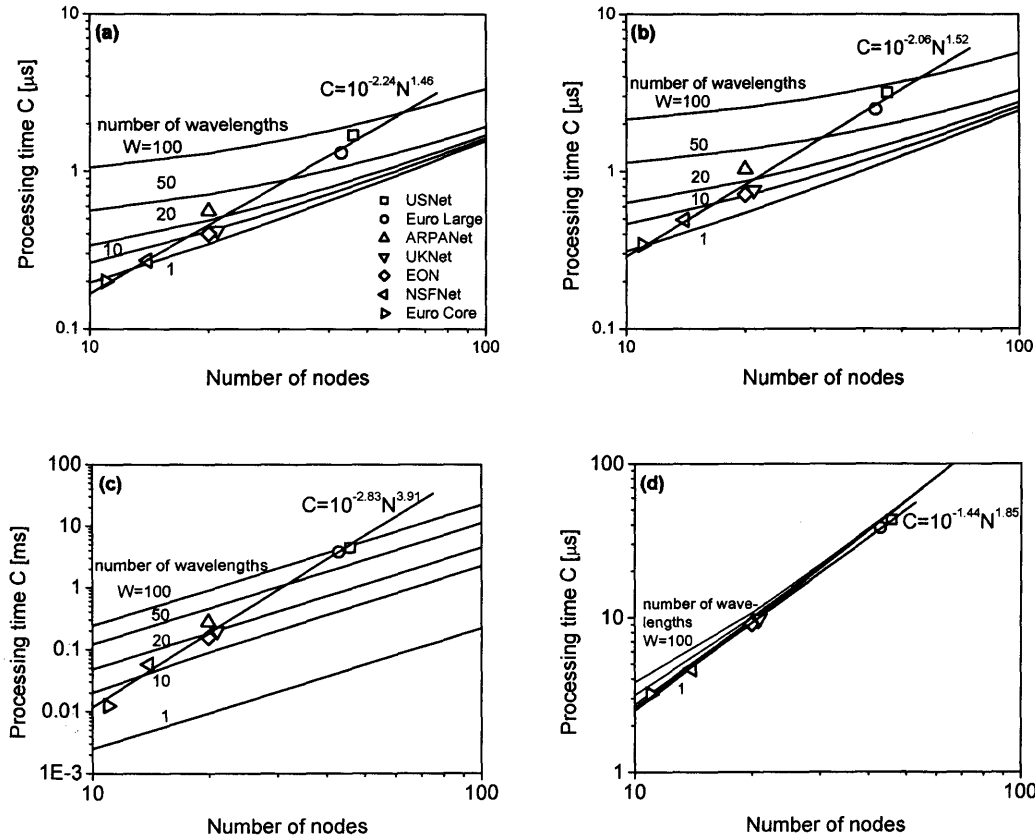


Figure 6.5. Maximum lightpath allocation processing time C as a function of the number of nodes for seven real network topologies and using SP-FF, 3-SP-FF and AUR-E algorithms in single or multiprocessor control node architectures: (a) single- or multiprocessor SP-FF and multiprocessor 3-SP-FF, (b) single processor 3-SP-FF, (c) single-processor AUR-E, and (d) multiprocessor AUR-E.

It can be seen that AUR-E in a single processor environment suffers from a severe computational overhead, scaling with a slope of 3.91, which can be reduced to 1.85 using a multi-processor architecture. The SP-FF algorithm and the parallel implementation of the 3-SP-FF algorithm achieve the lowest complexity, reflected in a slope of 1.46 only.

6.3. Results for the network scalability

The results obtained in the previous section can now be applied to quantify the network scalability in terms of the number of nodes and for given values of latencies and blocking probability (QoS constraints), as a function of the DRWA processing time under different scheduling algorithms.

6.3.1. Network scalability for operation at high network load

As shown in Chapter 3 and 4, dynamic networks do not save wavelengths compared to static networks at high traffic loads, since each wavelength will be highly utilized. Hence, the number of wavelengths required in the case of static network operation can be considered to be an upper bound for wavelength count in the dynamic case. Figure 6.6 shows the results for the achievable number of nodes as a function of the processing time when as many wavelengths were used as in the case of static network operation.

It can be seen that the AUR-E (single processor) and the SP-FF algorithm (as well as the case of multi-processor implementation of the k -SP-FF algorithm) give the lower

and the upper limit to the number of nodes, respectively. This is further bounded by the maximum allowable number of nodes for which a given latency (edge delay t_{edge}) can be guaranteed by the scheduling algorithms discussed in section 2. The results are plotted in for the same CoS values as previously in Figure 6.4, with a network diameter of 1,000 km and edge delays of 10, 20 and 50 ms.

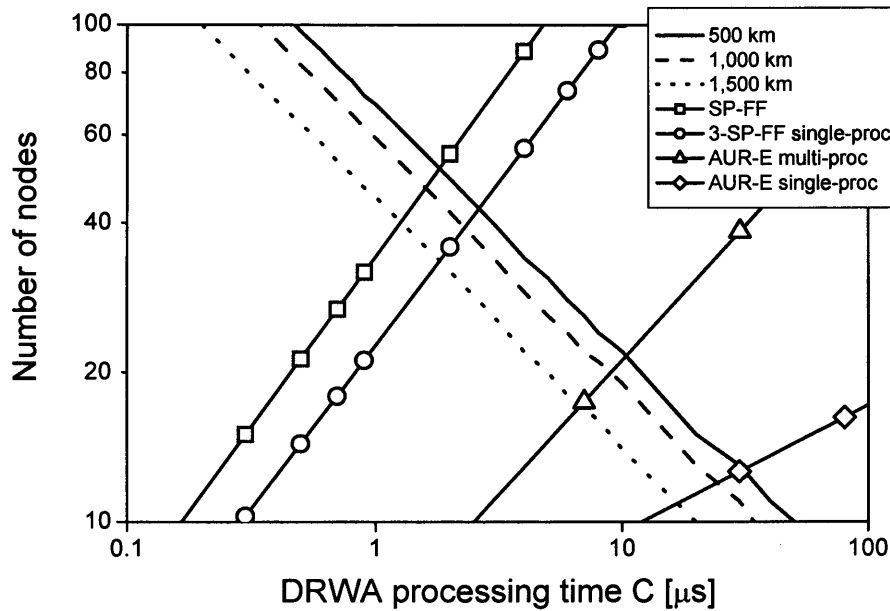


Figure 6.6. Number of nodes plotted against the lightpath allocation processing time per request C , for single and multiprocessor SP-FF and multiprocessor 3-SP-FF (squares), single-processor 3-SP-FF (circles), multiprocessor AUR-E (triangles), and single processor AUR-E (diamonds). The processing time is bounded by the QoS constraints, here plotted assuming the same values of Figure 6.4, with network diameters of 500 km (solid), 1000 km (dashed), and 1500 km (dotted), each of which was derived for 3 CoS with edge delays of 10, 20 and 50 ms.

It can be seen that only approximately ten nodes can be supported by a network using the AUR-E algorithm in a single processor environment, which prevents the utilization of this algorithm for most practical networks. The parallel implementations of the DRWA algorithms show significant improvements in scalability over the single-processor operation: AUR-E (about 20 nodes), SP-FF/3-SP-FF (40-50 nodes depending on the diameter of the network). Considering a SP-FF algorithm with a factor of 3 faster execution time (according to the validation described in section 4.3.3), up to 50-70 nodes can be then supported. These results correspond to lower bounds on the number of nodes and show that wavelength-routed optical networks with centralised control can be implemented for medium-size networks.

6.3.2. Impact of hardware improvements on network scalability

Among the parameters affecting the DRWA algorithms' execution time, the memory access time (t_{mem}) and the ALU operation time ($t_{A/L}$) can potentially be reduced through improvements in the electronic processing technology. In those cases, the number of nodes supported by a centralized architecture will be higher than those predicted by Figure 6.6.

Using a value of t_{mem} ten times faster than assumed previously (i.e. 0.1ns) leads to a significant increase in the achievable number of nodes which can be supported, from 40-50 to 55-70 for the SP-FF and the parallel implementation of the 3-SP-FF algorithms. The AUR-E algorithm exhibits a lower increase, now able to support 13-15 nodes and 24-30 nodes for the single- and multi-processor

environment, respectively. Decreasing $t_{A/L}$ instead, results in a negligible effect on the scaling for all the algorithms. This shows that faster memories have a much higher impact on scalability than faster processors.

6.3.3. Network scalability for operation at low network load

In terms of the number of wavelengths, it has until now been assumed that the same network capacity is required by all the studied lightpath allocation algorithms and that this capacity is equal to the number of wavelengths required in a static network. This, however, is an unrealistic assumption as at low loads dynamic operation results in wavelength savings as it has been shown in Chapters 3 and 4. Moreover, in the same chapters it was shown that different lightpath allocation algorithms require different network capacity to achieve the same blocking probability. In fact, the SP-FF algorithm (the highest scalable algorithm) requires significantly higher number of wavelengths to achieve a target blocking probability than the AUR-E algorithm. As a result, the SP-FF execution time is increased (linearly with the number of wavelengths). This highlights a complex trade-off between lightpath allocation processing time, wavelength savings and blocking probability, which needs to be optimized for each given topology and given input traffic matrix.

To study this trade-off, the results of Chapter 3 on the capacity required by the SP-FF, 3-SP-FF and AUR-E algorithm to achieve an average blocking probability lower than 10^{-3} have been used to calculate a best-case scalability. Table 6.4 shows the corresponding processing times with the newly considered wavelength count when the traffic load is reduced (case $\rho=0.1$).

Network	Process. time C SP-FF single/multiproc.	Processing time C 3-SP-FF		Processing time C AUR-E	
		(single- proc.)	(multi- proc.)	(single- proc.)	(multi- proc.)
USNet	0.81 μ s	1.29 μ s	0.74 μ s	705 μ s	42.5 μ s
Eurolarge	0.59 μ s	0.94 μ s	0.54 μ s	440 μ s	37.4 μ s
ARPANet	0.40 μ s	0.63 μ s	0.38 μ s	67.8 μ s	8.76 μ s
UKNet	0.33 μ s	0.54 μ s	0.32 μ s	56.7 μ s	9.69 μ s
EON	0.33 μ s	0.54 μ s	0.32 μ s	52.1 μ s	8.93 μ s
NSFNet	0.23 μ s	0.35 μ s	0.21 μ s	22.0 μ s	4.53 μ s
EuroCore	0.20 μ s	0.32 μ s	0.20 μ s	6.22 μ s	3.19 μ s

Table 6.4. Processing time of SP-FF, 3-SP-FF and AUR-E algorithms

for the same seven topologies as used in table 6.2 for $\rho=0.1$

From results of Chapters 3 and 4 and data in Table 6.4 a trade-off between processing time and capacity requirements of the analysed algorithms can be observed: whilst SP-FF is the fastest algorithm (Table 6.4), it requires the highest capacity (Chapter 3 and 4) to achieve the target blocking probability. Conversely, AUR-E is the slowest algorithm, but achieves the lowest capacity requirement. The conclusion of a trade-off, however, is based only on the three analysed lightpath allocation algorithms. Other lightpath allocation algorithms may not exhibit a compromise between processing time and blocking. For example, Shortest-Path Random-Fit (SP-RF) has a higher processing time than SP-FF, but also a higher blocking. Also, potentially new algorithms for achieving as good blocking as the best but at reduced computational would not suffer from this trade-off (see section 6.4, for the proposal of a new scalable lightpath allocation algorithm).

Applying a linear-fit to the data of Table 6.4 and using the same technique as applied in Figure 6.6, the scalability of the algorithms considering the wavelength count

reduction was quantified. Although significant in most cases, the impact of the wavelength count reduction on the scalability is lower than a decrease in the memory access times. The number of nodes supported by the AUR-E algorithm in a multi-processor environment remains virtually unchanged (with one processor per wavelength, the processing time is mostly insensitive to the number of wavelengths) whilst the scaling of the 3-SP-FF algorithm improves with the wavelength reduction, leading to an increase from 40-50 to 50-65 nodes. These results lead to the following recommendations on the choice of lightpath allocation algorithm in a centralized network, namely:

- 1) The SP-FF algorithm requires significant over-provisioning of wavelengths (with respect the other dynamic alternatives) to achieve an acceptable blocking probability and, since the parallel implementation of the k -SP-FF algorithm requires reduced resources with the same computational complexity, the SP-FF algorithm should not be used in these applications.
- 2) Although requiring significantly lower resources, the AUR-E algorithm implemented in a single processor core node only allows networks with low number of nodes (approximately 10). A parallel version of the algorithm is more suitable for implementation in real networks, leading to a node count of about 20.
- 3) The choice between the k -SP-FF and AUR-E algorithm implemented in a multiprocessor environment will be determined by the size of the network, the maximum number of nodes supported by the lightpath allocation algorithms and the *cost* of implementing the k -SP-FF or AUR-E algorithm.

Let N and $N_{k\text{-SP-FF}}$ ($N_{\text{AUR-E}}$) be the number of nodes of the network and the maximum number of nodes supported by a central node executing the $k\text{-SP-FF}$ (AUR-E) algorithm, respectively. From results obtained here, $N_{k\text{-SP-FF}} > N_{\text{AUR-E}}$. Then, if:

- $N > N_{k\text{-SP-FF}}$: a centralized dynamic implementation is not possible
- $N_{\text{AUR-E}} < N < N_{k\text{-SP-FF}}$: $k\text{-SP-FF}$ should be used
- $N < N_{\text{AUR-E}} < N_{k\text{-SP-FF}}$: either the $k\text{-SP-FF}$ or AUR-E algorithm can support the network

In the last case ($N < N_{\text{AUR-E}} < N_{k\text{-SP-FF}}$) the choice of the lightpath allocation algorithm is likely to be determined by the cost of its implementation. Assuming that cost is mostly determined by the number of processors (k and W processors required for the $k\text{-SP-FF}$ and AUR-E algorithm, respectively) and required network capacity (line card plus optical transmitter/receiver per wavelength), it is then possible to select the algorithm which minimizes the cost for a given network architecture.

Given this choice between 3-SP-FF and AUR-E, a new algorithm aiming to obtain such good scalability as 3-SP-FF but with the reduced wavelength requirements of AUR-E would be desirable. In the next section a new algorithm which significantly improves the scalability of AUR-E whilst maintaining its low wavelength requirements is proposed.

6.4 A new scalable algorithm for centralised wavelength routed optical networks

In this section a novel lightpath allocation algorithm, called Scalable AUR-E (S-AUR-E), is proposed. S-AUR-E achieves the same performance of AUR-E, but with significantly increased scalability, making it highly practical for future dynamic optical networks.

S-AUR-E decreases the processing time of lightpath requests by combining the fast first-fit (FF) wavelength allocation with a set of optimised (in terms of traffic balance) pre-computed shortest routes and the selective on-line execution of Dijkstra algorithm.

S-AUR-E includes the following steps:

- A. Compute (off-line) the optimal shortest routes (those balancing the traffic load to minimise the wavelength count, e.g. [Zap03]) per node pair according to the traffic demand matrix
- B. Compute (off-line) additional $k-1$ disjoint routes per node pair
- C. For every lightpath request (on-line operation):
 - i. Attempt to establish a lightpath using k -SP-FF with the k optimised pre-computed routes
 - ii. If k -SP-FF fails, execute AUR-E
 - iii. If AUR-E fails, block the request

Steps A and B decrease the processing time by pre-computing up to k optimal disjoint routes (failing to optimise the routes leads to higher blocking for k -SP-FF and thus, more executions of the Dijkstra algorithm). Step C attempts to find a lightpath by using the fastest algorithm first (optimised k -SP-FF). Only on failure,

slow AUR-E is executed. The pre-computed routes can be updated as the traffic matrix evolves, allowing S-AUR-E to adapt to traffic changes (fast, transient traffic changes are taken into account by the Dijkstra execution, if necessary). The computational complexity of the S-AUR-E algorithm is $O(N^2)+P \cdot O(N^4)$, where $P \in [0,1]$ is the probability of executing AUR-E.

6.4.1. S-AUR-E performance evaluation

As done in Chapter 3, in this section the number of wavelengths required by S-AUR-E to achieve a maximum blocking of 10^{-3} per node pair is quantified by means of simulation and compared to that of AUR-E. Five out of the seven physical mesh topologies studied in this chapter were considered (Eurolarge and USNet were not included due to their high simulation time).

Table 6.5 shows the mean number of wavelengths per link required by AUR-E and S-AUR-E for the studied networks for traffic loads ranging from 0.1 to 0.9.

traffic load	Eurocore		NSFNet		EON		UKNet		ARPANet	
	AUR-E	S-AUR-E	AUR-E	S-AUR-E	AUR-E	S-AUR-E	AUR-E	S-AUR-E	AUR-E	S-AUR-E
0.1	3	3	5	5	7	7	7	7	9	9
0.3	4	4	9	9	12	12	11	11	18	18
0.5	5	4	12	12	16	16	16	16	25	25
0.7	5	5	14	14	19	19	19	19	31	31
0.9	5	5	15	15	21	22	23	23	35	35

Table 6.5. Total wavelength requirements for AUR-E and S-AUR-E lightpath allocation algorithms for 5 real mesh topologies.

From data in Table 6.5. it can be seen that S-AUR-E achieves as low wavelength requirements as AUR-E. Next, the scalability of S-AUR-E is quantified.

6.4.2. S-AUR-E scalability

As studied in previous sections, the scalability of a centralised architecture is mainly determined by the request processing time of the lightpath allocation algorithm. In the case of S-AUR-E, this is given by:

$$C_{S-AUR-E} = C_{k-SP-FF} + P_{AUR-E} \cdot C_{AUR-E} \quad (6.7)$$

where C_x is the request processing time for a given algorithm and P_{AUR-E} is the probability of executing step c.ii of S-AUR-E (approximately equal to the blocking probability of k -SP-FF, according to simulation results).

$C_{3-SP-FF}$ (when implemented in a 3-processor machine) and C_{AUR-E} were evaluated using the formulae derived in Appendix A, considering the wavelength requirements obtained in the previous section for different traffic loads:

$$C_{3-SP-FF} \approx 10^{-a} N^b [\mu s]; a=f(\rho) \in [1.69, 2.04]; b=f(\rho) \in [0.93, 1.31] \quad (6.8)$$

$$C_{AUR-E} \approx 10^{-c} N^d [\mu s]; c=f(\rho) \in [2.37, 3.02]; d=f(\rho) \in [3.22, 4.13] \quad (6.9)$$

P_{AUR-E} (ratio of the number of AUR-E executions and the total number of lightpath requests) was evaluated from simulations with a total of 10^6 lightpath requests (high enough to obtain statistically valid results, given the range for P of 10^{-3} - 10^{-5}). Eqs. (6.7-6.9) were used, together with the value of P_{AUR-E} obtained from simulations, to calculate the worst-case scalability of S-AUR-E for different traffic loads, following the same methodology of section 6.4, i.e., the results for $C_{S-AUR-E}$ are plotted along

the maximum allowed time to process requests, C_{max} , under FIFO (First-In First-Out) scheduling. The maximum number of supported nodes, N_{max} , is given by the intersection points of these curves. Figure 6.7 shows N_{max} for S-AUR-E for a centralised optical network with a diameter of 1000 km, together with the results for AUR-E for comparison. For both algorithms, scalability degrades as the load increases because a higher number of requests must be processed by the control node.

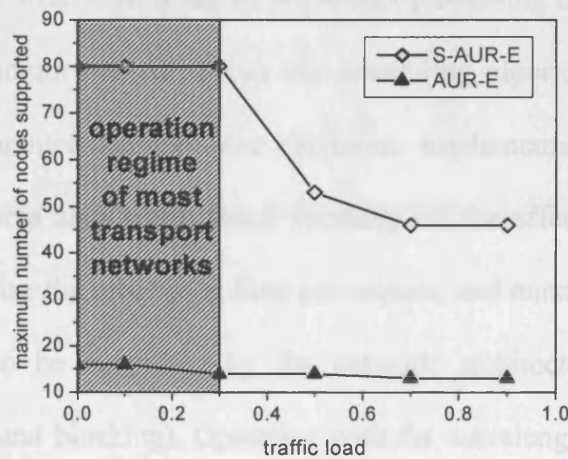


Fig.6.7. Scalability of AUR-E and S-AUR-E algorithms as a function of the traffic load

It can be seen that, irrespective of the load, S-AUR-E increases the scalability of AUR-E: by a factor between 3.5 (from 13 to 46 nodes at loads in excess of 0.7) and 5 (from 16 to 80 nodes for loads under 0.3), making it capable of supporting most real topologies. As most networks currently operate at low loads (typically <0.3 [Odz03, Bha01]), S-AUR-E will ensure the greatest benefits where it is needed most – that is in allowing the network size to increase without the need for additional resources.

6.5 Summary

Lower bounds on the maximum number of nodes supported by centralised dynamic optical networks with end-to-end lightpath assignment were obtained as a function of the processing of lightpath requests in the control node. Processing in the control node is comprised by scheduling algorithms (FIFO, Rate-Monotonic and Earliest-Deadline-First) and the execution of lightpath allocation algorithms (k -SP-FF and AUR-E). The worst-case in terms of network scalability was investigated by assuming the longest execution times of sequential processing of incoming requests arriving at the maximum rate for which the scheduling algorithms (RM and EDF algorithms) can guarantee fairness. The electronic implementation of the DRWA algorithms studied was also investigated, focusing on the effectiveness of parallel processing to minimize the processing time per request, and maximize the achievable number of nodes to be supported by the network architecture for given *QoS* constraints (latency and blocking). Operating with the wavelength count required in the static case (considered as an upper bound for the network capacity here) it was shown that using the SP-FF algorithm (and the parallel implementation of 3-SP-FF) in the control node can achieve a lower bound of 40-50 nodes whilst the AUR-E algorithm can only support up to 10 and 20 nodes in the cases of single- and multi-processor environments, respectively. It was shown that a reduction in the memory access times increase the scalability (by about 30% in the case of the SP-FF algorithm), whilst increasing the processors speed has a negligible effect.

The work further showed that there is a trade-off between processing time, blocking probability and resource requirements for the investigated DRWA algorithms, with the SP-FF algorithm typically operating more than 100-times faster, but suffering from blocking probabilities 100-times higher than the AUR-E

algorithm. This translates into significant resource requirements for the SP-FF algorithm compared to AUR-E, which in turn impacts its processing time. It was found that the parallel implementation k -SP-FF provides a good compromise between performance and scalability, with a scalability of up to 70 nodes for 1500km-diameter networks operating at traffic load of 10% (50 nodes for the same capacity required in the static case). However, the best compromise was achieved by the proposed algorithm, S-AUR-E, which decreases the processing time of lightpath requests whilst maintaining the good performance of AUR-E. This is achieved by combining the fast First-Fit (FF) wavelength allocation algorithm with a set of optimized (in terms of traffic balance) pre-computed shortest routes and the selective on-line execution of Dijkstra algorithm. S-AUR-E was shown to perform as well as AUR-E but with significantly increased scalability (from 16 to 80 nodes) for loads under 0.3, the operation range where dynamic operation of wavelength-routed optical networks bring benefits in terms of wavelength requirements compared to static WRONs. Achieving the best performance to date and supporting most of real topologies, S-AUR-E appears promising for application in dynamic optical networks and shows that a centralised support of the maximum number of nodes in present networks can be achieved.

Results show that medium-size networks of up to 50 nodes (exceeding the largest continental network studied here) can be easily deployed using centralised architectures and that the fastest algorithm to date (SP-FF) may be sub-optimal for implementation given its increased capacity requirement to yield an acceptable blocking performance. Given that the lowest blocking algorithm to date (AUR-E) scales poorly with the number of nodes, in this chapter a new algorithm is proposed.

Such algorithm maintains the good performance of AUR-E, but significantly increases the scalability in the range of traffic loads where dynamic operation is attractive.

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Chapter 7

Conclusions and future work

In this thesis the question of whether dynamic operation of wavelength-routed optical networks brings benefits with respect to the static approach (static WRONs) was addressed. To answer this question the dynamic centralised WR-OBS network architecture was selected for study because of its feasibility of implementation in the short term (compared to OPS) and higher efficiency in the resource allocation and achievable throughput compared to one-way reservation alternatives (OBS) or distributed two-way schemes.

Dynamic centralised WR-OBS and static WRON optical networks were compared in terms of resource (wavelength) requirements, delay and scalability.

In terms of wavelength requirements it was found that, under uniform traffic, dynamic wavelength-routed optical networks bring benefits in terms of wavelength requirements compared to the static approach only at low/moderated loads (<0.4) and mainly in sparsely connected networks ($\alpha < 0.2$). The fact that resource allocation cannot be optimised in dynamic wavelength-routed optical networks in the same way as in static architectures (dynamic networks must perform resource allocation in an on-line manner

without the prior knowledge of the future demand) leads to sub-optimal resource (wavelength) allocation which results in higher wavelength requirements. Additionally, highly connected networks ($\alpha > 0.2$) already require a very low number of wavelengths in the static case (for example, on average, 3.5 wavelengths per link for Eurocore, $\alpha = 0.45$) making it difficult to decrease further in the case of dynamic operation.

This situation does not change significantly when non-uniform traffic matrices are considered. In this case, the wavelength requirements of dynamic operation are slightly lower than in the case of uniform traffic (from 4% to 9% on average) because the concentration of the traffic load in some sectors of the network leads to a higher statistical gain (due to the higher number of connections sharing the same resources). However, the wavelength requirement decrease is not high enough so as to modify significantly the maximum traffic load at which wavelength savings are observed with respect to the uniform case (and the maximum traffic load value remains 0.3-0.4). These results allow for the assumption that the uniform traffic case, which is much simpler to analyse, is the worst case scenario for network analysis in terms of wavelength requirements.

For traffic loads in excess of 0.4, it was found that wavelength-routed optical networks do not benefit from dynamic operation. Wavelength-convertible networks, however, do benefit significantly from dynamic operation across a wide range of traffic load values (compared to static networks, wavelength savings were exhibited for loads of up to 0.9), however the additional cost of implementing such a network must be lower than the savings achieved due to the wavelength requirement decrease for this alternative to be feasible.

In terms of delay, it was found that the mean extra delay introduced in the end-to-end WR-OBS architecture compared to the static approach was mainly determined by the burst aggregation mechanism utilised to build the bursts. If the FBS (Fixed Burst Size) aggregation mechanism is discarded due to its unbounded delay at low loads, the investigation showed that in the worst case (using Fixed Aggregation Time aggregation scheme), the mean additional delay introduced by dynamic WR-OBS due to the aggregation process was approximately RTT (round trip time, the time required for the lightpath request to be propagated from the source node to the control node and back to the source node with an ACK or NACK message) and that this additional mean delay can be further decreased to half ($RTT/2$) by using the Unlimited Burst Size aggregation scheme.

Therefore, in networks covering small geographic areas (~ 1000 km diameter, such as most networks in Europe) the additional mean delay introduced by the WR-OBS architecture (compared to the static approach) should not exceed 2.5-5 ms whilst for larger areas (US continental topologies, ~ 5000 km diameter) this extra delay would be in the range 13-25 ms.

Given the current limit for end-to-end delay of 100 ms set by the ITU-T for time-critical network applications, a WR-OBS architecture would be feasible for time-critical applications only if the propagation time of information plus the extra delay introduced by dynamic operation does not exceed the delay limits. Considering that the information requires a maximum time of $RTT/2$ to be propagated in a network and that RTT is not likely to exceed a value of 25 ms, the additional delay introduced by the dynamic operation of a WR-OBS architecture is not high enough as to violate end-to-end delay limits. Thus, in terms of delay dynamic operation of wavelength-routed optical

networks remains attractive even for the largest studied networks (US continental networks, NSFNet and USNet).

Finally, the scalability of centralised WR-OBS was studied to verify whether the implementation of such architecture was feasible for networks of practical interest, at least in the operation range where WR-OBS bring benefits with respect to static WRONs (that is, offered traffic loads under 0.3-0.4). It was found that operating with the wavelength count required in the static case (considered an upper bound for the network capacity here) the SP-FF algorithm (and the parallel implementation of 3-SP-FF) in the control node can achieve a lower bound of 40-50 nodes whilst the AUR-E algorithm can only support up to 10 and 20 nodes in the cases of single- and multi-processor environments, respectively. It was also found that a reduction in the memory access times increase the scalability (by about 30% in the case of the SP-FF algorithm), whilst increasing the processors speed has a negligible effect.

The work further showed that there is a trade-off between processing time, blocking probability and resource requirements for the investigated DRWA algorithms, with the SP-FF algorithm typically operating more than 100-times faster, but suffering from blocking probabilities 100-times higher than the AUR-E algorithm. This translates into significant resource requirements for the SP-FF algorithm compared to AUR-E, which, in turn, impacts its processing time. It was found that the parallel implementation k -SP-FF provides a good compromise between performance and scalability, with a scalability of up to 70 nodes for 1500km-diameter networks operating at traffic load of 10% (a scalability of 50 nodes for the same capacity required in the static case). However, the best compromise was achieved by the proposed algorithm, S-AUR-E, which decreases the processing time of lightpath requests whilst maintaining

the good performance of AUR-E. This is achieved by combining the fast First-Fit (FF) wavelength allocation algorithm with a set of optimized (in terms of traffic balance) pre-computed shortest routes and the selective on-line execution of Dijkstra algorithm. S-AUR-E was shown to perform as well as AUR-E but allowed to achieve a significantly increased scalability (from 16 to 80 nodes) for loads under 0.3.

At the beginning of the research work which led to this thesis there was a lack of quantitative results regarding the benefits of dynamic operation with respect to the static approach, as shown in Table 1.1 (Chapter 1). The completion of this research work has allowed to quantitatively answer these questions, summarised in the following table:

	Static allocation	Dynamic allocation
Resource utilisation	✗ Low when not transmitting at maximum bit rate	✓ Higher than static, but only at loads under 0.3-0.4 and in sparsely connected networks ($\alpha < 0.2$)
Delay	✓ Propagation and edge queueing buffer	✗ Higher than static: a mean additional delay of $RTT/2$ is introduced by dynamic WR-OBS networks
Scalability	✓ High	✗ Lower than static: a centralised dynamic WR-OBS network with a maximum of 80 nodes can be implemented in the traffic load range where dynamic requires a lower number of wavelengths than static

Table 7.1. Comparison of static and dynamic resource allocation in optical networks.

Therefore, it can be concluded, that the dynamic wavelength-routed optical networks (based on a centralised WR-OBS architecture) are a better choice than static architectures only for sparsely connected networks ($\alpha < 0.2$) with a node count lower than 80 operating at low/moderate traffic loads (< 0.4) and implementing the S-AUR-E lightpath allocation algorithm. The geographic area covered by the network does not

impact the choice of a dynamic or static architecture in terms of delay as it is unlikely that the *RTT* exceeds 25 ms, in which case both types of networks comply with the end-to-end delay limits established for time-critical applications.

Whilst the results achieved in this work answered several open questions, they also raised a number of new issues representing important topics for future work.

Firstly, the design of an improved lightpath allocation algorithm, improving on the performance of AUR-E (the best performing to date) which exhibited a wavelength requirement 14% higher than the heuristic lower bound. This is important given that the wavelengths requirements mainly determine the cost of switches, terminating equipment and physical impairment-compensating equipment. However, this is expected to be a very difficult task given that since 1996 (when AUR-E was first proposed) no improvements to it have been made.

In the analysis of dynamic operation a centralised architecture was assumed due to its superior blocking performance compared to a distributed scheme. However, wide-area networks are typically operated in a distributed manner. It is thus important to investigate how a distributed architecture impacts the wavelength requirements, delay and scalability performance of a dynamic wavelength-routed optical network.

One feature of dynamic networks is their adaptability to time-variant traffic. The performance comparison of dynamic and static wavelength-routed optical networks under time-varying traffic as well as the design of robust dynamic lightpath allocation algorithms capable of efficiently dealing with traffic changes is of fundamental

importance given that networks are usually prone to traffic variations (due for example to the occurrence of failures or changes on the level of utilisation of content servers).

Appendix A

Processing time of dynamic lightpath allocation algorithms

A.1. Introduction

A description of the request processing time of two widely used dynamic routing and wavelength assignment (DRWA) algorithms: Shortest-Path First-Fit (SP-FF) [Chl89], and Adaptive Unconstrained Routing – Exhaustive (AUR-E) [Mok98] is provided in this Appendix. The k -SP-FF algorithm (for $k = 1, 2, \dots$) is derived from the SP-FF algorithm by simultaneously searching k disjoint shortest paths, hence reducing the blocking probability over the conventional SP-FF algorithm [Har97, Bal91, Sha99, Sen00]. The AUR-E and k -SP-FF algorithms can be implemented in both a single and multi processor environment, where the multi processor implementation will provide a significant speed-up. Since the number table lookups is a key constraint for the overall processing speed, analytical expressions for memory requirements and the number of lookups required for the implementation of the k -SP-FF and AUR-E algorithms are provided.

This Appendix is organized as follows: the formulae to calculate the processing times for the k-SP-FF and AUR-E algorithms are provided in section A.2., based on a detailed listing of all processing steps. Section A.3 investigates the processing time of the widely used *Dijkstra* algorithm for routing and wavelength allocation in optical networks, and section A.4 provides estimates for the memory requirements. The variables used in this Appendix are the same defined in the section 6.2.4 of Chapter 6.

A.2. Lightpath algorithm processing

A.2.1. k-SP-FF algorithm

For the k-SP-FF algorithm in a single processor machine, the static performance prediction technique gives the following formula for the execution time:

$$C_{SP-FF} = D(ak + b) + W(ck + d) + (ek + f), \quad (\text{A.1})$$

where: $a = t_{mem} (3 + 7\lceil W / 64 \rceil) + t_{A/L} (2 + \lceil W / 64 \rceil)$

$$b = t_{mem} (6 + 22\lceil W / 64 \rceil) + t_{A/L} (4 + 2\lceil W / 64 \rceil)$$

$$c = 3t_{mem} + 2t_{A/L}$$

$$d = 2t_{mem} + t_{A/L}$$

$$e = 10t_{mem} + t_{A/L}$$

$$f = t_{mem} (10 + 4\lceil W / 64 \rceil) + t_{A/L} + 10t_{buffer}$$

For a multiprocessor environment, the same formulae applies but with $k=1$.

A.2.2. AUR-E algorithm

For AUR-E in a single processor environment the upper bound for the execution time is given by:

$$C_{AUR-E} = W(N^2a + Nb + Lc + d) + We + Df + g \quad (\text{A.2})$$

where $a = 15t_{mem} + 4t_{A/L}$

$$b = 12t_{mem} + 4t_{A/L}$$

$$c = 24t_{mem} + 2t_{A/L}$$

$$d = 15t_{mem} - 3t_{A/L}$$

$$e = 11t_{mem} + 3t_{A/L}$$

$$f = 25t_{mem} + 6t_{A/L}$$

$$g = 14t_{mem} + t_{A/L} + 5t_{buffer}$$

Taking advantage of a multiprocessor environment, a parallel implementation of AUR-E can be executed much faster by dedicating one processor per wavelength to execute Dijkstra algorithm. In this case, neglecting the time required for the processors to exchange data, the longest execution time is given by the same formula above, except that the factor W at the beginning of the expression is dropped, i.e:

$$C_{AUR-E} = (N^2a + Nb + Lc + d) + We + Df + g. \quad (\text{A.3})$$

To obtain the formulae above the following assumptions were made:

- only arithmetic/logical operations (called A/L operations from now on) and memory accesses contribute to the execution time. Every time a constant or a variable appears in the algorithm's code, a memory access is counted. Every time an arithmetic (increasing counters) or logical operation (OR, AND, comparison) appears in the code, an A/L operation is counted.

- the processor executes the instructions in a sequential manner. Thus, pipelining or parallel execution of instructions -which are highly dependant on the particular code and computer hardware - are not considered.
- all data is in cache level 1 [Hen03] when the algorithm is executed, therefore, the fastest memory access time is considered, denoted t_{mem} (for Pentium 4 processors, this value is 1ns [Int01])
- all ALU operations take the same amount of time to be executed [Int01], denoted $t_{A/L}$ (for Pentium 4 processors this time is 0.83 ns [Int01])
- messages to configure the optical switches are sent in parallel with the answer to the edge node and are processed by a secondary simple processing unit. Therefore, they do not contribute to the processing time
- For any RWA algorithm, the processing time per request C is given by:

$$C = t_{lightpath_alloc} + t_{lightpath_release}$$

where $t_{lightpath_alloc}$ is the time to allocate a lightpath and $t_{lightpath_release}$ is the time to update the network state when transmission has finished and the lightpath is released.

In the following, the code used to obtain equations (1) – (3) is presented in more detail.

A.2.3. Execution time of the Shortest Path First Fit (SP-FF) algorithm

The left column of Table A.1 shows the generic code in C language for SP-FF algorithm. The right column shows the execution time of the corresponding line. In

those lines where the execution time depends on whether a condition is met or not, the symbol “/” separates the execution time of the condition’s evaluation from the execution time of the rest of the code in the line. N , W , L and \hat{P} correspond to the number of edge nodes, the maximum number of wavelengths per link, the number of links and the length of the longest path (in number of hops), respectively. R and H are static arrays where the routes and the length of routes in hops are stored. W_i arrays store availability of wavelengths per link. Because every array can store up to 64 wavelengths per link only, $\lceil W/64 \rceil$ of these arrays are necessary. Variable *result* store wavelength availability in the analyzed path while the variable *wav* stores the wavelength chosen for the lightpath (the value 1 is written in the bit corresponding to the chosen wavelength, 0 in the remaining bits).

Code	Execution time
Definition of variables	
<pre> int R[N][N][\hat{P}], H[N][N]; int_64 W1[L], W2[L], ..., W$\lceil W/64 \rceil$[L]; int_64 result1, result2, ..., result$\lceil W/64 \rceil$; int_64 wav1, wav2, ..., wav$\lceil W/64 \rceil$; int hops, i, src, dest, lightpath_wav; </pre>	
Lightpath scheduling	
<pre> //reading request from buffer read(src, dest); //initialising variables result1=0;... result$\lceil W/64 \rceil$=0; wav1=-1;...wav$\lceil W/64 \rceil$=-1; //obtaining the number of hops of path (*) hops=H[src][dest]; //getting current wavelength availability information from W_i arrays for (i=0; i<hops; i++) {result1 =W1[R[src][dest][i]]; result$\lceil W/64 \rceil$ =W$\lceil W/64 \rceil$[R[src][dest][i]]; } //searching for the first available wavelength if ((result$\lceil W/64 \rceil$&0x80...)==0) {wav=0x80...;goto updt;} ⋮ if ((result$\lceil W/64 \rceil$&0x1)==0) {wav=0x1;goto updt;} ⋮ if ((result1&0x80...0)==0) {wav=0x8...0;goto updt;} ⋮ (*)if ((result1&0x1)==0) {wav=0x1;goto updt;} //sending answer back to the edge node updt: write(src, dest, wav1, ..., wav$\lceil W/64 \rceil$, R[src][dest][0]); //updating network status after lightpath found for (i=0; i<hops; i++) </pre>	t_{buffer}^{**} $2\lceil W/64 \rceil t_{mem}$ $2\lceil W/64 \rceil t_{mem}$ $4t_{mem}$ $2t_{mem} + (3t_{mem} + 2t_{A/L}) \cdot hops$ $(7t_{mem} + t_{A/L}) \cdot hops$ $(7t_{mem} + t_{A/L}) \cdot hops$ $3t_{mem} + 2t_{A/L} / 4t_{mem} + t_{A/L}$ \vdots $3t_{mem} + 2t_{A/L} / 4t_{mem} + t_{A/L}$ \vdots $3t_{mem} + 2t_{A/L} / 4t_{mem} + t_{A/L}$ \vdots $3t_{mem} + 2t_{A/L} / 4t_{mem} + t_{A/L}$ $8t_{buffer}^{**}$ $2t_{mem} + (3t_{mem} + 2t_{A/L}) \cdot hops$

{ W1[R[src][dest][i]] = wav1; ⋮ W[W/64][R[src][dest][i]] = wav[W/64];}	$(11t_{mem} + t_{A/L}) \cdot hops$ ⋮ $(11t_{mem} + t_{A/L}) \cdot hops$
<i>t_{lightpath_release}</i>	
//reading release message from buffer read(src, dest, lighptah_wav, hops); Switch(lightpath_wav) { case W: result[W/64] = 0xYY; break; ⋮ case 1: result = 0xFFF...E; break; //updating network state for(i=0; i<hops; i++) { W1[R[src][dest][i]] &= result1; ⋮ W[W/64][R[src][dest][i]] &= result[W/64];}	t_{buffer}^{**} t_{mem} $2t_{mem} + t_{A/L} / 5t_{mem} + t_{A/L}$ ⋮ $2t_{mem} + t_{A/L} / 5t_{mem} + t_{A/L}$ $2t_{mem} + (3t_{mem} + 2t_{A/L}) \cdot hops$ $(11t_{mem} + t_{A/L}) \cdot hops$ ⋮ $(11t_{mem} + t_{A/L}) \cdot hops$

Table A.1. Code and execution time for SP-FF algorithm

(*) Code between lines marked with (*) must be executed k times in k -SP-FF algorithm

(**) Assuming a maximum of 256 nodes and 256 wavelengths and a memory buffer of 36bits width (for example, HITACHI SRAM HM66WP36512FP-40. 512 Kword x 36 bit). t_{buffer} : time to read/write in buffer memory

Considering the longest execution time, the sum of the execution time of every instruction gives the expression in equation (1) for the processing time C for k -SP-FF.

A.2.4. Adaptive Unconstrained Routing – Exhaustive (AUR-E) execution time

Table A.2 shows the execution time for AUR-E algorithm. Arrays T , R and H store the current topology (available links in every wavelength), routes available in every wavelength for the source node and number of hops in the obtained routes, respectively.

Code	Execution time
Definition of variables	
int T[W][N][N], R[W][N], H[W]; int hops, i, src, dest, wav;	
<i>t_{lightpath_scheduling}</i>	
//reading request from buffer read(src, dest); //Dijkstra algorithm for each wavelength dijkstra(src, dest, 0); ⋮	$t_{buffer}^{(*)}$ $t_{mem}(15N^2 + 12N + 24L + 15) + t_{A/L}(4N^2 + 4N + 2L - 3)^{(**)}$ ⋮

dijkstra (src,dest,W-1); //searching the shortest path wav=0; hops=H[0]; for(i=0;i<W;i++) if (H[i]<hops) { hops=H[i]; wav=i; } //sending message to source node write(src,dest,wav,hops,R[wav][1]); //updating network state; link length 999 means used if (hops<999) { for(i=0;i<hops;i++) T[wav][R[wav][i]][R[wav][i+1]]=999; }	$t_{mem}(15N^2+12N+24L+15)+t_{A/L}(4N^2+4N+2L-3)$ (**) $2t_{mem}$ $3t_{mem}$ $2t_{mem}+(3t_{mem}+2t_{A/L})W$ $(3t_{mem}+t_{A/L})W$ $3t_{mem}W$ $2t_{mem}W$ $2t_{buffer} (*)$ $3t_{mem}+t_{A/L}$ $2t_{mem}+(4t_{mem}+2t_{A/L})hops$ $(10t_{mem}+t_{A/L}) \bullet hops$
$t_{lightpath_release}$	
//reading release message from buffer read(src,dest,wav,hops,route) for(i=0;i<hops;i++) T[wav][route[i]][route[i+1]]=1;	$2t_{buffer} (*)$ $2t_{mem}+(3t_{mem}+2t_{A/L}) \bullet hops$ $(8t_{mem}+t_{A/L}) \bullet hops$

Table A.2. Code and execution time for AUR-E algorithm

(*) Assuming a maximum of 256 nodes and 256 wavelengths and a memory buffer of 36bits width (for example, HITACHI SRAM HM66WP36512FP-40. 512 Kword x 36 bit). t_{buffer} : time to read/write in buffer memory

(**) Dijkstra execution time details in section III.

Taking the longest execution time, the processing time C for AUR-E algorithm is given by equation (2). Considering a parallel execution of the Dijkstra algorithm (one processor per wavelength) the upper bound for the execution time is given by equation (3).

A.3. Execution time of the Dijkstra algorithm

Table A.3 shows the code for the Dijkstra algorithm implemented in the programming language C using static arrays (for the problem size considered in this work, static arrays achieve the fastest execution time). Since the Dijkstra algorithm consists of several loops, the second column denotes how many times a particular piece of code is executed.

The longest time required to perform the insertion procedure was considered. This occurs when an element is inserted in position 0 and the Core array holds $N-1$ elements and the time is given by $N(7t_{mem}+t_{A/L})+8 t_{mem} +2 t_{A/L}$. Multiplying the execution time of every piece of code by the number of times which must be executed, the worst case execution time for the Dijkstra algorithm is given by:

$$t_{mem}(15N^2+12N+24L+15)+t_{A/L}(4N^2+4N+2L-3)$$

A.4. Memory requirements

Considering the memory space used by every variable declared in the code of Table 1, the k-SP-FF DRWA algorithm requires a total memory space, M , of:

$$M_{k-SP-FF} = kN^2 \cdot (L+1) + 8 \cdot \left\lceil \frac{W}{64} \right\rceil \cdot (2L+1) + 5 \text{ (byte)}$$

With an analogous procedure for the AUR-E algorithm, the total memory requirement is given by:

$$M_{AUR-E} = WN^2 + W(N+1) + 4N + 9$$

Code	Execution time
Definition of variables	
int Result[N][3], Core[N]; int i, node, new_dist, pos_min=-1;	
Initialisation	Once
//initialisation of data structures for (i=0; i<N; i++) { Result[i][0]=0; //node not analyzed yet Result[i][1]=-1; //no predecessor yet Result[i][2]=15000; } // "∞" number of hops Core[0]=source; pos_min++; //-1 indicates end of elements Result[source][0]=1; Result[source][1]=source; Result[source][2]=0;	$2t_{mem} + N(3t_{mem} + 2t_{ALU})$ $4t_{mem}$ $4t_{mem}$ $4t_{mem}$ $3t_{mem}$ $t_{mem} + t_{ALU}$ $4t_{mem}$ $4t_{mem}$ $4t_{mem}$
Outer loop control	N times
//while there are elements in Core while(pos_min != -1)	$2t_{mem} + t_{ALU}$
Taking one element off the Core	N times
{ //picking the element in Core with the lowest number of hops to the source node=Core[pos_min]; pos_min--; //taking off the element	$3t_{mem}$ $t_{mem} + t_{ALU}$
Checking nodes at opposite end of node	N times
for (i=0; i<N; i++) {	$2t_{mem} + N(3t_{mem} + 2t_{ALU})$
Checking if node i is an opposite node	N² times
if (T[wav][node][i] != -1) //i is an opposite node {	$5t_{mem} + t_{ALU}$
Calculating distance for opposite node	L times
new_dist=Result[node][2]+T[wav][node][i]; //checking if node is visited by first time if (Result[i][0]==0)	$8t_{mem} + t_{ALU}$ $4t_{mem}$
Updating information about node i	(N-1) times
{Result[i][0]=1; Result[i][1]=node; Result[i][2]=new_dist;	$4t_{mem}$ $4t_{mem}$ $4t_{mem}$
Inserting one element in Core	(N-1) times
//inserting node in Core in an ordered way pos_min++; if (pos_min==0) Core[0]=new_node; else {i=0; while((core[i]>new_dist)&&(i>pos_min)) i++; for (j=pos_min; j>i; j--) Core[j]=core[j-1]; Core[i]=new_node; } //end of node insertion}	$t_{mem} + t_{ALU}$ $2t_{mem} + t_{ALU}$ $3t_{mem}$ $2t_{mem}$ $5t_{mem} + 3t_{ALU}$ $t_{mem} + t_{ALU}$ $2t_{mem} + (pos_min - i)(3t_{mem} + 2t_{ALU})$ $4t_{mem} + t_{ALU}$ $3t_{mem}$
Updating distance information	(L-N+1) times
else //node i has been visited before if (new_dist < Result[i][2]) { Result[i][1]=node; Result[i][2]=new_dist; } } //end if (T[wav][node][i] != -1) } //end for } //end while	$4t_{mem} + t_{ALU}$ $4t_{mem}$ $4t_{mem}$

Table A.3. Code and execution time for the Dijkstra algorithm

A.5. References

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