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Quality of Service Differentiation, Teletraffic Analysis and Network Layer Packet Redundancy in Optical Packet Switched Networks

Doctoral thesis
for the degree philosophiae doctor

Trondheim, May 2005

Norwegian University of Science and Technology

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Norwegian University of
Science and Technology

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ISBN 82-471-7127-9 (printed ver.)
ISBN 82-471-7126-0 (electronic ver.)
ISSN 1503-8181

Doctoral thesis 2005:122

Printed by NTNU trykk

Abstract

Optical Packet Switching (OPS) has emerged as a promising candidate for the next-generation Wavelength Division Multiplexed (WDM) based all-optical network. By enabling packet switching in the optical domain, OPS networks can provide cost-efficient and transparent transport services to higher layers. However, a commercial deployment of OPS requires not only a maturation of several key enabling technologies, but also a thorough investigation of a number of networking challenges related to OPS, since OPS networks are fundamentally different from today’s store-and-forward networks. This thesis addresses the latter issue by considering the following three OPS networking issues:

- Quality of Service (QoS) differentiation at the WDM layer, with focus on packet loss rate (PLR) and delay-jitter differentiation.
- Teletraffic analysis of OPS networks.
- How to combat packet loss in OPS networks by using network layer packet redundancy.

First, a crucial issue in OPS networks is packet loss at the network layer due to contention. Contention occurs when a packet is destined for a wavelength currently occupied by another packet. Several approaches to combat such packet loss have been proposed in recent literature, e.g. by utilizing wavelength conversion, buffering, deflection routing or traffic shaping.

This thesis considers a novel approach to combat packet loss in OPS: The proposed Network Layer Packet Redundancy Scheme (NLPRS) allows redundancy packets to be injected into the OPS network, thus enabling reconstruction of lost data packets at the OPS egress node. Results show that the NLPRS is able to reduce the end-to-end data PLR several orders of magnitude in an asynchronous OPS ring network with and without wavelength conversion.

Another crucial issue in OPS networks is QoS differentiation at the WDM layer. Due to the lack of optical random access memory, existing QoS differentiation schemes suitable for today’s WDM point-to-point architecture are not feasible to use in OPS networks. Hence, new schemes that utilize the WDM layer to provide QoS differentiation are needed.

A preemption based QoS differentiation scheme, the Preemptive Drop Policy (PDP), has been proposed for asynchronous bufferless OPS. With the PDP, high priority arrivals are allowed to preempt and take over a busy wavelength currently occupied by a low priority packet in the case of contention. This results in a lower PLR for high priority traffic compared to low priority traffic. The PDP has been extended into the Adaptive PDP (APDP), which provides absolute guarantees to the PLR for high priority traffic in OPS by using a measurement based preemption probability parameter adjustment.

An access-restriction based QoS differentiation scheme, the Wavelength Allocation algorithm (WA), has been studied. In the WA, which provides QoS differentiation in asynchronous bufferless OPS networks with full range output wavelength converters, a certain number of wavelengths at an output fibre are exclusively reserved for high priority traffic.

When QoS differentiation (with respect to the PLR) is introduced in asynchronous OPS, it has been shown that the average throughput decreases, often referred to as the throughput penalty of introducing QoS differentiation. The main cause for this throughput penalty is because network resources must be used in a non-optimal manner when employing QoS differentiation schemes that utilize the WDM layer to isolate the service classes. However, as shown in this thesis, the throughput penalty is only found in asynchronous OPS. For slotted OPS, the average throughput stays the same after the introduction of QoS differentiation.

An evaluation framework suitable for quantifying the throughput penalty when introducing QoS differentiation has been proposed. Using this framework, three fundamental different QoS differentiation schemes for asynchronous OPS, including the PDP and the WA, have been evaluated. It has been shown that preemptive techniques result in the lowest throughput penalty, followed by access-restriction and dropping based techniques. This is because, when using preemption, packets are dropped only when the output port is congested. With access-restriction, packets are dropped when the output port is highly strained, and with statistically packet dropping, packets are dropped independently of the state of the output port.

A QoS differentiation scheme for slotted OPS has been proposed and evaluated. The scheme isolates the service classes by ensuring that a certain number of high priority packets can be transmitted at an output port in a time-slot in the case of contention. Using the proposed scheme does not result in a reduced throughput when the service classes are isolated.

QoS differentiation schemes for asynchronous OPS with a share-per-node (SPN) contention resolution pool architecture consisting of Tunable Wavelength Converters (TWCs) and Fibre Delay Lines (FDLs) have been proposed. In particular, it has been shown that the PLR and delay-jitter may be independently differentiated in this switch architecture.

Analytical models of some of the proposed QoS differentiation schemes have been derived, providing explicit results of the PLR. In addition, an analytical framework regarding packet arrivals to an output port in an optical packet switch has been derived for both asynchronous and slotted OPS. This framework is particularly useful for studying the effects of non-uniform traffic. Furthermore, it has been shown that both the Erlang and Engset traffic models are suitable to model packet arrivals to an output port in an asynchronous optical packet switch. Regarding the Engset traffic model, it has been shown how the blocking probability can be evaluated using either the Engset lost calls cleared (LCC) traffic model or the Engset overflow (OFL) traffic model. For all Engset based traffic models, the time-, call- and traffic congestion have been derived. A numerical evaluation of the presented traffic models reveals that there is a small, but non-negligible, deviation between the observed blocking probabilities, which depends on the number of input/output fibres and the system load.

Preface

This dissertation is submitted in partial fulfillment of the requirements for the degree Philosophiae Doctor (PhD) at the Department of Telematics, Norwegian University of Science and Technology (NTNU). The presented work has been carried out in the period September 2002 – February 2005 at the Department of Telematics, and has been funded by Telenor R&D. My supervisors have been Associate Professor Norvald Stol at the Department of Telematics (NTNU), and Adjunct Professor Dag Roar Hjelme at the Department of Electronics and Telecommunications (NTNU). During the period September 2004 – October 2004, I spent one month at Research Centre COM at the Technical University of Denmark (DTU), where I was supervised by Associate Professor Villy B. Iversen.

I have participated in the European Network of Excellence (NoE) e-Photon/One, which started early 2004. In this project, I had the pleasure and opportunity to be a part of the advisory board for VD1. I have also been a Technical Program Committee member of the 3rd and 4th Workshop on All-Optical Routing (WAOR) 2004/2005.

The main part of this thesis consists of 9 papers published or submitted for publication in international journals and conferences. A number of these papers (5 in total) have been written in collaboration with other researchers. In the papers where I am the first author, I have contributed to all parts of the paper, including: defining the research hypothesis, developing the simulation- and/or analytical model, providing simulation- and/or analytical results, discussion of results, evaluating the research hypothesis, writing the paper, and presenting the paper (if it is a conference paper). However, in PAPER C, where I am the second author, my contributions include: defining the research hypothesis, discussion of simulation results, evaluating the research hypothesis, and writing the paper.

This thesis has been written in Microsoft Word, and the style used is adopted from the journal OSA Optics Express.

Acknowledgements

Several persons have helped me during the PhD period. First of all, I gratefully acknowledge my supervisor Associate Professor Norvald Stol at the Department of Telematics. Norvald has been an understanding and supportive mentor, and always available for discussions and questions. I am convinced that his advices and comments have significantly enhanced the quality of my work.

Thanks to Adjunct Professor Dag Roar Hjelme for being my co-supervisor, and for teaching me the basics of optical networking.

I wish to thank my colleagues at the Department of Telematics and at the Centre for Quantifiable Quality of Service in Communication Systems (Q2S), in particular Arne Lie, Professor Bjarne E. Helvik, Tønnes Brekne, Astrid Undset and Tor K. Moseng. Thanks to Randi Flønes, Pål Sæther and Asbjørn Karstensen for helping me with practical issues.

My sincere thanks go to Telenor R&D for funding my work, and to the people at Telenor R&D for showing interest in my work. In particular, my collaboration with Steinar Bjørnstad on the OpMiGua project has lead to many fruitful discussions. A special thanks goes to Martin Nord for collaboration on several papers, and for helping me out during my stay in Denmark.

I wish to express my sincere gratitude toward Professor Marian Marciniak at the National Institute of Telecommunications in Poland for kindly including me in the WAOR Technical Program Committee.

A sincere thanks goes to Associate Professor Villy B. Iversen for supervising me during my stay at Research Centre COM. Thanks to Tord Reistad and Andreas Kimsås for being supportive roommates and for proofreading this manuscript. Thanks to my family for being supportive through the PhD period. Last, but not least, big thanks to my girlfriend Janny for her love and support, and for always reminding me that there is more to life than writing a PhD thesis.

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List of papers

Table 1 lists papers published or submitted for publication that are included in part II of this thesis. Table 2 lists additional papers published as a part of my doctoral work, but not included in this thesis. The papers listed in Table 1 represent my main achievements, and have been selected in order to reduce the amount of overlap. The relation between all published papers can be found in section 2.4 in part I of this thesis.

PAPER A	H. Øverby, M. Nord, N. Stol, ”Evaluation of QoS differentiation mechanisms in asynchronous bufferless optical packet switched networks”, submitted to IEEE Communications Magazine, December 2004**.**
PAPER B	H. Øverby, N. Stol, ”Quality of Service in asynchronous bufferless optical packet switched networks”, Kluwer Telecommunication Systems 27(2-4) (2004) 151-179.
PAPER C	M. Nord, H. Øverby, “Packet loss rate and jitter differentiating Quality-of-Service schemes for asynchronous optical packet switches”, OSA Journal of Optical Networking 3(12) (2004) 866-881.
PAPER D	H. Øverby, “QoS in slotted bufferless optical packet switched networks”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 2, pp. 334-337, 2004.
PAPER E	H. Øverby, N. Stol, “Performance modelling of asynchronous bufferless optical packet switched networks”, submitted to Elsevier Optical Switching and Networking, December 2004.
PAPER F	H. Øverby, “Performance modelling of optical packet switched networks with the Engset traffic model”, accepted in OSA Optics Express, February 2005.
PAPER G	H. Øverby, N. Stol, “Effects of bursty traffic in service differentiated Optical Packet Switched networks”, OSA Optics Express 12(3) (2004) 410-415.
PAPER H	H. Øverby, “Performance modelling of synchronous bufferless OPS networks”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 22-28, 2004.
PAPER I	H. Øverby, “Network layer packet redundancy in optical packet switched networks”, OSA Optics Express 12(20) (2004) 4881-4895.

Table 1. An overview of the papers included in part II of this thesis.

[1] A. Undheim, H. Øverby, N. Stol, ”Absolute QoS in Synchronous Optical Packet Switched Networks”, in Proceedings of the Norwegian Informatics Conference (NIK), pp. 137-148, 2004.

[2] T. K. Moseng, H. Øverby, N. Stol, ”Merit based scheduling in asynchronous bufferless optical packet switched networks”, in Proceedings of the Norwegian Informatics Conference (NIK), pp. 126-136, 2004.

[3] H. Øverby, N. Stol, ”Exploiting network layer packet redundancy to reduce the end-to-end data packet loss rate in optical packet/burst switched networks”, in Proceedings of Nordic Teletraffic Seminar (NTS), pp. 335-346, 2004.

[4] H. Øverby, N. Stol, “Evaluating and Comparing Two Different Service Differentiation Methods for OPS: The Wavelength Allocation Algorithm and the Preemptive Drop Policy”, In Proceedings of the 3rd International Conference on Networking (ICN), vol. 1, pp. 8-15, 2004.

[5] H. Øverby, N. Stol, “Providing Quality of Service in Optical Packet/Burst Switched Networks with the Preemptive Drop Policy”, in Proceedings of the 3rd International Conference on Networking (ICN), vol. 1, pp. 312-319, 2004.

[6] H. Øverby, N. Stol, ”Effects of the switching time in OPS/OBS networks”, Chinese Optics Letters 2(3) (2004) 131-134.

[7] H. Øverby, “A Study on Service Differentiation in Bufferless Optical Packet/Burst Switched Networks”, in Proceedings of Norwegian Informatics Conference (NIK), pp. 105-116, 2003.

[8] H. Øverby, N. Stol, “A Teletraffic Model for Service Differentiation in OPS networks”, in Proceedings of Optoelectronic and Communications Conference (OECC), vol. 2, pp. 677-678, 2003.

[9] H. Øverby, “An Adaptive Service Differentiation Algorithm for Optical Packet Switched Networks”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 158-161, 2003.

Table 2. An overview of additional papers published as a part of my doctoral work, but not included in this thesis.

Abbreviations

AM	Arrival Model
APDP	Adaptive Preemptive Drop Policy
AQM	Active Queue Management
AR	Access Restriction
BE	Best Effort
BTB	Back-To-Back
CID	Class Isolation Degree
CoS	Class of Service
DEMOS	Discrete Event Modelling on Simula
DiffServ	Differentiated Services
DP	Data Packet
DPLR	Data Packet Loss Rate
DSL	Digital Subscriber Line
D-WRON	Dynamic Wavelength Routed Optical Networks
E/O	Electrical-to-Optical
EAAM	Engset Asymmetric Arrival Model
EBTB	Exponential Back-To-Back
EDFA	Erbium-Doped Fibre Amplifiers
ENAM	Engset Arrival Model
ENLAM	Engset Non-looping Arrival Model
ERAM	Erlang Arrival Model
FDL	Fibre Delay Line
FOWC	Full Output Wavelength Converter
Gbps	Gigabit per second
HP	High Priority
IF	Input Fibre
IntServ	Integrated Services
IP	Internet Protocol
IPD	Intentional Packet Dropping
ITU	International Telecommunication Union
IW	Input Wavelength
IWL	Input Wavelength

JET	Just-Enough-Time
JF	Jitter Free
JT	Jitter Tolerant
Kbps	Kilobit per second
LCC	Lost Calls Cleared
LP	Low Priority
Mbps	Megabit per second
NLPRS	Network Layer Packet Redundancy Scheme
NOWC	No Wavelength Conversion
NWC	No Wavelength Converter
O/E	Optical-to-Electrical
OBS	Optical Burst Switching
OF	Output Fibre
OFL	Overflow
OPLR	Overall Packet Loss Rate
OPS	Optical Packet Switching
OT	Offset Time
OW	Output Wavelength
OWL	Output Wavelength
PCT-I	Pure Chance Traffic Type I
PCT-II	Pure Chance Traffic Type II
PDP	Preemptive Drop Policy
PJF	Partially Jitter Free
PLD	Packet Length Distribution
PLR	Packet Loss Rate
QoS	Quality of Service
RAM	Random Access Memory
RP	Redundancy Packet
RPLR	Reference Packet Loss Rate
RPSM	Redundancy Packet Scheduling Mechanism
RT	Real Time
SDE	Service Differentiation Efficiency
SPN	Shared Per Node
S-WRON	Static Wavelength Routed Optical Networks
TAG	Tell-And-Go

TAW	Tell-And-Wait
Tbps	Terabit per second
TCP	Transmission Control Protocol
TRA	Transmit Right Away
TWC	Tunable Wavelength Converter
VoIP	Voice over IP
WA	Wavelength Allocation algorithm
WC	Wavelength Conversion
WDM	Wavelength Division Multiplexing
WR	Wavelength Routing
WRON	Wavelength Routed Optical Networks

PART I: INTRODUCTION

Part I: Introduction

During the last decade, optical networking has become a hot research topic, and has received much attention from research communities worldwide. In particular, research in the field of Optical Packet Switching (OPS) has received increased interest in recent years. At the component level, researchers have dealt with issues such as all-optical wavelength conversion [Ran04][Gam98], all-optical processing [Dor03], optical Random Access Memory (RAM) and construction of fast optical packet switches [Chi03]. This research is crucial in order to provide the building blocks needed to form a complete OPS network. As reported in [Bjø04], most of the key enabling technologies needed to form a complete OPS network have been demonstrated in a laboratory environment, except from all-optical processing and optical RAM, which is still in its infancy [Yao01b].

When these building blocks are put together to form a complete OPS network, networking challenges arise. These challenges include for instance how to combat packet loss due to contention [Yao03][Dan97] [Hun98][Tur99], how to support Quality of Service (QoS) differentiation at the WDM layer [Cal02][Øve04h][Nor04a], teletraffic analysis of OPS networks [Øve04e][Zuk03][Iza02], node design [Che04] [Che03b][Cal99b] [Zho03], network design [Cal97][Whi02a][Zal04], packet assembly [Vok02d] and control architectures [Mah01] [Xio00]. This thesis addresses some of the networking challenges faced in OPS networks, covered by the following three topics:

- QoS differentiation in OPS, with focus on packet loss rate (PLR) and delay-jitter differentiation.
- Teletraffic analysis of OPS.
- Network layer packet redundancy in OPS.

The thesis is divided into three parts: part I: Introduction, part II: Included papers, and part III: Appendices:

- The main part of this thesis, part II, constitutes 9 papers published or submitted for publication in international journals and conferences. The papers are termed PAPER A – PAPER I, and are listed on p. xvii.
- Part III includes a number of unpublished works and supplementary results to the papers in part II, termed APPENDIX A – APPENDIX F.
- Part I provides an overview to the works presented in part II and part III. First, in part I, section 1 presents the background and motivation for optical networking, where the aim is to highlight some of the challenges faced by the optical networking community today. Section 2 presents an outline of the topics covered by this thesis, the major contributions, and

an overview of the papers in part II. In particular, guidelines for reading are given in section 2.5. Section 3 presents related works. An overview of the research methodology is given in section 4. Section 5 presents a summary of each paper in part II. Finally, a conclusion is drawn in section 6, followed by proposals for future works in section 7.

1. Background and motivation

This section presents the background and motivation for optical networking, with focus on Optical Packet Switching (OPS). We start by addressing the need for all-optical networks in section 1.1, before we move on to describe the various all-optical network architectures proposed in recent literature in section 1.2. Section 1.3 gives an overview of how packet loss due to contention can be combated in OPS, while section 1.4 motivates for employing Quality of Service (QoS) differentiation at the WDM layer in OPS. Finally, section 1.5 states the rationale for teletraffic analysis regarding OPS.

1.1. Motivation for optical networking

During the last decade, we have experienced an explosive growth of the Internet traffic in the core networks. As reported in [Odl03], the Internet traffic has sustained a growth of 70 % - 150 % each year from 1997 to 2002. This growth is driven by a number of factors such as the increased number of Internet users, the increased popularity of the Internet, and the increased access network capacity [Per02]. For instance, as seen in Fig. 1, the total number of Internet users has increased significantly during the last decade, as reported by the International Telecommunication Union (ITU) [ITU04]. Furthermore, the migration from dial-up Internet connections with line speeds up to 128 Kbps, to Digital Subscriber Line (DSL) connections with line speeds up to several Mbps, has increased the potential amount of data generated by each user. As reported by the DSL Forum, the number of DSL subscribers worldwide reached 63.84 millions in December 2003, an annual growth of 77.8 % [DSL04].

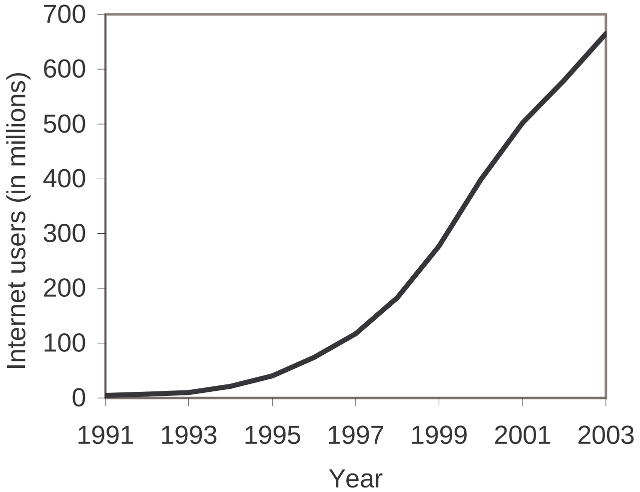

Fig. 1. The number of Internet users. Note that the value for 2002 is estimated and the value for 2003 is a forecast [ITU04].

Wavelength Division Multiplexing (WDM) has emerged as the most promising technology to satisfy the increasing capacity demands expected in future core networks [Mah01][Dit03]. With WDM, multiplexing of a high number of wavelengths is possible, leading to capacities of several Tbps in a single optical fibre. Today, WDM technology is utilized in a point-to-point architecture, which means that optical fibres (using WDM) are terminated by electronic routers. In such opaque optical networks, often referred to as *first-generation optical networks* [Her04], the signals undergo optical-electrical (O/E) and electrical-optical (E/O) conversions when entering and leaving the switches, respectively.

Due to a potential benefit of a more extensive use of optical technology, the research community has now turned their attention from optical transmission to optical networking, where the major aim is to move switching functionality from the electronic domain to the optical domain. Basically, this is achieved by replacing the electronic routers with all-optical switches, and thus removing the O/E/O conversions present in today’s WDM point-to-point architecture. This replacement enables *all-optical networking*[1], also referred to as *second-generation* or *third-generation optical networks*. The main benefits of *all-optical networks* over *first-generation optical networks* are:

- In all-optical networks, since the data is kept in the optical domain, expensive O/E and E/O converters are not needed, which contributes to a reduced switch hardware cost [Chi03].
- All-optical nodes may have less power consumption compared to first-generation optical nodes, since the O/E/O converters are removed [Dit03].
- All-optical networks are transparent, as opposed to opaque first-generation optical networks. This means greater flexibility regarding signal formats and bit-rates [Ram02], e.g. the bit-rate may be modified without replacing node equipment.
- Electronic routers have technological limits when it comes to handling high line speeds. Hence, in order to cope with the traffic volumes predicted in the future Internet, electronic routers must be built by cascading a number of smaller electronic routers. This cascading results in higher complexity, compared to a single router design, which leads to increased costs [Dit03][Kes03].

Looking at the above-mentioned factors, one can expect that the use of electronics results in an increased cost and less flexibility when the traffic volume in the core networks increases. In the future, this will make all-

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[1] In all-optical networks, at least in Optical Packet Switching, we assume electronic processing of the packet header, since optical processing is still in its infancy. However, in order to have “true” all-optical networks, the packet header should be processed optically.

optical networks increasingly attractive compared to first-generation optical networks [Dit03].

1.2. All-optical network architectures

All-optical networks include both *second-* and *third-generation optical networks*, as illustrated in Fig. 2. When we say *second-generation optical networks*, we mean Wavelength Routed Optical Networks (WRON) [Ram02], while *third-generation optical networks* usually refer to Optical Packet/Burst Switched networks (OPS/OBS). The next three sub-sections give an overview of these architectures, while section 1.2.4 presents a possible evolution scenario of all-optical networks.

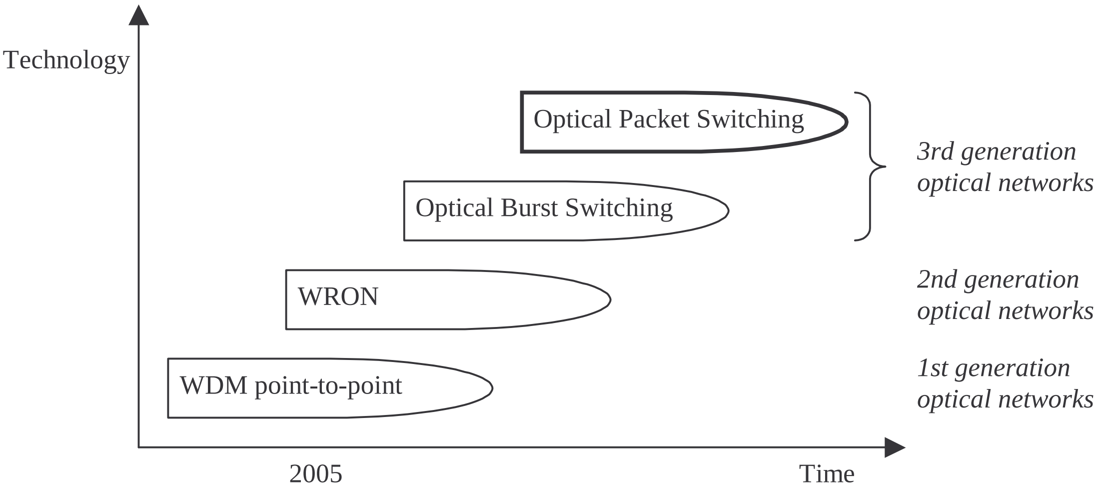

Fig. 2. Evolution of all-optical networks [Dol01].

1.2.1. Wavelength Routed Optical Networks (WRON)

In WRON, all-optical circuit switched connections, termed lightpaths, are established between edge nodes in the optical core network [Ram02]. When a lightpath is set-up, a dedicated wavelength on every link along the path the lightpath traverses, is reserved. With all-optical wavelength converters, the lightpath may be wavelength converted at intermediate nodes in order to reduce the number of physical wavelengths required [Ram02]. A lightpath is set-up before data transmission, and released when data transmission is completed. Hence, data transmitted on a lightpath between two edge nodes in a WRON needs no buffering, O/E/O conversion, nor processing at intermediate nodes. We often distinguish between static WRON (S-WRON) and dynamic WRON (D-WRON). In the former, lightpaths are set-up manually, and often last for several days or more. In the latter, lightpaths are automatically set-up according to traffic requests from higher layers. A major problem with WRON in general is non-optimal utilization of link resources, since there is no resource sharing among lightpaths traversing the same link. For instance, on a given link, one lightpath may be congested while other lightpaths traversing the same link may be under-utilized at the same time. A variant of WRON called “overspill routing” allows packets to be inserted at intermediate nodes of a lightpath [Che03d]. This technique enhances the performance of traditional WRON, since it benefits to some extent from statistical multiplexing.

1.2.2. Optical Packet Switched networks (OPS)

In OPS networks, packets are processed and forwarded hop-by-hop until they reach their destination node. An OPS network should be able to process, forward and buffer the packets entirely in the optical domain, which will make the network truly transparent [Mah01]. However, since optical processing is very primitive today, electronic processing of the packet header is envisaged until optical processing becomes mature. That is, when a packet arrives to an optical packet switch, the packet header is extracted and converted to the electronic domain for processing, while the packet payload is delayed using input FDLs [Bre03]. OPS benefits from statistical multiplexing, which ensures a better utilization of the network resources compared to a WRON. OPS networks operate in either asynchronous or synchronous mode [Nor03]. In asynchronous OPS, packets arrive at an optical core switch at non-deterministic instants. In synchronous OPS, packets arrive at an optical core switch in synchronized and equally spaced time slots. Synchronous OPS is sometimes referred to as slotted OPS. The impact of contention (see section 1.3) is generally less severe in slotted OPS compared to asynchronous OPS [Yao01a]. This is because the contention window is smaller in slotted OPS compared to asynchronous OPS, which is analogue to the performance difference found between slotted and non-slotted ALOHA [Tan96]. However, slotted OPS requires synchronization stages at each switch input, which increases the switch cost and complexity. In both asynchronous and slotted OPS networks the packets may be of variable- or fixed size [Nor03]. In slotted OPS with variable sized packets, a packet is a multiple of several time-slots, while in slotted OPS with fixed sized packets, a packet is contained in a single time-slot. Both fixed-sized and variable sized packet architectures in slotted OPS require a packet aggregation mechanism at the OPS ingress node. This is also required for asynchronous OPS with fixed sized packets. However, packet aggregation can be avoided in asynchronous OPS with variable sized packets, which makes it better suited for the variable packet lengths found in the Internet [Nor04d].

1.2.3. Optical Burst Switched networks (OBS)

In OBS networks, incoming packets from the access network are aggregated into bursts at an OBS ingress router based on the destination node and possibly the service class of the packets [Tur99][Yoo00a]. When a burst has reached a certain size, or when a timer has expired, the burst is sent into the OBS network and forwarded hop-by-hop in the optical domain until it reaches its destination node [Vok02d]. Several data channel scheduling schemes have been proposed for OBS [Xu01][Xio00]. In the Tell-And-Wait (TAW) scheme, when an OBS ingress router has a burst to send, a control packet is first transmitted to all intermediate nodes along the path to the destination node [Xu01]. The control packet reserves resources to accommodate for the burst on all intermediate nodes, and then reports to the OBS ingress router whether the resources have been reserved successfully or not. The transmission of the burst can only start when all required resources have been reserved successfully. Hence, with the TAW scheme there is no packet loss due to contention, however, the delay at the OBS ingress node may be significant, especially if the destination is far away from the source. In the Tell-And-Go (TAG) scheme, the burst is transmitted immediately after the control packet (i.e. back-to-back) [Xu01]. When arriving to an intermediate node, the control packet attempts to reserve the necessary resources to schedule the burst. Meanwhile, the burst is typically delayed in the optical domain using input FDLs. From a network layer perspective, scheduling using the TAG scheme is similar to scheduling in OPS (except that a burst and not a packet is scheduled). Another much studied scheduling scheme is the Just-Enough-Time (JET) scheme. Here, right after the control packet has been transmitted, the burst waits a certain amount of time, called the Offset Time (OT), before it is transmitted. The control header attempts to reserve resources for the burst at intermediate nodes [Yoo02][Xu01]. Since the OT is typically larger than the time it takes to process the control packet at the intermediate nodes, the burst does not need to be buffered at intermediate nodes, which means that input FDLs are not required when using the JET scheme. As in the TAG scheme, packets may be dropped due to contentions. The JET scheme has many similarities with the TAG scheme, at least from a traffic modeling perspective. That is, exactly the same analytical models may be used to evaluate OBS employing the JET scheme [Yoo00a] and the TAG scheme [Tur99]. The JET scheme may be utilized to provide QoS differentiation by assigning different OT to the various service classes [Yoo00a]. This QoS differentiation scheme has also been adapted to OPS [Kim02].

1.2.4. All-optical networks evolution

Figure 2 shows a possible evolution scenario from first-generation optical networks, to the all-optical network architectures described in sections 1.2.1-1.2.3 [Dol01]. WRON is likely to be the next step in the evolution, since the enabling technologies required for WRON are more mature compared to third-generation optical networks. For instance, since lightpaths are set-up on a time-scale of seconds or longer, the switching requirement for WRON is in the order of ms, which is commercially available today.

The next step in this evolution may be third-generation optical networks. Compared to WRON, third-generation optical networks benefit from statistical resource sharing and finer switching granularity, which results in a more efficient utilization of network resources. Furthermore, OPS/OBS have benefits over WRON regarding resilience, since it is easier to share resources in packet switching compared to circuit switching [Dit03].

However, third-generation optical networks impose harder technological requirements on processing, switching matrix, wavelength conversion and possibly buffering. E.g., for OPS, the switching time should be much smaller than the duration of an OPS packet [Øve04f]. For instance, a 1500 byte packet on a 10 Gbps link has a duration of 1.2 μs, which means that the required switching time for OPS should be in the ns time scale. The switching time requirement for OBS is not so strict (usually on the μs time-scale), since a burst is generally 1-3 orders of magnitude longer than a packet.

This thesis investigates three OPS networking issues, introduced in the next three sections.

1.3. How can packet loss be combated in OPS networks?

A crucial issue in OPS networks is packet loss at the network layer due to contention [Yao03]. In asynchronous OPS, contention occurs when a packet is destined to an output wavelength that is currently transmitting another packet. In slotted OPS, contention occurs when two or more packets are destined for the same output wavelength in the same time-slot. In both cases, contending packets will be dropped and contribute to an increased packet loss rate (PLR) unless mechanisms to combat such packet loss are employed. In general, the PLR increase due to contention is mainly governed by the frequency of contentions and the average number of packets lost each time a contention occurs.

In order to combat such packet loss, two general approaches may be utilized:

- **Contention resolution:** By using contention resolution [Yao03], the PLR is decreased by reducing the average number of packets lost when contention occurs. That is, contending packets are either converted to an idle wavelength and transmitted on the intended fibre, delayed in time and scheduled to the intended wavelength when it becomes free, or transmitted on the same wavelength, but on another fibre. These mechanisms are presented in section 1.3.1.

- **Intelligent packet loss combating mechanisms:** This category includes a number of packet loss combating mechanisms that utilize intelligent network behavior to reduce the PLR. These mechanisms are different from contention resolution, since no effort is being made to reduce the number of packets lost when contention occurs. A number of these approaches are presented in section 1.3.2.

1.3.1. Contention resolution mechanisms

The contention resolution mechanisms proposed in recent literature can be grouped into the following three domains [Gau02][Yao03]:

- **Wavelength domain:** When utilizing the wavelength domain for contention resolution, in the case of asynchronous OPS, the contending packet is converted to an idle wavelength on the same fibre and immediately transmitted [Tur99]. In slotted OPS, one packet is transmitted on the wavelength the packets contended for, while the rest of the packets are converted to idle wavelengths on the same fibre, and transmitted in the same time-slot [Dan98a]. In order to realize such wavelength conversion in the optical domain, all-optical wavelength converters are required [Ran04]. Wavelength converters may be placed at each output wavelength [Yoo00a], or in a pool shared by all output wavelengths [Gau02][Era00]. Furthermore, wavelength converters may either be full range converters, which means that they can convert to any output wavelength, or limited range wavelength converters [She01][Era04], which means that they can convert to a subset of available wavelengths.
- **Time domain:** When utilizing the time domain for contention resolution, contending packets are delayed using FDLs or electronic buffers, and attempt to seize the same wavelength a later point in time. Shared electronic buffering has been proposed in [Bjø02b]. Buffering using FDLs has been studied in e.g. [Hun98]. The FDLs may be placed at the output ports [Yoo00a] or in a pool shared by all output ports [Gau02].
- **Space domain:** When utilizing the space domain for contention resolution, contending packets are transmitted on the same physical wavelength, but on another fibre where the intended wavelength is free [Che03a][Bon99]. This fibre may lead to another destination than the original fibre, which means that the packet takes an alternative route to its destination. This may lead to additional delay, and increased load in the network since (generally) deflected packets follow a non-optimal route. This technique is also referred to as deflection routing [Che03a] or hot-potato routing [Bon99].

In OBS networks, segmentation may be used to reduce packet loss in the case of contention [Vok03b][Det02b][Vok02c]. Here, only the contending part of the burst is dropped instead of the whole burst.

A key issue is that the wavelength- time- and space domains are orthogonal, which means that any technique from any domain can be combined. This results in a potential high number of different contention resolution schemes.

1.3.2. Intelligent packet loss combating mechanisms

The packet loss combating approaches described in this section include a number of functionally very different techniques. All they have in common is that they do not attempt to resolve contentions as they occur, but attempt to reduce the PLR by using intelligent network behavior.

In [Maa04], the PLR is kept below an upper limit by utilizing an adaptive rate control algorithm. Here, the PLR is continuously monitored, and as long as the PLR is within an acceptable limit, all traffic is admitted to the network. However, if the PLR is above the pre-set limit, the senders are informed to reduce their transmission rate in order to reduce the load on the network. Such rate-adaptive algorithms have also been studied for store-and-forward networks [Lie04][Aus04].

The authors of [Xue02] investigate the gain from shaping self-similar traffic to make it less bursty at an OPS ingress node, since reduced burstiness generally results in a reduced PLR (see [Lel94] and [Pax95] for a thorough treatment of self-similarity in the Internet). They show that using a combination of time-based and threshold-based aggregation can reduce the PLR, but only to a limited extent. A study on how a time-based aggregation algorithm reduces the self-similarity is performed in [Ge00]. They concluded that the Hurst parameter[2] is reduced as the shaping algorithm is applied, which results in a reduced PLR. This result is also obtained in [Hu03]. However, [Hu03] also show that using a threshold-based aggregation mechanism does not make the traffic pattern less self-similar.

The use of a hop-based or merit-based priority scheme for reducing the overall network PLR has been examined in [Whi02d][Kim02][Mos04]. In these studies, in the case of contention, the packets that have traversed the highest number of links [Kim02][Mos04] or achieved the highest merit [Whi02d], are given priority. The priority mechanism is enabled by using preemption [Whi02d] [Mos04] or Offset Time (OT) [Kim02]. It has been shown that using this approach leads to a reduced overall network PLR, in particular if the system load is high, but only to a limited extent [Mos04].

A challenge regarding how to combat packet loss in OPS is how efficient the various approaches are depending on network parameters such as system load, number of wavelengths per fibre, network topology etc. Such a study is crucial in order to provide network operators and switch designers the necessary information for choosing an optimal contention resolution architecture for future OPS. Possible novel approaches to combat packet loss should be examined as well, in order to complement existing mechanisms.

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[2] The Hurst parameter is a measure of the degree of self-similarity of the arrival process.

1.4. Quality of Service differentiation in OPS networks

Quality of Service (QoS) is a broad term, which has many interpretations [Ems00]. In this thesis, we adopt the definition used by [Ems00], where a service has a set of QoS parameters with specified values. The considered service in this thesis is delivery of packets to the correct destination, and the quality of this service is described by its performance, dependability and security. This definition of QoS is quite similar to the term ‘network performance’ in [Ive99]. In this thesis we focus performance-related issues, where the most significant QoS parameters (or at least the QoS parameters most addressed in the context of optical networking [Tur99][Yoo00a][Vok03c][Yao03]) include the packet loss rate (PLR), throughput, delay and delay-jitter. That is, when we talk about the quality of a service (i.e. the QoS), we focus on the quantitative values of the above-mentioned QoS parameters regarding the considered service. Furthermore, when we later address the issue ‘QoS differentiation’, we mean differentiated traffic handling that aim to achieve different values of one or more QoS parameters (i.e. the PLR or delay-jitter) among a set of service classes or traffic flows. A similar definition of QoS differentiation has also been adopted by [Zha04].

Today’s Internet provides only the best-effort service, where each packet is handled equally and as good as possible given available resources [Xia99]. This means that no guarantees can be given regarding the PLR, delay or delay jitter. The best-effort service works fine when there are enough resources available. However, when network resources become scarce, all traffic in the network will be equally degraded since there is no differentiation between the traffic. We believe that future OPS networks should support QoS differentiation for two major reasons:

- In future core networks based on IP technology, a growing number of real-time and interactive Internet applications are expected to emerge. These applications include e.g. Voice-over-IP (VoIP), video-on-demand, online gaming and video-conferencing. Also, as the networks become increasingly data centric, we see that mission critical services such as emergency services and business services become packet based. As both of these types of services demand a stricter QoS than the current best-effort service can offer, QoS differentiation should be supported in OPS [Xia99]. Another approach to solve this problem is over-provisioning of network resources, but this is not a future-proof solution, as argued in [Bon02].

- Although the best-effort service is not suited to carry real-time, interactive or mission-critical applications, it is well suited for web browsing, file transfers and other services that are either not packet loss or delay sensitive. As demanded by economics, we should strive for an optimal utilization of network resources, which means that each service

> should receive the needed amount of QoS and nothing more. That is, increasing the offered QoS beyond the demanded level will increase the cost and the use of resources, but not the user-perceived quality. Hence, in order to tailor the offered QoS to each application, QoS differentiation should be supported in OPS [Chr03a]. However, note that this is only beneficial when the cost of the QoS differentiation does not exceed the gains from the QoS tailoring.

QoS differentiation can be provided based on a per-flow or on a per-class classification of the traffic [Chr03a], analogue to the IETF IntServ [Bra94] and DiffServ [Bla98] architectures, respectively. With a per-flow classification, admitted traffic flows are differentiated and given appropriate network resources based on the application requirements. In the core network where thousands of flows are aggregated, per-flow classification results in an enormous overhead and state information. In order to avoid this, a per-class classification may be utilized. Here, admitted traffic is grouped into a finite set of service classes, which are managed according to their service class only. In this thesis, we focus on a per-class classification of the traffic.

In the per-class architecture, QoS parameters can be expressed as relative- or absolute guarantees. Relative guarantees can further be divided into qualitative guarantees and proportional guarantees [Chr03a]. With relative qualitative guarantees, the QoS parameters of the various classes are qualitatively ordered, e.g. PLR for class 0 traffic < PLR for class 1 traffic. With relative proportional guarantees, QoS parameters of a certain class are given quantitatively relative to another class, e.g. PLR for class 1 traffic / PLR for class 0 traffic = 10^2. With absolute guarantees, QoS parameters of a certain class are given upper bounds, e.g. PLR for class 0 traffic < 10^{-4}. As argued by [Chr03a], absolute guarantees are crucial for the successful operation of interactive applications, multimedia applications and mission-critical applications.

Existing QoS differentiation schemes for traditional store-and-forward networks mandate the use of buffers to isolate the different traffic classes, i.e. by the use of Active Queue Management (AQM) algorithms [Wyd02][Chr03b]. Here, all packet arrivals to a switch are stored in an electronic buffer and managed according to an AQM algorithm. However, as pointed out by [Yoo00a], such schemes are not suitable for the WDM layer. First, electronic buffering necessitates the use of O/E and E/O converters, which results in a significant increase in the switch cost and loss of data transparency. Second, although optical buffering can be realized by utilizing Fibre Delay Lines (FDLs), this approach can only give limited buffering capabilities compared to electronic buffering, because data is delayed by traversing a fixed length optical fibre. As pointed out by [Yoo00a], we must utilize the WDM layer in order to isolate the different service classes in future OPS networks.

In recent research we find several proposals for QoS differentiation schemes with focus on PLR differentiation for OPS (and OBS) [Nor03]. These schemes can be based on preemption, access-restriction or intentional packet dropping, as detailed in PAPER A on p. 63 in this thesis.

A crucial issue when introducing QoS differentiation in asynchronous OPS, is the associated reduction in the average throughput as the isolation between the service classes increases. This throughput penalty is due to the non-optimal resource utilization required when utilizing the WDM layer to isolate the service classes [Øve04b][Zha03b].

To summarize this section, we see that there are several challenges related to QoS differentiation in OPS:

- How to provide QoS differentiation in OPS by utilizing the WDM layer is highly dependent on the contention resolution architecture used. For instance, access restriction may be given to e.g. output wavelengths, wavelength converters and buffering slots. Hence, as only a subset of the possible contention architectures has been considered for QoS differentiation, further research on the various types of QoS differentiation schemes for OPS is needed.
- The various QoS differentiation schemes may have different throughput penalties. First, there is a need to quantify the throughput penalty, in order to have a fair comparison between proposed QoS differentiation schemes. Second, a performance evaluation and comparison of the various QoS differentiation schemes regarding the throughput penalty should be performed.
- Most proposals for QoS differentiation in OPS and OBS provide relative QoS guarantees. However, in order to provide a guaranteed level of performance of a service, absolute QoS should be offered.

1.5. Teletraffic analysis of OPS networks

Future OPS networks will be different from today’s WDM point-point architecture, also from a teletraffic analysis point of view. Basically, today’s store-and-forward networks are modeled as delay systems [Ive99], while OPS networks are modeled as loss systems [Tur99][Dan98a]. This is a simplification of the reality, since packet loss may occur in store-and-forward networks due to e.g. buffer overflow, and queuing delay may occur in OPS from e.g. FDLs and OPS ingress buffering. However, generally regarding OPS, it has been shown that the delay contribution from buffers is negligible, even when the time domain is utilized to resolve contentions [Bjø02b][Yoo00a]. Note, however, that although the delay is negligible, the relative delay-jitter may be significant, as argued in [Nor04d].

A challenge in OPS is to provide accurate analytical models for network layer related issues [Rob01]. Several models that capture the effects of wavelength conversion [Tur99][Dan97], buffering [Tur99][Hlu88], and deflection routing [Che03a] have already been proposed. However, there is a lack of models that capture the effects of QoS differentiation.

Moreover, it is important to clearly distinguish asynchronous and slotted OPS, since these two architectures have different modeling approaches. More exactly, asynchronous OPS is modeled using continuous-time Markov chains, while slotted OPS is modeled using discrete-time Markov chains. For each architecture, there are several ways of modeling packet arrivals to an output port in an optical packet switch, as will be shown later in this thesis.

During the last decade, there has been much debate regarding arrival processes in the core networks. Earlier works suggested that the Internet traffic had a self-similar pattern, that is, the traffic appears to be equally bursty when viewed over different time-scales [Lel94][Pax95]. However, as these results were based on measurements of the Internet over a decade ago, they may not be valid today. Results from a more recent measurement study of the Internet core network has been presented in [Kar04], where it was shown that the Internet traffic in the core networks is more Poisson like than suggested by [Lel94]. More exactly, on a sub-second time-scale, the packet inter-arrival times are close to being exponentially distributed, while on a multi-second timescale, the arrival process is well modeled using a time-dependent Poisson process. Similar results are also found in [Iza02] and [Arv99].

2. Thesis topic, contributions and limitations

This thesis addresses several OPS networking issues. The main contributions are found in the papers and appendices included in part II and part III, respectively. The papers are termed PAPER A – PAPER I, and correspond to the references in the bibliography, given in Table 3. We use the terms PAPER A – PAPER I instead of the bibliographical references, when referring to these works. The appendices include a number of non-published works and additional results to the papers in part II, and are termed APPENDIX A – APPENDIX F.

The issues addressed in this thesis are structured into three topics: “QoS differentiation in OPS”, “Teletraffic analysis of OPS”, and “Network layer packet redundancy in OPS”. Each topic is covered by a number of papers and appendices, as seen in Table 4. The topics “Network layer packet redundancy in OPS” and “QoS differentiation in OPS” do not overlap, while the topic “Teletraffic analysis of OPS” has some overlap with the two other topics, as seen in Fig. 3.

	Reference in the bibliography	Comment	Contribution covered
PAPER A	n/a[3]	Journal paper	C1,C2
PAPER B	[Øve04h]	Journal paper	C1,C3,C5
PAPER C	[Nor04d]	Journal paper, co-author	C2,C4
PAPER D	[Øve04d]	Conference paper	C1,C5
PAPER E	n/a[3]	Journal paper	C6
PAPER F	n/a[3]	Journal paper	C6
PAPER G	[Øve04g]	Journal paper	C5
PAPER H	[Øve04e]	Conference paper, invited talk	C7
PAPER I	[Øve04i]	Journal paper	C8,C9
APPENDIX A	n/a[4]	Additional material to PAPER A	C5
APPENDIX B	n/a[4]	Additional material to PAPER D	C1,C5
APPENDIX C	n/a[4]	Additional material to PAPER H	C7
APPENDIX D	n/a[4]	Additional material to PAPER H	C7
APPENDIX E	n/a[4]	Additional material to PAPER I	C8
APPENDIX F	n/a[4]	Additional material to section 4 in part I: Research methodology	-

Table 3. Overview of included papers and appendices. The full reference of the papers can be found on p. xvii.

There are 9 major contributions in this thesis, identified as C1-C9, which will be detailed in the following sub-sections. Each contribution concerns one or two topics, as seen in Fig. 3, and is addressed by a number of papers and appendices, as seen in Table 3. For instance, contribution C4 concerns the topic “QoS differentiation in OPS” and is covered by PAPER C only,

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[3] This material has been submitted, but not published, and has therefore no reference in the bibliography.

[4] This material has not been submitted for publication.

while contribution C5 concerns both the topics “QoS differentiation in OPS” and “Teletraffic analysis of OPS” and is covered by PAPER B, PAPER D, PAPER G, APPENDIX A and APPENDIX B.

	Covered by	
Topic	PAPER	APPENDIX
QoS differentiation in OPS	*A,B,C,D,(G)*	*A,B*
Teletraffic analysis of OPS	*E,F,G,H,(B,D,I)*	*C,D*
Network layer packet redundancy in OPS	*I*	*E*

Table 4. Overview of the topics in this thesis, and which papers/appendices that are covered within each topic.

In sections 2.1-2.3, we provide an overview of the three topics, where the aim is to introduce the reader to the topic in general, as well as stating the main contributions within each topic. Summary and main contributions of each paper can be found in section 5. Hence, overlap between section 2 and 5 is unavoidable. In section 2.4, relation and overlap between all published papers are presented. Section 2.5 presents suggested reading guidelines. At last, the limitations of the work presented in this dissertation can be found in section 2.6.

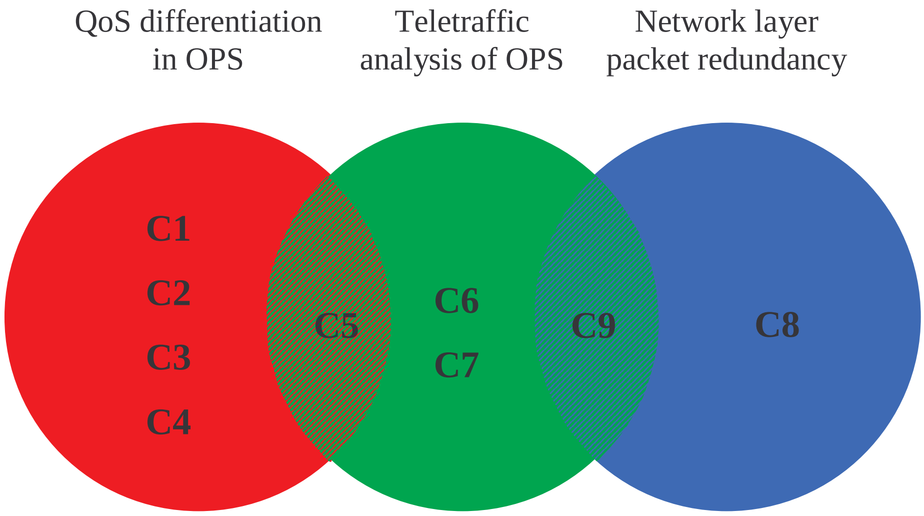

Fig. 3. Illustration of how the different contributions are covered by the various topics.

2.1. Quality of Service differentiation in OPS

As identified in section 1.4, there are several challenges related to Quality of Service (QoS) differentiation in OPS, where some of these challenges have been addressed in this thesis.

Two QoS differentiation schemes for asynchronous OPS have been studied, that is, the Preemptive Drop Policy (PDP) and the Wavelength Allocation algorithm (WA). The PDP provides QoS differentiation with respect to the packet loss rate (PLR) in asynchronous bufferless OPS with and without wavelength conversion by allowing a high priority arrival to preempt and take over a wavelength currently occupied by a low priority packet. The PDP has been extended into the Adaptive PDP (APDP), which provides absolute guarantees to the PLR in asynchronous bufferless OPS. That is, by enabling a measurement based preemption probability parameter adjustment, an upper bound for the PLR for high priority traffic can be statistically guaranteed. The PDP is presented in both PAPER A and PAPER B, while the APDP and analytical models of the PDP is found in PAPER B only.

The WA provides QoS differentiation with respect to the PLR in asynchronous OPS with full wavelength conversion by reserving a certain number of wavelengths for high priority traffic. The WA is presented in PAPER A, and an analytical model of the WA can be found in APPENDIX A. PAPER G presents an analytical model of the WA in the case of a hyper-exponential arrival process.

A major challenge related to QoS differentiation in OPS is how to quantify the throughput penalty when introducing QoS differentiation in asynchronous OPS. This has been addressed in PAPER A, by presenting a quantitative evaluation framework for measuring the throughput penalty as a function of the isolation degree, in the case of two service classes. This framework has been applied to evaluate the throughput penalty when using the PDP, WA and the Intentional Packet Dropping scheme (IPD) for QoS differentiation in asynchronous bufferless OPS with full-range output wavelength conversion.

Several QoS differentiation schemes for asynchronous OPS employing a shared contention resolution pool consisting of tunable wavelength converters and FDLs are presented in PAPER C. Here, QoS differentiation with respect to the PLR and delay-jitter is achieved by utilizing a combined access-restriction to wavelengths, wavelength converters and FDLs. Also, the throughput penalty of the proposed schemes is considered.

A QoS differentiation scheme for slotted OPS is presented in PAPER D, and an extended analytical model of this scheme can be found in APPENDIX B.

Within the topic “QoS differentiation in OPS”, the major contributions include:

C1. Performance of QoS differentiation schemes for asynchronous and slotted OPS has been studied. Regarding asynchronous OPS, it has been shown that preemption and access-restriction based QoS differentiation schemes are suitable to isolate service classes at the WDM layer. Regarding slotted bufferless OPS, it has been shown that QoS differentiation can be provided by ensuring that a certain number of high priority packets can be transmitted in a single time-slot in the case of contention.

C2. It has been shown that QoS differentiation in asynchronous OPS leads to a throughput penalty as the isolation degree between the service classes increases, whereas the various QoS differentiation mechanisms have different penalty. A quantitative evaluation of the PDP, WA and the IPD showed that the PDP has the least throughput penalty, followed by the WA and the IPD. In slotted OPS, the proposed QoS differentiation scheme does not result in a throughput penalty when the isolation degree between the service classes increases.

C3. By using the Adaptive PDP (APDP), absolute guarantees to the PLR can be achieved in asynchronous bufferless OPS. It has been shown that the APDP operates properly in a changing system load scenario.

C4. It has been shown that the packet loss rate (PLR) and delay jitter are orthogonal QoS parameters regarding asynchronous OPS with a shared contention resolution pool consisting of tunable wavelength converters (TWCs) and fibre delay lines (FDLs). That is, the service classes may be differentiated based on different PLRs and delay jitter. This is achieved by utilizing a combined access-restriction to wavelengths, wavelength converters and FDLs.

C5. Analytical models of the WA, PDP, IPD, and the QoS differentiation scheme for slotted OPS have been proposed and validated using simulations. In particular, an analytical model of the WA with a hyper-exponential arrival process has been proposed.

2.2. Teletraffic analysis of OPS

There are several challenges related to teletraffic analysis of OPS, as indicated in section 1.5. This thesis has focused on general traffic models for OPS, analytical models for various QoS differentiation schemes, and an analytical model of the Network Layer Packet Redundancy Scheme (NLPRS). PAPER E presents various Erlang and Engset based traffic models suitable for asynchronous OPS. In particular, the Engset arrival model (ENAM), the Engset non-looping arrival model (ENLAM), and the Engset asymmetric arrival model (EAAM), which are all based on the Engset lost calls cleared (LCC) traffic model, have been presented. PAPER F extends PAPER E by presenting arrival models for asynchronous OPS based on the Engset overflow (OFL) traffic model. For all Engset based traffic models, the time-, call-, and traffic congestion are derived. As seen in Fig. 4, a crucial observation is that the choice of traffic model, performance metric and routing operation is orthogonal. This leads to a high number of combinations regarding how to evaluate the blocking probability in asynchronous OPS using the Engset traffic model, where only a subset of the possible combinations have been addressed in this thesis. In PAPER H, traffic models for slotted OPS with full wavelength conversion have been presented. Additional results to PAPER H can be found in APPENDIX C and APPENDIX D. In particular, the latter appendix considers traffic models for slotted OPS without wavelength conversion.

The QoS differentiation schemes presented in the previous section have all been modeled using teletraffic theory, as stated in contribution C5. At last, PAPER I presents an analytical model of the NLPRS, based on Erlang reduced load fixed point analysis, as stated in contribution C9.

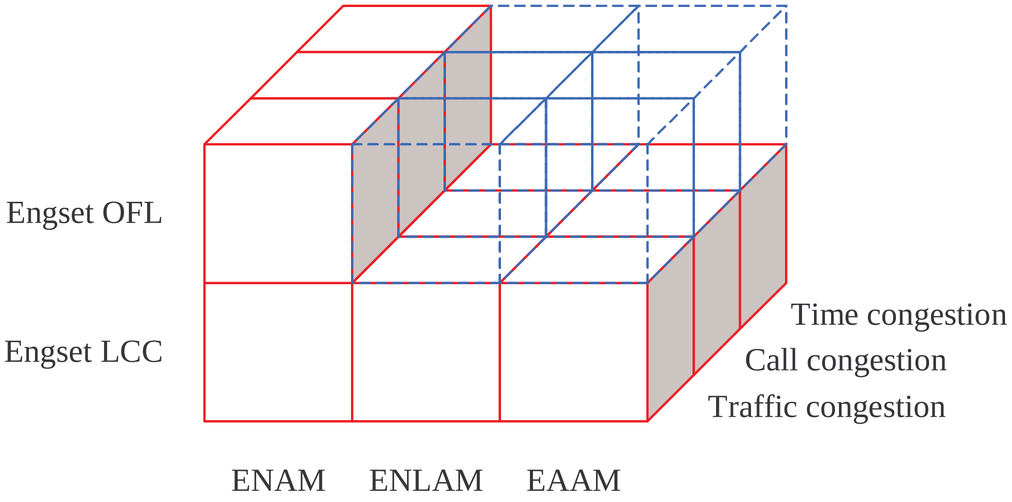

Fig. 4. Overview of the various Engset based traffic models suitable for asynchronous OPS. The red bold-lined boxes illustrate the possible combinations considered in this thesis, while the blue dotted lines illustrate combinations left for future research.

The major contributions within this topic include:

C6. Several traffic models for asynchronous OPS, including both Erlang and Engset based traffic models, have been presented. Regarding the Engset based traffic models, both the Engset LCC and Engset OFL traffic model have been considered, as well as the ENAM, ENLAM and EAAM scenarios. For all Engset based traffic models, the time-, call-, and traffic congestion is derived. The blocking probability may be evaluated using any combination of traffic model, performance metric and assumed traffic pattern, as illustrated in Fig. 4. It has been shown that the choice of traffic model and performance metric influences the observed blocking probability. In particular, the Engset OFL traffic model is shown to be the most accurate, followed by the Engset LCC traffic model and the Erlang traffic model. On the other hand, the Erlang traffic model is the least complex of these traffic models, followed by the Engset LCC and the Engset OFL traffic model.

C7. Several traffic models for slotted OPS have been presented. These models include the Asymmetric arrival model, the Binomial arrival model, the Binomial Non-looping arrival model and the Poisson arrival model. It has been shown that the choice of traffic model influences the observed blocking probability. In particular, the Binomial arrival model is shown to be the most accurate, followed by the Poisson arrival model. On the other hand, the Poisson arrival model is the least complex of these models, followed by the Binomial arrival model.

2.3. Network layer packet redundancy in OPS

As seen in section 1.3, there are several approaches to combat packet loss in OPS. In this thesis, we introduce a novel scheme, the Network Layer Packet Redundancy Scheme (NLPRS), which utilizes redundancy in order to reduce the end-to-end data PLR in OPS networks.

The NLPRS is presented in PAPER I, which considers an asynchronous OPS ring network with full wavelength conversion. An extension to PAPER I, which considers the NLPRS performance in an asynchronous OPS ring network without wavelength conversion, is found in APPENDIX E. The major contributions are:

C8. It has been shown that packet redundancy at the network layer is a viable approach to reduce the end-to-end data PLR in asynchronous OPS with and without wavelength conversion. In particular, the efficiency of the NLPRS is dependent on the number of data- and redundancy packets in a packet set, the system load, network size, data packet arrival process, redundancy packet scheduling mechanism and packet length distribution. The NLPRS performance degrades with increased system load, with increased network size, and with increased burstiness of the data packet arrival process. However, the NLPRS is able to reduce the end-to-end data PLR several orders of magnitude in OPS ring networks (with wavelength conversion) with less than 7 nodes when the normalized system load is 0.30 or less. For networks without wavelength conversion, the NLPRS is efficient when the system load is less than 0.15. Although this limits the scheme’s applicability, note that many of today’s IP networks are lightly loaded. Hence, the NLPRS is attractive if “over dimensioning” of WDM resources is cheaper than deploying extensive resources for contention resolution.

C9. An analytical model of the NLPRS based on Erlang reduced load fixed point analysis has been presented. The observed deviation between the analytical and simulation results is mainly due to the increased burstiness caused by the redundancy packets, which is not reflected in the analytical model.

2.4. Relation and overlap between published papers

A complete list of papers published as a part of this thesis can be found on p. xvii-xviii. However, as the papers included in part II are only a subset of the total number of published papers, this section will show how all the published papers are related, as illustrated in Fig. 5.

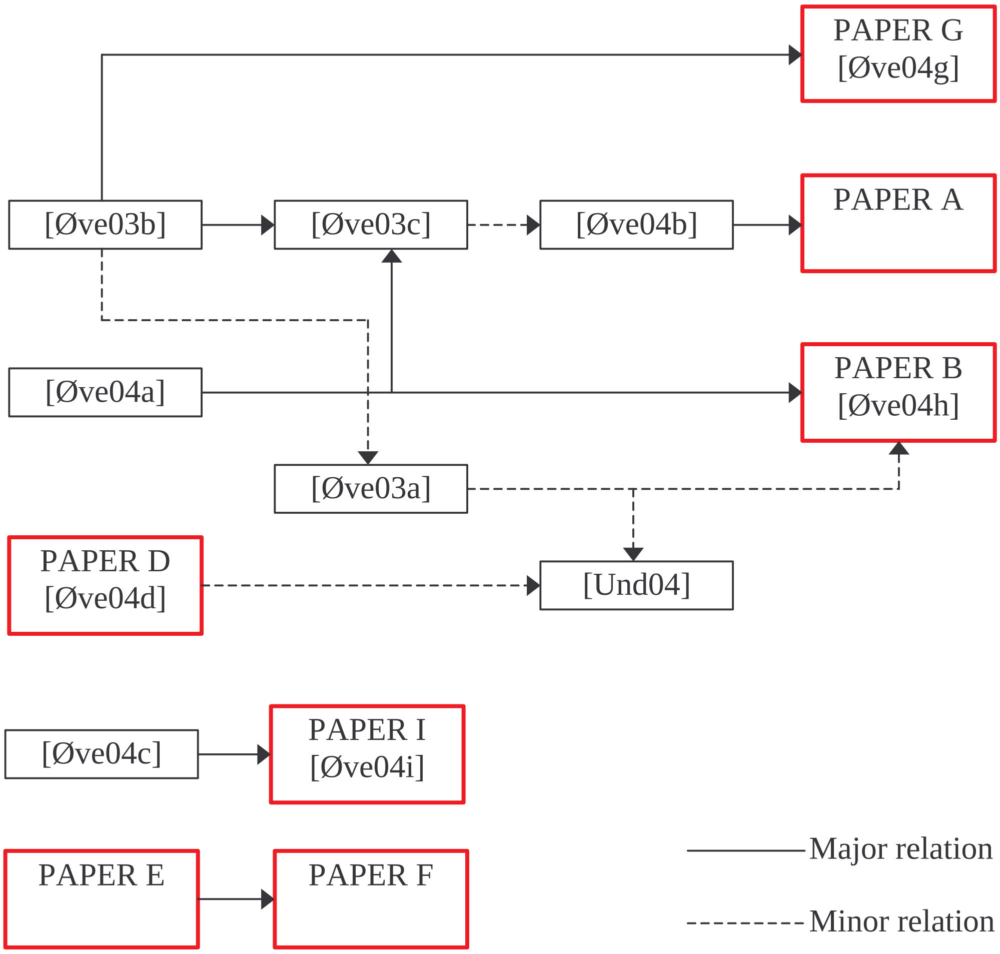

Fig. 5. The relation between published papers listed on p. xvii-xviii. The papers marked in red are those listed in table 1 on p. xvii, and included in part II of this thesis. The papers marked in black are those listed in table 2 on p. xviii, and are not included in this thesis.

[Øve03b] presents the WA and an accompanied analytical model, similar to the one found in APPENDIX A. This analytical model has been extended in PAPER G by considering a bursty H_2 arrival process instead of a Poisson arrival process. The PDP, accompanied with analytical models for switches with and without wavelength conversion, was originally published in [Øve04a]. [Øve03c] summarizes the work presented in [Øve03b] and [Øve04a], and considers how the end-to-end PLR can be calculated using Erlang reduced load fixed point analysis, similar to the model presented in [Ros03b]. A performance study of the WA and PDP regarding the throughput penalty was initially presented in [Øve04b], and has been extended in PAPER A to cover the IPD as well. [Øve03a] considers how absolute QoS guarantees can be provided in asynchronous OPS by using the WA. In PAPER B, this absolute QoS framework has been applied to show how absolute QoS guarantees can be provided using the PDP. PAPER B also extends the analytical model of the PDP presented in [Øve04a]. In PAPER D, a QoS differentiation scheme for slotted OPS has been presented. This scheme has been extended to provide absolute QoS guarantees in [Und04]. The NLPRS was first presented in [Øve04c], but has been extended in PAPER I. PAPER E considers several traffic models for asynchronous OPS, including Engset LCC traffic models. PAPER F extends PAPER E by considering Engset OFL based traffic models as well. Note that PAPER C and PAPER H have no relation with the other papers.

PAPER A, section 3.1 **has some overlap with** PAPER G, section 3
PAPER A, section 3.2 **has significant overlap with** PAPER B, section 2.2
PAPER A, section 4.2 **has some overlap with** PAPER D, section 4.
PAPER D, section 2 **has significant overlap with** PAPER H, section 3.2
PAPER E, sections 3.2 and 4.2 **have significant overlap with** PAPER F, section 3

Table 5. Overlap between the papers included in part II.

The papers in part II have been selected in order to cover the major contributions, while at the same time keeping the amount of overlap at a minimum. However, some overlap between the papers is unavoidable, as seen in Table 5.

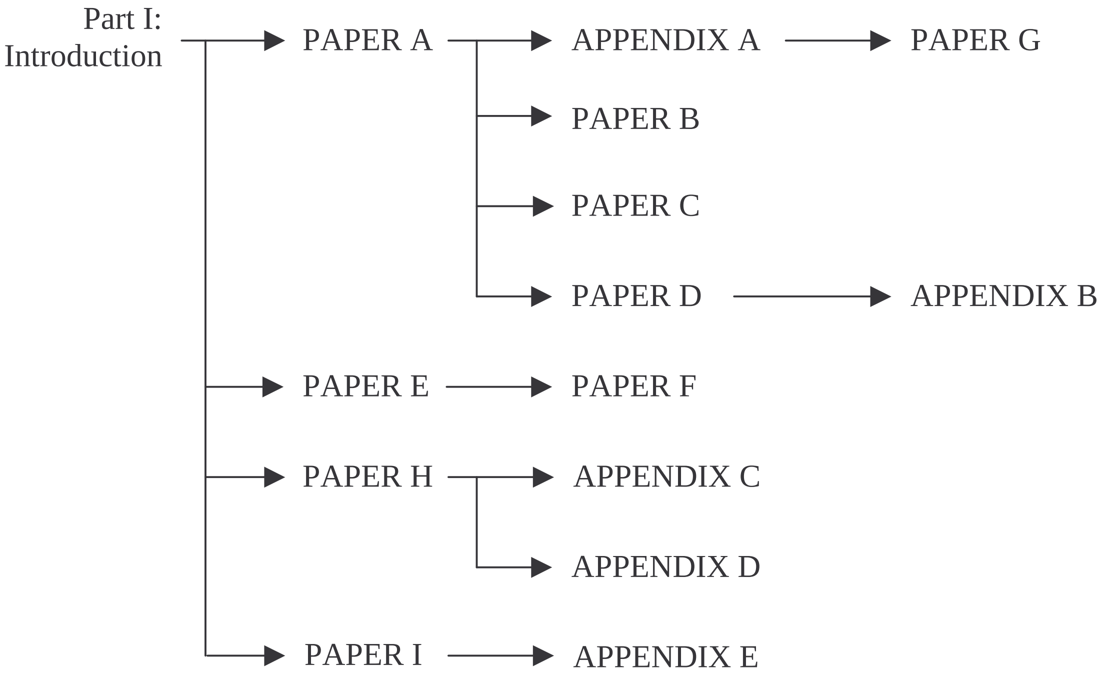

Fig. 6. Suggested reading order regarding the papers and appendices. For instance, PAPER A should be read before APPENDIX A, which in turn should be read before PAPER G.

2.5. Guidelines for reading

Part I should be read before moving on to part II and part III. Note that there is significant overlap between section 2 and section 5 in part I, as well as between section 3 in part I and the related works sections in the papers in part II.

The papers included in part II are self-contained, and only footnotes have been added to the original material in order to clarify confusing issues uncovered after publication. However, since the topics covered by the papers and appendices are linked, it is suggested to follow the reading guidelines illustrated in Fig. 6.

2.6. Thesis limitations

This thesis has the following three major limitations:

- In order to perform research on the issues faced at the OPS network layer, a certain level of abstraction is needed. This level of abstraction requires a simplification of the reality, i.e. by removing some of the technological constraints imposed by the OPS building blocks. For instance, regarding the papers in part II, the effect of the switching time is ignored, as well as the impact of bit-errors due to noisy transmission links. These simplifications may impact the results presented in this thesis.
- Future OPS networks may have a totally different traffic characteristic than the current Internet traffic. This is due to the uncertainty and the high number of alternatives when it comes to designing future OPS networks. In this thesis, the recent measurements of the Internet core network performed in [Kar04] have impacted the choice of packet inter-arrival times. The choice of packet length distribution (PLD) has been influenced by the measurements performed in [Cla98]. However, both the arrival process and PLD may be completely different in future OPS due to e.g. invention of new protocols, changing user behavior etc. This may impact the results presented in this thesis, especially the results in PAPER I.
- All QoS differentiation schemes examined in this thesis are based on the per-class QoS architecture, where packets are differentiated based on class-information obtained from the packet headers. Another viable QoS architecture is the flow-aware implicit QoS differentiation concept presented in [Kor04]. As argued in [Kor04], the flow-aware networking concept ensures a better utilization of Best-Effort (BE) traffic compared to the per-class QoS differentiation approach, while implicit QoS differentiation makes it less demanding to differentiate between the service classes (i.e. the packets do not need to be marked). The latter issue is, in short, realized by utilizing the packet inter-arrival time within a flow to differentiate between elastic and streaming traffic. The key issue here is that there are other approaches to provide QoS differentiation in the core networks than the one assumed in this thesis. How the results presented in this thesis are suited to other QoS

differentiation approaches, such as implicit QoS differentiation [Kor04], has not been considered.

3. Related works

This section presents related works regarding the topics presented in sections 2.1-2.3. Note that the selected publications do not represent an exhaustive list, and some works, which will be considered significant by others, may not be included here. Also note that a single publication may be referred to more than once, since it may cover several topics. At last note that the topic “Network layer packet redundancy in OPS” presented in section 2.3 has been considered in a broader context, i.e. “how to combat packet loss in OPS”, according to section 1.3.

3.1. Quality of Service differentiation in OPS

Fig. 7 shows an overview of publications on “QoS differentiation in asynchronous OPS”. On the vertical axis, publications are classified according to the QoS differentiation mechanisms described in PAPER A. Note that we have included the OT based QoS differentiation mechanism, as it may be applied to OPS (although it is most commonly applied to OBS). On the horizontal axis, publications are classified according to the switch architecture. Note that all QoS differentiation schemes considered in this section are based on the per-class QoS architecture [Chr03a].

A dropping based QoS differentiation scheme suitable for both OBS and OPS has been presented in [Che01]. In [Zha03a], this scheme has been modified to provide absolute QoS in asynchronous OBS/OPS. This is achieved by enabling an adaptive adjustment of the dropping probability for low priority traffic. However, as pointed out in PAPER A, [Zha03b] and [Zha04], the dropping based scheme has a very high throughput penalty as the isolation degree between the service classes increases, because packets are dropped although resources (output wavelengths) are available.

QoS differentiation schemes based on access-restriction for both asynchronous bufferless OPS and asynchronous OPS with FDL buffers have been presented in [Cal02]. Here, the service classes are isolated by employing access-restriction to input wavelength converters and buffers. A QoS differentiation scheme suitable for asynchronous OPS with shared electronic buffering has been presented in [Bjø02a]. Here, the service classes are isolated by employing access-restriction to the number of inputs to the electronic buffer.

The bufferless QoS differentiation scheme presented in [Cal02] has been an inspiration for the Wavelength Allocation algorithm (WA) presented in [Øve03b], [Øve03c], [Øve04b] and PAPER A. A QoS differentiation scheme similar to the WA can be found in [Zha03b]. In PAPER G, an analytical model of the WA has been derived in the case of a bursty hyper-exponential arrival process.

A QoS differentiation scheme for asynchronous bufferless OPS employing a shared contention resolution pool consisting of TWCs has been presented in [Nor04a]. Here, low priority traffic is given access to a limited number of wavelength converters in the pool, while high priority traffic is given access to all wavelength converters. In PAPER C, this scheme has been extended to provide QoS differentiation in asynchronous OPS with a shared contention resolution pool consisting of TWCs and FDLs. In particular, PAPER C showed that both the PLR and delay-jitter may be independently differentiated in such an OPS architecture.

QoS differentiation schemes based on preemption have been proposed for OBS [Vok03c][Loi02][Yan03] and OPS [PAPER B][Yao01a]. The use of preemption combined with segmentation has been addressed in [Can03] and [Vok03c]. [Can03] and [Loi02] propose to use preemption in order to achieve relative QoS guarantees in OBS. That is, an incoming packet to a congested output port is allowed to preempt a packet that is out-of-profile as long as the incoming packet is in-profile. The use of a preemption probability parameter to adjust the PLRs is proposed in [Yan03] and [Øve04a]. Here, a high priority arrival is allowed to preempt a low priority packet with a certain probability when the output port is congested. This scheme is modified in PAPER B in order to provide absolute QoS guarantees in asynchronous OPS. In [Yan03], the preemptive QoS differentiation scheme is shown to have no throughput penalty. However, this result is achieved by utilizing the Markovian analytical model proposed in [Yan03] and PAPER B, and do not agree with the results found in [Øve04b], which is based on simulations. More exactly, [Øve04b] showed that there is a small throughput penalty by using preemption, which is due to the fragments lost when preemption occurs. The analytical models in [Yan03] and PAPER B failed to capture this effect, due to the memory-less property of the exponential distribution.

Offset time (OT) based QoS differentiation schemes have been proposed for OBS [Pop02][Dol01][Yoo00a], but also for OPS [Kim02]. The OT based QoS differentiation scheme has several disadvantages, e.g. that the loss probability increases as the number of links traversed increases [Kim02], and that the loss probability is dependent on the burst duration distribution [Pop02]. Regarding the OT based QoS differentiation scheme for OPS, additional input FDLs are required in order to accommodate for the needed OT between the header and the payload (since the payload follows the header back-to-back) [Bre03].

QoS differentiation schemes for slotted OPS with FDL buffers have been presented in [Har02] and [Kli03], while PAPER D presents a QoS differentiation scheme for slotted bufferless OPS.

3.2. Teletraffic analysis of OPS

Figure 8 shows an overview of publications on “Teletraffic analysis of OPS”. On the horizontal axis, we classify publications according to the network architecture considered. On the vertical axis, we classify publications whether they regard contention resolution, QoS differentiation or other issues.

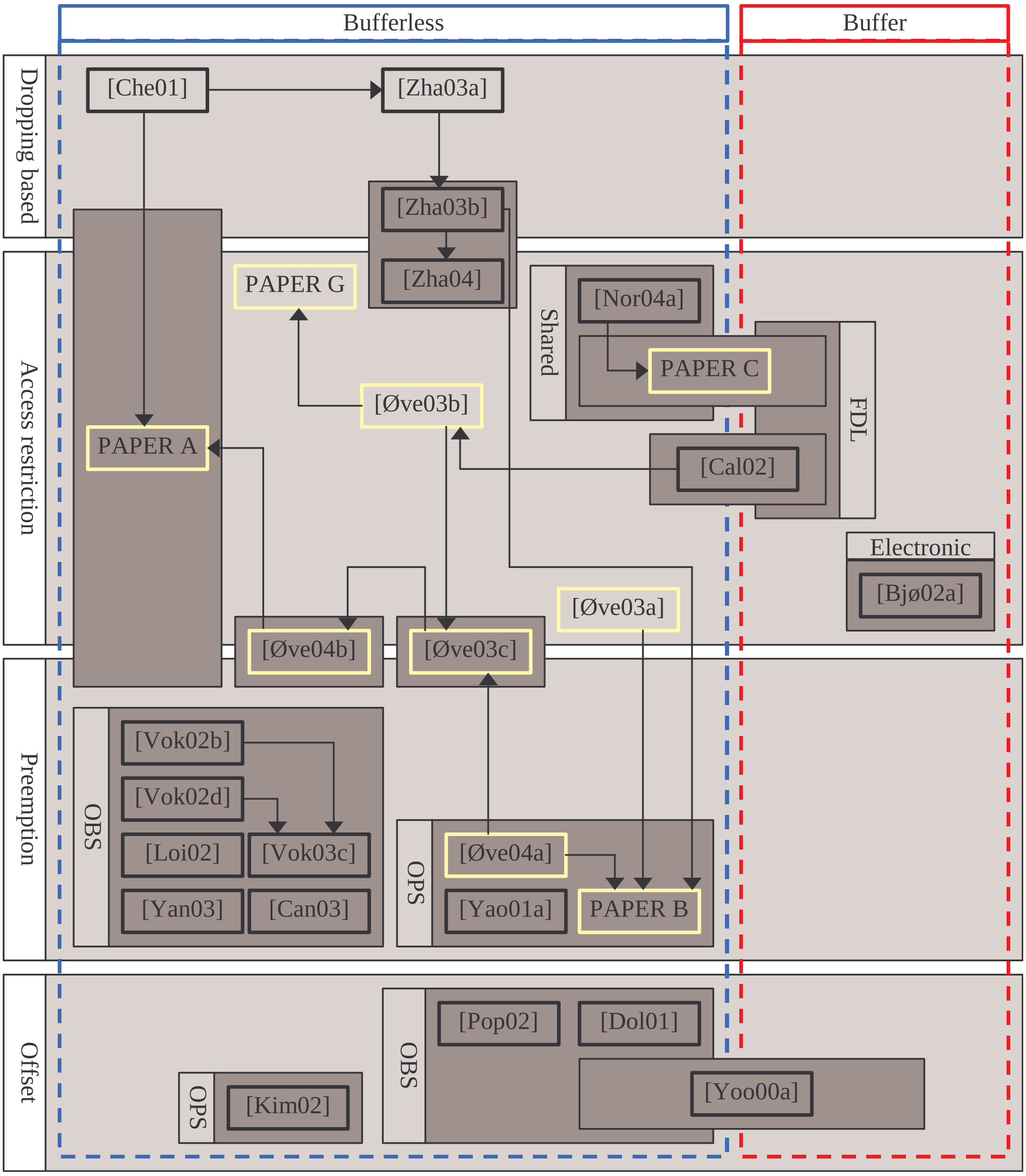

Fig. 7. Publications on “QoS differentiation in asynchronous OPS”. The square-brackets refer to publications listed in the bibliography on p. 47. The yellow boxes indicate publications where the author of this thesis has contributed.

[Tur99] proposed to use the Erlang traffic model to calculate the PLR on an output fibre in an optical packet/burst switch. More exactly, by assuming Poisson arrivals (which means an infinite number of input wavelengths) and exponential packet lengths, an output fibre with full-range output wavelength converters and without buffering capabilities can be modeled as a M/M/N/N system, where N is the number of output wavelengths per fibre. By enabling “burst storage locations” for d bursts [Tur99], the output fibre can be modeled as a M/M/N/N+d system. PAPER E extends the bufferless model in [Tur99], by relaxing the assumption of uniform traffic and infinite number sources. Furthermore, PAPER F extends PAPER E by considering the Engset overflow (OFL) traffic model in addition to the Engset lost calls cleared (LCC) traffic model.

[Dan97] presents an analytical model suitable for uniform traffic to calculate the PLR at an output port in slotted OPS with full wavelength conversion. PAPER H extends [Dan97] by presenting additional analytical models suitable for evaluating a non-looping and a non-uniform traffic scenario.

Analytical models of OPS with limited wavelength conversion can be found in [Era04] and [Zha03c], while analytical models for OPS with a shared contention resolution pool consisting of TWCs can be found in [Era00].

An analytical model of deflection routing can be found in [Che03a], where an optical burst switch has been modeled as an F-dimensional continuous-time Markov chain (where F is the number of input/output fibres).

[Ros3b] adapts the Erlang reduced load fixed point analysis to OBS. In [Øve04c] and PAPER I, this model is used to assess the performance of the NLPRS.

Analytical models for QoS differentiation schemes based on access-restriction can be found in [Øve03b], [Øve03c], PAPER G and [Zha03b], while analytical models for QoS differentiation schemes based on preemption are presented in [Øve03c], [Øve04a], PAPER B, [Vok03c] and [Yan03]. The model presented in [Vok03c] considers OPS without wavelength conversion, while the models in PAPER B and [Yan03] consider OPS with wavelength conversion.

3.3. How to combat packet loss in OPS

Fig. 9 shows an overview over publications on “How to combat packet loss in OPS”. On the vertical axis, publications are classified according to the approaches described in sections 1.3.1 and 1.3.2. Regarding the wavelength-, and time domain, we orthogonally classify the publications depending on whether the wavelength converters or buffers are employed at the outputs or in a shared pool (see e.g. [Hun98] and [Gau02] for details on the output and shared architecture).

Note that some of the publications presented here are originally designed for OBS, but the results apply to OPS as well. This is reasonable, since packet loss at the network layer can be combated using the very same techniques in OPS and OBS (note that segmentation is an exception, since it may be used in OBS only).

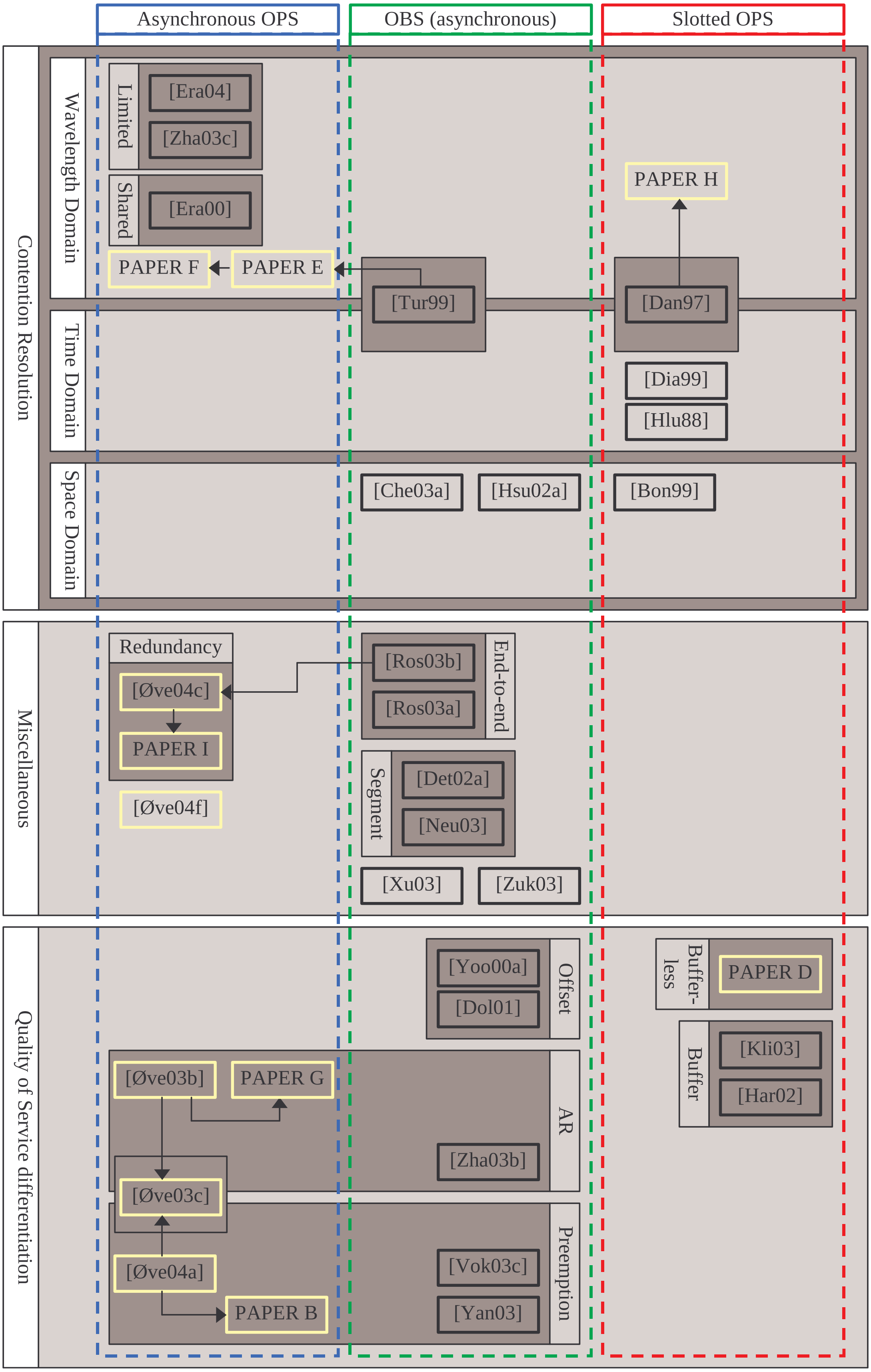

Fig. 8. Publications on “Teletraffic analysis of OPS”. The square-brackets refer to publications listed in the bibliography on p. 47. The yellow boxes indicate publications where the author of this thesis has contributed.

The use of the wavelength domain to resolve contentions has been considered by [Tur99], PAPER E and PAPER F for asynchronous OPS, and by [She01], [Zha03c], [Era04], [Dan97] and PAPER H for slotted OPS. [Tur99] showed that the PLR decreases when the buffer size increases and when the number of wavelengths per fibre increases, assuming a fixed normalized system load. A similar study has been conducted in [Dan97], where the same results were found for slotted OPS.

[She01], [Zha03c], and [Era04] consider the performance of limited-range wavelength converters in slotted OPS. They found that limited-range wavelength converters match the performance of full-range wavelength converters, even though the conversion distance is much less than the conversion distance covered by full-range converters. Hence, a viable approach for future OPS is to utilize limited-range wavelength converters, in order to reduce the hardware cost.

The use of the time domain to resolve contentions has been investigated by [Cal00] and [Hun98] in the case of FDLs, and by [Bjø02b] in the case of shared electronic buffering. By increasing the buffer size [Hun98], or the number of inputs/outputs to the electronic buffer [Bjø02b], the PLR can be reduced to any extent. However, as pointed out by [Yao03], a practical issue encountered using FDLs for contention resolution is the noise accumulated as the packets traverse the FDLs. This noise limits the number of circulations a packet may perform during its stay in the network, and therefore also puts a limit on the efficiency of FDL buffering.

A shared contention resolution pool architecture has been studied by [Era00], [Nor04c], [Gau02], [Tan01], [Hun98], [Li03], and [Dia99]. First, the contention resolution pool may consist of only TWCs [Era00], FDLs [Tan01] [Hun98], or a combination of TWCs and FDLs [Nor04c] [Gau02].

[Era00] presents a study of slotted OPS with a shared contention resolution pool consisting of TWCs. They showed that the performance of this architecture matches the performance of the output architecture (i.e. employing full-range wavelength converters at each output wavelength) with only a small number of TWCs in the pool, e.g. for a 256x256 switch, the number of needed converters has been reduced from 256 to 10. [Hun98] proposed a shared contention resolution pool consisting of FDLs. This architecture has been further studied by [Tan01] for slotted OPS. [Nor04c] and [Gau02] investigated the performance of asynchronous OPS employing a shared contention resolution pool consisting of both tunable wavelength converters and FDLs. In particular, [Nor04c] considers the proportion of TWCs and FDLs that give optimal performance, i.e. the lowest PLR, for a given value of the number of inputs/outputs to the shared contention resolution pool.

The performance gain from utilizing the space domain to resolve contentions has been investigated in [Bon99] for slotted OPS, and in [Hsu02], [Che03a], [Wan00], and [Lee03] for asynchronous OPS. First, [Che03a] showed that there is a performance gain of using deflection routing, also when the normalized system load is initially high (i.e. >0.75). However, [Che03a] failed to capture the extra load imposed by the fact that deflected packets choose a non-optimal path to their destination, and thus over-estimated the performance gain from deflection routing. As argued in [Wan00], deflection routing is only efficient in networks with low load (<0.40). However, it should be noted that the efficiency of deflection routing is highly dependent on the network topology and the traffic matrix.

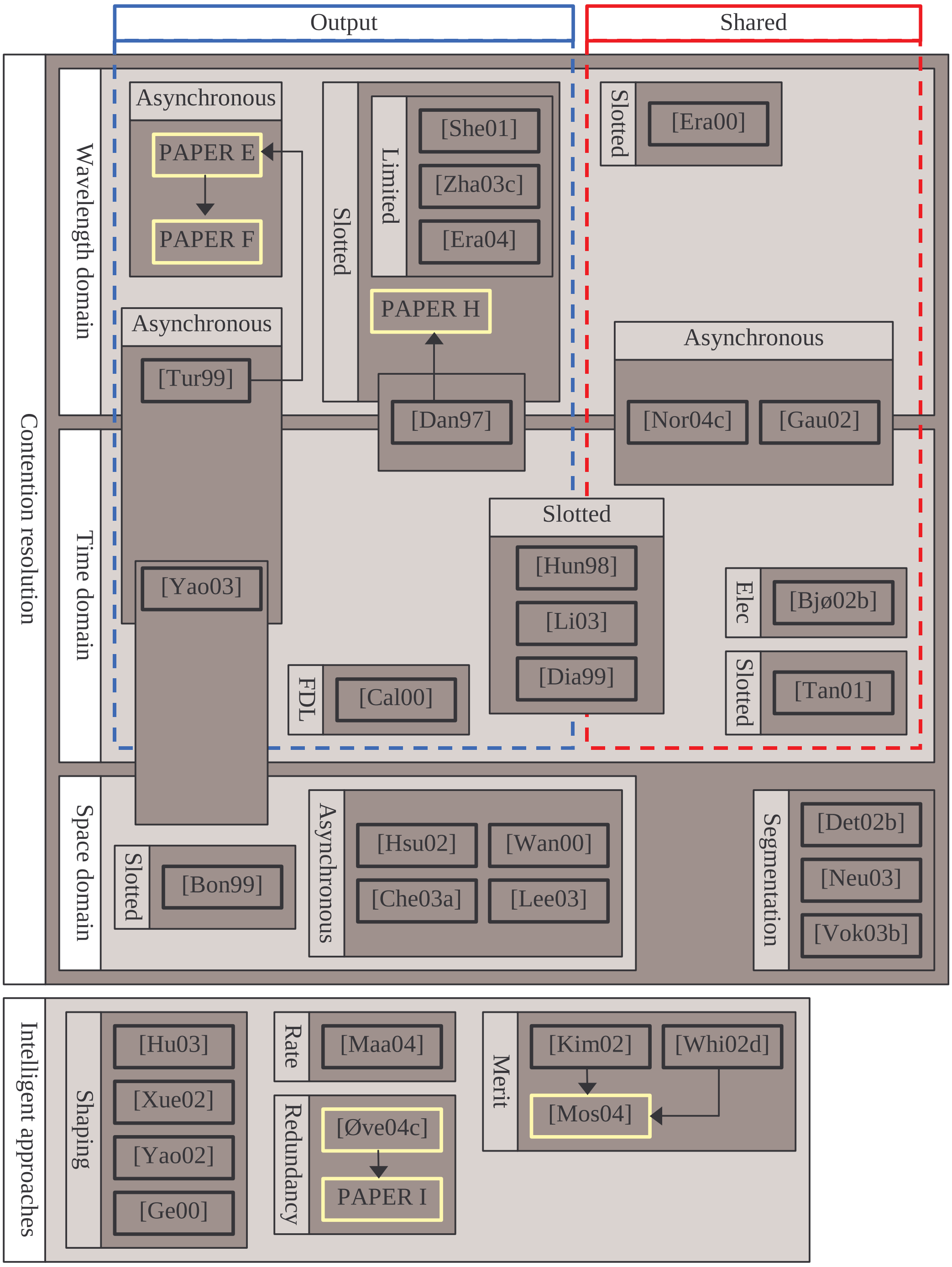

Fig. 9. Publications on “How to combat packet loss in OPS”. The square-brackets refer to publications listed in the bibliography on p. 47. The yellow boxes indicate publications where the author of this thesis has contributed.

4. Research methodology

The research performed as a part of this thesis follows a common research methodology in order to ensure sound and reproducible results. As illustrated in Fig. 10, each work starts with a research hypothesis, from where a system model is designed. The hypothesis is evaluated using either teletraffic analysis [Ive99] or discrete event simulations [Bir78]. The following steps outline the general research process:

- **Hypothesis:** Each work is based on a research hypothesis, which could be e.g. a novel QoS differentiation scheme, as in PAPER B. The hypothesis typically poses a question such as “Is the PDP a viable approach to isolate service classes in asynchronous OPS?” or “What is the throughput penalty of the PDP compared to the WA?”. The main goal with the rest of the process is to answer the questions posed.
- **System model:** Based on the hypothesis, a system model is designed. This model incorporates all the essential features that may impact the evaluation of the hypothesis. Note that the system model is generally formulated using a combination of text and figures in an informal way, and is an abstraction of the real world. The system model lays the basis for further investigation of the hypothesis.
- **Investigation method:** In order to evaluate the hypothesis, either simulations or analysis has been employed. Some works (papers) use only simulations or analysis, while other works use a combination, as seen in Table 6. The simulations may incorporate more details than the analysis, which can make the results obtained from the simulations more accurate than the results obtained from the analysis. However, with an accurate analytical model, a wide range of parameter settings can be examined using significantly less time compared to simulations. Also, a sound analytical model can give a good understanding of the underlying factors that influences the results [Flo01]. On the other hand, some of the issues considered in this thesis are too complex to be fully captured by an analytical model, e.g. the NLPRS presented in PAPER I.
    - **Simulations:** If simulations are used to investigate the hypothesis, a simulation program is implemented. The simulation program is based on the system model, but in order to produce results within reasonable time limits, several assumptions have to be made. These assumptions are very important to document in order to make the results reproducible. For all simulations, the Discrete Event Modelling on Simula (DEMOS) tool has been utilized [Bir78]. All simulation programs have been built “from scratch” using only modules available in DEMOS. If not stated otherwise, 10 independent simulation runs have been performed for each plot, and

the resulting 95 % confidence limits have been calculated using the Student-t distribution with 9 degrees of freedom [Wal98].

  - **Analysis:** All analytical models are based on teletraffic theory [Gro74][Kle75][Kle76][Ive99]. As for the simulations, it is important to document the assumptions made for the analysis as well.

- **Results:** The results obtained from the simulations or the analysis are used for two purposes, listed below:
  - **Model validation:** When both simulations and analysis are used to investigate the hypothesis, the results obtained are first used to validate the models. That is, the results obtained from the simulations are compared to the results from the analysis, in order to eliminate possible errors and bugs in the models. A useful approach is to make the same assumptions for the simulation model as for the analytical model. We will then expect the simulations and analysis to produce the exact same results, after statistical errors have been accounted for. By relaxing some of the assumptions made for the analytical model in the simulation model, the impact of the assumptions made for the analysis can be investigated [Flo01].
  - **Evaluation of the hypothesis:** Eventually, the results should be used to evaluate the hypothesis. If both simulations and analysis are used, some assumptions for the simulation model can be relaxed in order to achieve more realistic results. However, the hypothesis may be evaluated using the analytical model only. Anyway, an evaluation of the hypothesis can only be done after varying the input parameters, and exploring the parameter space.

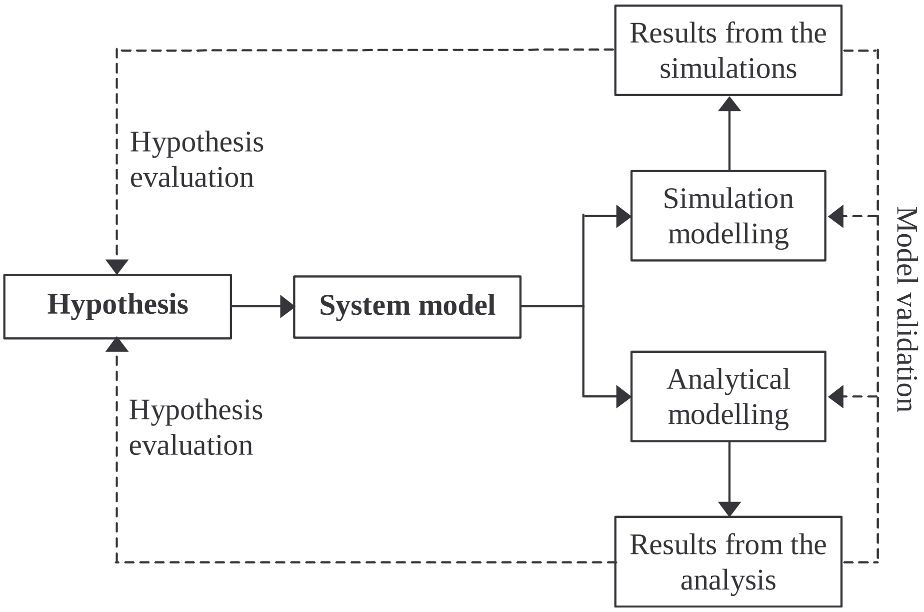

Fig. 10. Overview of the research process.

APPENDIX F shows how the research methodology can be applied to evaluate the NLPRS.

	Investigation method	
	Simulations	*Analysis*
PAPER A	x	
PAPER B	x	x
PAPER C	x	
PAPER D	x	x
PAPER E		x
PAPER F		x
PAPER G	x	x
PAPER H		x
PAPER I	x	x

Table 6. Investigation method used by the papers included in part II.

Assessing the performance of the Internet by using simulations or analysis is generally hard, due to the heterogeneity and lack of invariants in the Internet [Flo01]. Also, the ever-changing nature of the Internet along multiple dimensions makes it hard to determine what parameters to use. In this thesis, the choice of arrival process is influenced by the measurements performed in [Kar04], while the choice of packet lengths is influenced by [Cla98].

5. Summary of the papers included in part II

Sections 5.1-5.9 give a summary of the papers included in part II, as well as reference to additional material.

5.1. PAPER A: Evaluation of QoS differentiation mechanisms in asynchronous bufferless optical packet switched networks

Existing QoS differentiation schemes for today’s IP over point-to-point Optical WDM networks take advantage of electronic RAM to implement Active Queue Management (AQM) algorithms in order to isolate the service classes. Since practical optical RAM is not available, these techniques are not suitable for a future all-optical network. Hence, new schemes are needed to support QoS differentiation in OPS networks. In this article we first present an overview over existing QoS differentiation mechanisms suitable for asynchronous bufferless OPS. We then compare the performance of the presented schemes, as well as qualitatively discussing implementation issues, in order to evaluate the mechanisms. In particular, we present an evaluation framework, which quantifies the throughput reduction observed when migrating from a best-effort scenario to a service-differentiated scenario. We have shown that the Preemptive Drop Policy (PDP) has the best performance, followed by the Wavelength Allocation algorithm (WA) and the Intentional Packet Dropping scheme (IPD). This difference is more accentuated when the switch is highly strained, which is also the scenarios in which QoS differentiation is needed the most. However, regarding implementation complexity, the PDP is the most complex followed by the WA and the IPD.

Analytical models of the WA and the IPD are proposed in APPENDIX A, while an analytical model of the PDP can be found in PAPER B.

5.2. PAPER B: Quality of Service in asynchronous bufferless optical packet switched networks

This paper presents the Preemptive Drop Policy (PDP), which provides service differentiation in asynchronous bufferless OPS networks. In the case of contention at an output port, the PDP allows new high priority arrivals to preempt low priority packets already in transmission. As a part of the PDP, we introduce the preemption probability parameter, which enables an explicit control of the isolation degree between the service classes. Based on continuous-time Markov chains, we present an analytical model of the PDP for switches with and without wavelength conversion in the case of two service classes. We derive explicit results for the PLR in a general case, as well as simplified results for the PLR under certain parameter settings. Simulations of a single optical core switch with on/off sources at each input wavelength show that the analytical model is accurate.

We extend the PDP into the Adaptive PDP (APDP), which provides absolute QoS guarantees in asynchronous bufferless OPS networks. The APDP measures the PLR for high priority traffic over a time window, and adjusts the preemption probability parameter so that the PLR for high priority traffic stays within absolute bounds. Simulations show that the APDP operates properly in a changing system load scenario.

A study on how absolute QoS can be achieved in slotted bufferless OPS can be found in [Und04].

5.3. PAPER C: Packet loss rate- and jitter differentiating QoS schemes for asynchronous optical packet switches

This paper proposes access restriction based QoS differentiation schemes, suitable for an asynchronous optical packet switch with a shared-per-node (SPN) contention resolution pool that contains both TWCs and FDLs. The schemes aim at obtaining a high degree of PLR isolation, for a low increase in overall PLR, at the same time respecting the jitter tolerance of each Class of Service.

The study shows that very large isolation values can be obtained, but that overall PLR detoriates with reduced jitter tolerance of the traffic, quantified to a decade decrease in overall PLR, for PLR isolation values ranging from 1 to above 10^4. Moreover, when having a jitter free CoS and a jitter tolerant CoS, overall PLR increases by a factor of ~2-4 in the isolation range from 100-700, when offering a ‘super-priority CoS’ with low-PLR and jitter-free operation, as opposed to a low-PLR, jitter-tolerant CoS. Still, all these schemes are better than the QoS scheme that does not employ FDLs. These properties suggest that both the PLR and jitter properties of the network’s expected traffic matrix should be carefully analyzed before dimensioning the optical packet switch and choosing a QoS differentiation scheme.

5.4. PAPER D: QoS in slotted bufferless optical packet switched networks

This paper presents a novel QoS differentiation scheme suitable for slotted bufferless OPS networks with full range output wavelength conversion. The scheme works by allocating a larger share of resources (i.e. time-slots at an output fibre) to high priority traffic compared to low priority traffic in the case of contention. An analytical model of the proposed scheme in the case of two service classes is derived. Simulations have been performed to validate the analytical model.

We have shown that the proposed scheme is highly efficient as there is no reduction in the throughput as the isolation degree between the service classes increases. This is a favourable property, since the isolation degree between the two service classes can be varied without influencing the throughput.

We have also shown that the isolation degree between the two service classes can be controlled by adjusting a design parameter L, which denotes the maximum number of high priority packets that can be transmitted in a single time-slot in the case of contention. This feature has been exploited to achieve absolute QoS in slotted OPS, as shown in [Und04].

Additional results to PAPER D can be found in APPENDIX B.

5.5. PAPER E: Performance modelling of asynchronous bufferless optical packet switched networks

Analytical models based on stochastic processes have been widely employed in order to assess the performance of OPS networks. A crucial issue regarding analytical models is how to model packet arrivals to an output port in an optical packet switch, and how to evaluate the blocking probability. This article presents various Markovian arrival models for asynchronous bufferless OPS networks. In addition to the well-known Erlang (ERAM) and Engset lost calls cleared (LCC) arrival models (ENAM), we present two novel Engset LCC based arrival models, i.e. the Engset Asymmetric arrival model (EAAM) and the Engset Non-looping arrival model (ENLAM). We consider optical packet switches with and without wavelength conversion. Analytical expressions for the time-, call- and traffic congestion are derived for each Engset LCC based arrival model. The major findings can be summarized as:

- Among the considered arrival models, we should expect the EAAM, ENAM and ENLAM to be the most accurate, i.e. closest to a realistic scenario, since they take into account the limited number of input wavelengths in the optical packet switch. Whether the EAAM, ENAM or the ENLAM is the most accurate depends on the uniformity of the traffic pattern and whether looping is allowed or not. However, it should be noted that both the ENAM and ENLAM are simplifications of the EAAM.
- A numerical evaluation shows that there is a significant difference in the blocking probability between the presented arrival models depending on the chosen performance metric, system load, number of input/output fibres and the number of wavelengths per fibre. These results should be carefully analyzed when choosing an appropriate arrival model and performance metric for analytical modeling of asynchronous OPS.
- Using the time congestion for evaluating the blocking probability has several drawbacks. First, the time congestion does not capture the increased variance due to an increasing number of input fibres in OPS without wavelength conversion. Second, the time congestion does not show that the blocking probability in the NOWC-ENLAM and WC-ENLAM should be zero when the number of input/output fibres is F=2.

5.6. PAPER F: Performance modelling of optical packet switched networks with the Engset traffic model

Stochastic processes have been widely employed in order to assess the network layer performance of asynchronous OPS networks. This paper presents two types of the Engset traffic model, i.e. the Engset lost calls cleared (LCC) traffic model and the Engset overflow (OFL) traffic model. For both traffic models, the time- (E), call- (B), and traffic (C) congestion have been derived. A numerical evaluation reveals the following major findings:

- We observe that $E_{LCC} \geq B_{LCC} \geq C_{LCC}$ and $E_{OFL} \geq B_{OFL} = C_{OFL}$ for all parameter settings.
- As C_{OFL} is the most accurate measure for the blocking probability, we see that C_{LCC} tends to underestimate the blocking probability, while E_{LCC}, B_{LCC}, and E_{OFL} tend to overestimate the blocking probability.
- The blocking probabilities C_{LCC}, B_{LCC}, and C_{OFL} increase as the number of input/output fibres (F) increases. This is expected, since an increase in the parameter F leads to an increased variance regarding arrivals to the tagged output port, which in turn leads to an increased blocking probability. However, we see that this effect is not captured by neither E_{LCC} nor E_{OFL} in the NOWC scenario. Hence, the time congestion is not an adequate performance metric for asynchronous bufferless OPS without wavelength conversion.
- The blocking probabilities converge as the parameter F increases. Hence, the choice of traffic model and performance metric has greater impact on the observed blocking probability in switches with a small number of input/output fibres than in switches with a high number of input/output fibres.

5.7. PAPER G: Effects of bursty traffic in service differentiated optical packet switched networks

In this paper we examine how bursty traffic influences the performance of a QoS differentiated OPS network. QoS differentiation is achieved by using the Wavelength Allocation algorithm (WA), which reserves a number of output wavelengths at an output fibre exclusively for high priority traffic. By using continuous-time Markov chains, we derive explicit results for the PLRs for a two-service class scenario in the case of a bursty hyper-exponential arrival process. Results indicate that the PLR increases as the burstiness of the arrival process increases.

5.8. PAPER H: Performance modelling of synchronous bufferless OPS networks

In this paper we introduce new and review existing arrival models for synchronous bufferless OPS networks employing full wavelength conversion. The existing models reviewed include the Binomial arrival model and the Poisson arrival model, while the novel models include the Asymmetric arrival model and the Non-looping arrival model. For each model, we provide analytical expressions of the PLR. The Asymmetric arrival model takes into account unique loads and routing probabilities for each input wavelength, which is required for studying the effects of non-uniform traffic. The Non-looping arrival model assumes that packets are not allowed to be routed to the same fibre pair they arrived from.

A numerical evaluation of the presented models shows that there is a significant difference in the PLR between the arrival models for the same parameter settings. In particular, the Poisson arrival model gives a higher PLR than the Binomial arrival model, which in turn gives a higher PLR than the Non-looping arrival model. This is because in the Poisson arrival mode, packets arrive from an infinite number of sources (input wavelengths), while in the Binomial and Non-looping arrival model, packets arrive from FN and (F-1)N sources, respectively.

The Binomial and Non-looping arrival models are closer to a realistic scenario than the Poisson arrival model, since packets arrive from a finite number of sources. However, it should be noted that the Poisson arrival model is computational simpler than both the Binomial arrival model and the Non-looping arrival model. Hence, the choice of arrival model is a trade-off between the desired accuracy of the analytical model and the computational complexity.

Additional results to PAPER H can be found in APPENDIX C. Furthermore, APPENDIX D presents arrival models for synchronous bufferless OPS without wavelength conversion.

5.9. PAPER I: Network layer packet redundancy in optical packet switched networks

A crucial issue in OPS networks is packet loss at the network layer caused by contention. This paper presents the Network Layer Packet Redundancy Scheme (NLPRS), which is a novel approach to combat packet loss in OPS networks. At the OPS ingress node, r redundancy packets are added to a set of m data packets by using the FSRaid application. At the OPS egress node, the NLPRS enables a possible reconstruction of data packets that are lost due to contention. This will, under certain conditions, lead to a reduced data PLR. An analytical model of the NLPRS based on Erlang reduced load fixed point analysis is presented. We have investigated the NLPRS performance in an asynchronous OPS ring network for various system loads, network sizes, packet arrival processes, packet length distributions and redundancy packet scheduling mechanisms. Our results show that:

- The NLPRS is a viable approach to combat packet loss in OPS, as the resulting end-to-end data PLR can be reduced several orders of magnitude.
- The NLPRS performance is degraded for an increasing system load.
- The NLPRS performance is degraded for an increasing network size.
- The NLPRS performance is degraded as the burstiness of the data packet arrival process increases.

- For the empirical packet length distribution (PLD), we have shown that the NLPRS is efficient for large values of the parameter m only. For the deterministic PLD, the NLPRS is efficient for small values of the parameter m as well.
- The redundancy packet scheduling mechanism influences the performance of the NLPRS significantly. That is, using the transmit-right-away (TRA) scheme results in no performance gain from using the NLPRS, while using the back-to-back (BTB) and exponential back-to-back (EBTB) schemes results in a significant improvement in the network performance from using the NLPRS.

A performance study of the NLPRS in an asynchronous OPS ring network without wavelength conversion can be found in APPENDIX E.

6. Concluding remarks

As the Internet traffic keeps increasing, all-optical network architectures become increasingly attractive due to their ability to provide transport services to upper layers with low cost and complexity, and high data transparency compared to its electronic counterpart. The latter issue is crucial, since it makes possible for different services to use a single infrastructure, but also that existing network components most likely can be re-used for new protocols and bit-rates [Ram02].

As seen in this dissertation, OPS is a particularly promising candidate among the all-optical network architectures proposed in recent literature. In order to have a commercial successful deployment of OPS, several issues need to be solved. First, the enabling technologies required to build OPS networks must become mature and cost-efficient in order to compete with existing electronic technology. Second, since OPS networks are fundamentally different from today’s store-and-forward networks regarding networking issues, new performance schemes and tools for network planning are required. This thesis has dealt with the latter issue, with particular focus on how to combat packet loss, provide QoS differentiation at the WDM layer, and how OPS networks can be modeled analytically using well-known teletraffic theory [Ive99]. The overall major scientific contributions in this thesis include:

- A novel approach to combat packet loss by utilizing network layer packet redundancy in OPS has been presented. It has been shown that the proposed scheme is able to reduce the end-to-end data PLR several orders of magnitude in asynchronous OPS. However, the performance of the scheme is highly sensitive to variations in the system load, arrival process and packet length distribution.
- A quantitative framework suitable for evaluating the throughput penalty when QoS differentiation is employed in asynchronous OPS has been proposed. This framework has been applied to evaluate existing QoS differentiation schemes for asynchronous OPS.
- Several traffic models suitable for evaluating the blocking probability in asynchronous and slotted OPS have been investigated. In particular, several Engset based traffic models have been proposed for asynchronous OPS.

7. Future works

This section presents proposals for future works.

7.1. QoS differentiation in OPS networks

- The QoS differentiation schemes presented in this thesis are suitable for bufferless OPS only (except for the schemes presented in PAPER C). Making these QoS differentiation schemes suitable for OPS with buffering capabilities should be performed.

- The adaptive framework presented in PAPER B for the PDP and in [Øve03b] for the WA should be applied to other QoS differentiation schemes.

- In the PDP, a random class 1 packet is dropped when preemption occurs. As indicated in [Kim02] and [Whi02d], there is a performance gain from discarding packets that have used the least amount of resources. Hence, the throughput penalty of the PDP may be reduced by letting class 0 packets preempt the latest class 1 arrival currently in transmission. How such a scheme influences the overall packet loss rate in a QoS differentiated OPS network should be studied.

7.2. Teletraffic analysis of OPS networks

- PAPER E, PAPER F and PAPER H present general traffic models for OPS. A comprehensive evaluation of these and possibly other traffic models suitable for OPS should be studied regarding accuracy and complexity.

7.3. Contention resolution in OPS

- As seen in [Gau02] and [Era00], the shared contention resolution pool architecture may reduce the hardware cost significantly in both asynchronous and slotted OPS. Further cost reductions may be achieved by replacing the full-range TWCs in the pool with limited-range wavelength converters. Although limited-range wavelength converters have shown good performance in the output architecture [Era04], the performance of employing such converters in a shared architecture has not been studied.

7.4. Network layer packet redundancy in OPS networks

- The NLPRS has been shown to be particularly efficient for networks operating at low system loads. In such networks, the use of deflection routing is also a viable approach to reduce the PLR [Wan00]. A study that compares the efficiency of the NLPRS with deflection routing under various network scenarios should be performed.

- Regarding the NLPRS, it was shown that the performance is highly dependent on the packet length distribution, whereas fixed sized packets yielded much better performance compared to an empirically derived packet length distribution. Hence, we should aim at using fixed sized packets when employing the NLPRS, but this requires a packet aggregation at the OPS ingress node. A study on how this packet aggregation affects the arrival process when employing the NLPRS should be performed.

- A crucial issue when employing the NLPRS is the additional delay experienced by data packets that need to be reconstructed. For small values of the packet set size (m), this delay is negligible, but may be significant for larger values of the parameter m. First, a scheme that provides an upper bound on this delay should be presented. Second, an analytical model that shows the delay (and possibly the distribution of the delay) as a function of the parameters m, r and the system load should be derived.
- A major challenge in the NLPRS is how the parameters r and m should be set. As shown in PAPER I, the performance is highly dependent on these parameters, and the optimal choice of r and m is in turn dependent on the system load and the traffic pattern. How the parameters r and m should be set according to changes in the traffic pattern should be examined.
- As stated in APPENDIX F, there must exist a mechanism that can inform an egress node when to start reconstruction. How such a mechanism can be realized should be studied.

Bibliography

The bibliography includes papers **published** in national and international journals and conferences. **Non-published** works have not been included in the bibliography.

[And04] R. Andreassen, B. E. Helvik, ”A note on traffic performance gain for optical burst/packet switching”, in Proceedings of the 8th IFIP Working Conference on Optical Network Design & Modelling (ONDM), 2004.

[Arv99] Å. Arvidsson, P. Karlsson, “On Traffic Models for TCP/IP”, in Proceedings of International Teletraffic Congress (ITC-16), pp. 457-466, 1999.

[Aus04] E. Austreim, P. J. Emstad, ”Study of rate-control policies for streaming sources based on feed-back from a congested buffer”, in Proceedings of Nordic Teletraffic Seminar (NTS), pp. 183-194, 2004.

[Bal02] I. Baldine, G. N. Rouskas, H. G. Perros, D. Stevenson, “JumpStart: A Just-in-Time Signaling Architecture for WDM Burst-Switched Networks”, IEEE Communications Magazine 40(2) (2002) 82-89.

[Bar02] P. Baran, “The Beginnings of Packet Switching: Some Underlying Concepts”, IEEE Communications Magazine 40(7) (2002) 42-48.

[Bat03] T. Battestilli, H. Perros, ”An introduction to optical burst switching”, IEEE Communications Magazine 41(8) (2003) 10-15.

[Bir78] G. Birtwistle, “DEMOS: Discrete Event Modelling on Simula” (MacMillan, 1978).

[Bjø02a] S. Bjørnstad, N. Stol, D. R. Hjelme, “Quality of service in optical packet switched DWDM transport networks”, in Proceedings of SPIE Asian-Pacific Optical and Wireless Communications Conference and Exhibition (APOC), Proceedings of SPIE vol. 4910, pp. 63-74, 2002.

[Bjø02b] S. Bjørnstad, N. Stol, D. R. Hjelme, “An Optical Packet Switch Design with Shared Electronic Buffering and Low Bit Rate Add/Drop Inputs”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 69-72, 2002.

[Bjø03] S. Bjørnstad, M. Nord, D. R. Hjelme, ”QoS differentiation and header/payload separation in optical packet switching using polarization multiplexing”, in Proceedings of the 29th European Conference on Optical Communication (ECOC), 2003.

[Bjø04] S. Bjørnstad, ”Packet switching in optical networks”, PhD thesis at the Faculty of Information Technology, Mathematics and Electrical Engineering, Norwegian University of Science and Technology, July 2004.

[Bla98] S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, W. Weiss, “An architecture for differentiated services”, IETF RFC 2475, December 1998.

[Bon02] T. Bonald, S. Oueslati-Boulahia, J. Roberts, “IP traffic and QoS control: the need for a flow-aware architecture”, in Proceedings of World Telecommunications Congress, 2002.

[Bon99] A. Bononi, G. A. Castañón, O. K. Tonguz, “Analysis of Hot-Potato Optical Networks with Wavelength Conversion”, IEEE Journal of Lightwave Technology 17(4) (1999) 525-534.

[Bra94] R. Braden, D. Clark, S. Shenker, “Integrated services in the internet architecture: an overview” IETF RFC 1633, July 1994.

[Bre03] E. Van Breusegem, J. Cheyns, B. Lannoo, A. Ackaert, M. Pickavet, P. Demeester, “Implications of using offsets in all-optical packet switched networks”, in Proceedings of the 7th IFIP Working Conference on Optical Network Design & Modelling (ONDM), 2003.

[Cal00] F. Callegati, G. Corazza, C. Raffaelli, “Design of a WDM Optical Packet Switch for IP traffic”, in Proceedings of Global Telecommunications Conference (GLOBECOM), pp. 1283-1287, 2000.

[Cal02] F. Callegati, G. Corazza, C. Raffaelli, “Exploitation of DWDM for Optical Packet Switching With Quality of Service Guarantees”, IEEE Journal on Selected Areas in Communications 20(1) (2002) 190-201.

[Cal97] F. Callegati, “Which Packet Length for a Transparent Optical Network?”, Proceedings of SPIE vol. 3233, 1997.

[Cal99a] F. Callegati, M. Casoni, C. Raffaelli, “Packet Optical Networks for High-Speed TCP-IP Backbones”, IEEE Communications Magazine 37(1) (1999) 124-129.

[Cal99b] F. Callegati, H. C. Cankaya, Y. Xiong, M. Vandenhoute, “Design Issues of Optical IP Routers for Internet Backbone Applications”, IEEE Communications Magazine 37(12) (1999) 124-128.

[Can03] H. C. Cankaya, S. Charcranoon, T. S. El-Bawab, ”A Preemptive Scheduling Technique for OBS Networks with Service Differentiation”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), 2003.

[Che01] Y. Chen, M. Hamdi, D. H. K. Tsang, C. Qiao, “Providing Proportionally Differentiated Services over Optical Burst Switching Networks”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), 2001.

[Che03a] Y. Chen, H. Wu, D. Xu, C. Qiao, “Performance Analysis of Optical Burst Switched Node with Deflection Routing”, in Proceedings of IEEE International Conference on Communication (ICC), vol. 2, pp. 1355-1359, 2003.

[Che03b] J. Cheyns, E. Van Breusegem, C. Develder, A. Ackaert, M. Pickavet, P. Demeester, “Performance Improvement of an Internally Blocking Optical Packet/Burst Switch”, in Proceedings of IEEE International Conference on Communication (ICC), vol. 2, pp. 1304-1308, 2003.

[Che03c] Y. Chen, C. Qiao, “Proportional Differentiation: A Scalable QoS Approach”, IEEE Communications Magazine 41(6) (2003) 52-58.

[Che03d] J. Cheyns, E. V. Breusegem, D. Colle, M. Pickavet, P. Demeester, “ORION: a Novel Hybrid Network Concept: Overspill Routing in Optical Networks”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 144-147, 2003.

[Che04] J. Cheyns, C. Develder, E. V. Breusegem, D. Colle, F. De Turck, P. Lagasse, M. Pickavet, P. Demeester, ”Clos Lives On in Optical Packet Switching”, IEEE Communications Magazine 42(2) (2004) 114-121.

[Chi03] D. Chiaroni, “Packet Switching Matrix: A Key Element for the Backbone and the Metro”, IEEE Journal on Selected Areas in Communications 21(7) (2003) 1018-1025.

[Chr03a] N. Christin, “Quantifiable Service Differentiation for Packet Networks”, PhD thesis at the Faculty of the School of Engineering and Applied Science, University of Virginia, August 2003.

[Chr03b] N. Christin, J. Liebherr, “A QoS Architecture for Quantitative Service Differentiation”, IEEE Communications Magazine 41(6) (2003) 38-45.

[Cla98] K. Claffy, “The nature of the beast: recent traffic measurements from an Internet backbone”, Caida, 1998.

[Dan97] S. L. Danielsen, B. Mikkelsen, C. Joergensen, T. Durhuus, K. E. Stubkjaer, ”WDM Packet Switch Architectures and Analysis of the Influence of Tunable Wavelength Converters on the Performance”, IEEE Journal of Lightwave Technology 15(2) (1997) 219-227.

[Dan98a] S. L. Danielsen, C. Joergensen, B. Mikkelsen, K. E. Stubkjaer, ”Optical Packet Switched Network Layer Without Optical Buffers”, IEEE Photonics Technology Letters 10(6) (1998) 896-898.

[Dan98b] S. L. Danielsen, P. B. Hansen, K. E. Stubkjaer, ”Wavelength Conversion in Optical Packet Switching”, IEEE Journal of Lightwave Technology 16(12) (1998) 2095-2108.

[Det02a] A. Detti, V. Eramo, M. Listanti, ”Optical Burst Switching With Burst Drop (OBS/BD): An Easy OBS Improvement”, in Proceedings of IEEE International Conference on Communication (ICC), vol. 5, pp. 2717-2721, 2002.

[Det02b] A. Detti, V. Eramo, M. Listanti, ”Performance Evaluation of a New Technique for IP Support in a WDM Optical Network: Optical Composite Burst Switching (OCBS)”, Journal of Lightwave Technology 20(2) (2002) 154-165.

[Dia99] J. Diao, P. L. Chu, “Analysis of Partially Shared Buffering for WDM Optical Packet Switching”, IEEE Journal of Lightwave Technology 17(12) (1999) 2461-2469.

[Dit03] L. Dittmann, C. Develder, D. Chiaroni, F. Neri, F. Callegati, W. Koerber, A. Stavdas, M. Renaud, A. Rafel, J. Solé-Pareta, W. Cerroni, N. Leligou, L. Dembeck, B. Mortensen, M. Pickavet, N. Le Sauze, M. Mahony, B. Berde, G. Eilenberger, ”The European IST Project DAVID: A Viable Approach Toward Optical Packet Switching”, IEEE Journal on Selected Areas in Communications 21(7) (2003) 1026-1040.

[Dol01] K. Dolzer, C. Gauger, J. Späth, S. Bodamer, “Evaluation of Reservation Mechanisms for Optical Burst Switching”, AEÜ International Journal of Eletronic Communication 55(1) (2001) 1-8.

[Dor03] H. J. S. Dorren, M. T. Hill, Y. Liu, N. Calabretta, A. Srivatsa, F. M. Huijskens, H. de Waardt, G. D. Khoe, ”Optical Packet Switching and Buffering by Using All-Optical Signal Processing Methods”, IEEE Journal of Lightwave Technology 21(1) (2003) 2-12.

[DSL04] Global DSL statistics from DSL forum, March 2004 (url: http://www.dslforum.org/).

[Düs02a] M. Düser, P. Bayvel, “Performance of a Dynamically Wavelength-Routed Optical Burst Switched Network”, IEEE Photonics Technology Letters 14(2) (2002) 239-241.

[Düs02b] M. Düser, P. Bayvel, ”Analysis of a Dynamically Wavelength-Routed Optical Burst Switched Network Architecture”, IEEE Journal of Lightwave Technology 20(4) (2002) 574-585.

[El02] M. El-Sayed, J. Jaffe, “A View of Telecommunications Network Evolution”, IEEE Communications Magazine 40(12) (2002) 74-81.

[Elb02] T. S. El-Bawab, J. Shin, “Optical Packet Switching in Core Networks: Between Vision and Reality”, IEEE Communications Magazine 40(9) (2002) 60-65.

[Ems00] P. J. Emstad, P. E. Heegaard, B. E. Helvik, ”Pålitelighet og ytelse i informasjons- og kommunikasjonssystem – Grunnlag (in norwegian)” (Department of Telematics, Norwegian University of Science and Technology, 2000).

[Era00] V. Eramo, M. Listanti, “Packet Loss in a Bufferless Optical WDM Switch Employing Shared Tunable Wavelength Converters”, IEEE Journal of Lightwave Technology 18(12) (2000) 1818-1833.

[Era04] V. Eramo, M. Listanti, M. Di Donato, ”Performance Evaluation of a Bufferless Optical Packet Switch With Limited-Range Wavelength Converters”, IEEE Photonics Technology Letters 16(2) (2004) 644-646.

[Far03] F. Farahmand, V. M. Vokkarane, J. P. Jue, ”Practical Priority Contention Resolution for Slotted Optical Burst Switching Networks”, in Proceedings of IEEE/SPIE Workshop on Optical Burst Switching (WOBS), 2003.

[Flo01] S. Floyd, V. Paxon, ”Difficulties in Simulating the Internet”, IEEE/ACM Transactions on Networking 9(4) (2001) 392-403.

[FSR04] Fluid Studios, FSRaid documentation, http://www.fluidstudios.com/fsraid.html (accessed March 2004).

[Gam98] P. Gambini, M. Renaud, C. Guillemot, F. Callegati, I. Andonovic, B. Bostica, D. Chiaroni, G. Corazza, S. L. Danielsen, P. Gravey, P. B. Hansen, M. Henry, C. Janz, A. Kloch, R. Krähenbühl, C. Raffaelli, M. Schilling, A. Talneau, L. Zucchelli, ”Transparent Optical Packet Switching: Network Architecture and Demonstrators in the KEOPS Project”, IEEE Journal on Selected Areas in Communications 16(7) (1998) 1245-1259.

[Gau02] C. M. Gauger, “Performance of Converter Pools for Contention Resolution in Optical Burst Switching”, in Proceedings of SPIE Optical Networking and Communications (Opticomm), Proceedings of SPIE vol. 4874, pp. 109-117, 2002.

[Gau03] C. M. Gauger, “Trends in Optical Burst Switching”, in Proceedings of SPIE ITCOM, 2003.

[Ge00] A. Ge, F. Callegati, L. S. Tamil, “On Optical Burst Switching and Self-Similar Traffic”, IEEE Communications Letters 4(3) (2000) 98-100.

[Gro74] D. Gross, C. M. Harris, “Fundamentals of Queueing Theory” (John Wiley & Sons, 1974).

[Har02] H. Harai, M. Murata, ”Performance Analysis of Prioritized Buffer Management in Photonic Packet Switches for DiffServ Assured Forwarding”, in Proceedings of SPIE Optical Networking and Communication Conference (OptiComm), 2002.

[Her04] M. Herzog, M. Maier, M. Reisslein, ”Metropolitian area packet-switched WDM networks: A survey on ring systems”, IEEE Communications Surveys 6(2) (2004) 2-20.

[Hlu88] M. G. Hluchyj, M. J. Karol, “Queueing in High-Performance Packet Switching”, IEEE Journal on Selected Areas in Communications 6(9) (1988) 1587-1597.

[Hsu02] C. Hsu, T. Liu, N. Huang, “Performance Analysis of Deflection Routing in Optical Burst-Switched Networks”, in Proceedings of IEEE INFOCOM, vol. 1, pp. 66-73, 2002.

[Hu03] G. Hu, K. Dolzer, C. M. Gauger, “Does burst assembly really reduce the self-similarity?”, in Proceedings of the IEEE/OSA Optical Fibre Conference (OFC), 2003.

[Hun00] D. K. Hunter, I. Andonovic, “Approaches to Optical Internet Packet Switching”, IEEE Communications Magazine 38(9) (2000) 116-122.

[Hun98] D. K. Hunter, M. C. Chia, I. Andonovic, ”Buffering in Optical Packet Switches”, IEEE Journal of Lightwave Technology 16(12) (1998) 2081-2094.

[Hun99] D. K. Hunter, M. H. M. Nizam, M. C. Chia, I. Andonovic, K. M. Guild, A. Tzanakaki, M. J. O’Mahony, J. D. Bainbridge, M. F. C. Stephens, R. V. Penty, I. H. White, ”WASPNET: A Wavelength Switched Packet Network”, IEEE Communications Magazine 37(3) (1999) 120-129.

[ITU04] International Telecommunication Union, ICT – Free Statistics, April 2004 (url: http://www.itu.int/ITU-D/ict/statistics/).

[Ive99] V. B. Iversen, “Data- og teletrafikteori (in danish)” (Den Private Ingeniørfond, 1999).

[Iza02] M. Izal, J. Aracil, “On the Influence of Self-similarity on Optical Burst Switching Traffic”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), 2002.

[Kah02] A. Kaheel, T. Khattab, A. Mohamed, H. Alnuweiri, “Quality-of-Service Mechanisms in IP-over WDM Networks”, IEEE Communications Magazine 40(12) (2002) 38-43.

[Kar04] T. Karagiannis, M. Molle, M. Faloutsos, A. Broido, ”A Nonstationary Poisson View of Internet Traffic”, in Proceedings of IEEE INFOCOM, 2004.

[Kes03] I. Keslassy, S. Chuang, K. Yu, D. Miller, M. Horowitz, O. Solgaard, N. McKeown, ”Scaling Internet Routers Using Optics”, in Proceedings of the Special Interest Group on Data Communication (SIGCOMM), 2003.

[Kim02] B. Kim, Y. Cho, J. Lee, Y. Choi, D. Montgomery, “Performance of Optical Burst Switching Techniques in Multi-Hop Networks”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), vol. 3, pp. 2772-2776, 2002.

[Kle75] L. Kleinrock, “Queueing Systems Volume I: Theory” (John Wiley & Sons, 1975).

[Kle76] L. Kleinrock, “Queueing Systems Volume II: Computer Applications” (John Wiley & Sons, 1976).

[Kli03] M. Klinkowski, D. Careglio, M. Marciniak, J. Solé-Pareta, “Performance Analysis of the Simple Prioritized Buffering Algorithm in Optical Packet Switch for DiffServ Assured Forwarding”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 2, pp. 148-151, 2003.

[Kor04] A. Kortebi, S. Oueslati, J. Roberts, ”Cross-protect: implicit service differentiation and admission control”, in Proceedings of Workshop on High Performance Switching and Routing (HPSR), 2004.

[Lee03] S. Lee, K. Sriram, H. Kim, J. Song, ”Contention-based Limited Deflection Routing in OBS Networks”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), 2003.

[Lel94] W. E. Leland, M. S. Taqqu, W. Willinger, D. V. Wilson, “On the Self Similar Nature of Ethernet Traffic (Extended Version)”, IEEE/ACM Transactions on Networking 2(1) (1994) 1-15.

[Li03] L. Li, S. D. Scott, J. S. Deogun, ”A Novel Fiber Delay Line Buffering Architecture for Optical Packet Switching”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), 2003.

[Lie04] A. Lie, O. M. Aamo, L. A. Rønningen, ”On the use of classical control system based AQM for rate adaptive streaming media”, in Proceedings of Nordic Teletraffic Seminar (NTS), pp. 171-182, 2004.

[Loi02] C. Loi, W. Liao, D. Yang, ”Service Differentiation in Optical Burst Switched Networks”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), 2002.

[Maa04] A. Maach, G. V. Bochman, H. Mouftah, “Congestion Control and Contention Elimination in Optical Burst Switching”, Kluwer Telecommunication Systems 27(2-4) (2004) 115-131.

[Mah01] M. J. O’Mahony, D. Simeonidou, D. K. Hunter, A. Tzanakaki, “The Application of Optical Packet Switching in Future Communication Networks”, IEEE Communications Magazine 39(3) (2001) 128-135.

[Med96] D. Medhi, “Some Results for Renewal Arrival to a Communication Link”, Probability Models and Statistics, pp. 85-107, 1996.

[Mos04] T. K. Moseng, H. Øverby, N. Stol, ”Merit based scheduling in asynchronous bufferless optical packet switched networks”, in Proceedings of the Norwegian Informatics Conference (NIK), pp. 126-136, 2004.

[Neu03] M. Neuts, Z. Rosberg, H. Le Vu, J. White, M. Zukerman, “Performance Analysis of Optical Composite Burst Switching”, IEEE Communications Letters 6(8) (2003) 346-348.

[Nor03] M. Nord, S. Bjørnstad, C. M. Gauger, ”OPS or OBS in the Core Network? – A Comparison of Optical Packet- and Optical Burst Switching”, in Proceedings of the 7th IFIP working conference on optical network design & modeling (ONDM), 2003.

[Nor04a] M. Nord, “An efficient Quality of Service differentiation algorithm for buffer-less optical packet switches with partially shared wavelength converters”, in Proceedings of Optoelectronic and Communications Conference (OECC), 2004.

[Nor04b] M. Nord, “Waveband based multi-plane optical packet switch with partially shared wavelength converters”, in Proceedings of the 8th IFIP Working Conference on Optical Network Design & Modelling (ONDM), 2004.

[Nor04c] M. Nord, “Replacing Shared-Per-Node Wavelength Converters by Fibre Delay Lines in an Asynchronous Optical Packet Switch”, in Proceedings of the 30th European Conference on Optical Communication (ECOC), 2004.

[Nor04d] M. Nord, H. Øverby, “Packet loss rate and jitter differentiating quality-of-service schemes for asynchronous optical packet switches”, OSA Journal of Optical Networking 3(12) (2004) 866-881.

[Odl03] A. Odlyzko, “Internet traffic growth: Sources and implications”, in Proceedings of SPIE 5247 (2003) 1-15.

[Øve03a] H. Øverby, “An Adaptive Service Differentiation Algorithm for Optical Packet Switched Networks”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 158-161, 2003.

[Øve03b] H. Øverby, N. Stol, “A Teletraffic Model for Service Differentiation in OPS networks”, in Proceedings of Optoelectronic and Communications Conference (OECC), vol. 2, pp. 677-678, 2003.

[Øve03c] H. Øverby, “A Study on Service Differentiation in Bufferless Optical Packet/Burst Switched Networks”, in Proceedings of Norwegian Informatics Conference (NIK), pp. 105-116, 2003.

[Øve04a] H. Øverby, N. Stol, “Providing Quality of Service in Optical Packet/Burst Switched Networks with the Preemptive Drop Policy”, in Proceedings of the 3rd International Conference on Networking (ICN), vol. 1, pp. 312-319, 2004.

[Øve04b] H. Øverby, N. Stol, “Evaluating and Comparing Two Different Service Differentiation Methods for OPS: The Wavelength Allocation Algorithm and the Preemptive Drop Policy”, In Proceedings of the 3rd International Conference on Networking (ICN), vol. 1, pp. 8-15, 2004.

[Øve04c] H. Øverby, N. Stol, ”Exploiting network layer packet redundancy to reduce the end-to-end data packet loss rate in optical packet/burst switched networks”, in Proceedings of Nordic Teletraffic Seminar (NTS), pp. 335-346, 2004.

[Øve04d] H. Øverby, “QoS in slotted bufferless optical packet switched networks”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 2, pp. 334-337, 2004.

[Øve04e] H. Øverby, “Performance modelling of synchronous bufferless OPS networks”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 22-28, 2004.

[Øve04f] H. Øverby, N. Stol, ”Effects of the switching time in OPS/OBS networks”, Chinese Optics Letters 2(3) (2004) 131-134.

[Øve04g] H. Øverby, N. Stol, “Effects of bursty traffic in service differentiated Optical Packet Switched networks”, OSA Optics Express 12(3) (2004) 410-415.

[Øve04h] H. Øverby, N. Stol, ”Quality of Service in Asynchronous Bufferless Optical Packet Switched Networks”, Kluwer Telecommunication Systems 27(2-4) (2004) 151-179.

[Øve04i] H. Øverby, “Network layer packet redundancy in optical packet switched networks”, OSA Optics Express 12(20) (2004) 4881-4895.

[Pap01] G. I. Papadimitriou, M. S. Obaidat, A. S. Pomportsis, “Advances in optical networking”, International Journal of Communication Systems 15 (2001) 101-113.

[Paw02] K. Pawlikowski, H. J. Jeong, J. R. Lee, ”On Credibility of Simulation Studies of Telecommunication Networks”, IEEE Communications Magazine 40(1) (2002) 132-139.

[Pax95] V. Paxon, S. Floyd, “Wide Area Traffic: The Failure of Poisson Modeling”, IEEE/ACM Transactions On Networking 3(3) (1995) 226-244.

[Per02] S. D. Personick, “Evolving toward the Next-Generation Internet: Challenges in the Path Forward”, IEEE Communications Magazine 40(7) (2002) 72-76.

[Pop02] F. Poppe, K. Laevens, H. Michiel, S. Molenaar, “Quality-of-Service differentiation and fairness in optical burst-switched networks”, in Proceedings of Optical Networking and Communications (Opticomm), Proceedings of SPIE 4874, pp. 118-124, 2002.

[Qia00a] C. Qiao, M. Yoo, “Choices, Features and Issues in Optical Burst Switching”, SPIE/Kluwer Optical Networks Magazine 1(2) (2000) 104-114.

[Qia00b] C. Qiao, “Labeled Optical Burst Switching for IP-over-WDM Integration”, IEEE Communications Magazine 38(9) (2000) 104-114.

[Ram02] R. Ramaswami, K. N. Sivarajan, “Optical Networks: A Practical Perspective” (Morgan Kaufmann, 2002).

[Ran04] S. Rangarajan, Z. Hu, L. Rau, D. J. Blumenthal, ”All-Optical Contention Resolution with Wavelength Conversion for Asynchronous Variable-Length 40 Gb/s Optical Packets”, IEEE Photonics Technology Letters 16(2) (2004) 689-691.

[Rob01] J. W. Roberts, “Traffic Theory and the Internet”, IEEE Communications Magazine 38(1) (2001) 94-99.

[Ros03a] Z. Rosberg, H. Le Vu, M. Zukerman, J. White, “Blocking Probabilities of Optical Burst Switching Networks Based on Reduced load Fixed Point Approximations”, in Proceedings of IEEE INFOCOM, 2003.

[Ros03b] Z. Rosberg, H. Le Vu, M. Zukerman, J. White, “Performance Analyses of Optical Burst-Switching Networks”, IEEE Journal on Selected Areas in Communications 21(7) (2003) 1187-1197.

[Sch98] A. L. Schmid, I. Iliadis, P. Droz, “Impact of VC Merging on Buffer Requirements in ATM Networks”, in Proceedings of the International Conference on High Performance Networking, pp. 203-217, 1998.

[She01] G. Shen, S. K. Bose, T. H. Cheng, C. Lu, T. Y. Chai, ”Performance Study on a WDM Packet Switch With Limited-Range Wavelength Converters”, IEEE Communciations Letters 5(10) (2001) 432-434.

[Sri86] K. Sriram, W. Whitt, ”Characterizing Superposition Arrival Processes in Packet Multiplexers for Voice and Data”, IEEE Journal on Selected Areas in Communications 4(6) (1986) 833-846.

[Tan00] L. Tancevski, S. Yegnanarayanan, G. Castanon, L. Tamil, F. Masetti, T. McDermott, “Optical Routing of Asynchronous, Variable Length Packets”, IEEE Journal on Selected Areas in Communications 18(10) (2000) 2084-2093.

[Tan01] L. Tancevski, A. Ge, G. Castanon, “Optical Packet Switch with Partially Shared Buffers: Design Principles”, in Proccedings of IEEE/OSA Optical Fibre Conference (OFC), TuK3, 2001.

[Tan96] A. S. Tanenbaum, ”Computer Networks” (Prentice Hall, 1996).

[Taq97] M. S. Taqqu, V. Teverovsky, “Is network traffic self-similar or multifractal?”, Fractals 5(1) (1997) 63-73.

[Ten03] J. Teng, G. N. Rouskas, “A Comparison of the JIT, JET and Horizon Wavelength Reservation Schemes on A single OBS Node”, in Proceedings of IEEE/SPIE Workshop on Optical Burst Switching (WOBS), 2003.

[Tur99] J. S. Turner, “Terabit burst switching”, Journal of High Speed Networks 8(1) (1999) 3-16.

[Und04] A. Undheim, H. Øverby, N. Stol, ”Absolute QoS in Synchronous Optical Packet Switched Networks”, in Proceedings of the Norwegian Informatics Conference (NIK), pp. 137-148, 2004.

[Ver00] S. Verma, H. Chaskar, R. Ravikanth, “Optical Burst Switching: A viable Solution for Terabit IP Backbone”, IEEE Network 14(6) (2000) 48-53.

[Vik01] B. Viken, P. J. Emstad, ”Accuracy of Intrusive Measurements of the Waiting Time in an $M/G/1/\infty$ Queue”, in Proc. of International Teletraffic Congress (ITC-17), 2001.

[Vok02a] V. M. Vokkarane, K. Haridoss, J. P. Jue, “Threshold-Based Burst Assembly Policies for QoS Support in Optical Burst-Switched Networks”, in Proceedings of SPIE Optical Networking and Communication Conference (OptiComm), Proceeding of SPIE vol. 4874, pp. 125-136, 2002.

[Vok02b] V. M. Vokkarane, J. P. Jue, “Prioritized Routing and Burst Segmentation for QoS in Optical Burst-Switched Networks”, in Proceedings of IEEE/OSA Optical Fibre Conference (OFC), vol. 1, pp. 221-222, 2002.

[Vok02c] V. M. Vokkarane, J. P. Jue, S. Sitaraman, ”Burst Segmentation: An Approach For Reducing Packet Loss In Optical Burst Switched Networks”, in Proceedings of IEEE International Conference on Communication (ICC), vol. 5, pp. 2673-2677, 2002.

[Vok02d] V. M. Vokkarane, Q. Zhang, Jason P. Jue, B. Chen, “Generalized Burst Assembly and Scheduling Techniques for QoS Support in Optical Burst-Switched Networks”, in Proceedings of IEEE Global Telecommunication Conference (GLOBECOM), 2002.

[Vok03a] V. M. Vokkarane, G. P. V. Thodime, V. U. B. Challagulla, J. P. Jue, “Channel Scheduling Algorithms using Burst Segmentation and FDLs for Optical Burst-Switched Networks”, in Proceedings of IEEE International Conference on Communication (ICC), 2003.

[Vok03b] V. M. Vokkarane, J. P. Jue, “Burst Segmentation: An Approach for Reducing Packet Loss in Optical Burst-Switched Networks”, SPIE/Kluwer Optical Networks Magazine, November/December 2003.

[Vok03c] V. M. Vokkarane, J. P. Jue, “Prioritized Burst Segmentation and Composite Burst Assembly Techniques for QoS Support in Optical Burst-Switched Networks”, IEEE Journal on Selected Areas in Communications 21(7) (2003) 1198-1209.

[Vu02] H. Le Vu, M. Zukerman, “Blocking Probability for Priority Classes in Optical Burst Switching Networks”, IEEE Communications Letters 6(5) (2002) 214-216.

[Wal98] R. E. Walpole, R. H. Myers, S. L. Myers, “Probability and statistics, 6th edition” (Prentice Hall, 1998).

[Wan00] X. Wang, H. Morikawa, T. Aoyama, “Deflection routing protocol for burst switching WDM mesh networks”, in Proceedings of SPIE Optical Networking and Communication Conference (Opticomm), Proceeding of SPIE vol. 4213, pp. 242-252, 2000.

[Wan03] J. Wang, Q. Zeng, S. Xiao, S. Wang, Z. Zhang, “Segment Technology of Differentiated Services Supporting in Optical Burst Switched networks”, in Proceedings of IEEE/SPIE Workshop on Optical Burst Switching (WOBS), 2003.

[Whi02a] J. White, M. Zukerman, H. Le Vu, “A Framework for Optical Burst Switching Network Design”, IEEE Communications Letters 6(6) (2002) 268-270.

[Whi02b] I. M. White, “A new architecture and technologies for high capacity next-generation metropolitian networks”, Ph.D. thesis at Stanford University, August 2002.

[Whi02c] I. White, R. Penty, M. Webster, Y. Jun Chai, A. Wonfor, S. Shahkooh, “Wavelength Switching Components for Future Photonic Networks”, IEEE Communications Magazine 40(9) (2002) 74-81.

[Whi02d] J. A. White, R. S. Tucker, K. Long, “Merit-based Scheduling Algorithm for Optical Burst Switching”, in Proceedings of Conference on Optical Internet and Photonic Switching (COIN/PS), 2002.

[Whi03] I. M. White, M. S. Rogge, K. Shrikhande, L. G. Kazovsky, “A summary of the HORNET project: A Next-Generation Metropolitian Area Network”, IEEE Journal on Selected Areas in Communications 21(9) (2003) 1478-1494.

[Wid95] I. Widjaja, “Performance analysis of burst admission-control protocols”, IEE Proceedings of communications 142(1) (1995) 7-14.

[Wyd02] B. Wydrowski, M. Zukerman, “QoS in Best-Effort Networks”, IEEE Communications Magazine 40(12) (2002) 44-49.

[Xia99] X. Xiao, L. M. Ni, “Internet QoS: A Big Picture”, IEEE Network 13(2) (1999) 8-18.

[Xio00] Y. Xiong, M. Vandenhoute, H. C. Cankaya, ”Control Architecture in Optical Burst-Switched WDM Networks”, IEEE Journal on Selected Areas in Communications 18(10) (2000) 1838-1851.

[Xu01] L. Xu, H. G. Perros, G. Rouskas, “Techniques for Optical Packet Switching and Optical Burst Switching”, IEEE Communications Magazine 39(1) (2001) 136-142.

[Xu02] L. Xu, “Performance Analysis of Optical Burst Switched Networks”, PhD Thesis at the Department of Computer Science, North Carolina State University, 2002.

[Xu03] L. Xu, H. G. Perros, G. N. Rouskas, “A Queueing Network Model of an Edge Optical Burst Switching Node”, in Proceedings of IEEE INFOCOM, 2003.

[Xue02] F. Xue, S. Yao, B. Mukherjee, S. J. Ben Yoo, “The Performance Improvement in Optical Packet Switched networks by traffic shaping of self-similar traffic”, in Proceedings of IEEE/OSA Optical Fibre Conference (OFC), vol. 1, pp. 218-219, 2002.

[Xue03] F. Xue, Z. Pan, Y. Bansal, J. Cao, M. Jeon, K. Okamoto, S. Kamei, V. Akella, S. J. Ben Yoo, ”End-to-End Contention Resolution Schemes for an Optical Packet Switching Network With Enhanced Edge Routers”, IEEE Journal of Lightwave Technology 21(11) (2003) 2595-2604

[Yan03] L. Yang, Y. Jiang, S. Jiang, ”A Probabilistic Preemptive Scheme for Providing Service Differentiation in OBS Networks”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), 2003.

[Yao00] S. Yao, B. Mukherjee, “Advances in Photonic Packet Switching: An Overview”, IEEE Communications Magazine 38(2) (2000) 84-94.

[Yao01a] S. Yao, S. J. Ben Yoo, B. Mukherjee, “A comparison study between slotted and unslotted all-optical packet-switched network with priority-based routing”, in Proceedings of IEEE/OSA Optical Fibre Conference (OFC), vol. 2, Paper TuK2-1-3, 2001.

[Yao01b] S. Yao, S. J. Ben Yoo, B. Mukherjee, S. Dixit, “All-Optical Packet Switching for Metropolitan Area Networks: Opportunities and Challenges”, IEEE Communications Magazine 39(3) (2001) 142-148.

[Yao02] S. Yao, F. Xue, B. Mukherjee, S. J. Ben Yoo, “Electrical Ingress Buffering and Traffic Aggregation for Optical Packet Switching and Their Effects on TCP-Level Performance in Optical Mesh Networks”, IEEE Communications Magazine 40(9) (2002) 66-72.

[Yao03] S. Yao, B. Mukherjee, S. J. Ben Yoo, S. Dixit, “A Unified Study of Contention-Resolution Schemes in Optical Packet-Switched Networks”, IEEE/OSA Journal of Lightwave Technology 21(3) (2003) 672-683.

[Yoo00a] M. Yoo, C. Qiao, S. Dixit, “QoS Performance of Optical Burst Switching in IP-Over-WDM Networks”, IEEE Journal on Selected Areas in Communications 18(10) (2000) 2062-2071.

[Yoo00b] M. Yoo, C. Qiao, S. Dixit, “A Comparative Study of Contention Resolution Policies in Optical Burst Switched WDM Networks”, in Proceedings of SPIE Conference on Terabit Optical Networking: Architecture, Control and Management Issues, Proceedings of SPIE vol. 4213, pp. 124-135, 2000.

[Yoo02] M. Yoo, C. Qiao, S. Dixit, “Optical Burst Switching for Service Differentiation in the Next-Generation Optical Internet”, IEEE Communications Magazine 39(2) (2002) 98-104.

[Yoo99] M. Yoo, C. Qiao, “Supporting Multiple Classes of Services in IP over WDM Networks”, in Proceedings of IEEE Global Telecommunications Conference (GLOBECOM), vol. 1b, pp. 1023-1027, 1999.

[Zal03] A. Zalesky, H. Le Vu, Z. Rosberg, E. W. M. Wong, M. Zukerman, ”Reduced Load Erlang Fixed Point Analysis of Optical Burst Switched Networks with Deflection Routing and Wavelength Reservation”, in Proceedings of IEEE/SPIE Workshop on Optical Burst Switching (WOBS), 2003.

[Zal04] A. Zalesky, E. W. M. Wong, M. Zukerman, H. Le Vu, R. S. Tucker, ”Performance Analysis of an OBS Edge Router”, IEEE Photonics Technology Letters 16(2) (2004) 695-697.

[Zha03a] Q. Zhang, V. M. Vokkarane, B. Chen, J. P. Jue, “Early Drop Scheme for Providing Absolute QoS Differentiation in Optical Burst-Switched Networks”, in Proceedings of IEEE Workshop on High Performance Switching and Routing (HPSR), 2003.

[Zha03b] Q. Zhang, V. M. Vokkarane, B. Chen, J. P. Jue, “Early Drop and Wavelength Grouping Schemes for Providing Absolute QoS Differentiation in Optical Burst-Switched Networks”, in Proceedings of IEEE Global Telecommunication Conference (GLOBECOM), 2003.

[Zha03c] Z. Zhang, Y. Yang, ”Performance Modeling of Bufferless WDM Packet Switching Networks with Wavelength Conversion”, in Proceedings of IEEE Global Telecommunication Conference (GLOBECOM), 2003.

[Zha04] Q. Zhang, V. M. Vokkarane, J. P. Jue, B. Chen, ”Absolute QoS Differentiation in Optical Burst-Switched Networks”, IEEE Journal on Selected Areas in Communications 22(9) (2004) 1781-1795.

[Zho03] W. Zhong, X. Niu, ”Impact of Number of Add/Drop Ports of OXCs on LSP Blocking Performance”, in Proceedings of OptoElectronics and Communications Conference (OECC), pp. 683-684 2003.

[Zse02] T. Zseby, “Deployment of Sampling Methods for SLA Validation with Non-Intrusive Measurements”, in Proceedings of Passive and Active Measurements Workshop (PAM), 2002.

[Zuk03] M. Zukerman, E. W. M. Wong, Z. Rosberg, G. Myoung Lee, H. L. Vu, “Teletraffic Modeling of Optical Burst Switching”, in Proceedings of International Conference on Transparent Optical Networks (ICTON), vol. 1, pp. 82-86, 2003.