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The use of the Network Layer Packet Redundancy Scheme in the OpMiGua hybrid network

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Master of Science in Communication Technology
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Problem Description

The OpMiGua hybrid network has been proposed as viable migration approach from circuit switched all-optical networks to 3rd generation packet based optical networks. A special feature in the OpMiGua network compared with other hybrid optical network architecture proposals, is the combination of service guarantees with high performance. In order to achieve this, the OpMiGua network features two different service classes, Guaranteed Service (GS) and Best-effort service (BE). A crucial issue in this context is how the performance of these service classes, in particular the BE class, may be improved. To this aim, the Network Layer Packet Redundancy Scheme (NLPRS) is a viable candidate to reduce the packet loss rate in such networks. The NLPRS has earlier been studied in Optical Packet Switched (OPS) networks, but has never been considered used in hybrid optical network architectures.

In this master thesis, the student shall perform the following tasks:

- Explore the use of the NLPRS with respect to performance in hybrid optical network architectures such as OpMiGua.
- Propose one or more schemes, combining NLPRS and OpMiGua
- Investigate the performance of the proposed schemes using simulations and/or teletraffic analysis

Assignment given: 16. August 2006
Supervisor: Steinar Bjørnstad, ITEM

Abstract

This thesis proposes three schemes combining **Op**tical **Mi**gration Capable Networks with Service **Gua**rantees (OpMiGua) and the Network Layer Packet Redundancy Scheme (NLPRS) in order to improve the packet loss rate performance of the Best Effort (BE) class in OpMiGua. The proposed schemes send redundancy packets as BE-packets or over the Guaranteed Service (GS) path, while the regular data packets are sent as BE-packets. This thesis also investigates the performance of the proposed schemes. First, the OpMiGua and NLPRS are described. Second, a simulator model of the combined is presented. Based on the results obtained from simulation, the performance of the proposed schemes is quantified and presented.

The simulations have revealed that all three schemes reduce the packet loss rate for the evaluated scenarios. Hence, the proposed schemes improve the performance of the BE-class. By combining OpMiGua and NLPRS with the proposed schemes, the NLPRS increases its tolerance for high offered load.

Preface

This thesis is the result of my MSc degree at the Norwegian University of Science and Technology (NTNU). The workload in this thesis is 30 European Credit Transfer System (ECTS) credits. My supervisor has been Post.doc Harald Øverby at Department of Telematics and my subject teacher has been Adjunct Associate Professor Steinar Bjørnstad at Department of Telematics.

Thanks go to Andreas Kimsås, Steinar Bjørnstad and Harald Øverby, co-authors on the on-going OSA OpticsExpress paper. I would also like to thank OpMiGua PhD-student Vegard Tuft. They have all been an important part of my academic society ever since I become acquainted with them during a PhD-course in the spring of 2005.

Trondheim, January 31, 2007

Arnt Erling Skavdal

Acronyms

AWG	-	Array Waveguide Grating
APC	-	Automatic Polarization Controller
BE	-	Best Effort
BP	-	Buffer Priority
CS	-	Circuit Switching
DEMOS	-	Discrete Event Modelling on Simula
DPLR	-	Data Packet Loss Rate
FDL	-	Fibre Delay Line
FLP	-	Fixed Length Packet
FWC	-	Fixed Wavelength Converter
GS	-	Guaranteed Service
GST	-	Guaranteed Service Transport
HCT	-	High Class Transport
ITU-T	-	International Telecommunications Union Technical standards group
LATW	-	Length Aware Time-Window
MTBF	-	Mean Time Between Failure
MUX	-	Multiplexer
NCT	-	Normal Class Transport
NLPRS	-	Network Layer Packet Redundancy Scheme
OE	-	Opto-Electronic
OpMiGua	-	Optical Migration capable networks with service Guarantees
OPS	-	Optical Packet Switch

OSA	-	Optic Society of America
OXC	-	Optical Cross Connect
PDM	-	Polarization Division Multiplexing
PL	-	Packet Length
PLR	-	Packet Loss Rate
QoS	-	Quality of Service
RFC	-	Request For Comment
RIB	-	Reservation Induced Blocking
SOP	-	State Of Polarization
STW	-	Single Time-Window

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Chapter 1

Introduction

1.1 Introduction

The OpMiGua hybrid network has been proposed as viable migration approach from circuit switched all-optical networks to 3rd generation packet based optical networks [1]. A special feature in the OpMiGua network compared with other hybrid optical network architecture proposals, is the combination of service guarantees with high performance. In order to achieve this, the OpMiGua network features two different service classes, Guaranteed Service (GS) and Best-effort service (BE). A crucial issue in this context is how the performance of these service classes, in particular the BE class, may be improved. To this aim, the Network Layer Packet Redundancy Scheme (NLPRS) is a viable candidate to reduce the packet loss rate in such networks [2]. The NLPRS has earlier been studied in Optical Packet Switched (OPS) networks [2], but has never been considered used in hybrid optical network architectures.

1.2 Tasks to fulfil

For this master thesis, three tasks have been identified:

- Explore the use of the NLPRS with respect to performance in hybrid optical network architectures such as OpMiGua.
- Propose one or more schemes, combining NLPRS and OpMiGua.
- Investigate the performance of the proposed schemes using simulation analysis.

1.3 Research method

The methodology and structure in this thesis have been adopted from the theme in "TTM9 Traffic and dependability, laboratory in tools and methodology", a theme which Bjarne E. Helvik at Q2S held. Q2S is the Centre for **Q**uantifiable **Q**uality of **S**ervice in Communication Systems, a Norwegian Centre of Excellence at the Norwegian University of Science and Technology.

1.4 Tools

Simulations are performed with Discrete Event Modelling on Simula (DEMOS) software [12] and are conducted on private computers, Department of Telematics" "Pride" cluster and two computers from the OpMiGua research project. The obtained results are intermediate processed in Microsoft Excel and imported into MatLab from the MathWorks for graph plotting. Microsoft PowerPoint has been used for drawing of illustrations and this report is written in Microsoft Word.

1.5 Outline

This report is divided into three parts. Chapter 2 gives an introduction to OpMiGua, while chapter 3 presents NLPRS. In the chapter 4 the concept, design and hypothesis is presented. Chapter 5 to 7 covers the description of the simulation model, results and discussions from the simulation runs. Chapter 8 lists up the proposed further work.

The appendixes for this thesis are enclosed in the electronic appendix. It is recommended to scan through it.

Chapter 2

OpMiGua

This chapter describes **Op**tical **Mi**gration Capable Networks with Service **Gua**rantees (OpMiGua) which is a hybrid network proposed by Steinar Bjørnstad in his doctoral thesis [3]. Telenor Research and Innovation (R&I) initiated the OpMiGua project in cooperation with the Norwegian University of Science and Technology (NTNU) and Network Electronics.

2.1 Introduction

The OpMiGua architecture has previously been presented in several publications where [1] gives an in-depth understanding of the networking aspects. OpMiGua is a hybrid network combining optical cross connects (OXC) and optical packet switches (OPS). With these two components in a node the network operates as a wavelength routed optical network (WRON) and as an OPS network, where the traffic over the WRON is circuit switched and the traffic over the OPS network is packet switched. The OXC supports a guaranteed service transport (GST) class and the OPS supports a statistical multiplexing (SM) class. These two classes share the link bandwidth by time division multiplexing. The GST-class is given absolute priority over the SM-class enabled by a reservation technique. In the remaining of this thesis the GST-class and the SM-class is denoted respectively as the Guaranteed Service (GS) class and the Best Effort (BE) class, because the SM-class will be modelled as best effort.

A hybrid network with this combination gives the potential to exploit the excellent Quality of Service (QoS) properties *and* the low processing requirements of an OXC together with the high throughput enabled by an OPS. When combining the OPS with the OXC, the OXC will relieve the OPS from high processing demands, which could reduce the price and complexity of the OPS [1].

2.2 The OpMiGua hybrid network concept

In figure 2.1 the hybrid network model presented. The basic idea in the OpMiGua hybrid network is that GS-packets follow pre-assigned light paths through a static or dynamic WRON from the source to the destination. The light paths are constructed by the interconnection of fibres and wavelengths through one or many, static or dynamic optical cross connects. By applying optical packet switches, a hybrid network is created where BE-packets are for each node switched in the OPS on the basis of their processed header information.

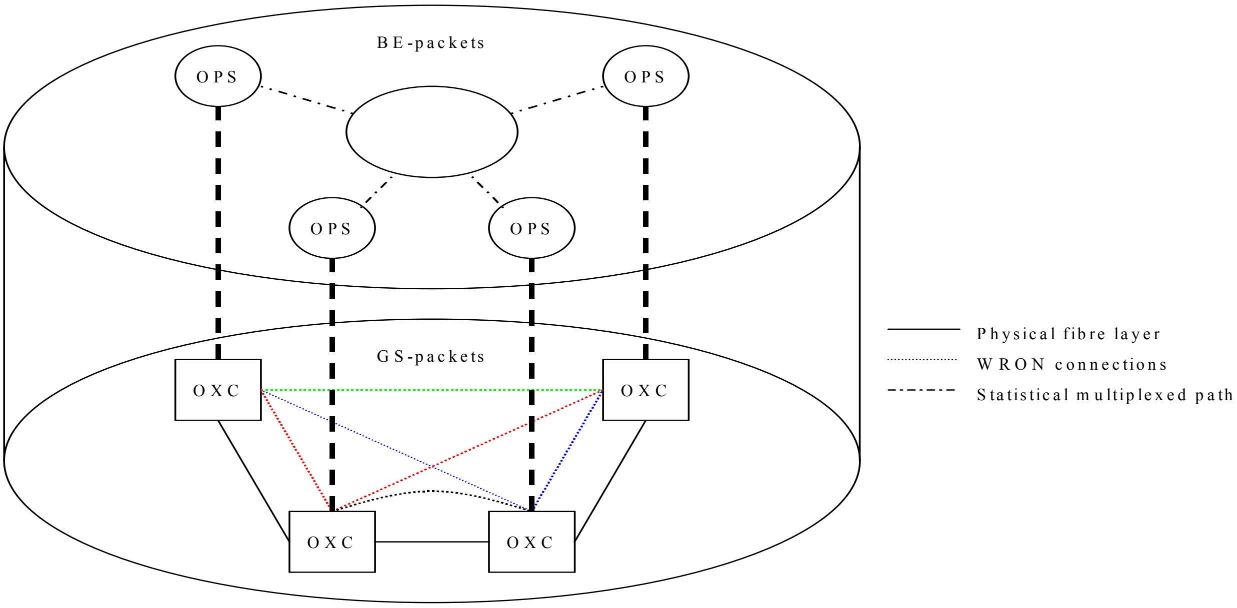

Figure 2.1: A hybrid network model illustrating the sharing of the physical fibre layer. The optical cross connects and optical packet switches are co-located, either as separate units or as one integrated unit. The WRON can be a Static or a Dynamic-WRON.

For a GS-packet, a strict priority is achieved considering possible contention with other GS or BE-packets due to two important design principals. The GS-packets do not contend with other

GS-packets since there is at least one wavelength for a given source-destination combination. Considering the potential problem of contention between GS and BE-packets, this is taken care of by implementing a reservation technique. In [1] a time-window approach is presented and in [4] a pre-emptive approach. [5] introduce two new techniques, which are an improved time-window approach and a combined time-window and pre-emptive approach. The principle behind the time-window approach presented in [1] will be described in detail in section 2.3.2.

2.3 Node design

In figure 2.2 a functional illustration of the hybrid node design is presented. The GS-class and the BE-class are combined/multiplexed into a given wavelength by a polarization beam combiner (PBC) [6]. GS and BE-packets are time division multiplexed and transmitted on orthogonal polarizations. This means that the capacity of a given wavelength channel is not doubled as in traditional polarization multiplexing where the two polarizations are transmitted simultaneously, but that the two different polarizations are utilized to label the two traffic classes. In [7] a sub-carrier modulation method is presented, an optional optical label technique.

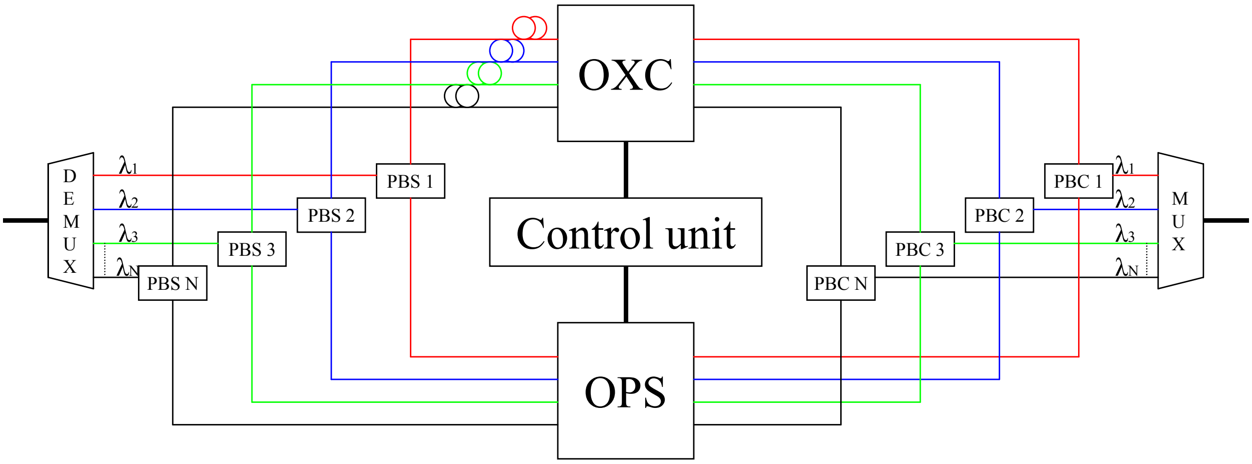

Figure 2.2: A functional illustration of a hybrid node with N wavelengths from one fibre. GS-packets are delayed in the fibre delay lines as a part of the reservation-method. By this, contention between GS and BE-packets is avoided.

At the next node the GS-packets and BE-packets are separated by polarization demultiplexing at each wavelength input. A polarization beam splitter (PBS) is placed in front of the OXC and the OPS where the PBS demultiplexes the GS-packets through the fibre delay lines (FDL) to the OXC and the BE-packet to the OPS. [1] presents three main advantages of using polarization to optically label GS-packets and BE-packets:

- No fast switches operating on a per packet basis
- No separate header is required, meaning no fast electronics for header processing
- No guard band is required because there is no processing and insertion of headers

2.3.1 Physical aspects

Due to environmental variations along the fibre transmission line, the SOP will fluctuate, meaning that counteractions have to be made to suppress the effect of this phenomenon. An automatic polarization controller (APC) placed in front of the PBS will adjust the state of each SOP so that the PBS can separate the different classes [6]. This APC operates on a timescale corresponding to the fluctuations of the SOP, a timescale of milliseconds to seconds. In figure 2.3 the APC is presented.

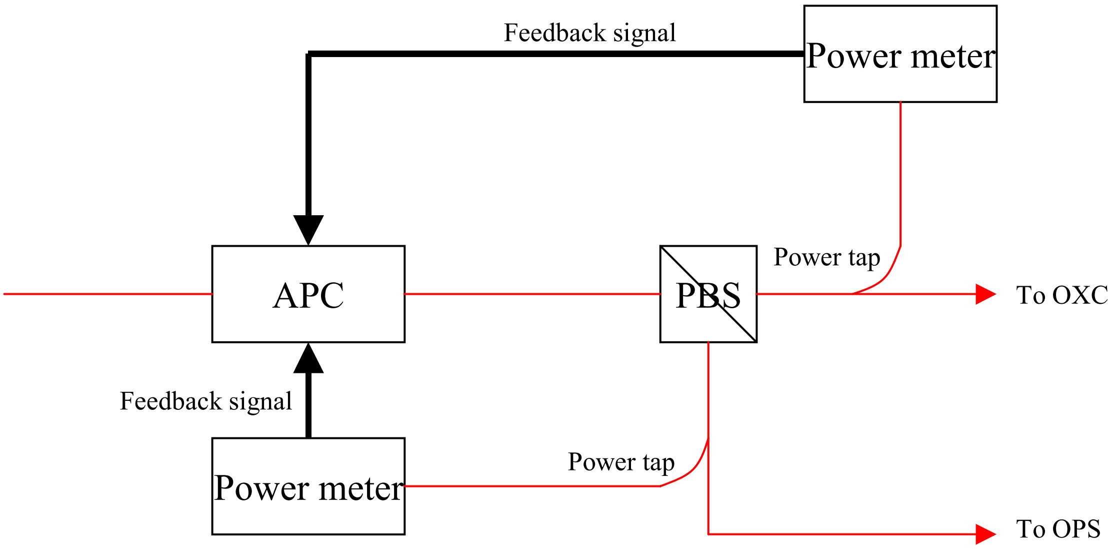

Figure 2.3: An illustration of the automatic polarization controller (APC). The APC maximizes the power of each polarization beam splitter (PBS) output based on the fed back signal from the power meters.

At the PBS the signals are separated and the power level is measured and fed back to the APC, which maximizes the power of each PBS output.

2.3.2 Network aspects

One reservation technique, ensuring strict priority for the GS-class, is a time-window approach. In this chapter the simple time-window (STW) [5] scheme is presented, because it is the basis for the simulation model. The STW scheme schedules BE-packets without taking the length of the BE or GS-packets into consideration. For a network with variable length packets (VLP) this is an ineffective scheme compared with the length aware time-window (LATW) scheme. The LATW scheme takes, as the name implies, the length of the BE-packets into consideration when the scheduling-decision is made. For a network with fixed length packets (FLP) will the LATW scheme have the same performance as the STW scheme [5].

The control-logic in the STW scheme will schedule BE-packets as longs as the output wavelength is vacant and not reserved. The system for detection of GS-packets can be made with detectors in the front of fibre delay lines. As seen in figure 2.2 the FDL is placed between PBS and the OXC. Before a GS-packet arrives to the OXC it must propagate through the FDL, the propagation time must correspond to at least the maximum length of a BE-packet [1]. In simulation models the reservation time is typically set to be equal the maximum length of a BE-packet, because it is not necessary to consider e.g. switch fabric setup-time and header processing.

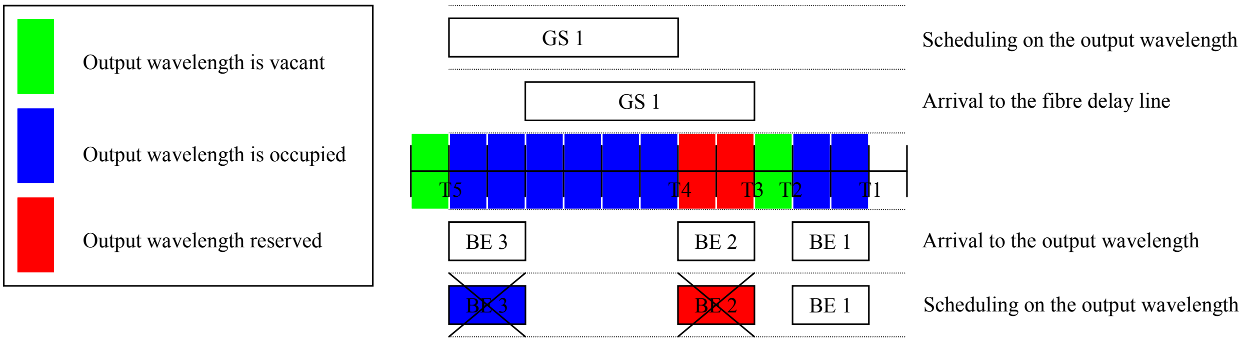

Figure 2.4: Arrival and scheduling of GS and BE-packets on a given wavelength. T1 = Arrival of BE1, T2 = Scheduling of BE1 finished, T3 = Arrival of GS1, T3 = Arrival of BE2, T4 = Scheduling of GS1 begins, T5 = Scheduling of GS1 is finished. BE1 is scheduled immediately, BE2 is blocked by the reservation of GS1 and BE3 is blocked by the scheduling of GS1.

In [1] a phenomenon is presented, called Reservation Induced Blocking (RIB), which is an additional blocking experienced by the BE-packets. The illustration over in figure 2.4 concerns the time-window reservation technique. At time T1 a BE-packet is scheduled immediately after arrival because both the output and the FDL are vacant. The blue time-period from T1 to T2 is coloured blue to illustrate that the output is occupied. At time T3 a GS-packet enters the input of the FDL and propagates through it, which means that BE-packets cannot be scheduled on the given output wavelength. The reservation time coloured red corresponds to the propagation time through the FDL, which is decided from the maximum BE-packet length. From time T3 and until the GS-packet is scheduled out at time T5, any new packets will not be able to be scheduled on the given output wavelength. So when a new BE-packet arrives at time T3 it is blocked by the reservation of the GS-packet. The time gap from T3 to T4 stresses the BE-class with an additional blocking, called RIB, to the regular blocking experienced in the blue time-period between T4 and T5. Please note that BE-packets may also block each other, but that problem is not a part of this illustration.

2.4 QoS in OpMiGua

The purpose of this section is to present part of the work regarding the performance of the BE-class. For this section the BE-class should not be called BE, but SM since the class does not necessarily behave as best effort. [1] introduces three traffic classes named GST bearer service, high class transport (HCT) bearer service and normal class transport (NCT) bearer service. The HCT and NCT-class are sub-classes of the SM-class. In [1] a node design is presented with optical cross connects, optical packet switches and electronic buffers.

The differentiation between the HCT and NCT-class is performed in the electronic buffer. By giving the HCT-class absolute priority when a wavelength to the destination becomes vacant, will the HCT-class experience lower delay than the NCT-class. This scheme is called the buffer priority (BP) scheme. For packet loss differentiation has the HCT-class access to all inputs of the buffer, while the NCT-class has limited access to the inputs. The number of inputs, which the NCT-class has access to, must also be shared with the HCT-class. This means that a given number of inputs on the buffer will be reserved for HCT-class [1], by this will the HCT-class have a increased probability to be buffered compared to the NCT-class.

The GST-class experiences constant switch delay, which means that there will be no jitter. There is no re-sequencing of packets and no packet loss is caused by contention. Mean time between failure (MTBF) for the node equipment must be high to support the high reliability envisioned. The class may support the requirements covered by RFC 2212 and ITU-T Y.1541 [1].

For the HCT-class the delay and jitter is kept at a minimum. The packet loss rate should be 10^{-6} or better, when considering the class serving services like MPEG2 and MPEG4 [1]. This class will not be able to meet RFC 2212, but it will fulfil the requirements in ITU-T Y.1541 class 0 up to 4 [1].

The NCT-class is proposed to service the ITU-T Y1541 class 2 up to 4, and it is recommended that the NCT service these three classes instead on the HCT-class. If the NCT shall service this class, the packet loss rate should be 10^{-3} or better and the delay variations should be lower than 10^3 durations of mean packet length (time units) [1].

Chapter 3

NLPRS

3.1 Introduction

In future lossy optical networks arises a new issue, contention, when two or more packets are simultaneously contending for the same output wavelength [8]. In [8] are three contention resolution methods presented such as wavelength conversion, deflection routing and optical buffering with fibre delay lines. This chapter presents the Network Layer Packet Redundancy Scheme (NLPRS), which is not a traditional contention resolution scheme, but an approach exploiting redundant packets. If contention has occurred this scheme is able to reconstruct lost packets at the egress node based on the successfully arrived packets. Compared with telecommunication systems, where high bit error rate is combated with error correcting codes on the bit level [9], NLPRS performs the combat on a bundle of bits, i.e. a packet on the network layer. The scheme has the advantage that it can be combined with the traditional contention resolution schemes [2]. An introduction, to wavelength conversion, is given at the end of this chapter.

3.2 NLPRS

NLPRS is based on Reed Solomon coding [2], an action taking place on the ingress and egress node of an OPS core network. The ingress node construct r_s redundancy packets out of m_s data packets received from the connected metro and access networks, together these packets forms a packet set with $r_s + m_s$ packets. By copying the data packets before they are scheduled, the ingress node can perform the creation of the redundancy packets when all data packets in the packet set are received. The length of the redundancy packets must equal the longest packet among the data packets in the packet set [2]. Only data packets with a common destination node are grouped together in a packet set [2]. When the creation of the redundancy packets is finished they are also scheduled to the destination egress node where the potential reconstruction is performed if any packet loss has occurred.

At the egress node, some packets may have been dropped on their way traversing through the lossy network due to contention. Received packets are denoted r_r ($r_r \leq r_s$) and m_r ($m_r \leq m_s$) and together they form what is left of the sent packet set. Possible lost packets equal m_s - m_r and r_s-r_r. If $m_r + r_r \geq m_s$ possible lost data packets can be reconstructed, but if $m_r + r_r < m_s$ then reconstruction is not possible and the number of lost data packets equals $m_s - m_r$ [2].

Figure 3.1 gives an example where m_s=4 and r_s=1. Due to contention in the lossy network one data packet is lost. Since $m_r + r_r \geq m_s$, reconstruction is possible and lost data packets equals 0 [2].

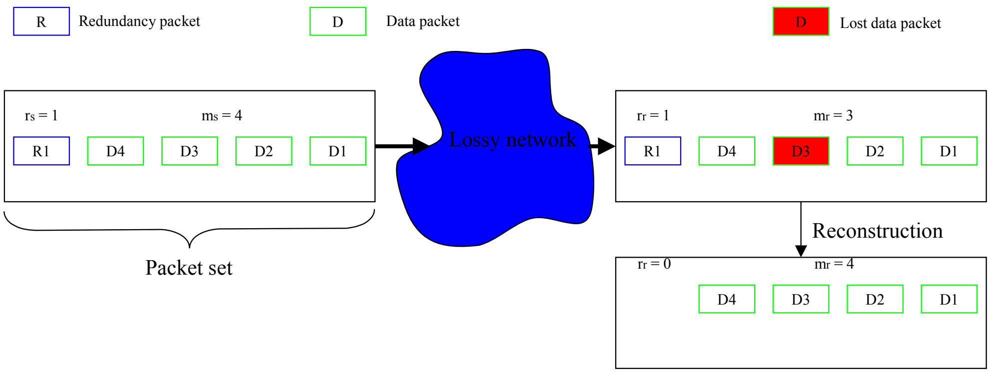

Figure 3.1: Illustration of the NLPRS. At the ingress node one redundancy packet is constructed out of four data packets. One data packet is lost due to contention, but it is reconstructed at egress node since $r_r + m_r \geq m_s$.

NLPRS has the potential benefit of reducing the packet loss rate for data packets if applied in a suited setting. The performance of the scheme depends on the parameter value of m_s and r_s, the offered system load, number of traversing hops, data packet arrival process, packet length distribution and redundancy packet scheduling mechanism [2].

The redundancy effect is the effect of enabling NLPRS when considering the reduction of the data packet loss rate. The drawback of applying NLPRS is that the offered load on the network is increased and that it increases the burstiness. Eq. (1) gives the total offered load after applying NLPRS in the OpMiGua architecture. Please see table 4.1 in chapter 4 for definition of the various parameters.

$$A_{Tot} = A_{GS} + A_{BE} + A_R = A_{GS} + A_{BE} + A_{BE} \cdot \frac{r}{m} \qquad (1)$$

In [2] a simulation and analytical study is performed, of the NLPRS in an asynchronous OPS network where wavelength conversion is applied as a contention resolution scheme. NLPRS reduced the packet loss rate with several orders of magnitude. The performance depends on parameters m and r, the system load, network size, data packet arrival process, redundancy packet scheduling mechanism and packet length distribution. Holding the product r/m constant and increasing m improves the performance, however the end-to-end delay is also increased as a consequence of the increase in the size of the packet set (it takes longer time to account for all packets in one packet set). When increasing system load, burstiness of packet arrival process and network size, the performance is degraded. NLPRS is efficient for large values of m for empirical PLD, but for deterministic PLD it is efficient for both large and small values of m.

3.3 Wavelength conversion

Wavelength conversion is a method to perform contention resolution. If two or more packets are contending for the same output wavelength at the same time this problem can be resolved by converting one or more packets over to a different wavelength [8]. Wavelength conversion is as shown in [8] the most beneficial resolution scheme considering the aspect of extra packet latency, jitter and re-sequencing. When the number of wavelengths in one fibre increases, the utilization of wavelength conversion has a larger effect, i.e., better throughput performance [8].

Wavelength conversion can be implemented in several degrees, limited or full. A design with full degree is capable of converting any input wavelength to any output wavelength. A limited degree design is only capable to convert to a fraction of the total wavelengths applied in the network. For more details about wavelength conversion and other contention resolution schemes such as deflection routing and optical buffering see [8].

Chapter 4

Concept, Design and Hypothesis

This thesis suggests two main methods to adapt the NLPRS scheme for use in OpMiGua. In this chapter the architecture and prerequisites are presented together with the two proposed schemes, combining the OpMiGua architecture and the NLPRS scheme. The goal of both schemes is to improve the packet loss rate for the BE-class, which is a traffic class added to the GS-class where the intention of the BE-class is to improve the utilization of the remaining bandwidth. This intention has no meaning if the packet loss rate of the BE-class is too high. The first method suggests sending NLPRS redundancy packets as GS-traffic (the BE-GS scheme), while the second method sends NLPRS data packets as regular BE-traffic (the BE-BE scheme). At the end of this chapter a quantitative hypothesis, concerning the performance of these two schemes, is presented.

4.1 Architectural design and prerequisites

This section presents the architectural design and the prerequisites and limitations taken into consideration for the simulation model. In table 4.1 is the important parameters and their definitions presented, the parameters presented here is in force for the entire thesis.

Table 4.1: Definition of parameters.

Parameter	Definition
G	Number of nodes in the network
F	Number of fibres between two nodes
N	Number of wavelengths per fibre
n	Number of wavelengths per connectivity
C	Capacity on one wavelength
A	Offered load
A_{GS}	Offered GS-load
A_{BE}	Offered BE-load
A_{R}	Offered redundancy-load
A'	Carried load
A'_{GS}	Carried GS-load
A'_{BE}	Carried BE-load
A'_{R}	Carried redundancy-load
r	Number of redundancy packets in a packet set
m	Number of data packets in a packet set
PL_{GS}	GS-packet length
PL_{BE}	BE-packet length
AM	Arrival model

Because of the potential of a symmetrical behaviour, a unidirectional core ring-network is studied. It is unidirectional because it is more effective for a simulation model to operate in that mode if it is planned to investigate the behaviour of the network for various number of nodes. The topology of a ring-architecture is well arranged, and because of this fact it suits very well for mapping-purposes. It could on a general basis be argued that a ring-network is not relevant considering the topology of today's networks tends to be mesh. A counter-argument to this is that ring-networks have been adopted more and more by network-architecture engineers because it is more suitable for capacity planning, providing resilience and for its ring failure isolation properties, i.e. the fault is isolated and does not affect the rest of the network to such a large degree as a mesh network could.

The number of wavelengths in the unidirectional ring-network depends on the number of nodes [1]. Since the GS-packets are wavelength-routed through the network it is necessary to have full connectivity between the nodes (at least one wavelength for each source-destination combination with reuse of wavelengths). From Eq. (2) it is shown that if the number of nodes equals four, the required number of wavelengths equals six or with five nodes the required number is ten.

$$N = \sum_{i=1}^{G-1} G-i \qquad (2)$$

Although it is possible to do a reuse-design with e.g. two, three or more wavelengths per source-destination combination, is it decided to keep the number of wavelengths to a minimum. Table 4.2 and figure 4.1 presents the wavelength-routing for an example with G=3 and n=1 which gives a total of N=3 wavelengths.

Table 4.2: Wavelength-routing for a ring-network with G=3 nodes.

Node	**1**	**2**	**3**
1	X	1	2
2	1	X	3
3	2	3	X

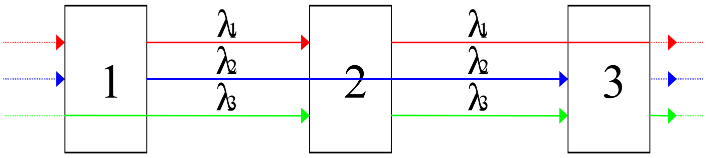

Figure 4.1: Illustration of the wavelength-routing for a ring-network with G=3 nodes and N=3 wavelengths. Wavelength 1 and 2 is dropped at node 1, wavelength 1 and 3 is dropped at node 2 and wavelength 2 and 3 is dropped at node 3.

It is argued for a high offered GS-load versus the offered BE-load in an OpMiGua network since the important idea behind the architecture is to reduce the required resources in an OPS [1]. In a non-hybrid network all traffic will go through the same module, e.g. an OPS in an all-optical network. Thus, by implementing a hybrid network, the traffic that is sent in the GS-class (if we consider the OpMiGua architecture) will relieve the offered load on the OPS. This will be a key-factor to reduce the cost, complexity and necessary resources in an OPS [10]. It has also been shown in [11] that the packet loss rate for the BE-class is reduced when the GS-share increases for a fixed total offered load, i.e. the packet loss rate for the BE-class is lower for a scenario with the A_{GS} equal 0.5 and the A_{BE} equal 0.2 compared with the A_{GS} equal 0.2 and the A_{BE} equal 0.5. Hence, we have therefore decided to conduct simulation runs with a high A_{GS} relative to the A_{BE}, assuming that the total offered load is not too high.

In studies regarding the total offered load it is shown that the OpMiGua architecture is effective for high loads considering the experienced packet loss for the BE-class [11]. Hence, we have therefore decided to run simulations with a relative high total offered load and the hypothesis applies for that scenario.

[1] show that the packet loss rate performance of a network is increased when the length of GS-packets is longer than BE-packets. It is not the purpose of this thesis to investigate the performance of the two proposed schemes regarding the length of the GS-packets and the BE-packets, even though this is considered to be very interesting. Based on the results in [1] we have therefore chosen to run simulations with a packet length difference, but the chosen one is a modest value (GS-packet length is set to be ten times longer).

When comparing the two proposed schemes it can be argued that the cost/value of a GS-bit is higher or lower than the cost of a BE-bit. It can be argued that the value of a GS-bit is higher than the BE-bit because the GS-bit is sent over a guaranteed class with zero packet loss rate, while the BE-bit is sent over a non-guaranteed class. On the other hand it can be said the complexity of the GS-class is lower than the BE-class because the traffic propagates through cheaper optical cross connects while the BE-packets propagates through more expensive optical packet switches, by this fact it should be inserted more traffic into the GS-class since it is cheaper and by this reduce the necessary complexity of the OPS. From the arguments above we have decided to set the cost-values to be equal. Hence, we will perform an equalized performance-evaluation of the proposed schemes.

The performance of the NLPRS has typically been best for settings where the number of redundancy packets in a packet set has exceeded the number of data packets [2]. This can not be tolerated for the BE-GS scheme as the motive for sending redundancy packets over the GS-path is useless if the redundancy added is higher than 100%, i.e. the number of redundancy packets must be lower than the number of data packets. What is then the purpose of sending e.g. 120% redundancy over the GS-path just for the intention of improving the performance for the BE-class? In this case the BE-class could be inserted with a lower load, which means that the total network load would also be lower. Hence, the maximum redundancy added in the BE-GS scheme during simulation runs is set to 100%, though it could be set even lower.

This restriction is also applied for the BE-BE scheme because, as an important design principle behind the OpMiGua architecture is to reduce the required resources, cost and complexity of the OPS. By avoiding a restriction like this, the resource-load on the OPS can be higher than intended because it is e.g. added 250% redundancy to improve the BE-class. Because of the attempt to minimize the OPS cost/complexity/resources, the maximum redundancy added in the BE-BE scheme during simulation runs is set to 100% also.

Figure 4.2 presents a detailed node design, which is based-on for the design of the simulation model. The example given in the figure is node number one in a network with G=3 nodes. This means that G-1 wavelengths are dropped and added for the GS-class, which also means that the number of lasers is 2×(G-1). Each laser is fed by a packet generator from the two traffic-classes with a back-to-back buffer interconnected between the laser and the packet generators. By having the number of lasers given by 2×(G-1) instead of N, it means that the design scales better for increasing numbers of G. The OPS switching matrix is strictly non-blocking by designing tuneable wavelength converters (TWC) on the input and fixed wavelength converters (FWC) on the output

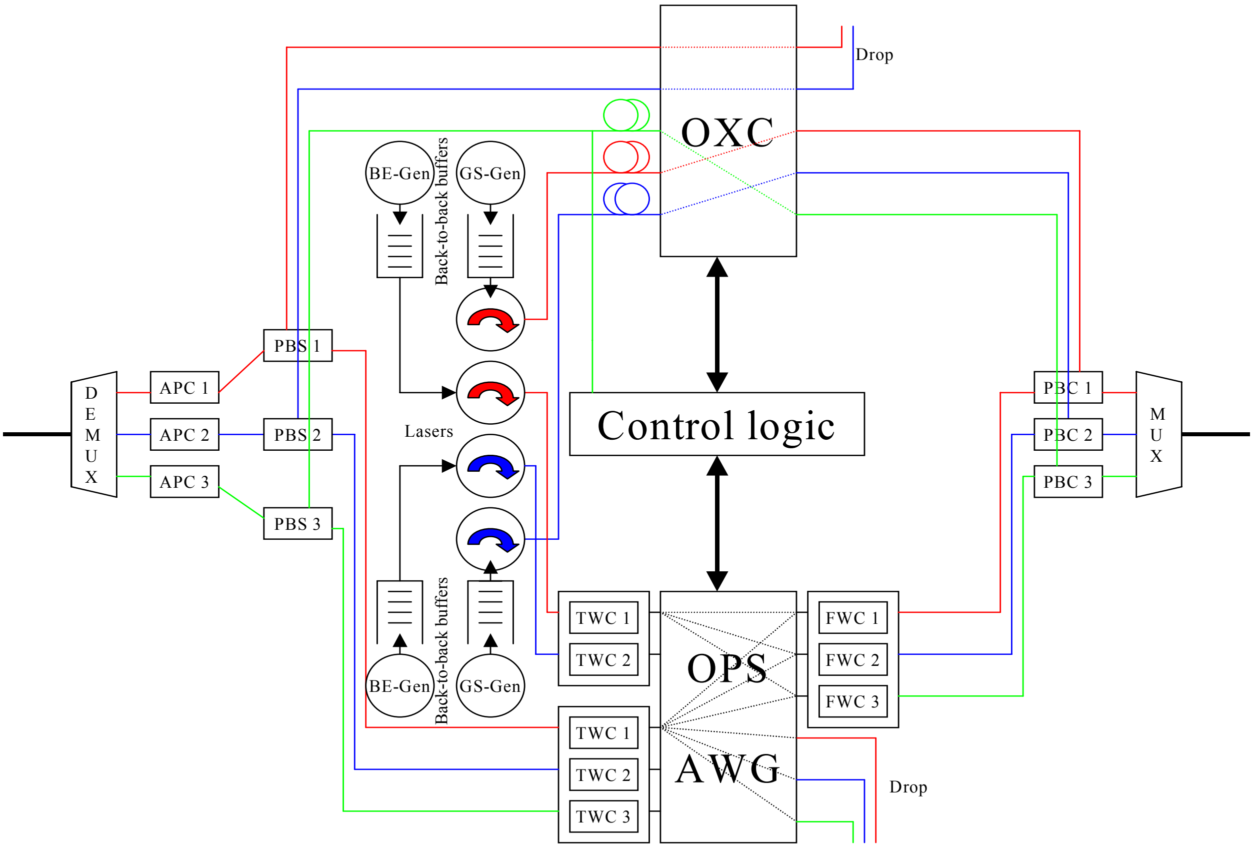

Figure 4.2: Illustration of the detailed node design at node 1 for a network with G=3 nodes and N=3 wavelengths. The OXC is as illustrated static, while the OPS is equipped with full-range tuneable wavelength converters (TWC) *and* fixed wavelength converters (FWC).

4.2 The OpMiGua-NLPRS BE-GS scheme

The name of this scheme implies that data packets are sent as regular BE-packets and that redundancy packets are sent as GS-packets over the GS-path, i.e. the OpMiGua-NLPRS BE-GS scheme, abbreviated to the BE-GS scheme. The principle behind the scheme is presented in figure 4.3, which is based on the illustration shown in figure 4.2

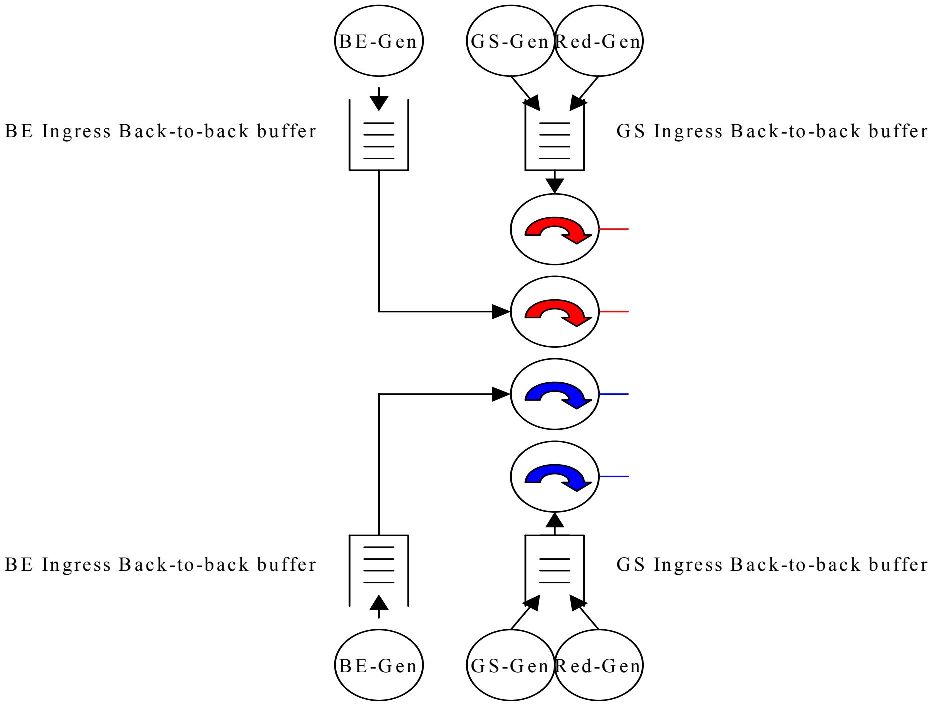

Figure 4.3: The principle behind the BE-GS scheme in relation to the designed simulation model and the illustration shown in figure 4.2.

Because of the reservation technique in the OpMiGua architecture it is theoretically possible to send packets over the GS-class without any loss (if we ignore the fact that bit error may happen *or* the possibility for buffer overflow at ingress nodes). The reservation technique is described in detail in the OpMiGua-chapter, but the main idea is that one fibre delay line per wavelength in the input of the hybrid node is used in the reservation process for a GS packet. By this the BE-packets cannot interfere with traffic over the GS-path. Since the GS-class is reserved and has zero PLR is it interesting to see how the PLR of the BE-class may be improved by sending redundancy packets of BE data packets embedded as packets in the GS-path.

We have in this study chosen GS-packet length set to be ten times longer than the BE-packet length. As discussed in chapter 3.2, the length of the redundancy packets must be equal to the maximum packet length among all data packets in a packet set. This means that the length of a redundancy packet sent over the GS-class as a GS-packet must be 1500 bytes. Even if the redundancy packet is 10 times shorter than regular GS-packets, the time it potentially can reserve the wavelength on the output of a hybrid node is given from the length of the FDL. If we rely on the facts mentioned above, this means that the RIB-effect will be increased since more packets will be reserved for when the redundancy packets are sent over the GS-path. We leverage the RIB-effect by setting the GS-packet length to be ten times longer, i.e. 15000 bytes.

The second argument for attempting to reduce the RIB-effect comes from the fact that the redundancy packets are relative short and in [1] it has been shown that the RIB-effect is increased for short packets. RIB may be an obstacle for the BE-GS scheme; a countermeasure towards this is to aggregate the redundancy packets into one GS-packet. This sub-method is named the BE-AggGS scheme and the main difference between this scheme and the regular BE-GS scheme is presented in figure 4.4.

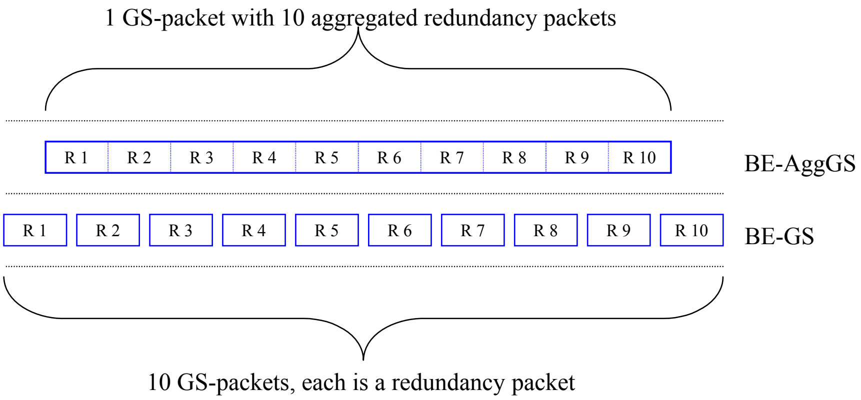

Figure 4.4: An illustration of the difference between the BE-GS scheme and the BE-AggGS scheme.

4.3 The OpMiGua-NLPRS BE-BE scheme

The main principle behind the OpMiGua-NLPRS BE-BE scheme, abbreviated to the BE-BE scheme, is to send both redundancy packets and data packets in the BE-class. The principle behind this second scheme is presented in figure 4.5, which is based on the illustration shown in figure 4.2

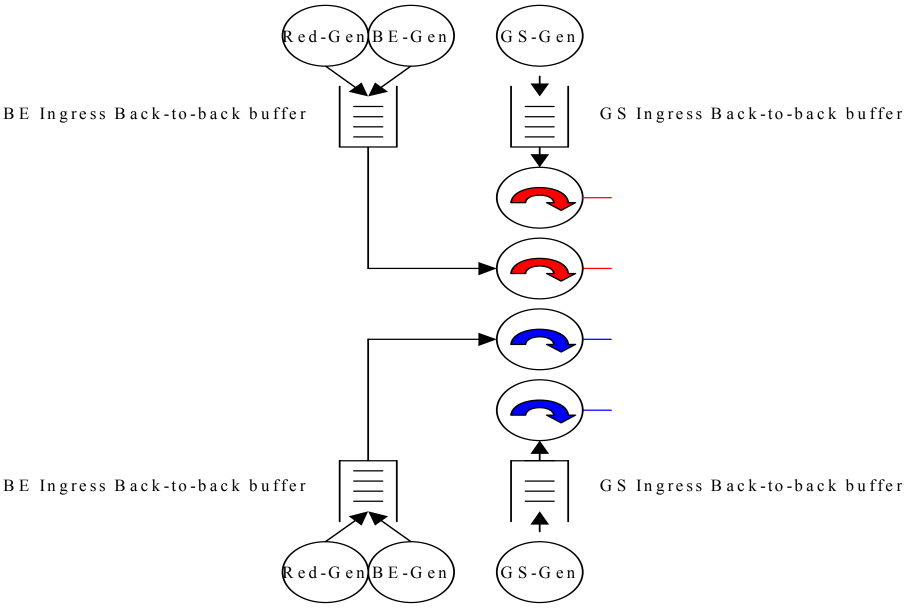

Figure 4.5: The principle behind the BE-BE scheme in relation to the designed simulation model and the illustration shown in figure 4.2.

The BE-BE scheme can be characterized to be more mainstream than the more original BE-GS scheme since the BE-BE scheme is based on the fact that both redundancy packets and data packets are sent through one class with mutual performance measures to deal with. The BE-BE scheme is more in line with what has been researched previously concerning the NLPRS [2].

One main advantage for the BE-BE scheme is that it does not have to deal with the increased RIB-effect, but it has to cope with the fact that the BE-class has no kind of guarantees, i.e. it must combat the potential for packet loss in the optical packet switches.

4.4 Assumed behaviour of the proposed schemes

The BE-GS scheme and the BE-BE scheme has one advantage and one disadvantage each, inverted compared to each other, namely the packet loss rate and the RIB-effect. By this the question then arises; which scheme will under the above-argued circumstances perform best when considering the packet loss rate?

The hypothesis states as follows: The BE-GS scheme will perform better than the BE-BE scheme and the BE-AggGS scheme will perform better than the BE-GS scheme. This is stated because it is thought that the increased RIB-effect will have less influence on the experienced packet loss rate, especially with the BE-AggGS scheme where the increased RIB-effect is reduced by aggregation of the redundancy packets.

The null-hypothesis to the stated hypothesis is: The BE-GS scheme will perform better than the BE-AggGS scheme and the BE-BE scheme will perform better than the BE-GS scheme.

Chapter 5

Simulation Model and Scenarios

The construction of the simulation model has been done based on the Discrete Event Modelling On Simula (DEMOS) software [12]. This chapter contains a description on the simulation model and the various simulation scenarios.

5.1 The simulation model

The simulation model is built up by 9 different entities. These entities are called GSPacketGenerator, BePacketGenerator, RedTokenGenerator, Packet, IngressbufferGS, IngressbufferBE, OXCNode, OPSNode and PacketSetCheck. The basis of this simulation-model is the entity-entity synchronization with *waitq's* [12], which is possible to implement with DEMOS. The synchronization is between entity Packet and entity IngressbufferGS, entity Packet and entity IngressBufferBE, entity Packet and entity OXCNode and between entity Packet and entity OPSNode.

5.1.1 The GSPacketGenerator entity

The "GSPacketGenerator" entity generates "Packet" entities with mean arrivals pr second defined by the *idist* "PacketArrivalGS". The entity has two parameters to itself, "source" and "destination". This means that it is generated one "GSPacketGenerator" for each source-destination combination. These two parameters are inserted as a part of the parameters to the "Packet" entity. The entity also inserts the two "Packet" entity parameters "type" and "length" with the correct value into the "Packet" entity. "Type" defines the type of traffic and for this entity the value is set to 1, which means that the "Packet" is a GS-packet.

5.1.2 The BEPacketGenerator entity

The "BEPacketGenerator" entity generates "Packet" entities with mean arrivals pr second defined by the *idist* "PacketArrivalBE". This entity has also two parameters to itself and it exist one "BePacketGenerator" for each source-destination combination. For this entity the "type" value equals 2, which means that the "Packet" is a BE-packet.

The entity operates in looped-manner with a WHILE-loop and a FOR-loop inside the while-loop. The for-loop takes care of *scheduling* "m" data packets, if the NLPRS is enabled the "RedTokenGenerator" is *scheduled* into the DEMOS event-list. This entity is described in the next section.

5.1.3 The RedTokenGenerator entity

The "RedTokenGenerator" entity is *scheduled* after the data packets of a packet set is sent. This means that the purpose of this entity is to *schedule* the remaining packets of a packet set, namely the redundancy packets. The entity receives three entity-parameters as input, named "source", "dest" and "NLPRScycle". These three parameters are inserted as a part of the parameters to the "Packet" entity. For each packet set, the entity increments by one through a FOR-loop until the increment-integer reach the number of redundancy packets in the packet set.

5.1.4 The Packet entity

The "Packet" entity has 7 parameters attached to it, they are named "source", "dest", "wavelength", "type", "NLPRStype", "length" and "NLPRScycle". The behaviour of the entity is dependent on the "type" parameter that means that the entity has two ways to operate, one for GS-traffic and for BE-traffic. For each GS-packet the wavelength is decided by extracting the pre-determined wavelength from a matrix. The first entity-entity synchronization occurs after this. For GS-traffic the entity has synchronization with the "IngressbufferGS" entity, this done by the *wait* command. When the entity comes back from the "IngressbufferGS" entity it *acquire* the FDL given by the wavelength set and node it is at. After this the entity will *release* the FDL and go on to the next entity-entity synchronization with the "OXCNode" entity. When it returns from the "OXCNode" it will update its node value. If it has not arrived at the destination yet, it will continue doing these operations until it arrives the destination.

5.1.5 The IngressbufferGS entity

This entity has 2 parameters named "node" and "inbuff", the "inbuff" is a reference to the *waitq*. It is the first entity that has entity-entity synchronization with the "Packet" entity. The entity operates in a looped-manner; it will always *coopt* "Packet" entities and *schedule* them again. But before it can do the same operation over again with a new "Packet" entity it must wait for a time-period equal the "length" value divided by the interface-bitrate, this ensures that "Packet" entities will not overlap each other in time, but transmitted back-to-back.

5.1.6 The IngressbufferBE entity

This entity has 2 parameters named "node" and "inbuff", the "inbuff" is a reference to the *waitq*. It is the second entity that has entity-entity synchronization with the "Packet" entity. The behaviour of the entity is equal the "IngressbufferGS" entity except that it deals with BE-packets instead of GS-packets. It is important to note two characteristics about these two entities; they do not perform any kind of QoS-buffering, only back-to-back buffering. If a BE-packet is generated and all wavelengths or the corresponding FDL to a wavelength are occupied, the BE-packet will be dropped. GS-packets will not experience dropping because of the FDL will reserve the wavelength for it. The second property to note is that there is no limit for the maximum number of "Packet" entities to be back-to-back buffered. From the DEMOS *report* the maximum limit observed is acceptable.

5.1.7 The OXCNode entity

The behaviour of this entity is close to the behaviour of the two entities mentioned above. It is the third entity that has entity-entity synchronization with the "Packet" entity. The entity operates in a looped-manner and *coops* "Packet" entities from the "inbuffOXC". Because of the importance of a parallel-operation between the two involved entities, this entity *schedules* the "Packet" entity back before it performs the *acquire* and *release* of the wavelength-interface named "Outport". The wavelength-interface is *held* for a time-period equal the "length" value divided by the interface-bitrate. After the *release* is executed, the entity is ready to perform the same operation with the next "Packet" entity. The function of the *coopt* command means that the "OXCNode" entity will stay and wait for a "Packet" entity to arrive. Immediately at the arrival it will *coopt* the "Packet" entity and perform the same operation described above.

5.1.8 The OPSNode entity

The behaviour of this entity is almost exact to the behaviour of the "OXCNode" entity. It is the fourth entity that has entity-entity synchronization with the "Packet" entity. The entity operates in a looped-manner and *coops* "Packet" entities from the "inbuffOPS", this is the only difference between the "OPSNode" entity and the "OXCNode" entity. Although it could be worthy to mention that there is a difference in the time-period a wavelength-interface is *held*. This is because the length of a GS-packet in simulation-runs is set to be ten times longer than a BE-packet.

5.1.9 The PacketSetCheck entity

When the "Packet" entity has accounted for all packets in a packet set, it *schedules* the "PacketSetCheck" entity. This means that all lost or arrived packets in a packet set is accounted for, achieved by updating a four dimensional matrix named "M" each time a packet is either arrived or dropped. The matrix "M" is described in table 5.1.

Table 5.1: Description of the dimension in the system state matrix M.

Dimension	**Description**
Source	Identifies the source
Destination	Identifies the destination
Cycle	Identifies the cycle
Type	Type=1: Identifies a successful data packet arrival. Type=2: Identifies a dropped data packet. Type=3: Identifies a successful redundancy packet arrival. Type=4: Identifies a dropped redundancy packet.

The procedure for updating the matrix "M" is described in table 5.2. Note that the update of this matrix is done in the "Packet" entity, but described in this section.

Table 5.2: How the system state matrix M is updated when a packet is dropped or arrived.

Type	**Trigger**	**Update in matrix M**
Data Packet	Arrived	M(j,k,c,1) = M(j,k,c,1) + 1
Data Packet	Dropped	M(j,k,c,2) = M(j,k,c,1) + 1
Redundancy Packet	Arrived	M(j,k,c,3) = M(j,k,c,1) + 1
Redundancy Packet	Dropped	M(j,k,c,4) = M(j,k,c,1) + 1

If the sum of dropped data packets and dropped redundancy packets for a given packet set is lower or equal the number of sent redundancy packets, it means that no data packets are lost. The entity will then update the "DPS" (Data Packets Successful) integer given by the number of sent data packets. On the other hand, if this sum is higher than the number of sent redundancy packets, this means that one or more data packets in the packet set is lost. The entity will in this case update the "DPL" (Data Packets Lost) integer given by the accounted number of dropped data packet/packets. The "DPLHop(hop)" array integer will also be updated so that it is possible to read out the average number of lost data packets for a given source-destination distance.

As mentioned above, all packets in a packet set must be accounted for before potential reconstruction is applied. The requirement in this simulation model is that all sent data packets and all sent redundancy packets is accounted for. NLPRS introduces extra delay that increases in proportion to the size of the packet set, so it is possible to set this requirement to be like all sent data packets. This is efficient if the reconstruction process is faster than the time it takes to account for all packets in a packet set.

5.2 Validation and Verification

To ensure that the simulation model of the OpMiGua architecture combined with the NLPRS scheme is functioning as intended and that the intended function is a correct, it is crucial to have an underlying methodology in the development process. During the development and after, several methods for validation and verification of the simulation model have been applied. This chapter presents the validation and verification of the simulation model. First, a brief definition on these two expressions:

- Validation: It is the process of ensuring that the function of the model is built as intended.
- Verification: It is the process of ensuring that the intended function of the model is correct.

5.2.1 Validation

The development of the simulation model was done in an incremental order. First where the "GSPacketGenerator" entity constructed and tested with the use of built-in DEMOS library functions such as *count* and *trace*. The *report* generated by DEMOS after the simulation testing runs has also been helpful through all parts of the development. After completion of the "GSPacketGenerator", began the initial work on the "Packet" entity and the "OXCNode" entity. Here where the first entity-entity synchronization between the "Packet" entity and the "OXCNode" entity constructed. The function of these three entities where tested and the network functioned as a purely circuit switched one. When these tests where completed was the first back-to-back buffer entity implemented successfully, named "IngressBufferGS". But before this part of the development could be finished, was the function of the reservation-technique validated and verified. The verification of the reservation-technique is presented in section 5.2.2.

The second milestone in the development was the implementation of the "OPSNode" entity, the "BEPacketGenerator" entity, the "IngressBufferBE" entity and the extension of the

"Packet" entity. The third milestone was the implementation of the "PacketSetCheck" entity and the extension of the "Packet" entity. When these implementations were finished the simulation model was tested and validated in circuit switch mode, packet switch mode and in hybrid node, with and without the NLPRS scheme activated. A presentation of the verification of the hybrid mode without the NLPRS scheme enabled is given in section 5.2.2.

For each little step during the development, the code has been compiled, keeping the bug fixing to a minimum level. This have also insured that the continuity of the work have been held up. When problems have been encountered, it has been important solving them as fast as possible.

In the simulation model different booby traps have been implemented. One example is the situation where the "OPSNode" entity *coopt* a "Packet" entity from the *waitq*. The forbidden operation in this example is if the packet have been delayed before the *coopt* operation was performed. Another example is in the same situation: if a "Packet" entity is *coopted* and the wavelength resource is not idle, then the simulator is in an illegal state. A third example is the check for zero packet loss for the GS-class.

5.2.2 Verification

This section presents the verification of the reservation-technique and the packet loss rate for an OpMiGua network without the NLPRS scheme enabled.

For a network with four nodes it is necessary with six wavelengths for full connectivity, which gives us a total of 24 fibre delay lines for implementation of the STW reservation scheme. Consider that the GS-load equals 0.6 and BE-load equals 0.1 for a network in hybrid mode without the NLPRS scheme enabled. The BE-packet length equals 1500 byte, which means that the propagation time through the fibre delay lines must equal the answer from Eq. (3).

$$FDL_{prop} \frac{PL_{BE} \cdot 8\,bit/byte}{C} = \frac{1500\,byte \cdot 8\,bit/byte}{10 \cdot 10^{9}\,bit/s} = 1.2 \cdot 10^{-6}\,s \tag{3}$$

The FDL occupied signal time from fibre delay line is given in Eq. (4).

$$FDL_{occTime} = FDL_{prop} \cdot \frac{C \cdot A_{GS}}{PL_{GS} \cdot 8\,bit/byte} \cdot 100\% = 1.2 \cdot 10^{-6} \cdot \frac{10 \cdot 10^{9} \cdot 0.6}{15000 \cdot 8}\ 100\%$$
$$FDL_{occTime} = 1.2 \cdot 10^{-6} \cdot 50000 \cdot 100\% = 6\% \tag{4}$$

From the DEMOS *report* generated after completion of a simulation run it is found that the average FDL occupied signal time from all 24 fibre delay line equals 5.99575%. When comparing this result with the result from Eq. (4), it is concluded that the STW reservation scheme is implemented in a correct way.

Consider a scenario as described for the reservation scheme. For this scenario is an analytical model for the packet loss rate presented in Eq (5).

$$PLR = (1-(1-(A_{GS}+A_{BE}(1-PLR)))\cdot(1-FDL_{occTime}))^{N}$$
$$\Downarrow$$
$$PLR = 0.124175 \tag{5}$$

From the results generated after 20 independent replications of a simulation run it is found that the average packet loss rate for packets traversing one hop equals 0.126324. The rough approximation presented in Eq. (5) is close to the average packet loss rate obtained from simulations. When comparing them it is concluded that the function of the simulation model is correct.

5.3 Simulation Process

In table 5.3 a set of parameters, which has been held fixed during simulations, is presented. Table 5.4 presents the parameters that have been varied.

Table 5.3: Definition and value of fixed parameters

Parameter	**Definition**	**Value**
G	Number of nodes in the network	4 - 8
F	Number of fibres between two nodes in one direction	1
N	Number of wavelengths per fibre	Given by G
n	Number of wavelengths per connectivity	1
C	Capacity on one wavelength	10 Gbit/s
AM	Arrival model	Poisson
PL_{GS}	GS-packet length	15000 byte
PL_{BE}	BE-packet length	1500 byte
t	Simulation runtime	1 sec

Table 5.4: Parameters that has been varied

Parameter	**Definition**	**Value**
G	Number of nodes in the network	4 - 8
N	Number of wavelengths per fibre	Given by G
r	Number of redundancy packets in a packet set	Various
m	Number of data packets in a packet set	Various
A	Offered load	Various
A_{GS}	Offered GS-load	Various
A_{BE}	Offered BE-load	Various
A_R	Offered redundancy-load	Various

In table 5.5 a summary of all final simulations is presented. A total of approximately 49 days have been necessary to conduct these simulations. The long simulation time comes from the fact that it takes longer time to register a packet loss when adding redundancy.

Table 5.5: Summary of all final simulations

Sim. Nr.	Scheme	G	N	A_{GS}	A_{BE}	m	r/m	Days
1	BE-GS	4	6	0.6	0.1	10, 20,30	0 → 1	1
2	BE-BE	4	6	0.6	0.1	10, 20,30	0 → 1	1
3	BE-GS	5	10	0.6	0.1	10, 20,30	0 → 1	1
4	BE-BE	5	10	0.6	0.1	10, 20,30	0 → 1	1
5	BE-GS	6	15	0.6	0.1	10, 20,30	0 → 1	2
6	BE-BE	6	15	0.6	0.1	10, 20,30	0 → 1	2
7	BE-GS	7	21	0.6	0.1	10, 20,30	0 → 1	6
8	BE-BE	7	21	0.6	0.1	10, 20,30	0 → 1	6
9	BE-GS	8	28	0.6	0.1	10, 20,30	0 → 1	10
10	BE-BE	8	28	0.6	0.1	10, 20,30	0 → 1	10
11	BE-AggGS	4	6	0.6	0.1	10, 20,30	0 → 1	1
12	BE-AggGS	5	10	0.6	0.1	10, 20,30	0 → 1	1
13	BE-AggGS	6	15	0.6	0.1	10, 20,30	0 → 1	2
14	BE-AggGS	7	21	0.6	0.1	10, 20,30	0 → 1	3
15	BE-AggGS	5	10	0.5	0.2	30	0 → 1	2

Before final simulation runs were conducted, the necessary transient time was tested for the simulation model. The simulation model had no noticeable transient time, so the final value is set very low.

5.3.1 Production

A catalogue system synchronized with an Excel-file has been the method to obtain the bookkeeping on high level of systematic trust. It is recommended to take a look at the electronic-appendix for deeper insight to the structure of the simulation process and simulation environment.

Chapter 6

Simulation Results

A simulation model of an asynchronous OpMiGua network combined with the NLPRS scheme has been utilized to evaluate the performance of the proposed schemes. The specific performance metrics is packet loss rate. A selection of the results from obtained from the simulation runs are presented in chapter 6.1, 6.2 and 6.3.

For each parameter setting, 20 replications with different seeds have been conducted. The average value of these replications has been plotted with 95 % confidence intervals with help of the *errorbar* plot function in MatLab. The intervals are computed according to the Student-t distribution with 19 degrees of freedom. The plots presents packet loss rate ranging from 0.25 down to 10^{-6}. Whenever the lower limit of the confidence interval exceeds the scale of the plot, the sample is not presented.

Table 6.1 contains a definition and value of each parameter used in the presented simulation runs. If a parameter is varied, the value is stated in the presented figure, except for the A_R and N, where A_R must be computed by Eq. (1) given in chapter 3. Table 6.2 contains the number of wavelengths N that corresponds to the specific ring-size of G nodes, as computed by Eq. (2) given in chapter 4. Please note that the "Reference" graphs are simulated packet loss rate without any redundancy added.

Table 6.1: Definition and value of parameters.

Parameter	**Definition**	**Value**
F	Number of fibres between two nodes in one direction	1
n	Number of wavelengths per connectivity	1
C	Capacity on one wavelength	10 Gbit/s
AM	Arrival model	Poisson
PL_{GS}	GS-packet length	15000 byte
PL_{BE}	BE-packet length	1500 byte
t	Simulation runtime	1 sec
G	Number of nodes in the network	4 – 7
N	Number of wavelengths per fibre	Given by G
r	Number of redundancy packets in a packet set	Various
m	Number of data packets in a packet set	Various
A	Offered load	Various
A_{GS}	Offered GS-load	Various
A_{BE}	Offered BE-load	Various
A_R	Offered redundancy-load	Various

Table 6.2: Value of parameter N for various values of G

G	**N**
4	6
5	10
6	15
7	21

6.1 Performance for different values of m

Figure 6.1 – 6.3 presents the packet loss rate as a function of r/m for values of m equal 10, 20 and 30. The offered GS-load equals 0.6, the offered BE-load equals 0.1 and the number of nodes equals 4. Each figure shows points for a specific value for m and presents the performance of the network for the different redundancy schemes. In all graphs, the reference curve is represented to enable comparison with a scenario without redundancy packets.

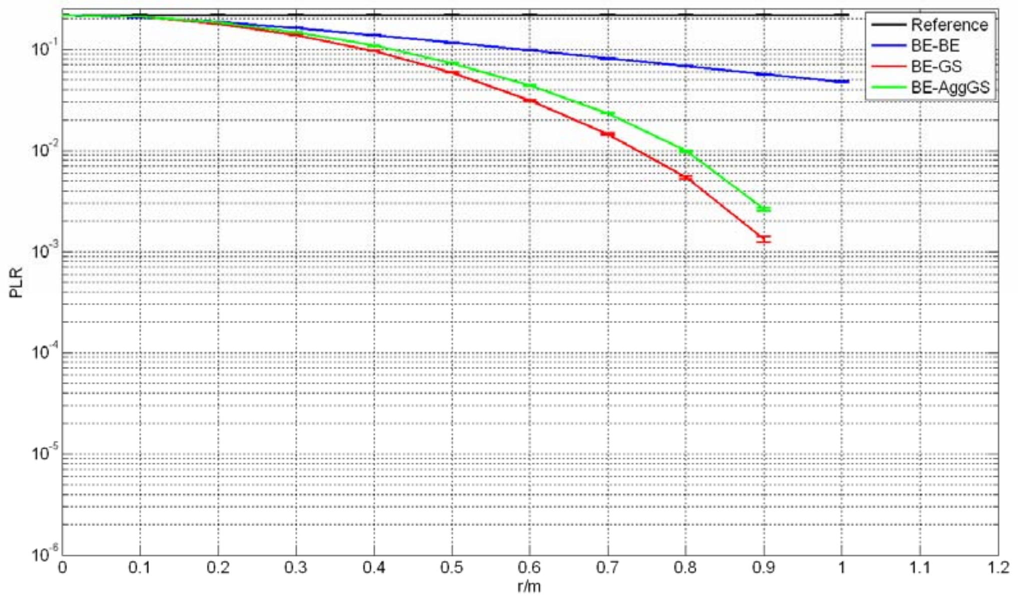

Figure 6.1: The PLR as a function of the product r/m for various schemes. G=4, A_{GS}=0.6, A_{BE}=0.1 and m=10

From figure 6.1 we see that the packet loss rate is reduced for increasing values of r/m for a fixed value of m equal 10. Regarding the BE-GS scheme where the r/m value equal 0.5, the packet loss rate is 7.3×10^{-2}. For the r/m value equal 0.7, the packet loss rate is 2.3×10^{-2}. When redundancy is added, the total offered load is increased which also increases the probability for packet loss. Since the packet loss rate is reduced for increasing values of r/m this means that the positive effect of adding redundancy suppresses the negative effect of increasing total offered load. For r/m values less than one, the packet loss rate decreases monotonically for increased shares of redundancy. Hence, the effect of adding redundancy is superior for all presented values of r/m.

Furthermore, we see that BE-GS and BE-AggGS correlate for all values of r/m. This is understandable since the BE-AggGS scheme is a modification of the BE-GS scheme, which is a successful one compared with the two other schemes. The reason for this will be commented in section 6.2.

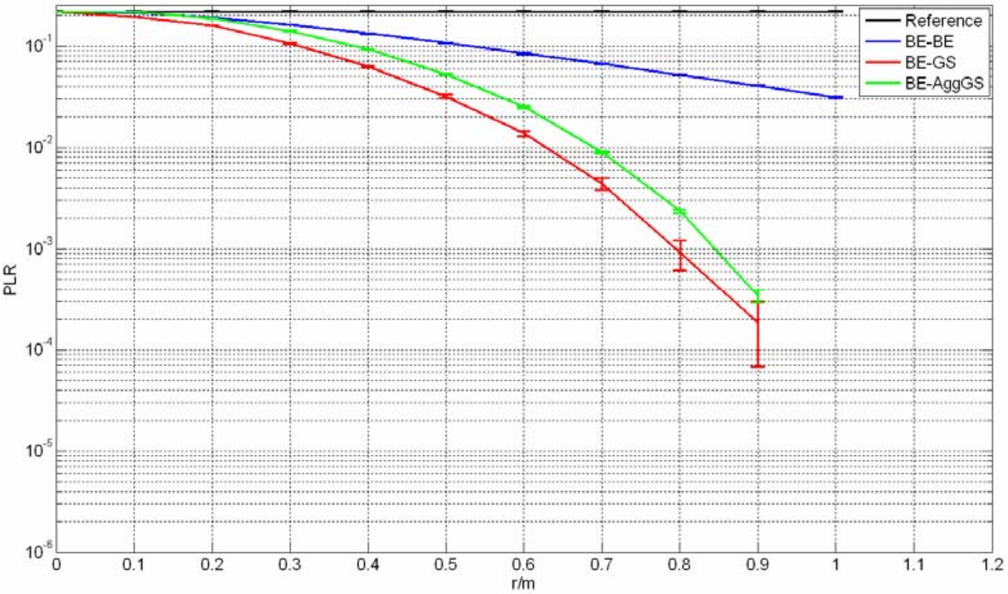

Figure 6.2: The PLR as a function of the product r/m for various schemes. G=4, A_{GS}=0.6, A_{BE}=0.1 and m=20

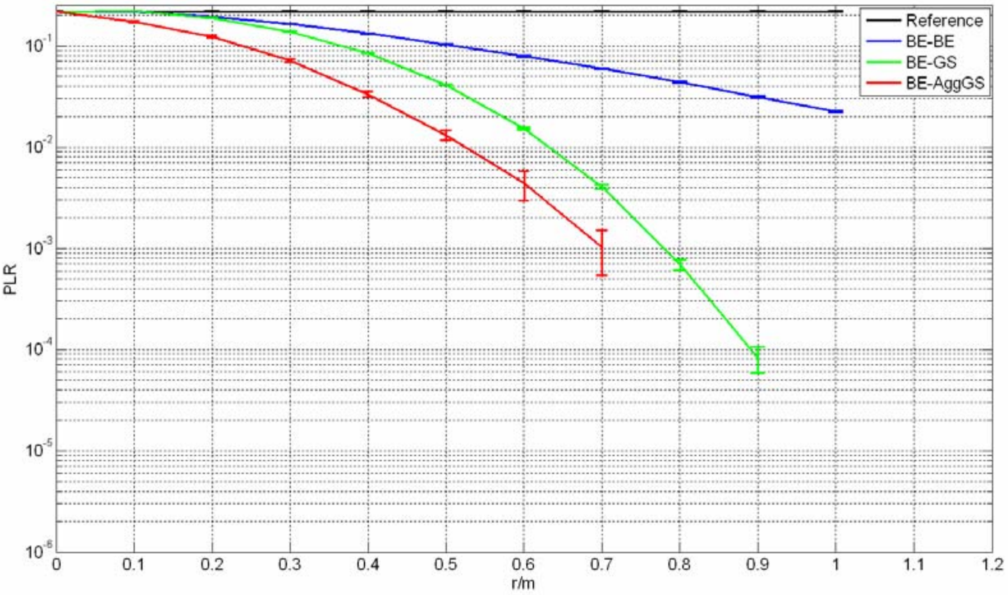

Figure 6.3: The PLR as a function of the product r/m for various schemes. G=4, A_{GS}=0.6, A_{BE}=0.1 and m=30

Figure 6.2 and 6.3 presents, respectively, the packet loss rate for a fixed value of m equal 20 and 30. From these two figures we also see that the packet loss decreases for increasing values of r/m, as we saw in figure 6.1. An important observation when comparing these three figures is the reduction in packet loss rate for increased values of the parameter m. For instance, the packet loss rate for the BE-AggGS scheme equals 9.6×10^{-2} for values of r/m equal 0.4 and m equal 10, as we see in figure 6.1. From figure 6.2 and 6.3 with m equal 20 and 30, we see that the packet loss rate equals 6.2×10^{-2} and 3.3×10^{-2}. When r/m is held constant and m is increased, this means that the length of the packet set is increased. The packet set length for r/m equal 0.4 is 14, 28 and 42 for values of m equal 10, 20 and 30. If a packet set with r equal 12 and m equal 30 shall experience packet loss, the received number of redundancy packets and data packets must be lower than 30. A packet set with r equal 4 and m equal 10 will experience packet loss if the received number is lower than 10. This means that the longer packet set has more power of resistance to handle periods with bursty packet loss, i.e. the probability to experience packet loss is decreased for an increased length of the packet set.

6.2 Performance for various values of G

Figure 6.4 – 6.6 presents the packet loss rate as a function of r/m for each redundancy scheme. The offered GS-load equals 0.6, the offered BE-load equals 0.1, the number of data packets equals 30 and the numbers of nodes equal 4, 5, 6 and 7. Each figure presents the performance of the network without redundancy *and* with redundancy.

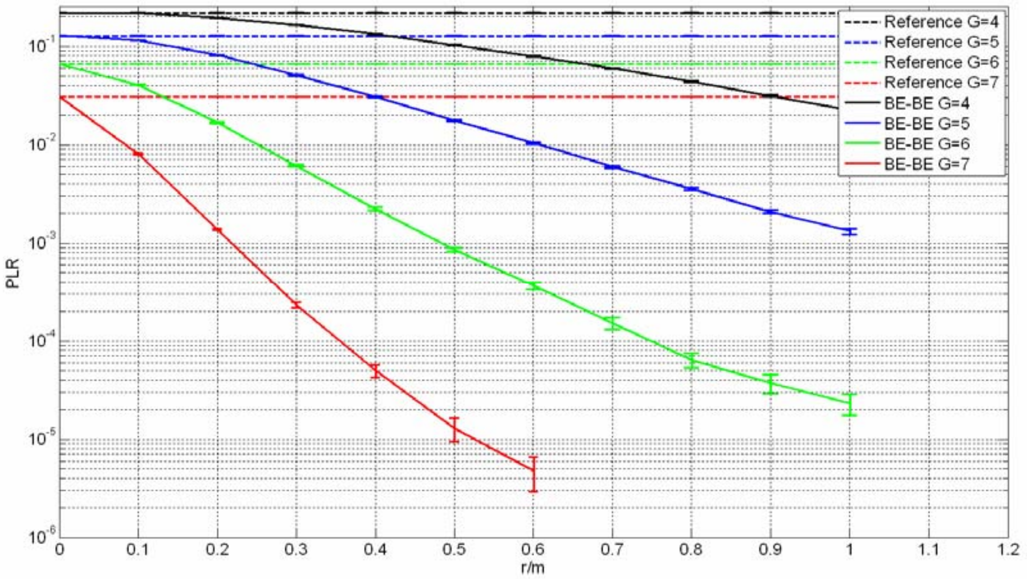

Figure 6.4: The PLR as a function of the product r/m for various numbers G of nodes with the BE-BE scheme. A_{GS}=0.6, A_{BE}=0.1 and m=30

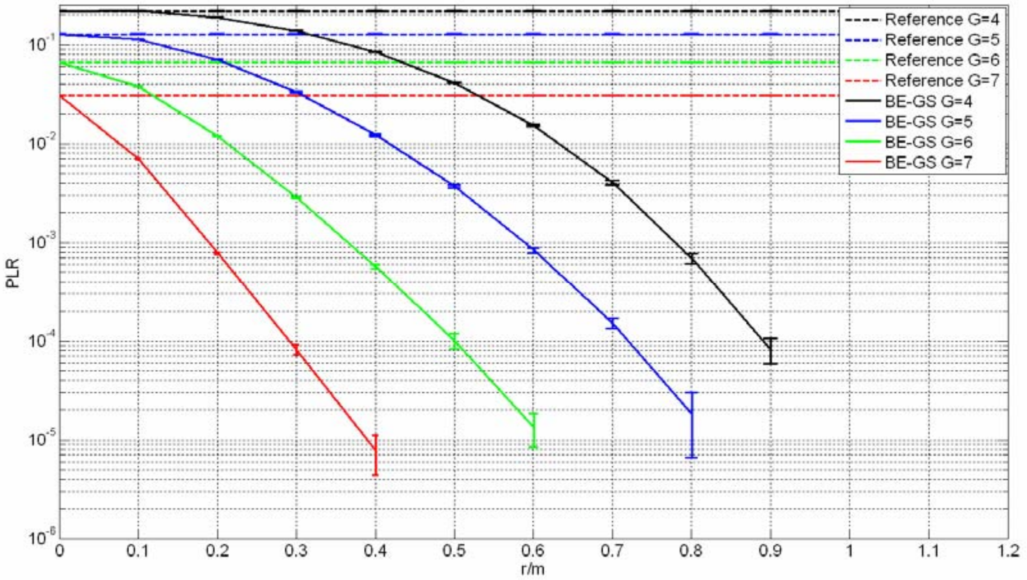

Figure 6.5: The PLR as a function of the product r/m for various numbers G of nodes with the BE-GS scheme. A_{GS}=0.6, A_{BE}=0.1 and m=30

Based on the results shown in figures 6.1 - 6.3 it is decided to present the results in this section with the m parameter equal 30. When we compare the packet loss rate for each scheme with respect to the number of nodes in the network we clearly see that for all three schemes, the packet loss rate is decreased for increasing number of nodes. Regarding the case in figure 6.6 when r/m equal 0.2 and G equal 7, we see that the packet loss rate for the BE-AggGS scheme is 4.09×10^{-4}. For G equal 6 the packet loss rate is 7.4×10^{-3}.

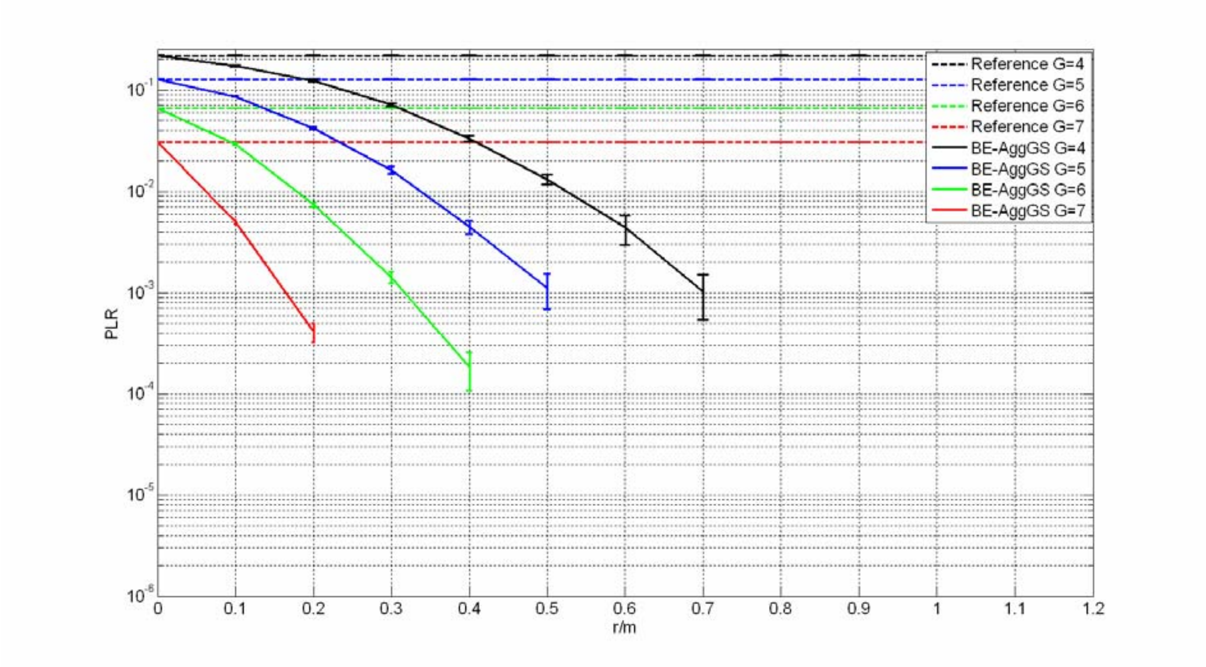

Figure 6.6: The PLR as a function of the product r/m for various numbers G of nodes with the BE-AggGS scheme. A_{GS}=0.6, A_{BE}=0.1 and m=30

The OpMiGua architecture need full connectivity between nodes, so when G is increased, then N is increased as we see in table 6.2. Two competing effects will modify the PLR as the size of the network is altered. First, by increasing the number of nodes the average number of hops is increased, meaning that the end-to-end packet loss rate is also increased. Second, for the network evaluated in our case, the number of wavelengths is not fixed which according to the Erlang B-formula [13] will decrease the node blocking-probability when the offered load is held constant. Since the number of wavelengths is increased, the tuneable wavelength converters in the optical packet switches are able to convert wavelengths to an increased number of wavelengths. Based on the results we see in figure 6.4 – 6.6, we conclude that the positive effect of an increased wavelength-conversion domain is superior to negative effect of an increased average number of hops.

When comparing the three figures with regard to the performance of the schemes, we see that the BE-AggGS scheme gives us the lowest packet loss rate. All schemes operate by sending data packets as BE-packets, the BE-BE scheme also sends the redundancy packets as BE-packets, while the two other schemes sends the redundancy packets over the GS-path. The BE-BE scheme will experience an increased probability for regular packet loss by adding redundancy, but it will not increase the probability of reservation induced blocking (RIB). The two other schemes will have guaranteed arrival of their redundancy packets, but the RIB-effect is increased and the data packets sent as BE-packets will experience an increased blocking-probability due to that. For the scenario presented in figure 6.4 – 6.6, we can conclude that the BE-GS and BE-AggGS perform the best since they have the benefit of guaranteed arrival of redundancy packets.

By aggregating the redundancy packets into larger packets, the number of reservations of output wavelengths is decreased. By this the RIB-effect is minimized, hence the BE-AggGS scheme performs better than the BE-GS scheme.

6.3 Performance for lower offered GS-load

Figure 6.7 presents the performance of the BE-AggGS scheme for m=30, for a different load than presented earlier in chapter 6.1 and 6.2.

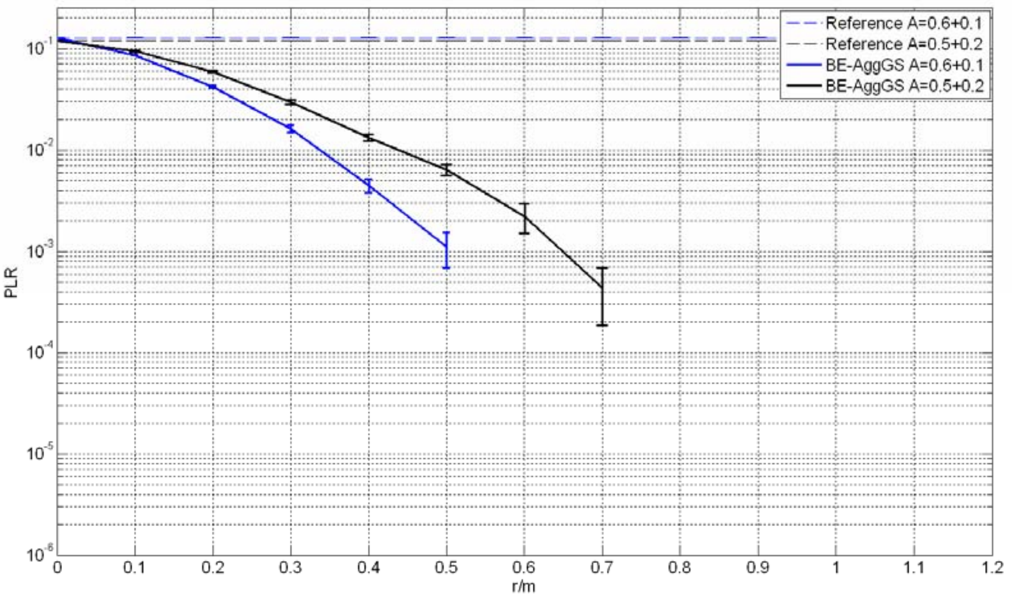

Figure 6.7: The PLR as a function of the product r/m with the BE-AggGS scheme. A_{GS}=0.6 (blue), BlueA_{BE}=0.1 (blue), A_{GS}=0.5 (black), A_{BE}=0.2 (black) and m=30

From the figure we see that the BE-AggGS scheme performs better for an offered GS-load equal 0.6 than 0.5. The total offered load is equal for both scenarios. This means that the BE-AggGS exploit the advantage for lower offered on the optical packet switches, since the packet loss is lower for A_{GS}=0.6 and A_{BE}=0.1.

Chapter 7

Conclusions

This thesis proposes two schemes combining OpMiGua and NLPRS, the BE-BE scheme and the BE-GS scheme with the sub-scheme BE-AggGS. The proposed schemes send redundancy packets as BE-packets or over the GS-path, while the regular data packets are sent as BE-packets. To evaluate the performance, a simulator model has been designed and developed. This is the first model of an OpMiGua ring-network; other researchers have developed and analyzed OpMiGua node models [1]. The results show that the proposed schemes are successfully implemented, with regards to improvement of the packet loss rate for the BE-class. It is shown that the performance is dependent on the number of redundancy packets, data packets, nodes (i.e. wavelengths), offered GS-load, offered BE-load and on the scheme being used.

By increasing the length of a packet set, while holding the relative share of redundancy packets constant, the performance with regard to packet loss rate is improved. The number of nodes in the OpMiGua ring-network has impact on the packet loss rate, since the number of necessary wavelengths to achieve all-to-all GS connectivity is given from the number of nodes. By increasing the number of nodes, the packet loss rate is reduced since the wavelength-conversion domain is increased, even though the average number of hops is increased for larger rings.

Among the proposed schemes, the BE-AggGS scheme performs best. The scheme aggregates the set of redundancy packets before transmitting them over a guaranteed GS-path and sends the data packets as BE-packets over the non-guaranteed BE-class. The aggregation process implies a reduced RIB when compared to the non-aggregated GS-BE scheme, which explains the improved performance. In chapter 4.4 a hypothesis was stated, by the results shown in chapter 6, we state that the null-hypothesis was falsified.

The main contribution is:

- The proposal of the schemes and the evaluation of them through simulations.
- All three schemes may potentially be used to subdivide the BE-class into two or more sub-classes.
- Other researchers can utilize the developed simulation model, either the complete program or some of the modules can be reused.
- The implementation of NLPRS combined with OpMiGua showed us that the proposed schemes was effective for high total offered loads, compared with results in [2] where the usage of NLPRS was suggested for network with relative low offered load. This result is interesting, therefore a paper is on the way and planned for submission to OSA OpticsExpress.

Chapter 8

Further work

In this chapter some suggestions are presented, based on the work done during this thesis.

- Explore the proposed schemes for various values of the offered GS-load and the offered BE-load. First, evaluate the schemes for a total offered load, without A_R, higher than the simulated load in this thesis. Second, evaluate the schemes for a total offered load, without A_R, lower than the simulated load in this thesis. We assume that the packet loss rate will be improved for lower loads.
- Explore the proposed schemes for various values of the GS-packet length and the BE-packet length. By increasing the PL_{GS} compared to PL_{BE}, we assume that the packet loss rate will be improved.
- Explore the proposed schemes for variable length packets, especially combined with alternative reservation schemes such as the length aware time-window scheme and compare the results with the results from this thesis or with new ones gained from network with fixed length packets and the simple time-window scheme.

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Appendix

Paper-appendixes is not enclosed, only electronic-appendixes. Please view "readme.txt" for description of the information enclosed.