Performance Evaluation of Optical Packet Switching Technology

Master's Thesis

Franz Röck

Institute for Broadband Communication
Graz University of Technology
&
Department of Electrical and Computer Engineering
Patras University

Supervisor: Prof. Dr. Erich Leitgeb
External supervisor: Prof. Dr. Michael Logothetis

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Abstract

During the last years the progress made in optical networks technologies has been enormous. Techniques for routing in optical networks are far ahead of the possibilities provided by current devices. In theory, techniques for all optical networks have already been developed and can therefore be applied as soon as proper devices are available. This thesis focuses on the optical routing technology in third generation optical networks. The author does not only provide an explanation of the two major routing techniques optical burst switching and optical packet switching but also evaluates the performance of two contention schemes and two Quality of Service policies in an optical packet switched network. Moreover, this thesis provides an analytical model for the calculation of the blocking probability in an optical switched network with wavelength conversion and proves the accuracy of this model with simulations.

Keywords: blocking probability, FDL, OBS, OPS, optical network, teletraffic engineering, wavelength conversion

Kurzfassung

In den letzten Jahren wurden enorme Fortschritte im Bereich der optischen Netzwerktechnologien erzielt. Techniken für Routing in optischen Netzwerken sind den von derzeitigen Geräten gegebenen Möglichkeiten weit voraus. In der Theorie wurden bereits Techniken für rein optische Netzwerke entwickelt und können somit auch angewandt werden, sobald passende Geräte verfügbar sind. Diese Arbeit konzentriert sich auf die optische Routing Technologie in optischen Netzwerken der dritten Generation. Der Autor bietet nicht nur eine Erklärung von den zwei bedeutenden Routing Techniken Optical Burst Switching und Optical Packet Switching, sondern auch die Leistung von zwei Contention-Maßnahmen und zwei Quality of Service Verfahren in Optical Packet Switched Netzwerken wird evaluiert. Außerdem beinhaltet diese Masterarbeit ein analytisches Modell für die Berechnung der Block-Wahrscheinlichkeit in einem optischen Netzwerk mit Wellenlängen Konvertern und untermauert die Genauigkeit dieses Modells mit Simulationen.

Schlüsselwörter: Blockierwahrscheinlichkeit, FDL, OBS, OPS, optisches Netzwerk, Traffic Engineering, Wellenlängen Konverter

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1 Introduction

Optical networks are getting more and more important. Internet service provider could not provide that much bandwidth without a powerful backbone. The need for capacity is increasing daily. New applications are coming on the market every day, providing all kinds of services over the network. End users want to have faster internet access. Because of this, fiber for the last mile can not be avoided forever. The solution for all these needs concering the backbone may be all-optical networks, which are able to provide a much higher capacity than nowadays networks.
The carrier used for optical networks is light (see Fig. 1.1). It can be divided into two parts, namely the visible and the invisible part. Following the spectrum of ultraviolet, visible light starts at wavelength of 380 nm and a frequency of 789 THz with the color of violet. The spectrum of visible light then moves towards red, passing colors of blue and yellow, where it finally ends at 780nm and a frequency of 384 THz. After the visible spectrum the light gets invisible, which is the beginning of the infrared spectrum.

1.1 History

One of the first principles of optical communication was demonstrated by Alexander Graham Bell in 1880. He developed the so called *photophone*. It transmitted his voice as a telephone signal over about 200 meters by using a beam of light as a carrier through free space (air). In 1930, the German medical student Heinrich Lamm created the first optics cable [21].
In the second half of the 20^{th} century, accelerated progress was made in fiber-optics technology. One big breakthrough was Snell's law. It explains that the angle at which light is reflected is dependent on the refractive indices of the two materials (the core and the cladding). In Fig. 1.2 it can be seen that the lower refractive index of the cladding (with respect to the core) causes the light to be angled back into the core. Another important invention was the laser technology because only the laser diode (LD) and the lower power light-emitting diode (LED) have the potential to generate a large amount of light in a periode of time which is short enough to be useful for fiber optics communication. Glass researchers began to work on the problem of purifying glass to achieve an attenuation of less than 20 decibels per kilometer (dB/km) because Charles Kao and Charles Hockham proposed in 1966 that it could be a suitable transmission medium. Finally, in 1970 Rober Maurer and his team developed the first fiber which exhibited attenuation of less than 20 dB/km [21].
Today, systems are using visible wavelengths near 650 nm, 850 nm, 1310 nm and 1550 nm, with each wavelength having its advantages. Longer wavelengths offer higher performance but always come with higher costs. Fig. 1.3 shows that while the attenuation of wavelengths near 850nm is relatively high with 3 dB/km, the attenuation at the second window with wavelengths near 1310 nm is only about 0.5 dB/km and the attenuation of the third window with wavelengths near 1550 nm offers even the theoretical minimum optical loss for silica-based

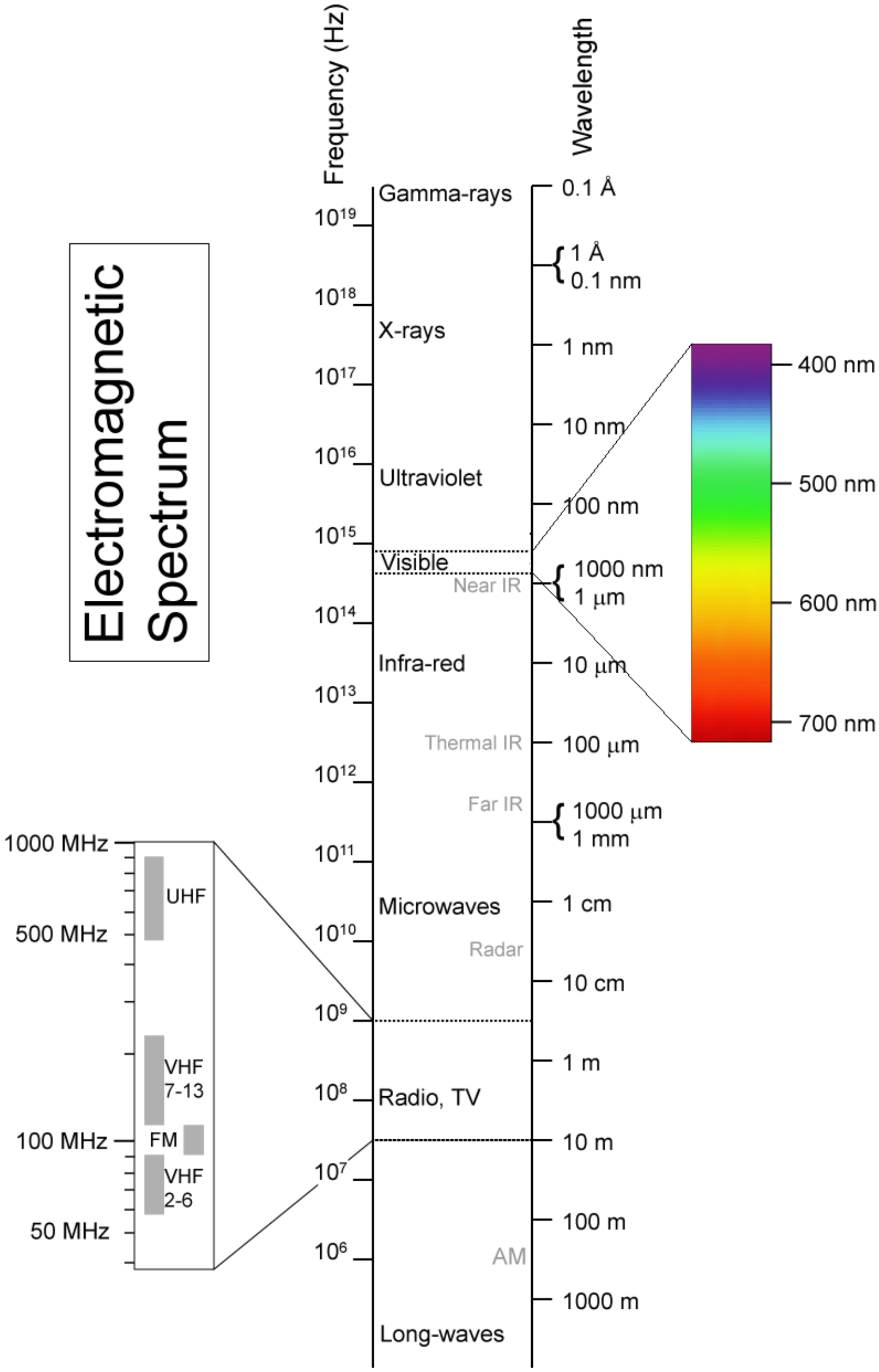


Figure 1.1: The electromagnetic spectrum [20]

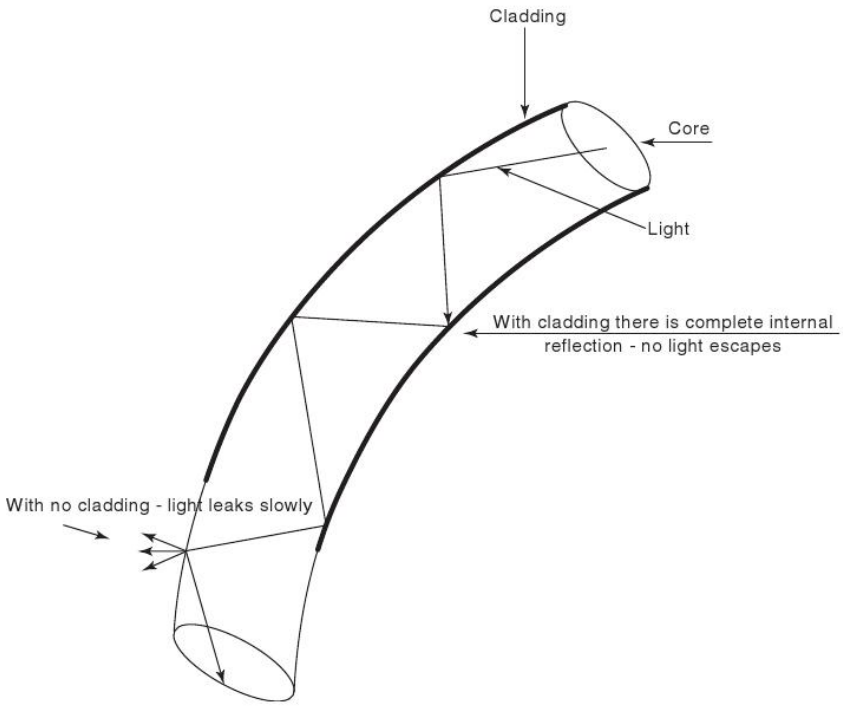


Figure 1.2: Optical fiber with glass coating/cladding [21]

fibers, namely 0.2 dB/km [21].

Snell's law This law is the basis of a successful light propagation in a fiber cabel. Only if the light stays in the communication channel, it can be used to transmit information (Fig. 1.2). Snell's law (see equation 1.1) explains the relation between the angles of a light ray and the normal to the surface [18].

$$n_1 sin I_1 = n_2 sin I_2 \tag{1.1}$$

If we take the angles between the light ray and the surface itself instead of the normal to the surface (see Fig. 1.4), it can be written as

$$n_1 cos\theta_1 = n_2 cos\theta_2 \tag{1.2}$$

There are two different cases for the law [5]:

Case 1 with $n_1 < n_2$: This case implicates $\theta_1 < \theta_2$ and will therefore always result in refraction to the normal of the surface.

Case 2 with $n_1 > n_2$: In this case $\theta_2 < \theta_1$ and the result is a refraction away from the normal and to the surface. However, refraction only occurs for angles of θ_1 where $\theta_2 > 0$. The angle, if $\theta_2 = 0$, is called critical angle of incidence (θ_{1c}) and the light propagates in parallel to the surface. If the angle of incidence is smaller than the critical value, meaning $\theta_1 < \theta_{1c}$, the partial reflection becomes a total reflection.

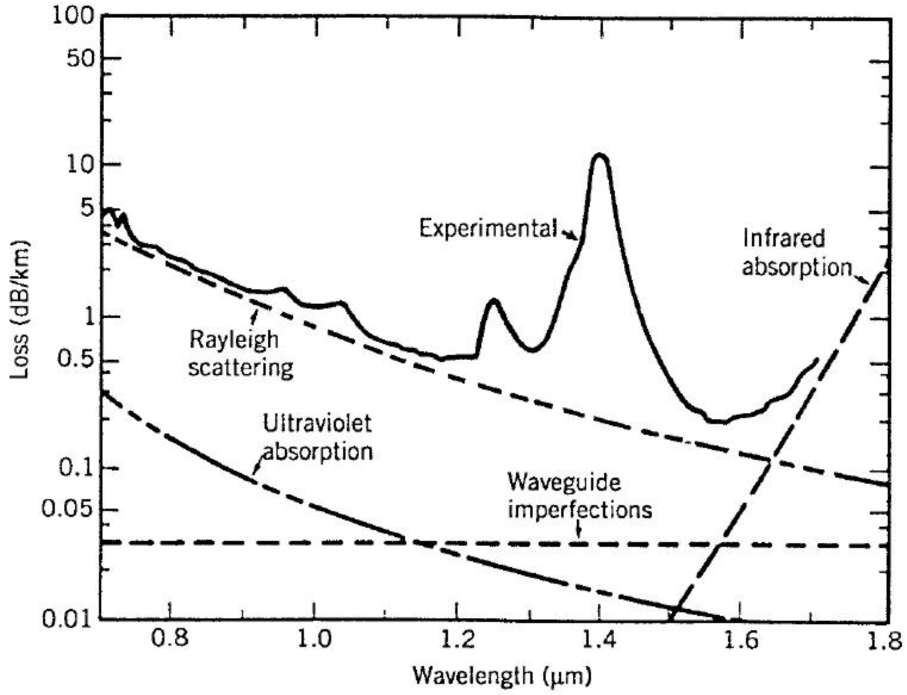


Figure 1.3: Loss spectrum of a single mode fiber produced in 1979 [1]

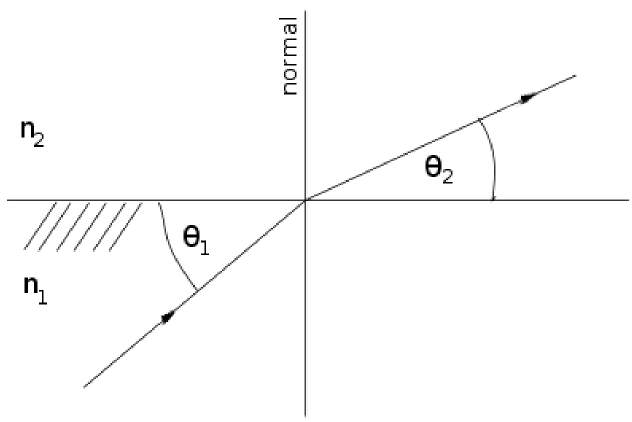


Figure 1.4: Refraction of a light ray

1.2 Advantages of Optical Systems

As in optical systems we do not transmit in the electrical domain but in the optical domain, the optical medium is not affected in the same way as the electrical medium. Because of this new medium we gain some advantages compared to the electrical medium [5]:

- Independent of electrical and magnetic interferences
- Totally electrically isolated from transmitter and receiver
- High capacity
- Low attenuation
- High bandwidth

If optical systems are used for free space transmissions, we gain further advantages [5]:

- Light does not contribute to electric smog
- Line of sight is needed but known, and therefore interferences can be calculated more easily
- Eavesdropping is harder/impossible
- Coding schemes can be taken from radio systems and do not have to be developed anew
- Infrared light is invisible and impalpable for humans
- Sender and receiver are much smaller compared to directional radio

Of course, we also have new disadvantages in optical free space transmission systems [5]:

- Connection requires line of sight
- Light gets attenuated in the atmosphere, which also affects the link-length
- Exact adjustment of sender and receiver is needed

1.3 Optical Communication System

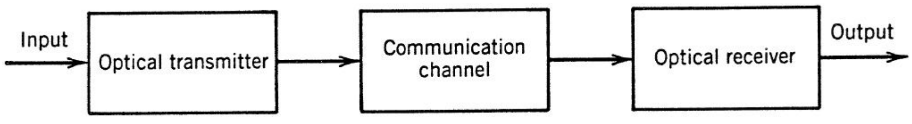


Figure 1.5: Generic optical communication system [1]

An optical communication system differs in principle from microwave systems only in the frequency range of the carrier frequency which is used to carry the information. Typical frequencies for an optical carrier are around 200 THz whereas for microwave systems carrier frequencies around 1 GHz are used. Because of these higher carrier frequencies for optical communication systems an increase in the information capacity is expected. Fig. 1.5 shows a generic block diagram of an optical communication system. The three elements (transmitter, communication channel and receiver) are common to all communication systems. Optical communication systems can be categorized, depending on how the beam spreads, into two broad categories: *guided* and *unguided*. In guided systems, the optical beam emitted by the transmitter remains confined in space, which in practice is realized by using optical fibers whereas in unguided systems the emitted beam spreads in space [1].

1.3.1 Transmitter

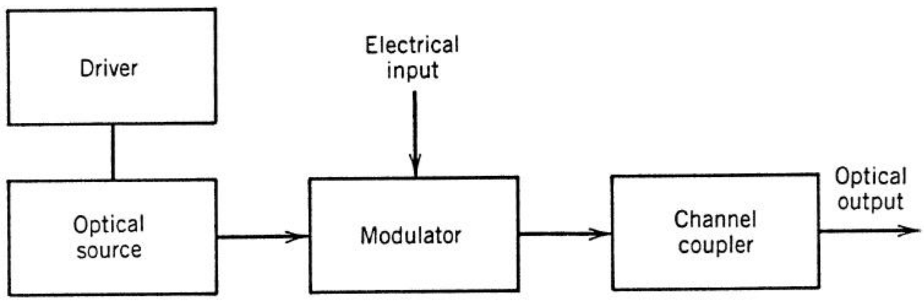


Figure 1.6: Components of an optical transmitter [1]

The task of the optical transmitter is to transfer the electrical signal to the optical domain. The resulting optical signal then has to be launched into the optical communication channel. In Fig. 1.6 you can see the block diagram of an optical transmitter. It consists of an optical source, a modulator and a channel coupler. As optical sources semiconductor lasers or light-emitting diodes are used. The optical signal itself is generated by modulating the optical carrier wave. This can either be done with an external modulator or by modulating the output of a semiconductor source directly by varying the injection current. The direct modulation simplifies the transmitter design and is generally cost-efficient. The coupler is typically a microlens, which focuses the optical signal into the optical communication channel, e.g. onto the entrance of an optical fiber, with the maximum possible efficiency [1].
The *launched power* is also an important design parameter. It is often expressed in 'dBm' units with 1 mW as the reference level [1]:

$$power(dBm) = 10log_{10}(\frac{power}{1mW}) \tag{1.3}$$

Thus 1 mW is 0 dBm but 1 μW corresponds to -30 dBm. If light emitting diodes are used as optical source, the launched power is rather low (< -10 dBm) but semiconductor lasers are able to launch powers $\sim$ 10 dBm. Most lightwave systems use semiconductor lasers as optical source because light emitting diodes are also limited in their modulation capabilities. Finally, at the moment the bit rate is more often limited by electronics rather than the semiconductor laser itself [1].

1.3.2 Communication Channel

The task of the optical communication channel is to transport the optical signal from the transmitter to the receiver without distorting it. The medium for the transport can be optical fibers, which are most common, because silica fibers have losses as small as 0.2 dB/km but also the air is a possible medium and used in free space optics. Therefore, as optical communication channels are also used for long distances, fiber losses remain an important design issue. The broadening of the individual optical pulses during transmission, which is called *fiber dispersion*, is another important design issue. It might even become impossible to recover the original signal with high accuracy if it is too much degraded. This problem is most common in multimode fibers, where pulses spread rapidly (typically at a rate of $\sim 10ns/km$) because of different speeds associated with different fiber modes. The frequency dependence of the refractive index is called *material dispersion*. It still leads to pulse broadening (typically $< 0.1ns/km$), but it is small enough to be acceptable for most applications [1].

Refraction index The index of refraction n of a medium is the ratio of the velocity of light in vacuum, which is approximately $3x10^8 m/s$, to the velocity of light in the medium itself [18]:

$$\text{Index of refraction n} = \frac{\text{velocity in vacuum}}{\text{velocity in medium}} \tag{1.4}$$

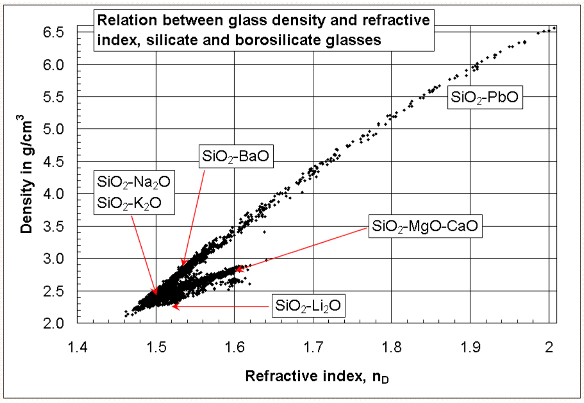


Figure 1.7: Relation between refractive index and density [19]

The ordinary air, for example, has an index of refraction of $n = 1,0003$ [18]. For silica based fibers the refractive index depends on the exact type of glass and its density (see Fig. 1.7).

Fiber optics The cable has a core which consists of a high-purity silica glass. The diameter of the core depends on the mode the cable will be used for (see also Table 1.1). The core is surrounded by another layer of silica glass, but with a different index of refraction, to keep the light in the core. A coating is added around the cladding, followed by some strengthening fibers to prevent that the cable breaks too easily, and finally a cover is added (see Fig. 1.8) [21]. Depending on how the light propagates in the core, different types of fiber are available (see also Fig. 1.9):

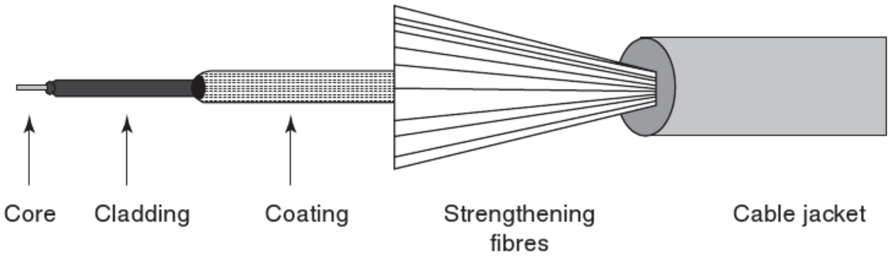


Figure 1.8: Fiber-optic cable construction [21]

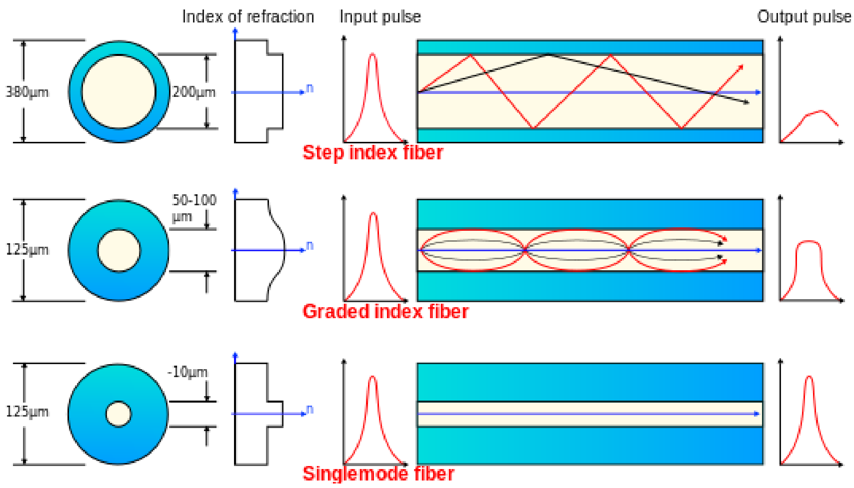


Figure 1.9: Optical fiber types [20]

Step index fiber: In this type of fiber the refractive index stays the same from the center of the core to its edge. The light propagates by using the principle of total internal reflection.

Graded index fiber: In the graded index fiber the refractive index decreases continuously with an increase of the distance to the core's center. This decrease causes the light ray to bend smoothly while it is getting closer to the coating.

Singlemode fiber: Like a step index fiber but with a smaller core diameter, which allows only one light ray.

Whereas the singlemode fiber allows only a single light path (Monomode), the step index fiber and the graded index fiber allow multi light paths (Multimode). The main differences of these two types for use in practice nowadays are listed in Table 1.1.

Table 1.1: Multimode vs. Monomode [21]

Multimode fiber	**Monomode fiber**
$\geq 62.5\mu m$ in core diameter	8.3 μm in core diameter
Generally uses cheap light-emitting diode light source	Utilizes expensive laser light
Multiple paths used by light	Light travels in a single path down the core
Short distances, < 5 miles	Long distances, > 5 miles
Power distributed in 100% of the fiber core and into the cladding	Power in the center of the fiber core only

Monomode In a single-mode fiber the light, emitted from a laser, travels in a straight path along the fiber, which makes it ideal for long distances. The core is usually 8.3 - 10 μm in diameter and has, as the name implies, only one mode of transmission. As the cables are usually not installed in a straight line, the light can not travel in a straight line neither. Because of this, if the cable is bent or curved, the light bounces off a transition barrier between the core and the cladding. Every time this happens the signal degrades a little bit, which is called chromatic distortion [21].

Multimode In this type of fiber the light, generated by light-emitting diodes (LED), can be sent on multiple paths along the fiber. This means that in a multimode fiber more than one frequency can be transmitted at the same time. The core is usually 62.5 - 100 μm in diameter and allows, as the name implies, multiple modes of transmission. Depending on the type of fiber used (step index or graded index), the light travels either in a zigzag path along the core (step index) and gets reflected back into the core every time it hits the coating, or it travels more smoothly, getting bent slowly the closer it comes to the coating, if a graded index fiber is used. The problem of a step index fiber is that, because of the different angles in which the light hits the coating, also the distances the different modes have to travel are different for the same length of cable [21].

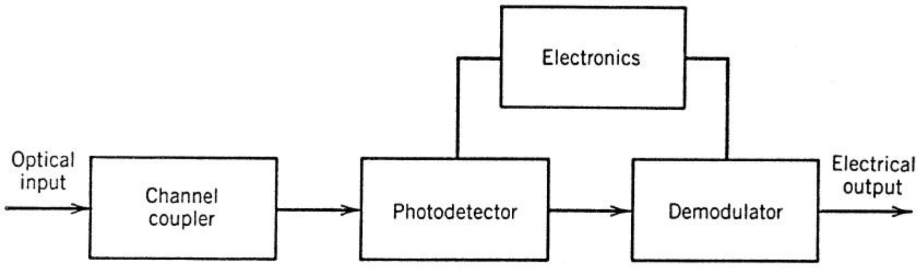


Figure 1.10: Components of an optical receiver [1]

1.3.3 Receiver

The task of the optical receiver is to get the signal from the output of the optical communication channel and convert it back to the electrical signal. In Fig. 1.10 you can see the block diagram of an optical receiver. It consists of a coupler, a photodetector, and a demodulator. The received optical signal is focused from the coupler onto the photodetector, which are usually semiconductor photodiodes. Finally, the modulation format used by the lightwave system decides the design of the demodulator [1].

1.4 Thesis Structure

In chapter 2 an overview of the evolution of optical networks is given. Furthermore, some key elements of optical switching technologies are described. In the following chapters 3 and 4 the most important switching techniques are explained and contention schemes and Quality of Service policies are presented. Moreover, for optical burst switching signaling-protocols which are used are explained. In chapter 5 an analytical model will be presented which provides a simple solution to calculate the packet blocking probability in an optical packet switching network with wavelength-convertible nodes. Finally, in chapter 6 two contention schemes and two Quality of Service policies for optical packet switching networks are evaluated, and in chapter 7 a conclusion is drawn.

2 Optical Networks

This chapter will describe the evolution of optical networks. First, a short introduction to different multiplexing techniques is given. The following sections will then explain the three generations of optical networks. With regard to the first generation, point-to-point networks are explained. With regard to the second generation, a closer look on the newly developed devices is taken. Finally, a short introduction to the third generation is given because two routing techniques of this generation, OBS and OPS, are explained more closely in chapters 3 and 4.

2.1 Multiplexing Techniques

Techniques for multiplexing are important to combine various signals into one single signal. Especially in systems in which a single node is not able to use the whole capacity of the channel these techniques have the advantage of increasing the total throughput. If, for example, the outgoing link of a router has a higher capacity than another incoming link, with multiplexing techniques multiple incoming links can be combined on one outgoing link so that the throughput on links with higher data-rates can be increased. Without these techniques all links would only have the same throughput as the slowest link. Increasing the capacity with multiplexing can be done by assigning timeslots (time division multiplexing), frequencies (frequency division multiplexing) or orthogonal codes (code division multiplexing) [14]. In CDMA (code division multiple access) all the data is encoded with a specific code before it is sent and so many data streams can be sent at the same time as long as the codes are orthogonal to each other. Basically, OCDMA (optical CDMA) is the same but for the optical domain special optical codes are used. For every databit '1' the codeword is sent, for the databit '0' nothing is sent [24]. In contrast, for time division multiplexing (TDM) you need hardware to provide the combination of the signals, assigning a timeslot to each. Therefore, the multiplexer has to work on the speed of the fastest stream. It has to take all the slower streams which should be combined and match them into a fast stream. The hardware could work even faster if all the multiplexing would be done in the optical domain. Hence, optical multiplexers are needed (OTDM, optical TDM). For frequency division multiplexing (FDM) different frequencies, which do not interfere with each other, are used for every stream. As a result, many streams can be transmitted at the same time. This technique is called wavelength division multiplexing (WDM) in the optical domain although it is the same technique as the FDM technique in radio communication.

2.2 First Generation

Optical networks of the first generation (see Fig. 2.1) are identical to electrical networks with the only difference that they use an optical transmission medium. These optical point-to-point

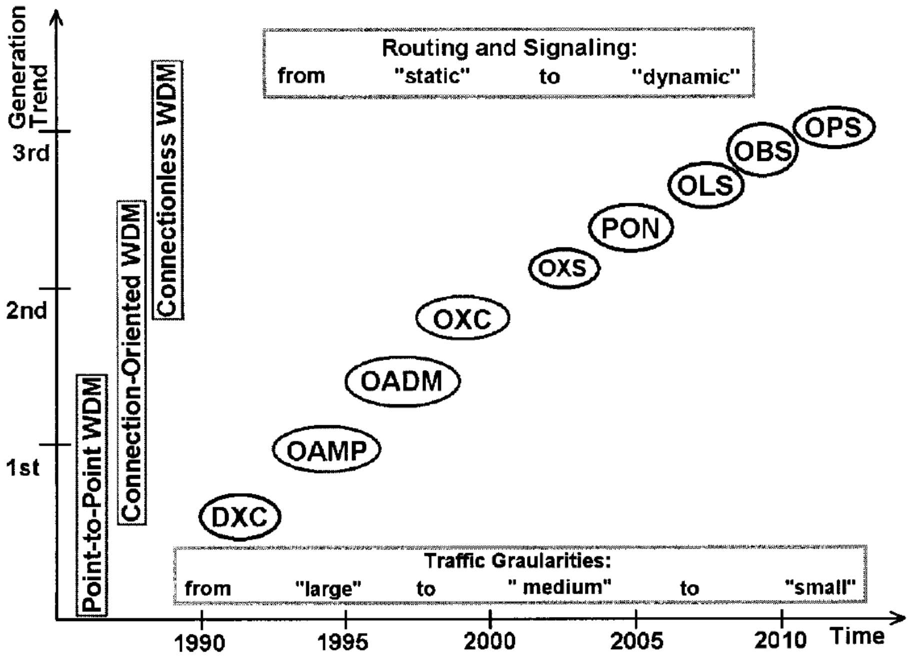


Figure 2.1: WDM network evolution [11]

networks use the optical medium only to transport information from one place to another with the least possible error rate and as fast as possible. The length of the link can vary from a few hundred meters up to thousands of kilometers. Depending on the location in which the optical link replaces the copper link different advantages and disadvantages of optics become more important. For example, for short distances the immunity to electromagnetic interference may play a big role whereas for an intercontinental optical link the losses become more important [1].

Point-to-Point WDM Network Point-to-point networks have been deployed by telecom network operators in the need of higher bandwidth. The WDM technology is deployed for mesh networks and ring networks as well. If the demand for capacity exceeds the current provided capacity of a fiber, it turns out that the WDM technology is a more cost efficient solution than laying more fibers [11].
The main disadvantage of the first generation networks is, as only the links between the nodes are replaced by an optical medium (see Fig. 2.2), that the packet has to be transferred to the electrical domain when it arrives at a node and transferred back to the optical domain when it is sent on the next link. This conversion consumes only little time but has to be done at every intermediate device, which finally affects the delay of the packets. Furthermore, the electronic devices reduce the performance-gain of fiber, as they still process the packet in the electrical domain so that the packets can be transmitted faster, but the electronic devices are a bottle neck for the end-to-end connection. A study [10] compared the solutions for an upgrade from OC-48 (2.5 Gpbs) to OC-192 (10 Gpbs) in a point-to-point transmission link:

- First solution, the so called 'multifiber' solution, is the burial and installation of additional fibers and equipment.

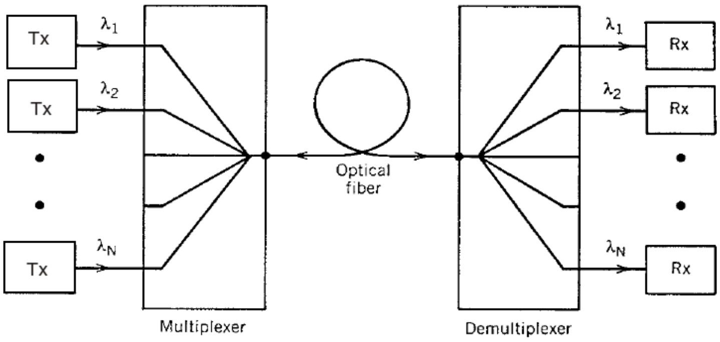


Figure 2.2: Multichannel point-to-point fiber link [1]

- In the second provided solution four independent data streams are combined with a WDM multiplexer on the sender side, every data stream sent on a unique wavelength. On the receiver side, the data streams are separated again by a WDM demultiplexer.
- The third provided solution is just using OC-192. This is a 'higher-electronic-speed' solution.

This study says that for links up to 50km the least expensive solution is the first one, namely laying new fibers. For higher distances the best solution in terms of cost is the WDM solution, closely followed by the 'higher-electronic-speed' solution. In modern WDM transmission systems, up to 160 channels per link are state-of-the-art and it is expected that 320 channels will become possible quite soon [11].

2.3 Second Generation

The optical networks of the second generation (see Fig. 2.1) offer connection-oriented end-to-end connections. Add/drop elements (WADM or OADM) and optical crossconnects (OXC) are the key elements that enable optical networking. Furthermore, technologies for routing and wavelength assignment, wavelength conversion, network control and management and others are developed. The network is managed and operated based on a virtual topology over the physical topology. If there are traffic changes, the virtual topology can be reconfigured dynamically [11].

2.3.1 Add/Drop Multiplexer

A wavelength add/drop multiplexer (WADM) is also called optical add/drop multiplexer (OADM) [11]. The input signals, which may have multiple wavelengths, can be either passed through or specific wavelengths can be dropped locally and new streams can be inserted instead (see Fig. 2.3). This is done by demultiplexing the input signal into N different wavelengths. This wavelengths can then be selectively dropped/removed and new data can be added within the same wavelength. Finally, all these wavelengths get multiplexed again in order to be transmitted in a single fiber [2].

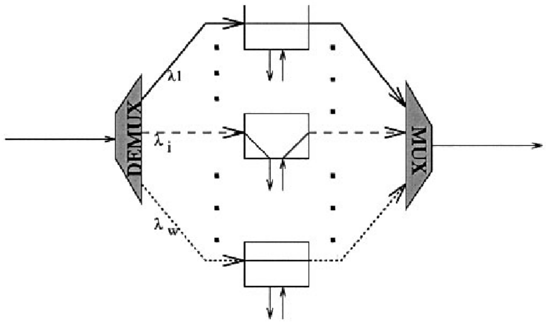


Figure 2.3: A wavelength add/drop multiplexer (WADM) [11]

The WADM can be configured electronically and the add/drop decision is made based on this configuration. According to the number of wavelengths, the OADM can add/drop or translate. The OADMs are classified into three categories [2]:

- *Fixed OADMs*: No or low reconfigurable add/drop functionality is provided
- *Reconfigurable Add/Drop Multiplexers (ROADM)*: Wavelength routing functionality is provided in a manner so that some wavelengths can be dynamically directed to the output
- *Reconfigurable and Wavelength Translating OADM*: Fully reconfigurable routing is provided

2.3.2 Optical Crossconnects

An optical crossconnect (OXC) performs a similar function as a WADM but at a much larger size [11]. They have a large number of ports (from a few tens up to thousands) and some types are able to switch wavelengths from one input port to another [14].
The small optical crossconnects can be divided into three categories [2]:

- *Fiber switching OXC*: The OXC simply connects the fibers according to the needs of the network. The architecture of these switches contains an optical space switch which is capable of connecting different pairs of fiber.
- *Lambda switching OXC*: These OXCs are a further improvement. They allow to switch not only based on the fiber but also based on the wavelength/lambda from one fiber to the next one. That is why they are also based on complex and complicated architectures which are using selectable/tunable filters and optical space switching mechanisms.
- *Wavelength conversion OXC*: Such OXCs are the most expensive and most complicated switches. Therefore, they offer the maximum of flexibility in terms of network design and provisioning. These OXCs can make their switching decisions based on the wavelength/lambda and even convert one or more of them into different wavelengths/lambdas if two or more different fibers with the same wavelength/lambda have to be switched onto the same fiber.

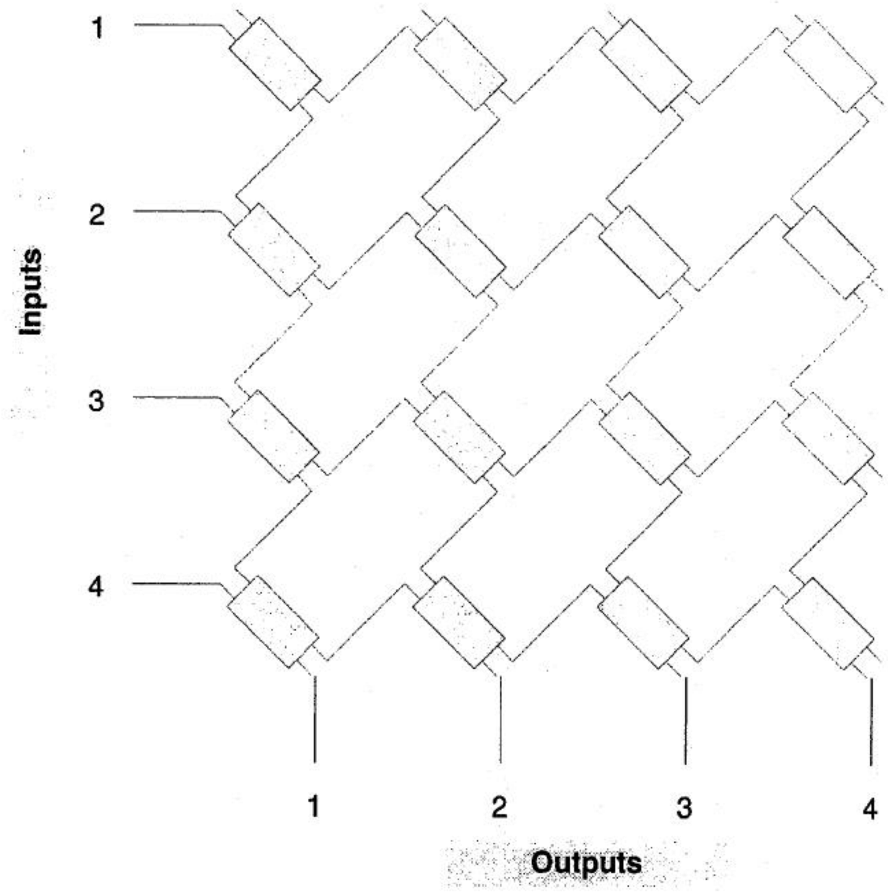


Figure 2.4: Switch using the crossbar architecture [13]

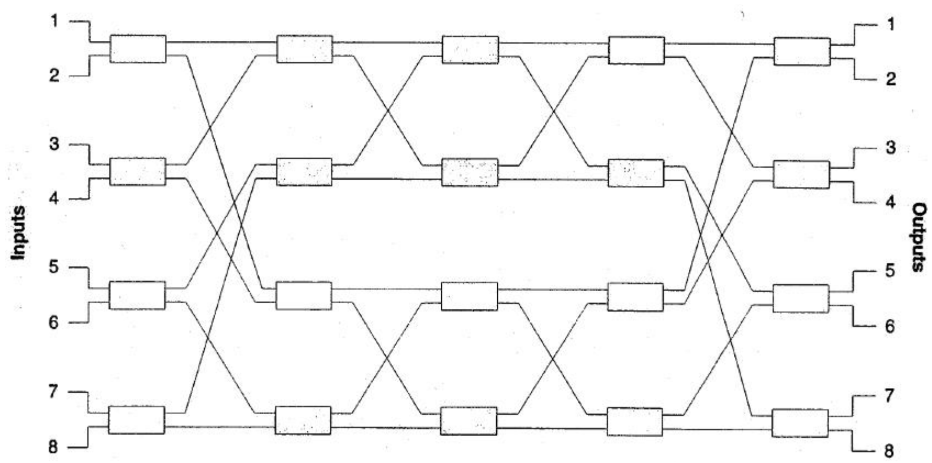


Figure 2.5: Switch using the Beneš architecture [13]

To achieve switch sizes larger than 2 x 2, small switches are cascaded in different ways [13]:

- *Crossbar*: To create a crossbar (Fig. 2.4 shows a 4 x 4 switch realized using 16 2 x 2 switches [13]) between n input rows and n output columns, n^2 2 x 2 switches are needed. A packet, arriving at input port i and desired output port j, travels through the crossbar in row i until it reaches column j. Here it traverses now in column j to the output port j. Following this interconnection rule, the crossbar architecture is wide-sense noneblocking. A main disadvantage of this architecture is that the path lengths vary from the shortest path of 1 to the longest path of $2n - 1$. Another drawback is the number of switches needed for this architecture.

- *Beneš*: This architecture (Fig. 2.5 shows a rearrangeably nonblocking 8 x 8 switch realized using 20 2 x 2 switches interconnected in the Beneš architecture [13]) is one of the most efficient architectures in terms of the number of used small 2 x 2 switches. A switch with size n x n needs $(n/2)(2log_2n - 1)$ small switches, n having to be a power of 2. The main advantage of this architecture is that all path lengths are equal, passing $2log_2n - 1$ small switches, and therefore all paths have the same loss. Two main drawbacks of this architecture are that it is not wide-sense nonblocking and that a number of waveguide crossovers are required, which makes it difficult to fabricate in integrated optics.

- *Spanke-Beneš*: In this architecture (Fig. 2.6 shows a rearrangeably nonblocking 8 x 8 switch realized using 28 2 x 2 switches [13]) a compromise between the Crossbar and the Beneš architecture is made. It requires $n(n - 1)/2$ switches having a shortest path length of $n/2$ and a longest path length of n with no need for crossovers. The main drawbacks in this architecture are that the loss still varies because of the different possible route lengths and that it is not wide-sense nonblocking.

- *Spanke*: To create an n x n switch with this architecture (Fig. 2.7 shows a strict-sense nonblocking 4 x 4 switch realized using 24 1 x 2 / 2 x 1 switches interconnected in the Spanke architecture [13]), n 1 x n and n n x 1 switches are combined. It requires $2n(n - 1)$ 1 x 2 switches. All paths have an equal length of $2log_2n$ and the architecture is strict-sense nonblocking.

2.4 Third Generation

The optical networks of the third generation (see Fig. 2.1) are meant to support connection-less networks. The most important invention therefore was the development of optical switching technologies named optical 'X' switching (OXS), where X is replaced with P for packet, B for burst, L for label and so on [11].

2.4.1 Optical Burst Switching (OBS)

Optical burst switching is quite attractive in research literature as optical packet switching is still not feasible. It is placed between optical circuit switching and OPS. OBS outcomes the disadvantages of the need for fast optical devices to detect and process short packets by

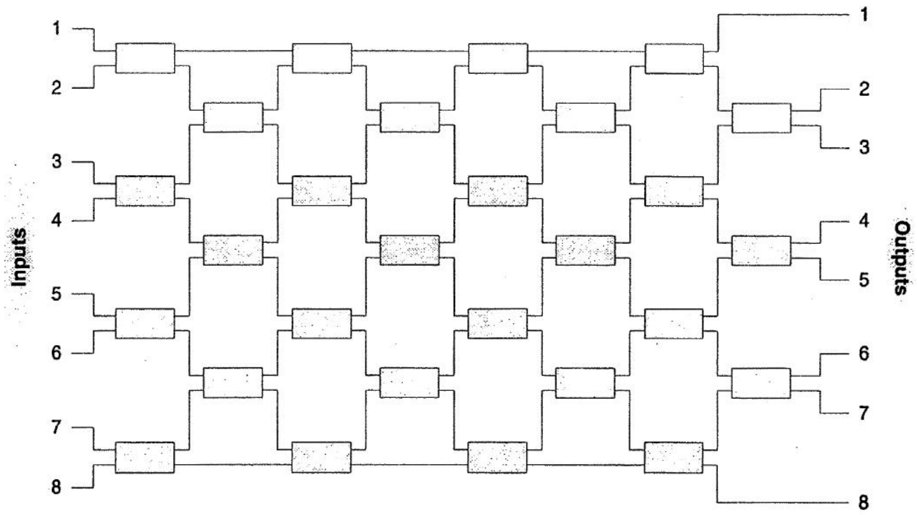


Figure 2.6: Switch using the Spanke-Beneš architecture [13]

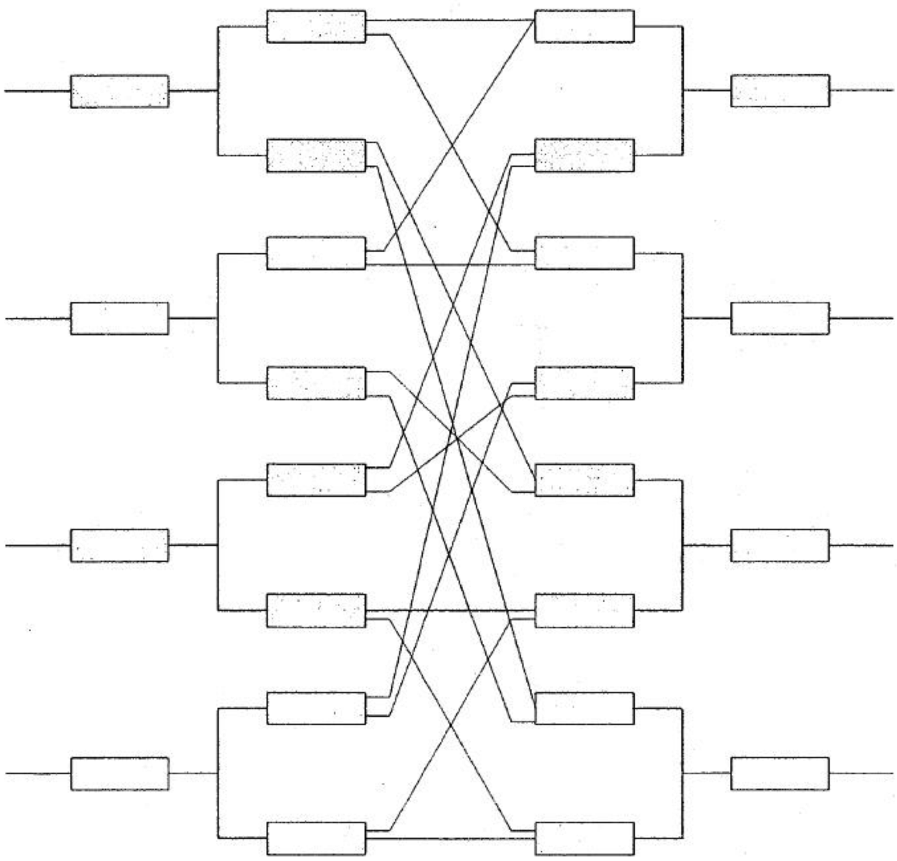


Figure 2.7: Switch using the Spanke archicture [13]

assembling packets for the same destination to a burst and using an appropriate signaling scheme.
The assembly process of course increases the mean delay of a single packet but in return the route from the source to the destination (two-way-scheme) or at least a part of the route (hybrid-scheme) can be reserved. In the one-way-scheme the burst tries to reach its destination without any reservation done before. Whereas the one-way-scheme usually comes with a higher data loss because of the higher chance that a burst gets dropped, the two-way-scheme suffers from an increasing packet delay the larger the distance between source and destination becomes. To get rid of these disadvantages hybrid-schemes are developed which try to combine the advantages of the one-way and the two-way-scheme. One approach is to do the reservation during the assembly process. Therefore the next burst size has to be estimated at the beginning of the assembly process. Then the header tries to make a reservation as far as it is possible within the designated assembly time [11].
In general, OBS will soon be interesting to become a state-of-the-art technique. However, still a lot of research has to be done to improve the signaling and scheduling schemes. A closer look at the optical burst switching technique is taken in chapter 3.

2.4.2 Optical Packet Switching (OPS)

The optical packet switching technique is meant to be the optical switching technique of the future. It works the same way as packet switched routing techniques nowadays in electronic networks. Every packet sent from the source to the destination tries to find its way through the network [11].
One of the main problems is still that the optical technologies operate at a much higher bitrate than electronic technologies. The packets are quite small and the header has to be detected and processed before the payload arrives as there do not exist appropriate buffers like the electronic RAM (random access memory). Alternative contention resolution schemes for the optical domain are discussed in section 4.4. Up to now there are no devices at all, or at least not with reasonable prizes, which do the header detection and processing in the optical domain. A more detailed explanation of the optical packet switching technique is given in chapter 4.

3 Optical Burst Switching

Optical burst switching is a routing technology of third generation optical networks. This routing technology collects incoming packets for the same destination at the ingress nodes for a certain time and then transmits all the packets together in a burst. In this chapter, first the burst assembly process and the differences between timer-based and threshold-based burst assembling is explained. Then, an overview of the different signaling protocols used in OBS networks is given and the just enough time and just in time protocols are described closer. After that, a contention mechanism for OBS is explained, before at the end of the chapter different Quality of Service policies are introduced.

3.1 Burst Assembly Process

The burst assembly process is done at the edge nodes of the OBS network. Incoming packets from a higher layer at the node are stored in electronic buffers according to their destination and service class. The burst assembly mechanism places these packets into bursts according to its assembling policy. Key parameter for burst assembling is the trigger criteria which determines when the burst is created and sent into the network. This parameter is very important, because it has a big influence on the traffic characteristics in the network, as it controls the burst size and the time between the bursts [8]. This trigger criteria can either be a fixed time or a certain threshold of the burstsize/timer or a mixture of them [11].

If a timer is used, the assembly process ends as soon as the timer expires. A new assembly process is either started immediately or as soon as the first new packet arrives in the queue. The timer has the advantage that the bursts are ready after a fixed time but the disadvantage that the burst might be very small or very large. If a threshold is used, the assembly process finishes as soon as the burst size reaches a fixed size (see Fig. 3.1). This mechanism guarantees bursts with only small differences in payload-size but has the drawback that the assembly time may vary a lot [8].

A common problem in OBS is how to choose the appropriate timer and threshold value. If the threshold is too low, bursts will be smaller and because of this also more bursts will be created. This higher number of bursts leads to a higher number of contentions. However, smaller bursts have the advantage that less packets will get lost whenever a burst is dropped because of contention. Furthermore, short bursts also increase the pressure on the control plane to process the control packets as switches have to be reconfigured more often. This might result in a high switching time overhead [8].

On the other side, if the threshold is too high, the bursts will become very long. This indeed decreases the total number of bursts in the network and therefore also the number of contentions. If, however, a burst gets dropped, more packets are lost. Thus, it becomes obvious that there exists a tradeoff between the number of contentions and the average number of packets lost per contention. Hence, the performance of the OBS network can be

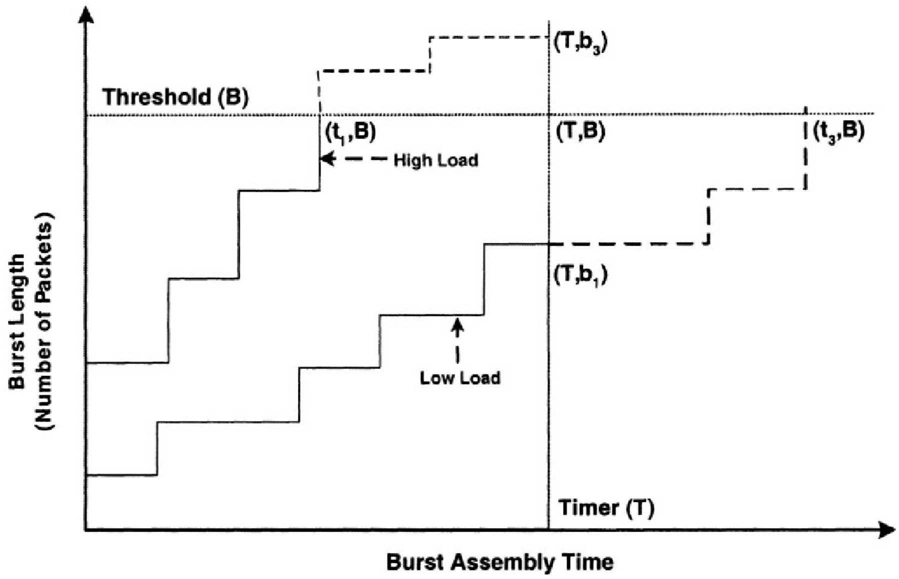


Figure 3.1: Effect of load on timer-based and threshold-based aggregation techniques [8]

improved if an optimal threshold value is chosen [8].
In OBS networks in which QoS is important, a timer may be the better choice as there is a fixed limit for the delay. If there are no QoS restraints, a burstsize-threshold may be the better choice, as the burstsize becomes more smooth. A good way to reduce the big differences in either assembly-time or burst-size is to use both, a timer and a threshold. Therefore the timer and the threshold can be combined in an arbitrary way to guarantee a minimum and/or maximum value in delay or/and burstsize. This mechanism introduces constraints and avoids that the burstsize/delay becomes an unwanted size but also the assembly process becomes more complex [8].
Another reason why this assembling is so important is that most signaling schemes need to know the arrival time of the burst, the length of the burst or both for resource reservation at the core nodes. For example, in JET (see section 3.2.2) the signaling scheme needs to know both to perform the resource reservation, whereas in JIT (see section 3.2.1) nothing needs to be known by the signaling scheme as it performs the reservation in a greedy manner [8].

3.2 Signaling Protocols

The signaling protocol is responsible to configure all the intermediate nodes. The data burst is going to pass later on transparently from the source to its destination. In OBS networks this signaling is usually done out-of-band which means that the header with the control information is sent on a separate wavelength, dedicated for control messages only. This header is going to inform the intermediate nodes and provides the necessary information so that the optical crossconnects can be set early enough for the arriving data burst which is going to pass through. Signaling schemes can be categorized (see also Fig. 3.2) based on three main characteristics [2]:

1. One-way, also called tell-and-go (TAG), or two-way, also called tell-and-wait (TAG). In the two-way scheme the source waits for an acknowledgment if the reservation succeeded, whereas in the one-way scheme the burst is sent immediately after a certain offset time to the header (see Fig. 3.3).
2. Immediate or delayed (also called timed) reservation. With an immediate reservation the resources at the intermediate nodes are reserved as soon the the control packet arrives, whereas with the delayed reservation the resources are reserved just before the data burst arrives.
3. Explicit or implicit release. The resources are released either explicit by an additional tear-down message or implicit, where the release is estimated based on the burst size which can be retrieved from the information in the header (see Fig. 3.4).

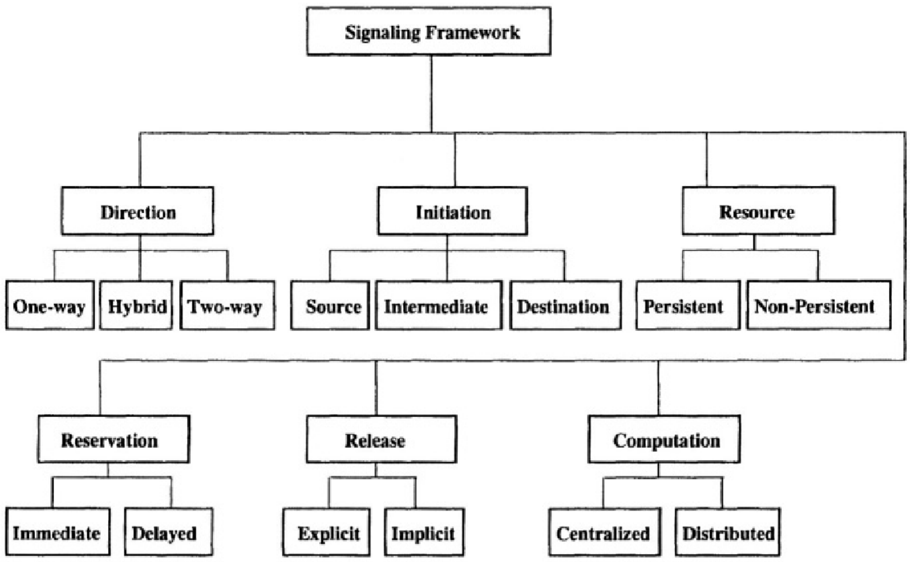
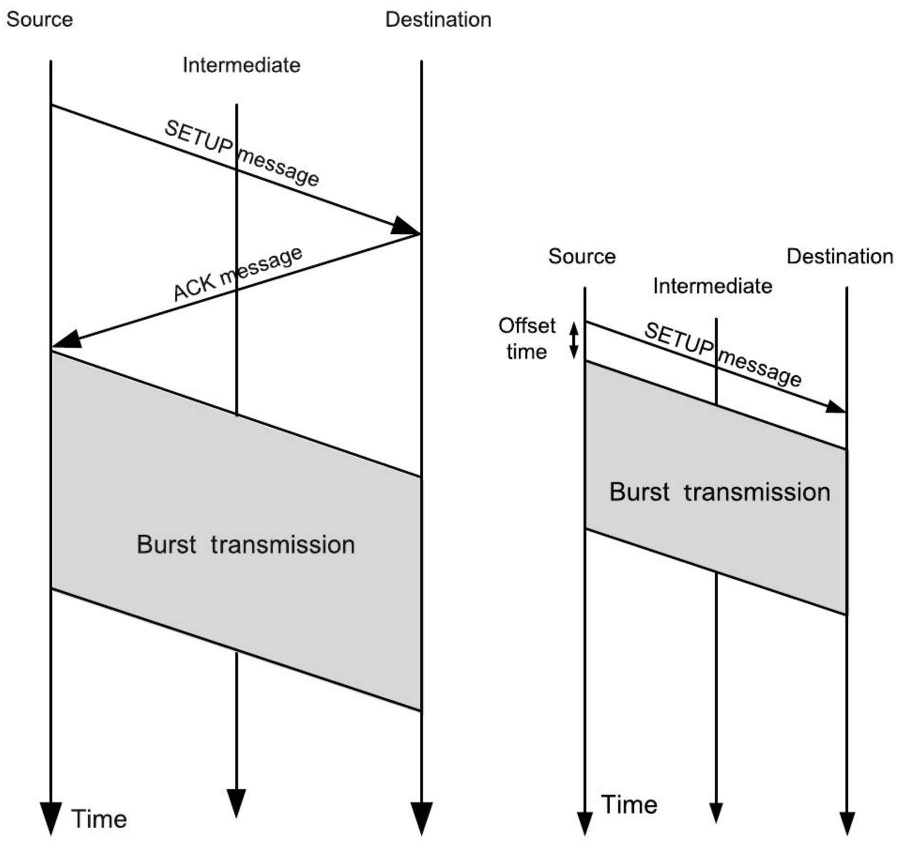


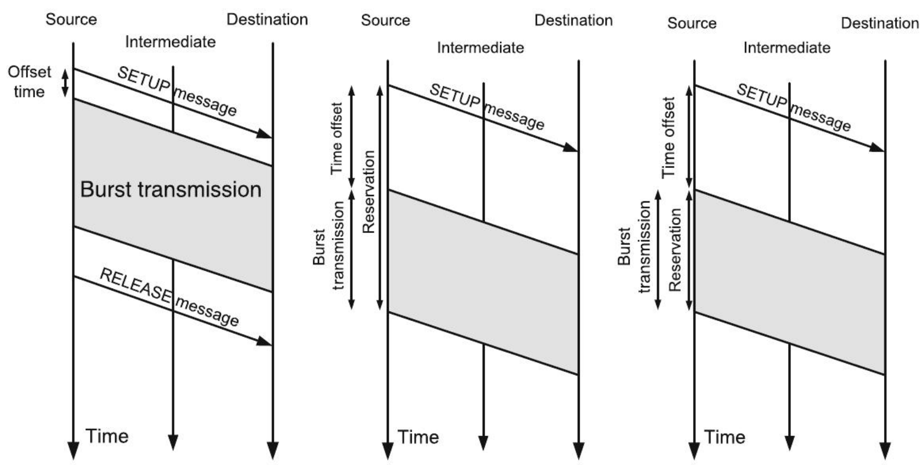
Figure 3.2: Signaling Classification [8]

Different signaling protocols are used based on the requirements of the OBS network. In an one-way scheme the delay of the burst can be kept low because there is only a short offset time between the header and the data but with the drawback that it is not guaranteed that the burst will reach its destination if the reservation of the header fails and therefore the burst gets dropped. The successful transmission can be guaranteed in a two-way scheme, but there a packet suffers from a high delay which is related to the round-trip time of the source-destination pair. If the final burst size is unknown at the moment when the header is sent, the resources may have to be released explicit because the intermediate node can not calculate the burst duration and therefore they also can not release the resources themself. To not waste any capacity delayed reservation might be used. However, in contrast to the immediate reservation in which the resources are reserved immediately with the arrival of the header, the delayed reservation is much more complex to implement and needs the offset time to be encoded in the header [8].



(a) Two-ways (b) One-way

Figure 3.3: One-way scheme compared to the two-way scheme [2]



(a) Explicit release (b) Immediate reservation (c) Delayed reservation

Figure 3.4: Explicit release and implicit and explicit reservation [2]

3.2.1 Just In Time (JIT) Protocol

The just-in-time protocol is a one-way scheme with immediate reservation and implicit release. This protocol works in the way that the header is sent a certain offset time ahead to the data burst. When the header with the control information reaches the first intermediate node at time t, the node processes the message, which takes $T_{process}$, and tries to make a hard reservation of a channel at the required output port. If the reservation succeeds, the node configures the optical switch fabric in T_{config} and the header is forwarded to the next node on the route. After the configuration is finished, which is at time $t + T_{process} + T_{config}$, the node is ready to (transparently) forward the data burst [2].

As the data burst is going to arrive after a certain offset time, the channel remains idle from $t + T_{process} + T_{config}$ until the burst finally arrives at $t + T_{offset}$. This idle time, which is $T_{offset} - T_{process} - T_{config}$, is a waste of bandwidth. From this calculation of the idle time it can also be seen that the time difference between the header and the data burst decreases along the route as the header is processed at every intermediate node. Therefore, the offset time is updated at every intermediate node and the minimum T_{offset} has to be at least $h * T_{process} + T_{configure}$, where h is the number of hops along the route [2].

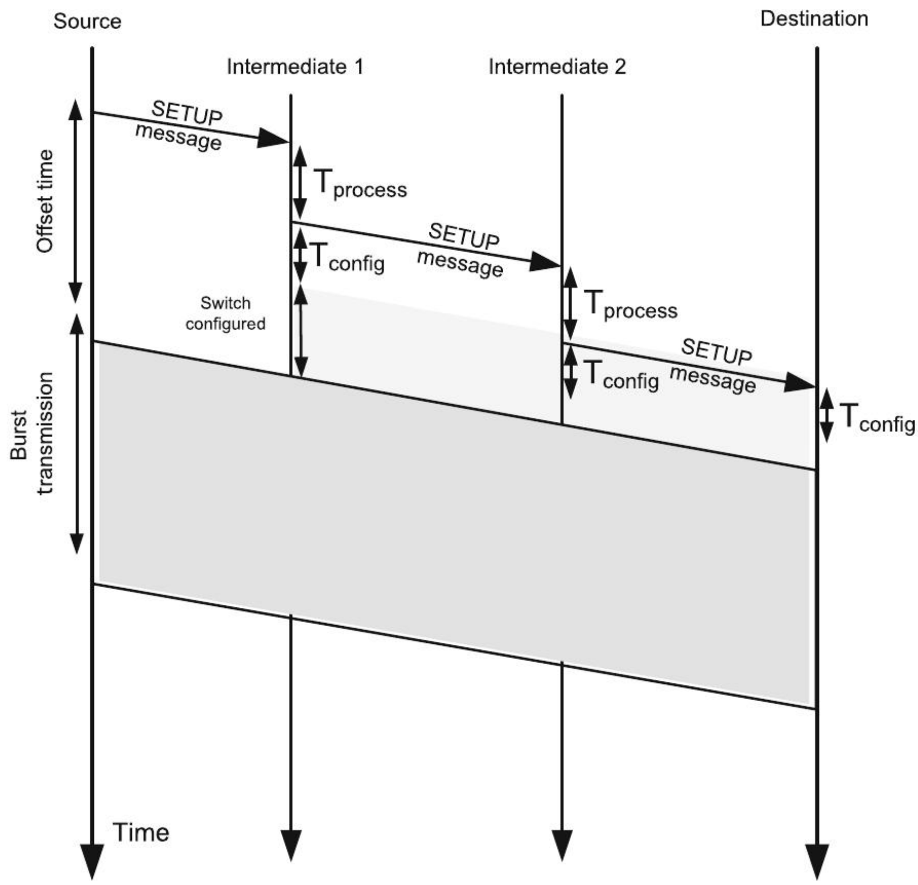


Figure 3.5: Message flow using the JIT protocol [2]

From Fig. 3.5, in which the message flow and the actual reservation is illustrated, it gets obvious that, because of the immediate hard reservation, any new reservation attempts arriving between t and $t + T_{offset} + T_{burst}$ (where T_{burst} is the burst duration) will be rejected even if the new burst would fit into the gap $t + T_{offset}$ without any downside for the original burst. Whereas this introduces, as already mentioned, a waste of capacity, the scheduling at the intermediate nodes becomes much more simple and follows a first-come first-serve principle [2].

3.2.2 Just Enough Time (JET) Protocol

The just-enough-time protocol is a one-way scheme with delayed reservation and implicit release. In this scheme the desired output wavelength is only reserved for the duration of the data burst. The hard reservation is done just before the burst arrives by configuring the switch so that the data burst can be routed transparently [2].
When the header with the control information reaches the intermediate node at time t, the node processes the message and makes a soft reservation by scheduling the actual arrival time and duration of the data burst. The data burst will then arrive at $t + T_{offset}$ and therefore the hard reservation is done at $t + T_{offset} - T_{config}$ to be ready to forward the data burst when the first bit of it arrives [2].
In Fig. 3.6 the flow of the messages and the actual hard reservation is visualized. It can be seen that, using this signaling protocol, more reservations for the same wavelength on the same output port can be scheduled as long as they do not overlap. The drawback of this advantage is that this scheme also introduces higher complexity with the reservation and scheduling [2].

3.2.3 Hybrid Protocols

Signaling protocols which try to combine the advantage of the short delay from the one way scheme with the advantage of the low drop rate from the two way scheme are called hybrid schemes.
One approach is presented in [22]. In this approach the reservation (based on a two-way scheme) starts immediately as soon as the first packet arrives in the queue. Therefore, a prediction filter is needed to predict the estimated burst size which is needed for the two-way scheme. This approach still suffers from the fact that the assembly time is related to the round-trip-time which might still introduce a high end-to-end delay.
Another approach is presented in [16]. In this approach the assembly time is used to reserve as many links as possible along the route. Again a prediction filter is needed to predict the burst size at the beginning of the assembly process. Then, the header-message travels as far as possible so that an acknowledgement can still be back in time at the end of the assembly process (see Fig. 3.7). If the reservation was successful the burst is sent. Otherwise the data is kept for the next assembly process. This approach profits from the advantages of the two-way scheme (low burst-drop rate) and the one-way scheme (low end-to-end delay). The assembly timer can be set to an arbitrary fixed time which will never be exceeded and still the two-way reservation is done for as many hops as possible.

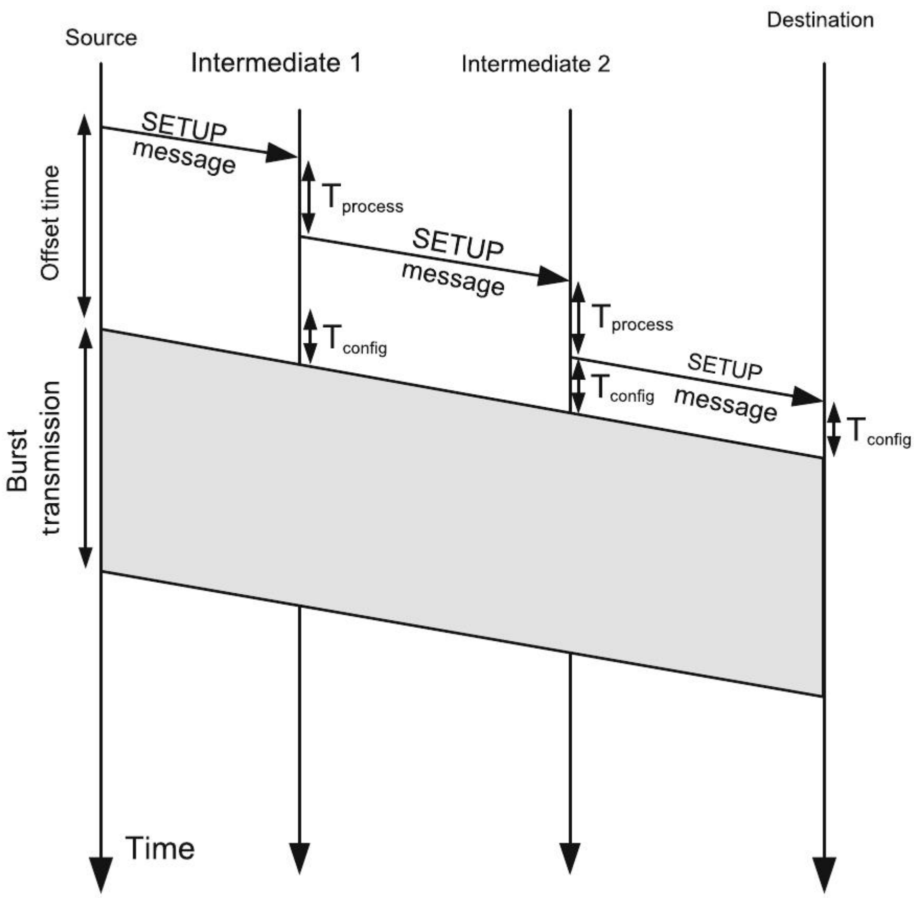


Figure 3.6: Message flow using the JET protocol [2]

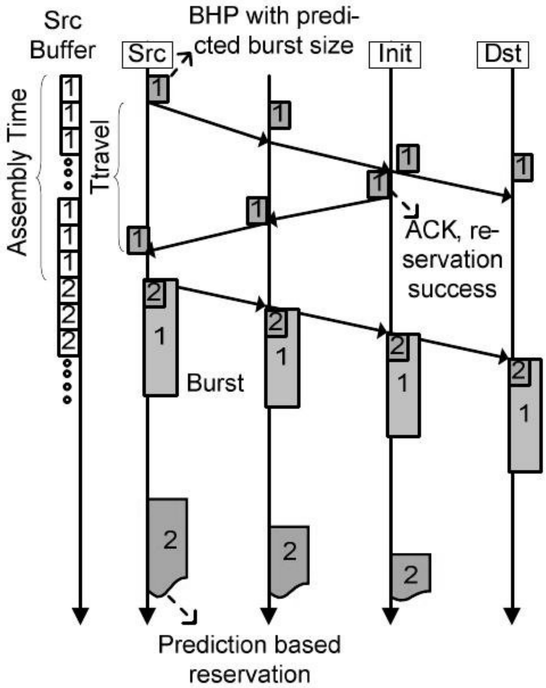


Figure 3.7: Timing of a hybrid scheme during a successful burst reservation [16]

3.3 Contention Resolution

As OPS networks are similar to OBS networks but with packets instead of bursts, it is obvious that the same contention resolution schemes used in OPS networks can also be used in OBS networks [11]. Therefore, contention resolution schemes are described in section 4.4. However, there is an additional contention resolution scheme for OBS networks called Burst Segmentation in which the overlapping part is segmented and because of this not the whole burst has to be dropped.

Burst Segmentation This approach avoids that all the data of a burst is lost, if it should be dropped only because part of it overlaps with another burst [23]. In this case the burst which overlaps is segmented. Either the tail of the first burst or the head of the second burst can be segmented. However, most of the times the tail of a burst is chosen, because then the probability that the assembled packets arrive in the correct order at the destination is higher. The segmented part can then be either dropped or handled according to another contention scheme like deflection routing and sent on another link.

3.4 Quality of Service

As OBS is a next generation network and applications with different requirements to the delay or loss rate become more and more common nowadays. Therefore, OBS has to be able to provide Quality of Service. QoS can be introduced in OBS networks at different points,

e.g. different offset times, different contention resolution policies, different burst assembly strategies and different scheduling methods. There are two basic models of QoS: *relative QoS* and *absolute QoS*. In the relative QoS model the performance of each service class is not defined in absolute terms, i.e. it is only defined that the class with a higher priority has to have a lower loss-probability than a class of lower priority. However, there is no upper bound guaranteed, whereas the absolute QoS model provides a worst-case QoS guarantee to the applications. Efficient admission control and resource provisioning mechanisms are needed to support the absolute QoS model [8].
Another approach to classify QoS models is how much the traffic of different services classes interferes each other. In a *isolated model* the traffic of the different service classes are completely independent of each other, whereas in a *non isolated model* the performance of the high priority traffic also depends on the performance of the low priority traffic [8]. In the next sections some QoS policies especially for OBS networks are presented. For more general QoS policies in optical networks see section 4.5.

3.4.1 Prioritized Signaling

This QoS policy provides relative quality of service by using different signaling schemes for different service classes. For example, for bursty traffic JET could be used, whereas for constant traffic a TAW scheme could be used.
The problem of this approach is to find the best signaling scheme for the network, as for a low network load a connection-less scheme provides a lower delay than a connection-oriented one, while still having a fairly low packet loss rate. However, if the network load is high, the packet loss rate may be unacceptable high for a connection-less scheme. Therefore, the selection of the signaling scheme may be based on either static parameters such as QoS requirements and hop distance or on dynamic parameters such as the current traffic conditions [8].

3.4.2 Offset Based QoS

Another relative QoS policy utilizes the offset time between the header and the burst to provide quality of service by adding an additional delay to the offset time of the higher priority bursts. Because of the increased offset time the requested reservation at the core-nodes will be further in the future and thus, more likely successful. This QoS policy also supports class isolation if the difference between the offset times of different classes is high enough. In [25] it has been shown that in order to achieve 99% class isolation under certain conditions the difference needs to be 5 times the maximum burst length size of the lower service class . This additional offset time will lead to (unacceptable) high end-to-end delays for high priority bursts which may not meet the QoS requirements anymore. In other words to have acceptable end-to-end delays for high priority bursts class isolation of 100% is not possible for this offset time based scheme. Furthermore, this scheme can also lead to unfairness with large low priority bursts experiencing higher losses than smaller low priority bursts [6].

3.4.3 Prioritized Contention Resolution

In this QoS policy relative quality of service is based on the concepts of burst segmentation and burst deflection (see also section 3.3). However, in this case priorities are assigned to

the bursts and contention is resolved through selective segmentation, deflection and burst dropping based on these priorities.
First, the possible segmentation and deflection policies which can be applied for this QoS approach are defined. Followed by defining the possible contentions which can occur between bursts of different length and priorities. Finally, specifying the policy to apply for each possible contention scenario [8].
One of the following contention policies may be applied to segment, deflect and/or drop a burst in case of contention [8]:

- *Segment First and Deflect Policy (SFDP)*: The contending burst wins the contention, the original burst is segmented and the tail segments of it are either deflected if an alternate output port is available or dropped.

- *Deflect First and Drop Policy (DFDP)*: The contending burst is deflected if an alternate output port is available. Otherwise it is dropped.

- *Deflect First, Segment and Drop Policy (DFSDP)*: The contending burst is deflected if an alternate output port is available. In case of no available alternate output port the original burst is segmented, its tail segments are dropped and the contending burst is sent on its original output port.

- *Segment and Drop Policy (SDP)*: The contending burst wins the contention. The original burst is segmented and its tail segments are dropped.

- *Drop Policy (DP)*: The original burst wins the contention and the entire contending burst is dropped.

Depending on the priorities and lengths of the contending and the original bursts, four different possible combinations for contention scenarios exist. The original burst can either have a higher or lower priority than the contending burst, or both bursts have the same priority. If they have equal priorities, it depends if the remaining tail of the original burst is shorter or longer than the contending burst. One of the above described contention policies can now be applied to one of these four contention-scenarios.
Figure 3.8 illustrates the four possible scenarios of contention. In case (a), in which the original burst has a higher priority than the contending one, the contending burst should be deflected or dropped, therefore DFDP should be applied. For case (b), in which the original burst has a lower priority than the contending one, the contending higher priority burst should win the contention, thus, SFDP should be applied. In case that both bursts have the same priority we should try to minimize the total number of packets which are deflected and/or dropped. Hence, in case (c) with a longer contending burst compared to the remaining tail of the original burst, we will either try to segment and deflect the tail of the original burst (SFDP) or try to deflect the contending burst (DFSDP). If the remaining tail of the original burst is longer than the contending burst, like in case (d), the contending burst should be deflected or dropped which results in applying the DFDP policy [8].

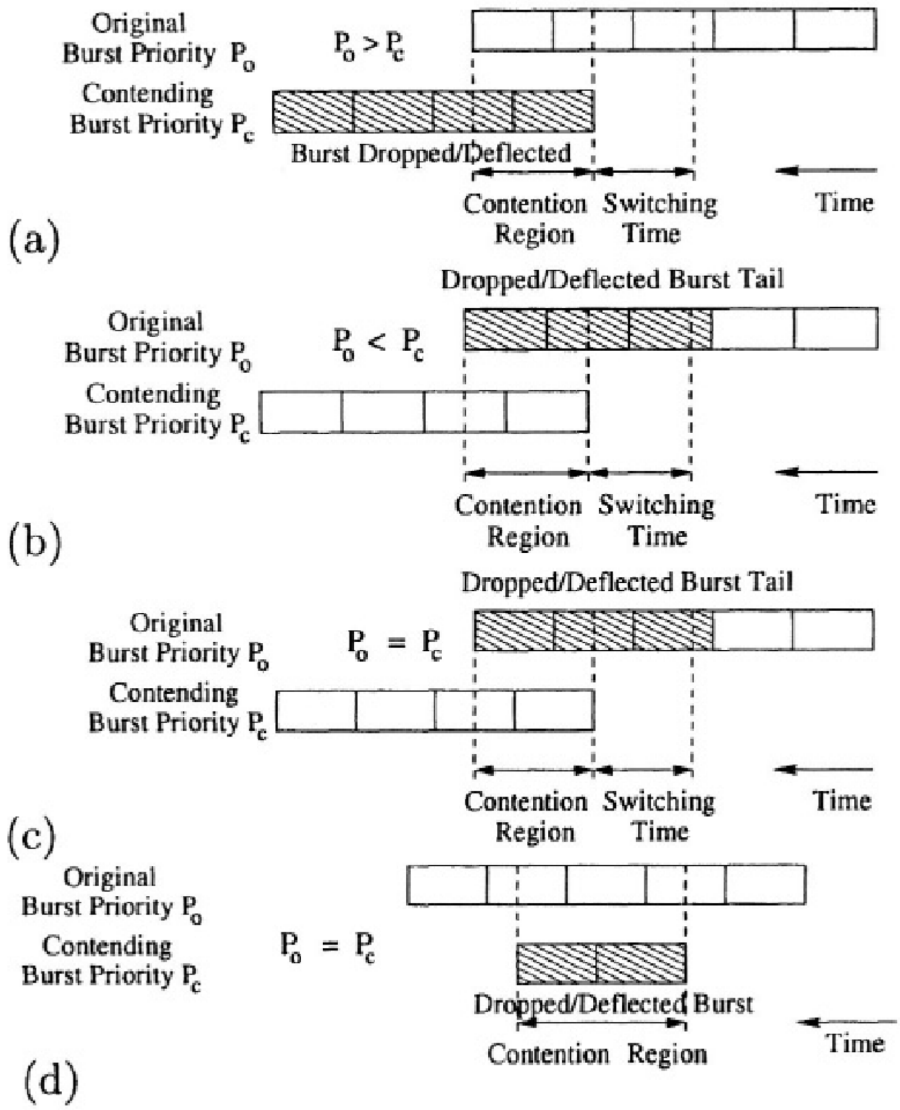


Figure 3.8: Possible contention scenarios using prioritized contention resolution [8]

4 Optical Packet Switching

Optical packet switching is a routing technology of third generation optical networks. This routing technology will maybe replace one day nowadays packet switching technologies and all necessary switching tasks will be done by all-optical devices. In the first section the basics of the OPS technology are described. A closer look at the differences between synchronous and asynchronous networks, the packet and its header and the overhead is taken. Then, contention schemes for optical networks are explained. Finally, a short look on Quality of Service in OPS networks is taken.

4.1 OPS Basics

An OPS network is generally the main network such as a backbone to which other packet-oriented networks (e.g. ATM, based on IP, ...) are connected. The OPS network consists of core nodes within the network which are only connected to other OPS routers and edge nodes which connect other networks to the OPS network (see Fig. 4.1). These ingress nodes are responsible for collecting the incoming data units and prepare them for the optical domain by creating the optical packets according to the network requirements. Therefore, incoming data may have to be assembled, if too small, or separated, if too big, depending on the used optical container. Moreover, an optical header for the payload has to be created containing all the necessary control information needed for successful routing within the OPS network [2].

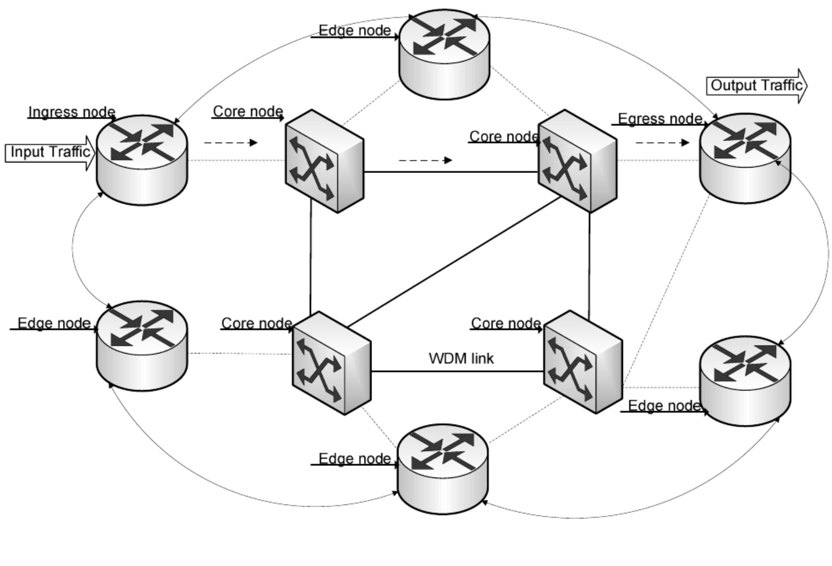


Figure 4.1: Demonstration of an OPS network [15]

When the packet enters this optical domain the packet is transparently switched by the routers according to a statistical multiplexing technique [2]:

1. Each core node processes the packet header and retrieves the routing information like the destination address or the virtual circuit identifier.

2. Then, a look-up in the routing table is done to find the associated output port for its next hop.

3. If the output port is not available, a contention resolution scheme can be applied to avoid the loss of the packet.

4. Finally, the packet is either transmitted to the next node or the implemented contention scheme is applied.

In the end, when the packet reached its egress node, the data has to be translated back to its original format and some packets may have to be reassembled again.
To sum up, core-nodes just forward the optical packet to its destination and edge nodes work as an ingress/egress system for the OPS network. However, in practice edge nodes and core nodes are not that clear differentiated. It is common that a node which is an ingress or egress node for one packet is just an intermediate node for another packet and a core node might also have 'clients' connected to it. Therefore, all nodes should be capable of both, the switching functionality for crossing packets and the add/drop mechanism for incoming and outgoing packets.

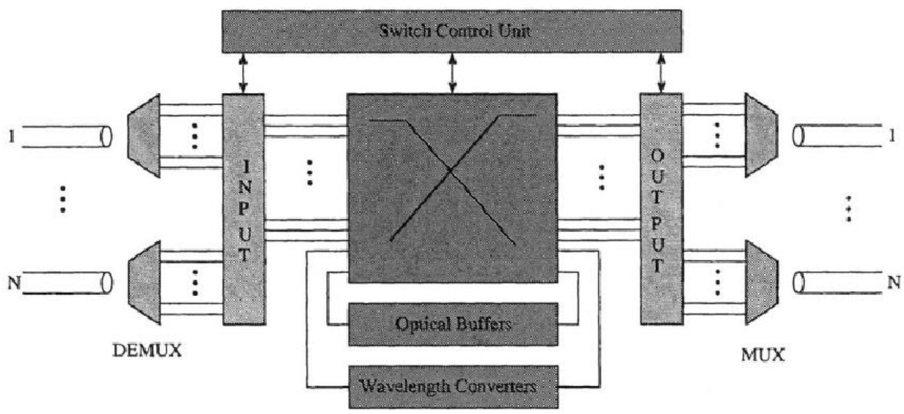


Figure 4.2: OPS node architecture [9]

A generic OPS node architecture, which can be seen in Fig. 4.2, consists of a set of multiplexers and demultiplexers, an input and an output interface, a space switch fabric with associated optical buffers (i.e. fiber delay lines) and wavelength converters and a switch control unit. A packet arriving on an input fiber gets first demultiplexed into its individual wavelengths and is then sent to the input interface. The input interface then extracts the header from the packet and forwards the header to the control unit for processing. The control unit processes

the header information, determines an appropriate output port for the packet with a free wavelength and configures the switch fabric to route the packet according to its route and contention scheme. For routing the packet, the switch fabric may need to buffer the packet and/or convert it to another wavelength. Furthermore, the switch controller also creates a new header for the packet and forwards it to the output interface. As soon as the packet arrives at the output interface the new header is attached and the packet is sent on the correct outgoing fiber to its next hop along the path to the destination [9].
OPS networks can be classified along several dimensions and the incoming packets then have to be handled according to the networks requirements [9]:

- *Synchronous vs. asynchronous switch operation*: In synchronous networks packets can only be injected into the network at a certain time, whereas in an asynchronous network packets can be injected at any time (see section 4.2).
- *Electronic vs. optical control*: In practice the only working approach is processing the header in the electronic domain, but in the future all-optical-processing should be possible.
- *Optic header format*: The header can either be sent on the same wavelength as the payload or on a different one (see section 4.3).
- *Switch fabric architectures*: As the switches play an important role, a wide variety of them has been proposed (see section 2.3.2).
- *Contention Resolution Strategies*: When two packets want to leave the switch on the same output port and wavelength at the same time, contention occurs (see section 4.4).

4.2 Slotted and Unslotted Optical Networks

Networks are, in general, either synchronous or asynchronous. Whereas in synchronous networks the nodes have to coordinate their times because packets can only be sent into the network at a certain time, in asynchronous networks packets can be sent into the network at any time.

4.2.1 Unslotted

Unslotted optical networks work asynchronous. This means that packets can be injected into the network from the edges at any time. As a result, size or duration of the packets may change from packet to packet and every value is possible [11].

- *Asynchronous variable length packet (AVLP)*: The incoming packet is sent in the optical payload as it is (see Fig. 4.5(b)). Therefore, the length of the optical packet is variable and it can be transmitted, switched and received at any time [2].
- *Asynchronous fixed length packet (AFLP)*: The incoming packet gets fragmented into optical packets with a fixed size (see Fig. 4.5(c)). Padding might be needed for the last fragment. The optical packet can still be transmitted, switched and received at any time [2].

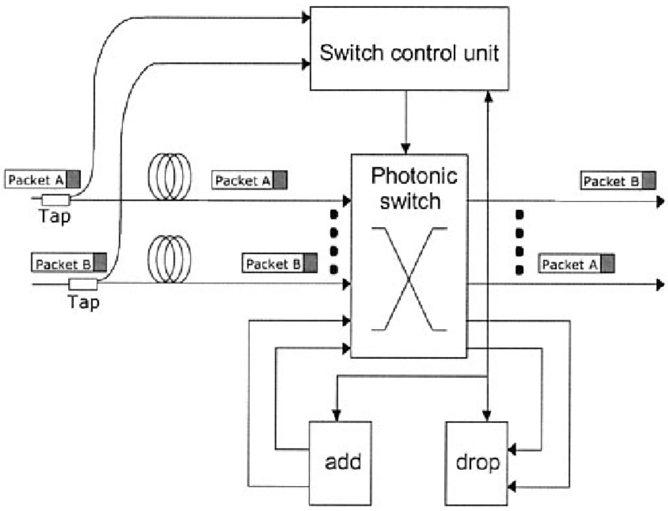


Figure 4.3: A generic node architecture of the unslotted network [11]

At the intermediate nodes the packet is sent to a fixed length fiber delay line, while the header is processed and the switches are reconfigured. Both, the packet and the header, are affected by the same delay and after processing and configuration the (new) header is sent again ahead of the packet on the fiber to the next node. Fig. 4.3 illustrates this process.

4.2.2 Slotted

Slotted optical networks work synchronous. Packets can only be injected at a certain time into the network from the edges. Because of this, all occurring packets in the optical network have the same fixed size or a multiple of it (packet train) [11].

- *Synchronous variable length packet (SVLP)*: The incoming packet is split onto a packet train of n optical packets with a fixed size. This packet train must not be splitted by inserting other optical packets in between. Because of this limitation only one packet header at the beginning of this train is needed (see Fig. 4.5 (d)). Moreover, padding may be needed for the last optical packet if the incoming packet does not fit exactly into the *n times size of slot* packet train [2].

- *Synchronous fixed length packet (SFLP)*: All optical packets have the same size and are independent of each other. If an incoming packet is larger than the optical packet size, it has to be segmented onto multiple optical packets (see Fig. 4.5 (e)). At the optical destination reordering and reassembling has to be done to provide a correct electronic data packet [2].

Fig. 4.4 illustrates how the header is processed while the packet is sent to a fiber delay line for the time of processing and switch configuration. Compared to the unslotted architecture, this architecture also has a synchronization stage which contains various length fiber delay lines at the beginning to align all the incoming packets in phase to each other.

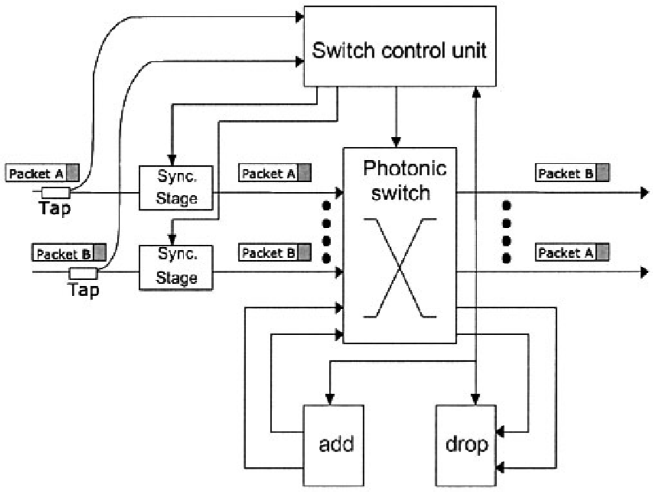


Figure 4.4: A generic node architecture of the slotted network [11]

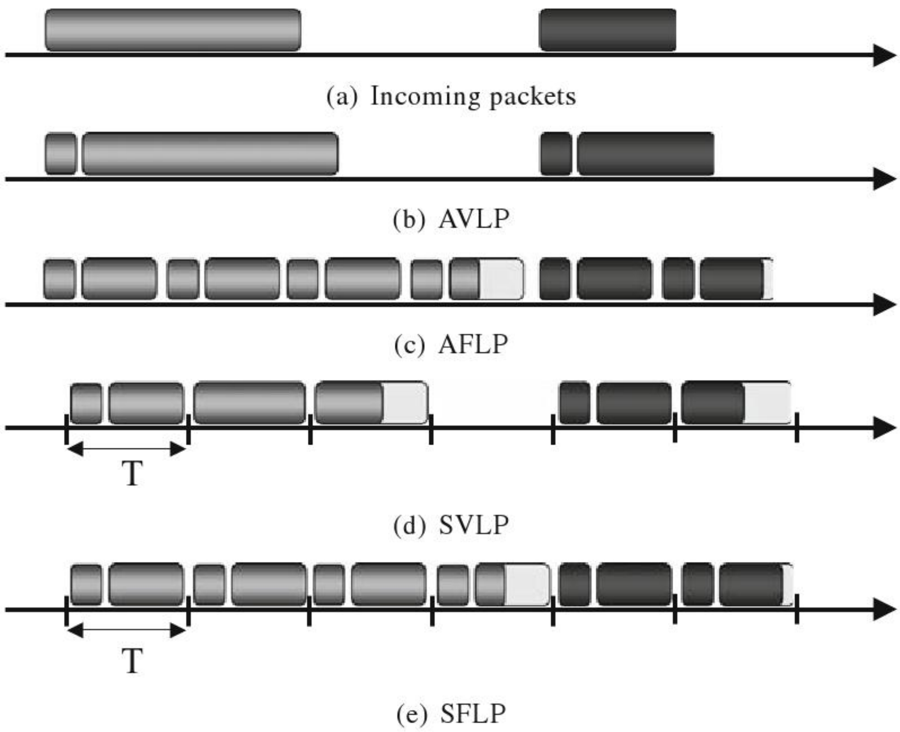


Figure 4.5: Different approaches, how to handle incoming data [2]

The main advantage of SVLP is that it needs only one header and therefore reduces the header processing at the core nodes to a minimum. This is very important as header detection and header processing is still the most critical point in optical networks. Moreover, reordering and reassembling is not needed which makes the control logic more simple [2].

4.3 Packet and Header

The header of a packet is either sent on the same wavelength as the payload, which is called in-band signaling, or it is sent on a different one, called out-of-band signaling. Out-of-band signaling also requires additional synchronization between the control and the data channels and is, for example, used in optical burst switching networks [2].
In optical networks the header can be detected and processed in two ways [11].
As the bandwidth is much higher in optical networks, one way is to detect and process the header at its rate, which is around 10 Gbps and higher. The detection and processing of the header at this rate can be done either electronically or optically but both require expensive switches which are able to work at this fast rate in the electronic domain or to detect and process the header in the optical domain.
The other way is to convert the header into the electronic domain with a slower rate and process it 'the old way'. This has the advantage of being cheaper and it can be done with state-of-the art techniques. However, it has the disadvantage of consuming more time. So the payload has either to be sent later after a certain offset time or the payload has to be stored longer in each switch while the header is being processed.

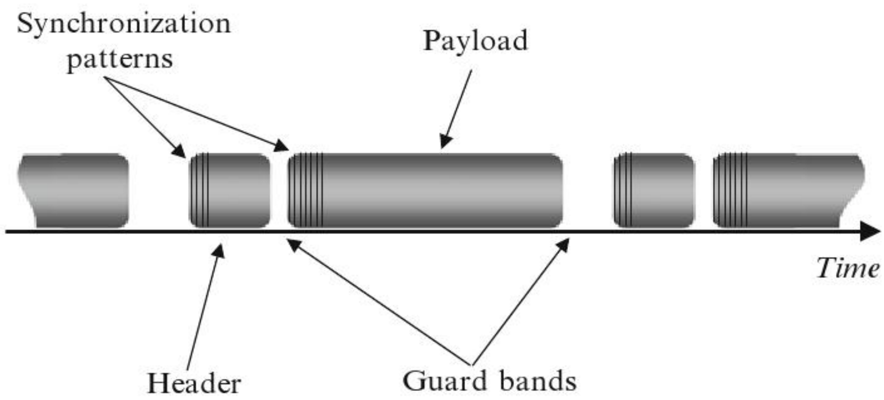


Figure 4.6: Typical format of an optical packet [2]

Overhead Assuming a multiplexing scheme for slotted networks described in section 4.2, three types of overhead are introduced by translating the data into optical packets [2]:

- *Header overhead*: A header is needed for every packet (or packet train).
- *Guard bands overhead*: Guard bands are needed between the time slots and between the header and the payload to avoid interference.

- *Padding overhead*: Padding is required to fit packets with variable length into slots with a fixed length.

As long as the header and the guard bands are much smaller than the time slots, their overhead can be neglected. The padding overhead is related to the size of the slot because all packets with variable size have to be rounded up with padding to fill the slot and therefore also increase the traffic load.

4.4 Contention Resolution

Contention occurs sooner of later if the traffic increases. To increase the performance in networks with higher traffic, contention resolution schemes are used. In an optical network contention occurs at a switching node if at least two packets try to leave the same output port at the same time on the same wavelength. In electrical packet switched networks the problem of contention is solved by using the store-and-forward technique. This technique stores the packets in case of contention in the memory and sends them whenever the output is free again. Whereas this works for packets in the electronic domain because of the availability of RAM (random-access-memory), there is no equivalent optical memory for packets in the optical domain. Therefore, other approaches exist. They do either store the packets for a certain time (Optical Buffering), use another available wavelength (Wavelength Conversion) or even send the packet on another free port (Deflection Routing). Some of this methods result in a higher delay of the packet or the need for additional hardware in the switches, like fiber optical delay lines or wavelength converters [11] [14].

4.4.1 Optical Buffering

Whereas in electronic networks it is simple to store a packet in an electronic buffer as soon as the packet enters the switch in the electrical domain, for optical switches optical buffers are needed if we want to avoid a conversion from the optical to the electrical domain, which would increase the packet delay and neutralize advantages we get from the optical transmission. Therefore, optical buffers like fiber delay lines (FDL) are used. The FDL works like a normal link but the destination of the link is the same switch, so the packet sent onto this 'link' is delayed for the time it takes the packet to travel along the FDL. This is also the main disadvantage of FDLs compared to electronic buffers. Whereas in electronic buffers packets can be stored for an arbitrary period of time, the packets in FDLs are stored for a fixed period of time or a multiple of it, related to the length of the delay line. The limitation for this approach is the number of FDLs, as it is the size of the buffer, but whereas in the electrical domain large buffer sizes can be reached very easy, it gets expensive and complicated to create large buffers with FDLs for the optical domain [11].
Fig. 4.7 (a) shows a FDL attached to a switch for single-wavelength optical-buffering. Multiple wavelengths can also use the same FDL as seen in Fig. 4.7 (b).

4.4.2 Wavelength Conversion

A different approach is focusing on the wavelength. Wavelength converters are a very expensive but also a very powerful equipment for optical switches. If every switch gets set up with

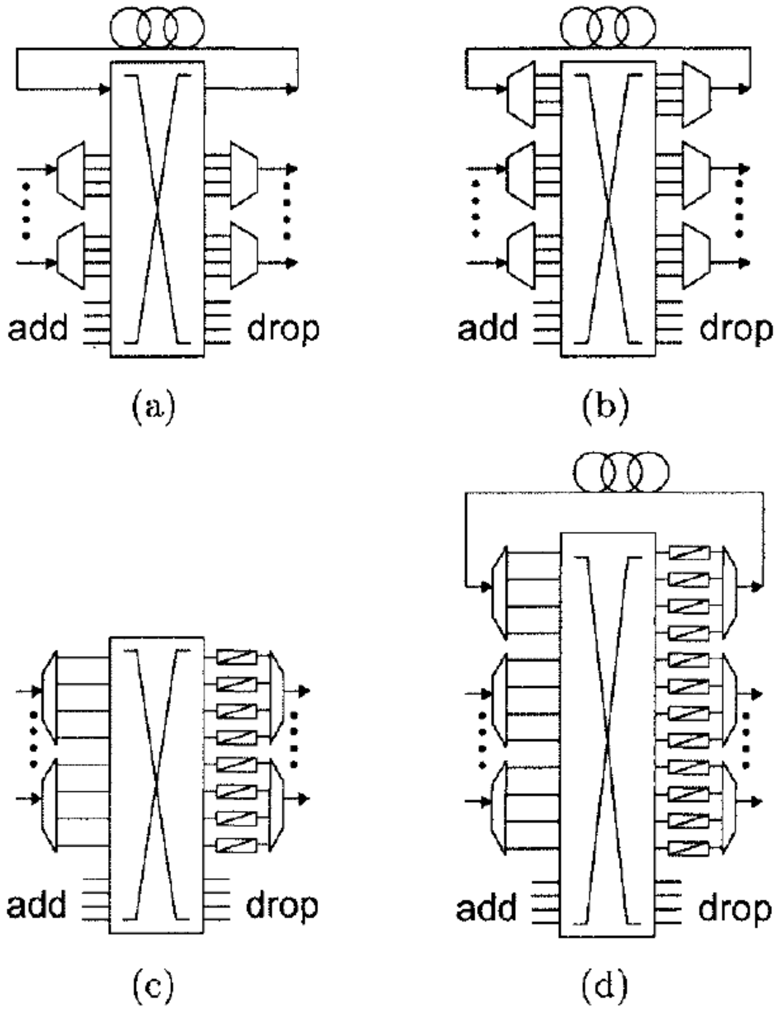


Figure 4.7: Node architectures for different contention resolution schemes [11]

wavelength converters, each switch can send the incoming packet on another free wavelength on the output port if the one the packet arrived on is already in use. As already said, this approach is only possible if there are more wavelengths on each link and each switch is equipped with the needed hardware [11].
Fig. 4.7 (c) shows wavelength converters attached to the output of the switch to convert the incoming wavelength from the switch to the specific outgoing wavelength.
Research is done on the number of wavelength converters and how they are attached to the switch, because as wavelength converters are quite expensive a reduction of needed converters in a switch would have a significant positive influence on the price of the switch. One approach is to share the wavelength converters between each other [26]. Another approaches focuses on using less convertible nodes [7].

4.4.3 Deflection Routing

This approach is kind of walking on the edge of the knife. The packet is sent on a different output port somewhere into the network if the original one is already occupied. Therefore, the packet stays longer in the network and its delay increases. The main disadvantage is that, as the packets stay longer in the network, the traffic increases. Furthermore, some additional mechanisms have to be implemented to avoid that a packet stays forever in the network because of loops. Such a mechanism could be to set a maximum hop count so that all packets which exceed this hop count get discarded. This technique is similar to the time-to-live mechanism for IP routing packets [11].

4.4.4 Combination of Schemes

The presented basic contention resolution schemes can be mixed to get combinations. However, keep in mind that a packet still can be dropped at any node because of (1) no free buffer at the node, (2) no free wavelength at the output port and/or (3) exceeding the maximum number of hops [11].
Fig. 4.7 (d) shows an example of a switch which is equipped with wavelength converters and FDLs.

4.5 Quality of Service

Nowadays, QoS is getting more and more desired. For some kind of traffic it is more important to not loose (too much) data as for some other kind of traffic. If the network wants to be able to handle packets of different service classes and provide service according to their priority, QoS mechanisms are needed. As most of the OPS technology is still not out of the lab, not that many research is focusing on QoS techniques but on more common problems of OPS. However, some general approaches which have already been suggested for OPS networks, are shown [11]:

- *Wavelength converter reservation*: This approach implies that the OPS network supports wavelength conversion. According to the number of service classes some wavelength converters can be reserved for only part or even only one of the service classes. If, for example, a network with six converters per link should support three different service classes, the switching can be done as followed: The first four converters can be used by traffic of every service class. Are all these converters already occupied, only the two higher priorities can use the next converter. The last available converter can only be used by traffic of the highest priority.

- *Packet threshold dropping*: If two packets of different service classes compete for the same output port, the packet with the lower service class is dropped if the buffer (e.g. FDLs) exceeds a certain threshold.
- *Fixed dropping*: A modification and also simplification of the threshold dropping policy is the fixed dropping which works even without a buffer. A fixed number of packets from the low priority class gets dropped automatically at every node, as a result, more capacity for the high priority packets is available.
- *Wavelength allocation with scheduling*: This approach implies the possibility of wavelength conversion. If there is no free wavelength found for a packet with higher priority, the delay of the packet is increased an the search is repeated. This solution decreases the probability for dropping packets of higher priorities.

All this schemes can, of course, be combined in an arbitrary way. For example, if an OPS network with FDLs and the possibility of wavelength conversion should support three service classes, one converter can be assigned only to the highest service class. The two lower service classes are separated by dropping the packets of the lowest service class whenever the buffer reaches a certain threshold.
Furthermore, all contention resolution schemes can also be used to provide QoS and the traffic profile can be reshaped on a higher level according to the service classes [11].

5 A Simple Model for the Blocking Probability in an OPS Network

The content of this chapter was published at the '14th Panhellenic Conference on Informatics (PCI 2010)' [15].
In an OPS network, packets are routed hop by hop in the optical domain from an ingress node to an egress node in the network. The edge nodes are responsible for the formation of optical packets and the transmission scheduling. At the core nodes optical packets are switched to output ports based on the information carried by a control packet and the availability of network resources. Ingress nodes collect data from end users or access networks and create the optical packets [3]. The transmission of optical packets is realized exclusively in the optical domain without being stored at intermediate nodes. Upon the reception of the packet the intermediate node forwards the packet to its destination. Ahead of the optical payload a control packet is sent to the destination node in order to request the intermediate nodes to allocate the necessary resources for the optical packet and to configure their switches.
In most of packet switched networks the packet blocking probability (PBP) is a significant QoS-factor beside the bandwidth requirement. Packet losses mainly occur, if two or more incoming packets need to be forwarded to the same output at the same time. Therefore a contention resolution method should be utilized. There are three general domains of recently proposed contention resolution mechanisms [12]:

a) Packets which are unable to locate a certain wavelength should be converted to an available wavelength using a wavelength conversion device. This procedure does not cause additional delay or reordering of the packets.

b) Packets which are unable to locate a specific time-slot in a certain wavelength should be delayed using Fiber Delay Lines (FDLs). This procedure causes additional delay and reordering of the packets, because the fixed length of FDLs does not provide the same flexibility as an electronic storage device does.

c) Packets which are unable to locate a specific time-slot in a certain wavelength should be transmitted through the same wavelength and at the same time-slot but in another optical fiber. This technique may cause additional delay, because the different fiber may lead to a node different than the predefined destination node.

All the aforementioned mechanisms introduce complexity and hardware cost but they result in a decreased PBP especially when wavelength converters and FDLs are considered. In this chapter, a simple analytical model for the calculation of the PBP in an OPS network that utilizes the wavelength conversion capability is presented. The analytical model is based on the Reduced Load Approximation (RLA) method [17]. It is assumed that optical packets arrive to the ingress nodes following a Poisson process, while the service time of the packet is a function of the offset time between the transmission of the control packet and the transmission of the optical packet. The calculation of the PBP is based on the derivation of the distribution of the occupied wavelengths in each link of the network. The proposed model is computationally efficient because it is based on recursive formulas. Furthermore, through simulations the effect of the wavelength conversion capability on the PBP is studied and the analysis is validated through simulations.

5.1 Service Model

For the analytical model an OPS network consisting of L links, which are connected in an arbitrary way, is considered. All links have a fixed number of wavelengths W in each direction. Furthermore, the OPS network is a wavelength convertible network in which all nodes are able to convert wavelengths in order to decrease the blocking probability at each node. The used routing scheme is fixed (e.g. shortest-path routing) and the route r is a subset of links [1,..,L]. The total number of routes in the OPS network is denoted by R. Optical packets, which are meant to be sent from a source to a destination, arrive at the source according to a Poisson process. Ahead of the payload with a certain offset time a header packet is sent to configure the switching devices at the intermediate nodes. Moreover, this header packet reserves the specific link for the offset time $T_{offset_{max}}$ so that the payload can pass through. For the model it is assumed that the offset time is fixed for all routes based on the route with the maximum number of links. The offset time is calculated by summing up the delays the header packet suffers at each node on the way to the destination. These delays only affect the header, because it has to be converted from the optical to the electronic domain, processed and finally converted back to the optical domain and be transmitted to the next hop, whereas the payload stays during the whole transmission in the optical domain and just passes through each hop. The calculation is done as followed:

$$T_{offset_{max}} = (T_{O-E} + T_{E-O} + T_{trans}) * L_{max} + T_{safe} \tag{5.1}$$

where T_{O-E} and T_{E-O} are the time intervals for the conversion from the optical to the electronic domain and vice versa. T_{trans} is the time needed to put the header packet back on the next link (transmission time). These delays occur at every intermediate node and either at the source (T_{E-O} and T_{trans}) or the destination (T_{O-E}). Therefore, they have to be multiplied with L_{max}, which is the number of links of the longest route in the network. Furthermore, a safety time interval T_{safe} is added to assure that the header reaches all nodes early enough to configure every switch properly. The transmission delay is given by

$$T_{trans} = \frac{l}{C} \tag{5.2}$$

where l is the packet length and C is the transmission capacity of each wavelength.
The assumption of the fixed offset time for all routes, which is pretty clear a waste of bandwidth for short routes, is essential in order to derive the distribution of the number of occupied wavelengths in each link. Therefore, a Markov Chain is formulated from the state transition diagram, see Fig. 5.1, in which each state w represents the number of occupied wavelengths in link j. The transition from state [w] to state [w+1] is realized $\lambda_j(w)$ times per unit time, where $\lambda_j(w)$ is the packet arrival rate if w wavelengths are occupied on the link.

To calculate $\lambda_j(w)$, the sum of the arrival rates of all routes containing link j is calculated. The arrival rate of each link of a route is multiplied by a factor which assures that the packet has successfully passed the previous link of its route. Thus, this factor is one minus the probability that the packet got blocked. A packet gets blocked if all wavelengths are occupied. Therefore, the arrival rate $\lambda_j(w)$ is given by:

$$\lambda_j(w) = \sum_{k \in r} \lambda_r \prod_n (1 - q_k(W)) \tag{5.3}$$

where n is the number of links the packet has to pass to reach link j in route k. The probability that all W wavelengths are occupied in the previous link k is $q_k(W)$. The product of 5.3 is based on the RLA link independence assumption.

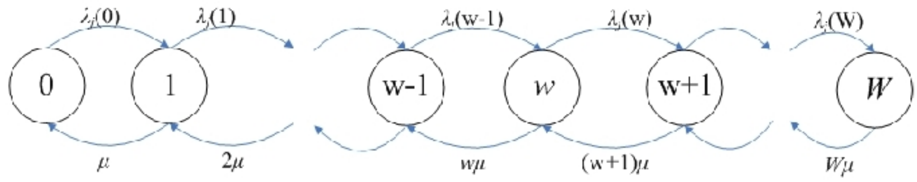


Figure 5.1: State transition diagram of link j in an OPS network

The distribution of occupied wavelengths in link j can be derived from the rate balance equations of the transition diagram in Fig. 5.1.
A Method for deriving the distribution of $q_j(w)$ can be found in [17]. More specifically, from the rate-out = rate-in, the steady-state equation can be derived:

$$\lambda_j(w-1)q(w-1) + (w+1) + \mu q_j(w+1) = [\lambda_j(w) + w\mu]q_j(w) \tag{5.4}$$

where $q_j(w) = 0$ for $w < 0$ and $w > W$. Summing up side by side of equation 5.4 from $w = 0$ to $w - 1$ results in the recurrence formula:

$$q_j(w) = \frac{\lambda_j(w)}{\mu j} q_j(w-1) \tag{5.5}$$

Consecutive applications of 5.5 yields to the equation:

$$q_j(w) = \frac{1}{w!\mu^w} (\prod_{s=0}^{w-1} \lambda_j(s)) q_j(0) \tag{5.6}$$

where $q_j(0)$ is the probability that no wavelength is occupied. Using the normalization condition,

$$\sum_{w=0}^{W} q_j(w) = 1 \tag{5.7}$$

it follows that:

$$q_j(0) = (1 + \sum_{s=0}^{W} \frac{1}{s!\mu^s} \prod_{k=0}^{s-1} \lambda_j(k))^{-1} \tag{5.8}$$

The service rate μ is assumed to be equal to the offset time given by equation 5.1, which is the maximum of all possible offset times in order to keep the same service rate for all wavelengths. As already mentioned, this assumption results in a waste of bandwidth for shorter routes but this assumption only influences the utilization significantly if it is applied to networks with big differences on the number of hops for each route.
The probability B_r that route r is blocked is given by the following approximate equation:

$$B_r \approx 1 - \prod_{i \in r} (1 - q_i(W)), r = 1, .., R \tag{5.9}$$

where $q_i(W)$ is given by 5.6 and 5.8 by substituting $w = W$.
Finally, a method for solving the set of nonlinear equations 5.1 to 5.9, which is based on a repeated substitution, is proposed:
Let B_r be the packet blocking probability (PBP) for a source-destination pair r.

1. Initialize: For every link j put $P_j = q_j(W) = 1$.
2. Calculate the arrival rate using equation 5.3.
3. Determine the occupancy distribution $q_j(w)$ of every link j using equations 5.6 and 5.8.
4. Now calculate the new blocking probability $q_j(W)$ for every link j using equation 5.6 which is denoted as new_P_j.
5. If $|new\_P_j - P_j| < \epsilon$ for all links, calculate the probability B_r using equation 5.9 that a packet of route r is blocked and terminate. Otherwise let $P_j = new\_P_j$ and go back to the second step.

5.2 Evaluation

In this section the accuracy of the analytical model is examined through simulation. The simulation tool Simscript II.5 [4] is used and a network consisting of 5 nodes and 5 links in a ring-topology is simulated. It is assumed that every node is sending to all other nodes which leads to a maximum number of 20 routes for this network. Half of the routes have a route with a length of two and the other half have a route with a length of one. Each link has 12 wavelengths for each direction and is passed by three routes in each direction. The transmission rate for each wavelength is assumed to be 1 Gbps. Furthermore, it is assumed that the refractive index of the optical fiber is $n = 1.55$ in all links. Packets have a fixed length of 15 bytes and the time for the optical-electronic conversion and vice versa is set to $5\mu sec$. With this data the blocking of each route is calculated. Finally, an average is made for the average PBP.
In Fig. 5.2 the simulation results and the analytical results of the average packet blocking probability (PBP) for different arrival rates are shown. Due to the assumption of a constant service rate for all wavelengths and the application of the RLA method, small differences occure.
Moreover, the influence of the number of wavelengths per link on the PBP is studied. Fig. 5.3 presents the simulation and analytical results of the PBP with a varying number of wavelengths per link. As expected, the PBP decreases with an increase in the number of

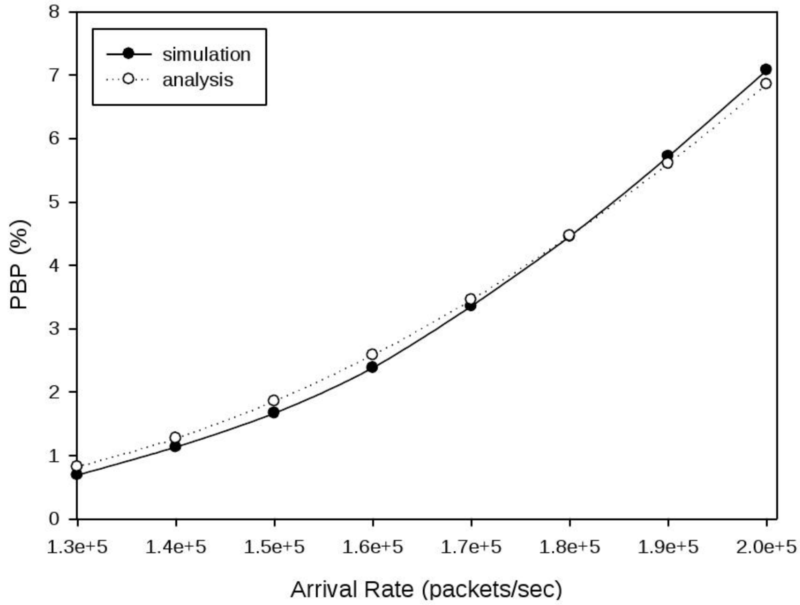


Figure 5.2: PBP of the analytical model and the simulation

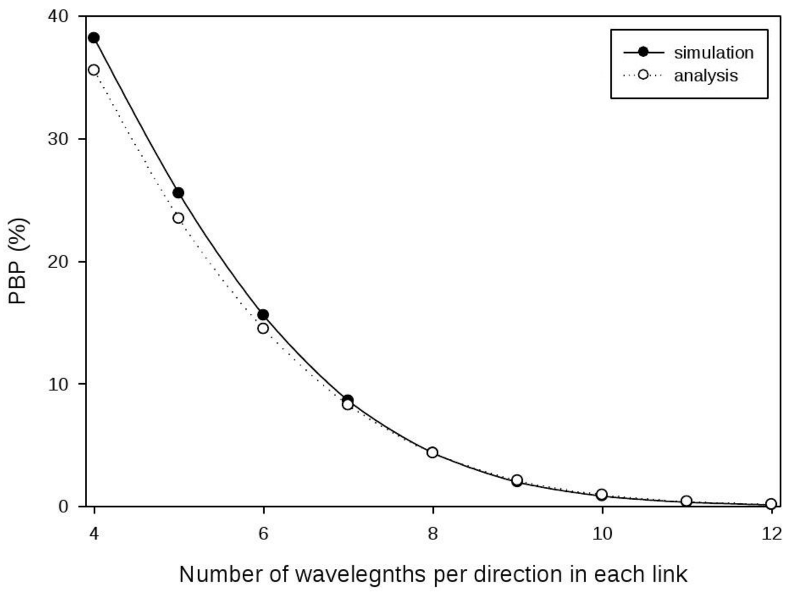


Figure 5.3: PBP with a varying number of wavelengths per link

wavelengths, because with a higher number of wavelengths per link more requests can be served.

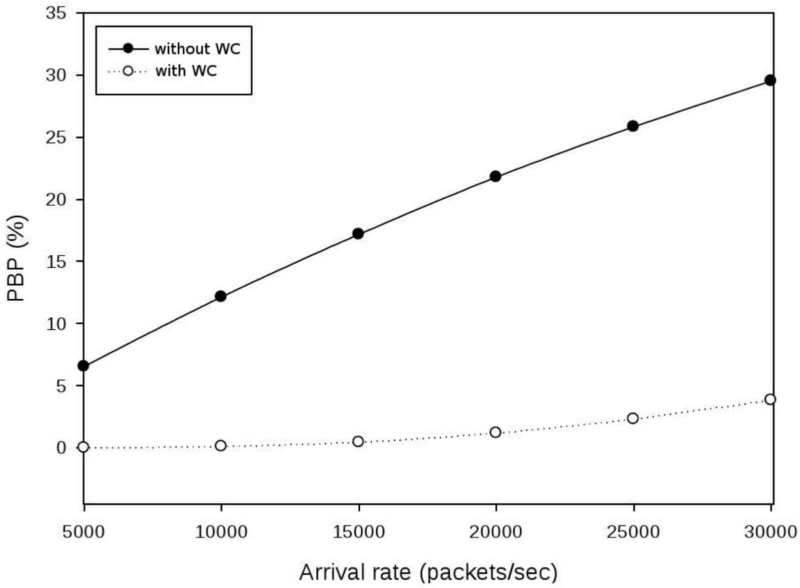


Figure 5.4: The advantage on wavelength converters

Finally, Fig. 5.4 shows the big advantage of wavelength converters in a network. The figure compares the PBP in a network without the possibility of wavelength conversion and the same network equipped with converters. As it is pretty clear to see, the network without converters suffers under a significant higher PBP than the network with converters. This results from the fact that a route in the network without the possibility for wavelength conversion has to find the same free wavelength at every node to successfully reach its destination, whereas with wavelength conversion a packet can be sent on another wavelength if the current wavelength is occupied.

6 Performance Evaluation

In this chapter contention schemes and Quality of Service techniques for optical packet switching networks are evaluated. To do this, at first the message flow of an optical packet has to be simulated in the simulation tool SimScript II.5 [4]. After that, networks have to be chosen which will be used for the evaluation. Finally, the networks have to be simulated with the applied contention schemes and Quality of Service techniques.

6.1 Message Flow

The simulated message flow follows the standard principle in optical networks (see section 4.1), which is simulated in the following way (it is shown graphically in Fig. 6.1):

1. The first hop on the route to the designated destination is looked up, and a free wavelength on the link is chosen.

   Wavelength found If a free wavelength is available, the packet is transmitted to the next node.

   Contention scheme In case no free wavelength is available, a contention scheme might be applied if implemented.

   Drop packet Otherwise the packet is already dropped at the source and the **transmission has failed**.

2. After successfully finding a free wavelength, this channel is reserved for a fixed period of time.

3. Then the packet travels to the next node.

4. If the next node is already the destination, the **transmission** of the packet has been **successful**.

5. If the next node is an intermediate node, the intermediate node looks up the next hop along the route and checks whether the same wavelength the packet arrived on is available on the specific outgoing link.

   Wavelength found If a free wavelength is available, the packet is transmitted to the next node.

   Contention scheme In case the wavelength on the specific outgoing link is not available, a contention scheme might be applied if implemented.

   Drop packet Otherwise the packet is dropped at the intermediate node and the **transmission has failed**.

6. Go back to 2.

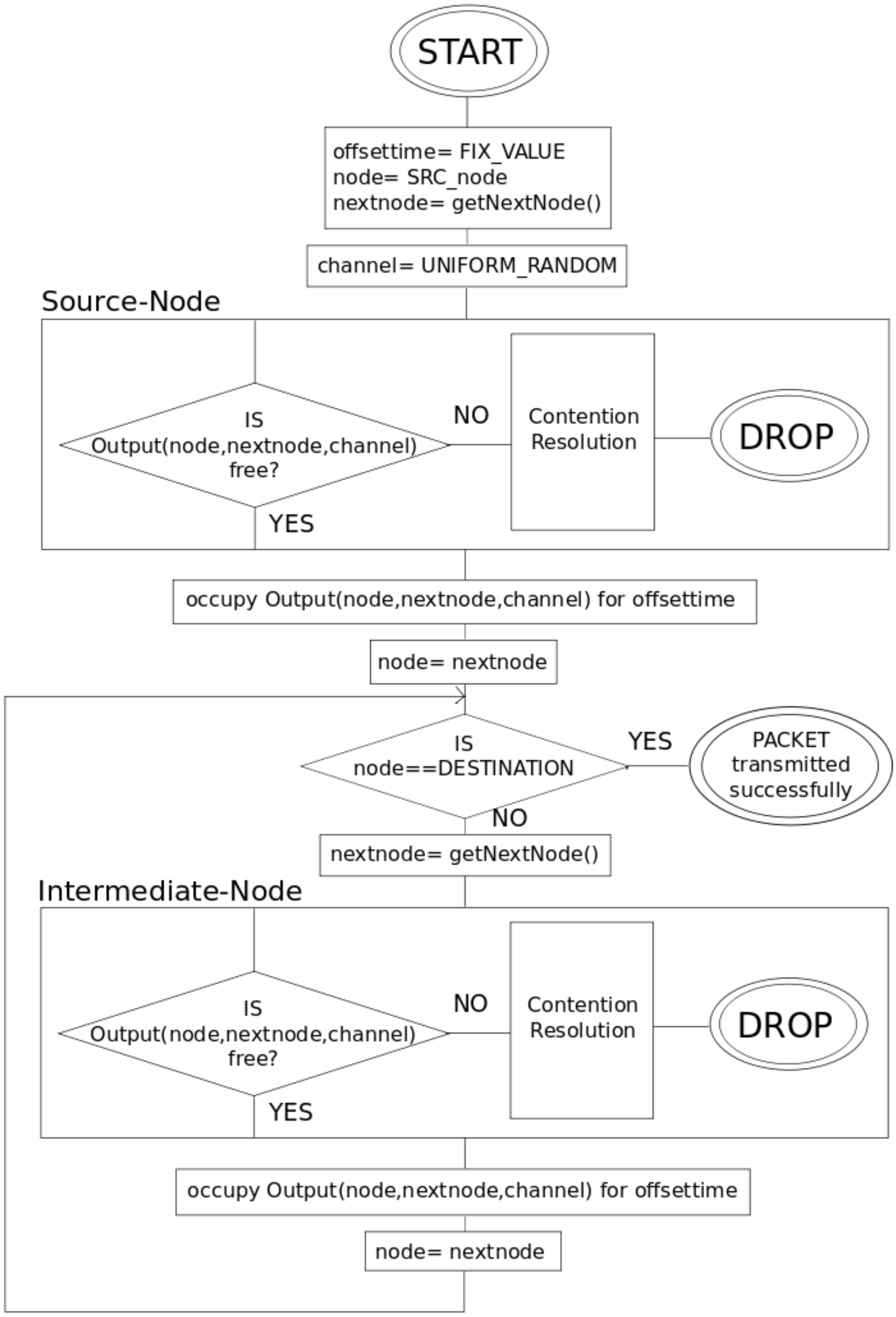


Figure 6.1: Main packet flow in simulation

When the packet reaches an intermediate node, the header has to be converted from the optical to the electrical domain. The time for this conversion is set to 5 μs. When the packet leaves a node, the header also has to be converted from the electrical to the optical domain, which is again 5 μs. The transmission time, which is the time it takes until the whole packet has left the node, is calculated by

$$T_{Transmission} = \frac{Length}{Capacity} \tag{6.1}$$

The capacity is assumed to be 1 Gbit/s. Assuming that the header has a size of 40 bytes, the equation results in $T_{Transmission} = 0,320\mu s$, which is negligible compared to the optical-electrical-optical conversion delay.
If the reservation of an output port and its wavelength was successful, it is reserved for a fixed time of 25 μs so that the payload will fit into this slot. The amount of data which can fit into this slot can be calculated with

$$data_{slot} = Capacity * T_{Window} \tag{6.2}$$

Applying this calculation to our settings with a capacity of 1 Gbit/s and a window-size of 25 μs, the size of the data fitting into this slot is $25.000bit = 3.125byte$, which is equivalent to $3kbyte$ and $53byte$.
This scheme which is used in the simulation is the so called *asynchronous fixed packet length scheme* (see section 4.2).

6.2 Network Setup

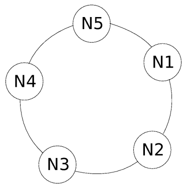
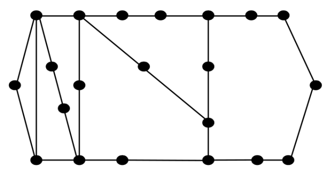
Ring-Topology		ARPA-2-Topology	
 			
Number of Nodes:	5	Number of Nodes:	21
Number of Routes:	20	Number of Routes:	210
Length of a link:	5km	Length of a link:	5km
max links per route:	2	max links per route:	8
Transmission Rate:	1 Gbps	Transmission Rate:	1 Gbps

Table 6.1: Network setup for simulation

First of all, the environment and the setup have to be chosen. For evaluating the schemes, two different networks are used (see Table 6.1).

The first network the simulation uses consists of 5 nodes and 6 links connected in a ring topology. All nodes will set up connections to all other nodes. In this network the longest route has to pass two links and every link is passed by the same number of routes, which is three in each direction.

The second network, the ARPA-2 network, consists of 21 nodes and 26 links connected in a kind of mesh topology. All nodes will set up connections to all higher nodes. This network is a more realistic one. The longest route has to pass 8 links and the links are passed by a different number of routes.

6.3 Applied Contention Schemes

In this section two typical contention schemes (see section 4.4) for OPS-networks are evaluated, namely wavelength conversion and FDLs. The two contention schemes are applied alone and also together in each of the two networks.

6.3.1 No Applied Contention Scheme

First of all, the networks are being evaluated without any contention scheme to show the advantages of the WDM-technology and the benefit in blocking for the networks if additional wavelengths are introduced. Therefore, the networks are simulated with four, eight and sixteen wavelengths for each direction per link.

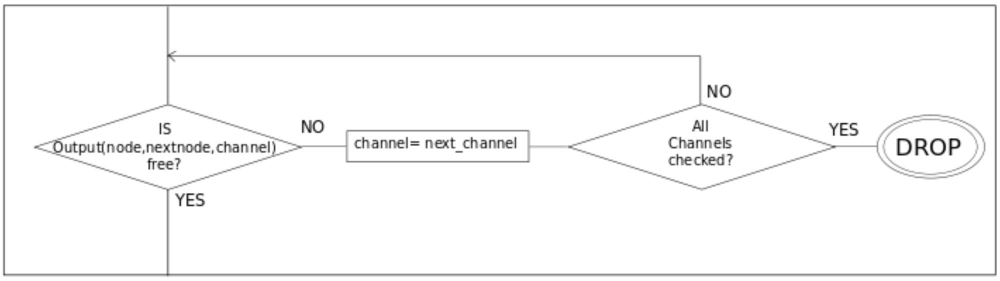
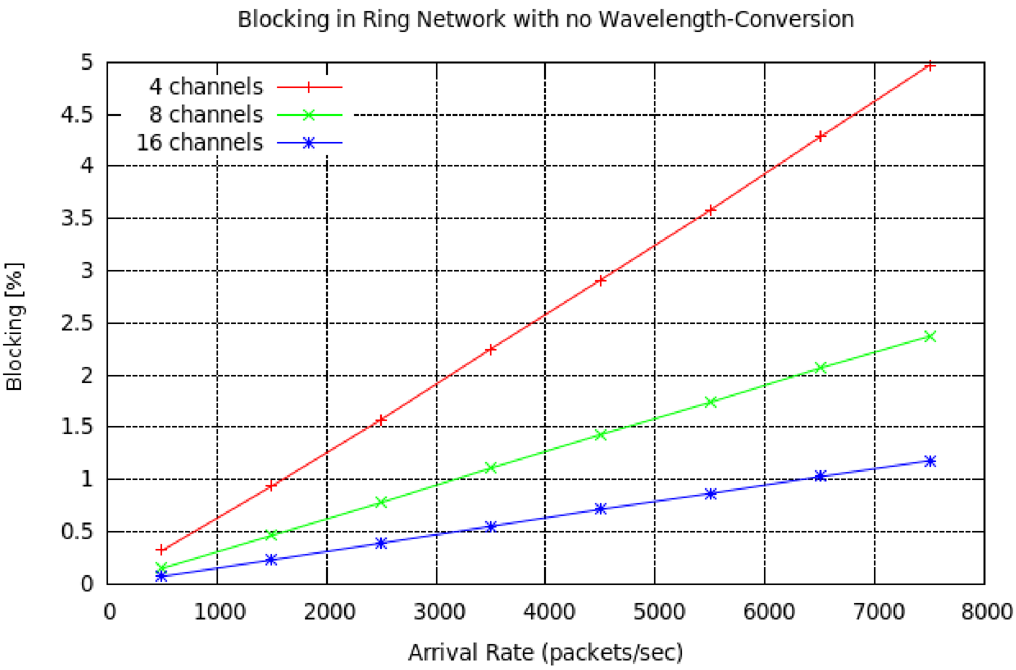


Figure 6.2: Contention resolution at the source without any contention scheme

At the source node a free wavelength is chosen. Otherwise the packet is dropped already at the source (see Fig. 6.2). Then the packet travels according to its route through the network to its destination, trying to pass all links on the same wavelength. If this wavelength is already occupied on an intermediate node, the packet gets dropped too.
As we can see in Fig. 6.3, if we double the number of wavelengths for each direction per link, the Blocking Probability is reduced by approximately the half. Therefore, a simple approach to reduce the Blocking Probability can be easily achieved by increasing the number of wavelengths per link. In other words, the network should use all available wavelengths.

6.3.2 Wavelength Conversion

In the next setup wavelength converters are used to show their impact on the blocking probability in the networks. The networks are simulated with 15, 16 and 17 wavelengths, each



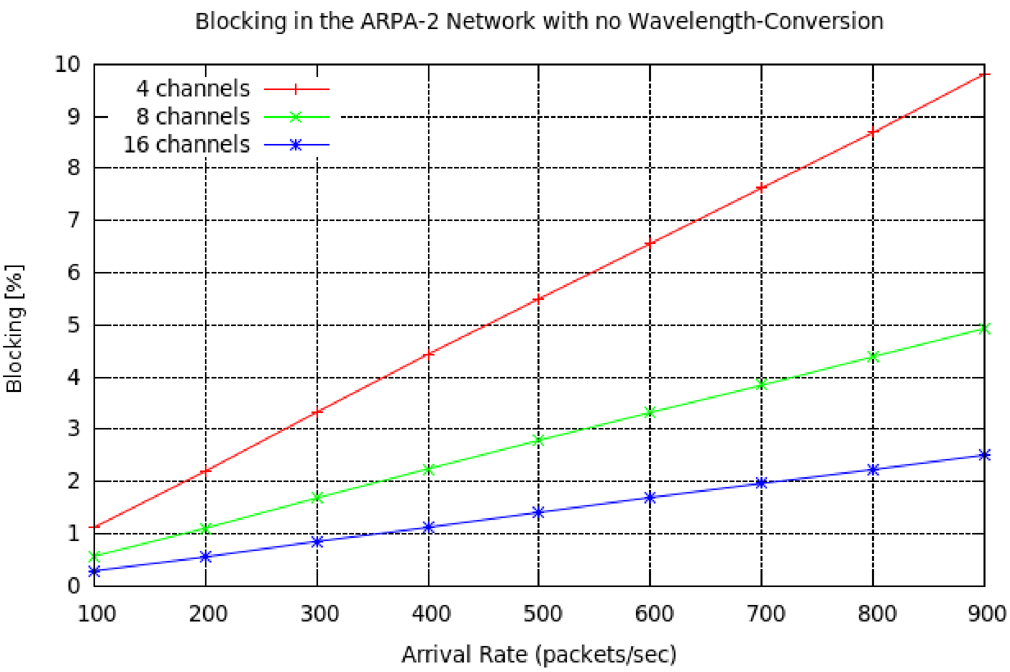


Figure 6.3: Blocking with no applied contention scheme

of them having its own wavelength converter, to show the benefit of an additional wavelength in a network with wavelength converters.

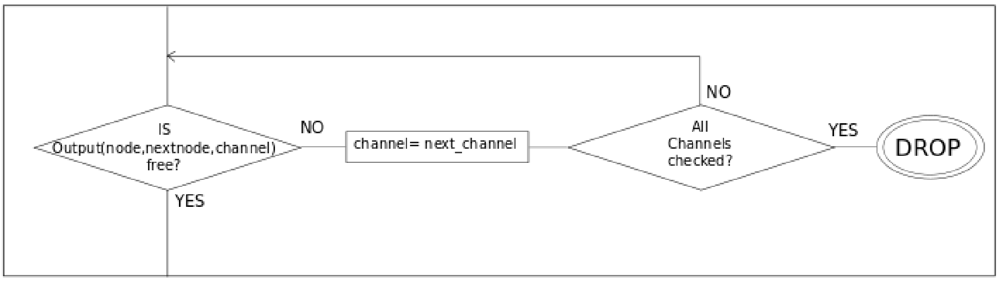


Figure 6.4: Contention resolution at each node using wavelength conversion

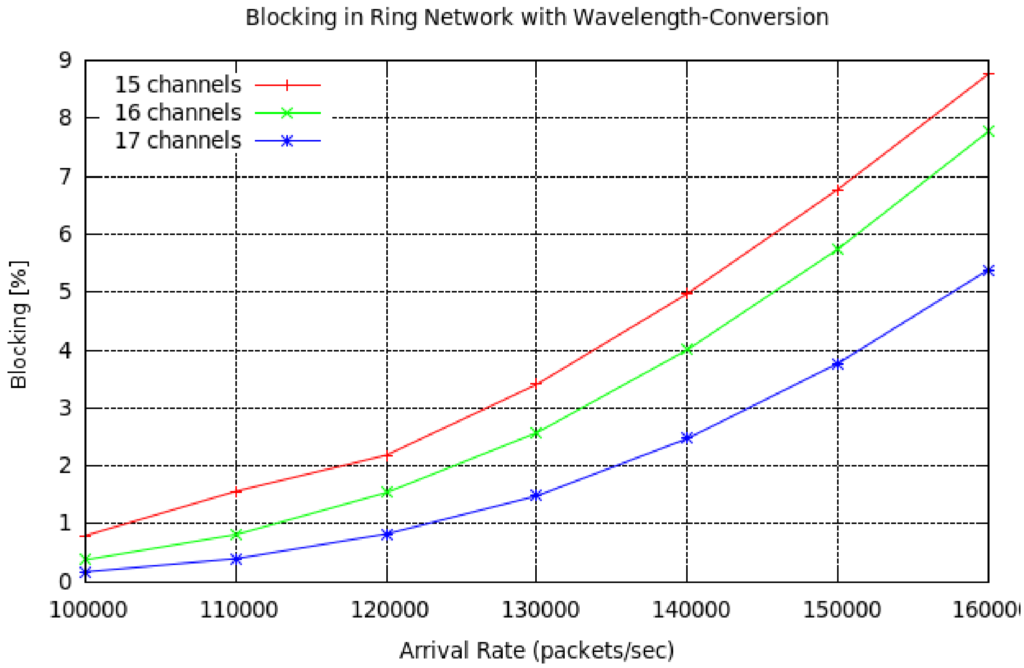
At the source node, a free wavelength is chosen. Otherwise the packet is dropped already at the source (see Fig. 6.4). Then the packet travels according to its route through the network to its destination, trying to pass all links. If the wavelength is already occupied, the intermediate node searches for another free wavelength on the same output. If it succeeds, the packet is converted to the new wavelength. Otherwise the packet gets dropped.
In Fig 6.5 we can see that using wavelength converters gives us the advantage that the packets at the nodes can have much higher arrival rates and the network still has an appropriate blocking probability. Furthermore we see that an additional wavelength does not lead to a big performance gain anymore. Therefore, as wavelength converters are very expensive, investigation on the optimum number of wavelength converters for the network should be done before the contention scheme with wavelength conversion is applied.

6.3.3 No Wavelength Conversion with FDLs

In this setup only FDLs are used as contention scheme. The networks are simulated with 16 wavelengths and two, one and zero FDLs per node.
At the source node a free wavelength is chosen. If no free wavelength is available, one is chosen randomly and the packet is sent to the FDL. If no FDL is free, the packet is already dropped at the source (see Fig. 6.6). The packet then travels along its route through the network to its destination, trying to pass all links. If the wavelength is already occupied, the intermediate node sends the packet to a free FDL on its specific wavelength or drops the packet if it can not find a free FDL (see Fig. 6.7).
Fig. 6.8 shows the performance gain which can be achieved by using only FDLs. It can be seen that already one FDL per node reduces the blocking a lot but, as we do not have wavelength converters, the blocking becomes already high at a low arrival rate.

6.3.4 Wavelength Conversion with FDLs

In this scenario both contention schemes are applied. Wavelength converters are available and FDLs are used. As wavelength converters are available, having one FDL means that only



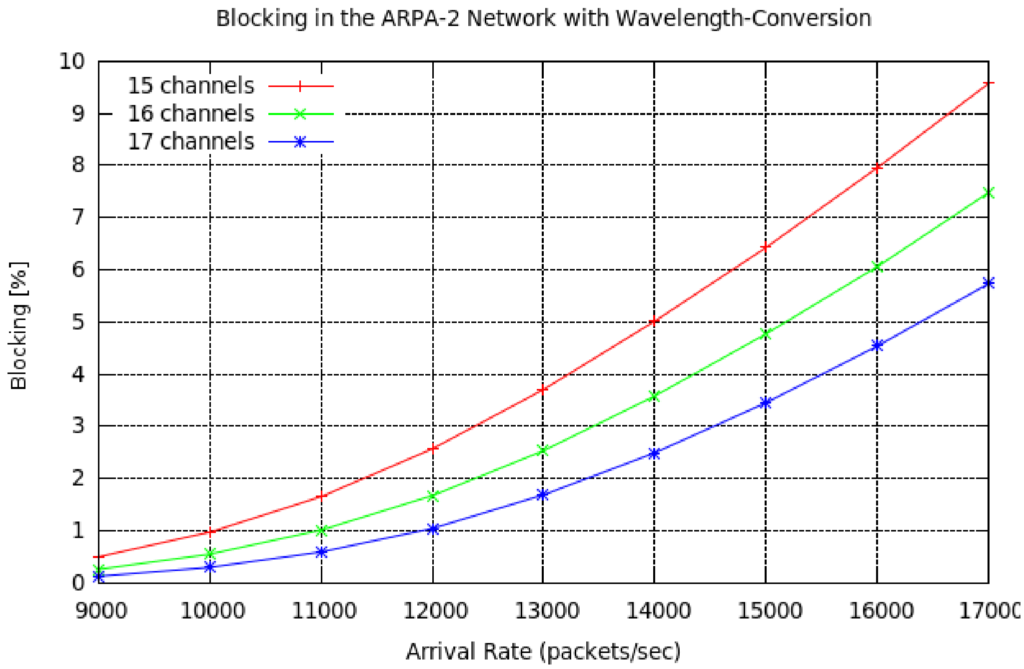


Figure 6.5: Blocking with wavelength conversion

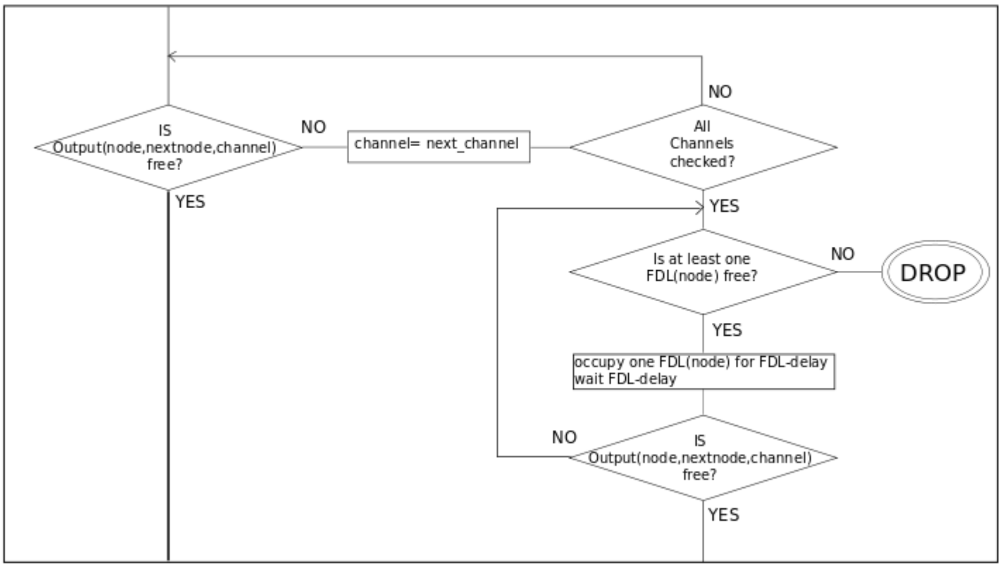


Figure 6.6: Contention resolution at the source using FDLs

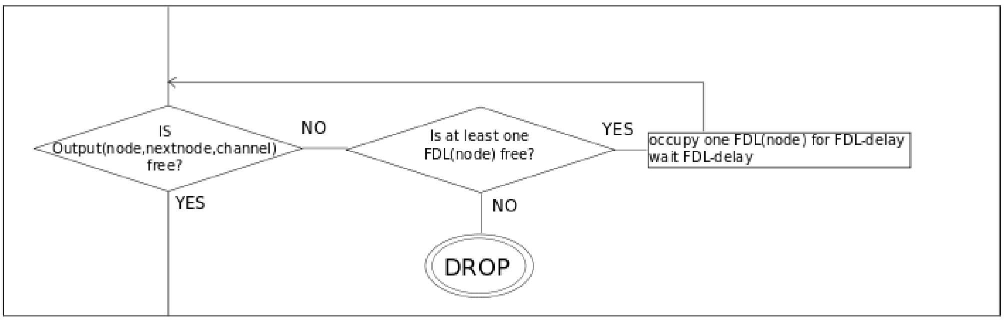


Figure 6.7: Contention resolution at the intermediate node using FDLs

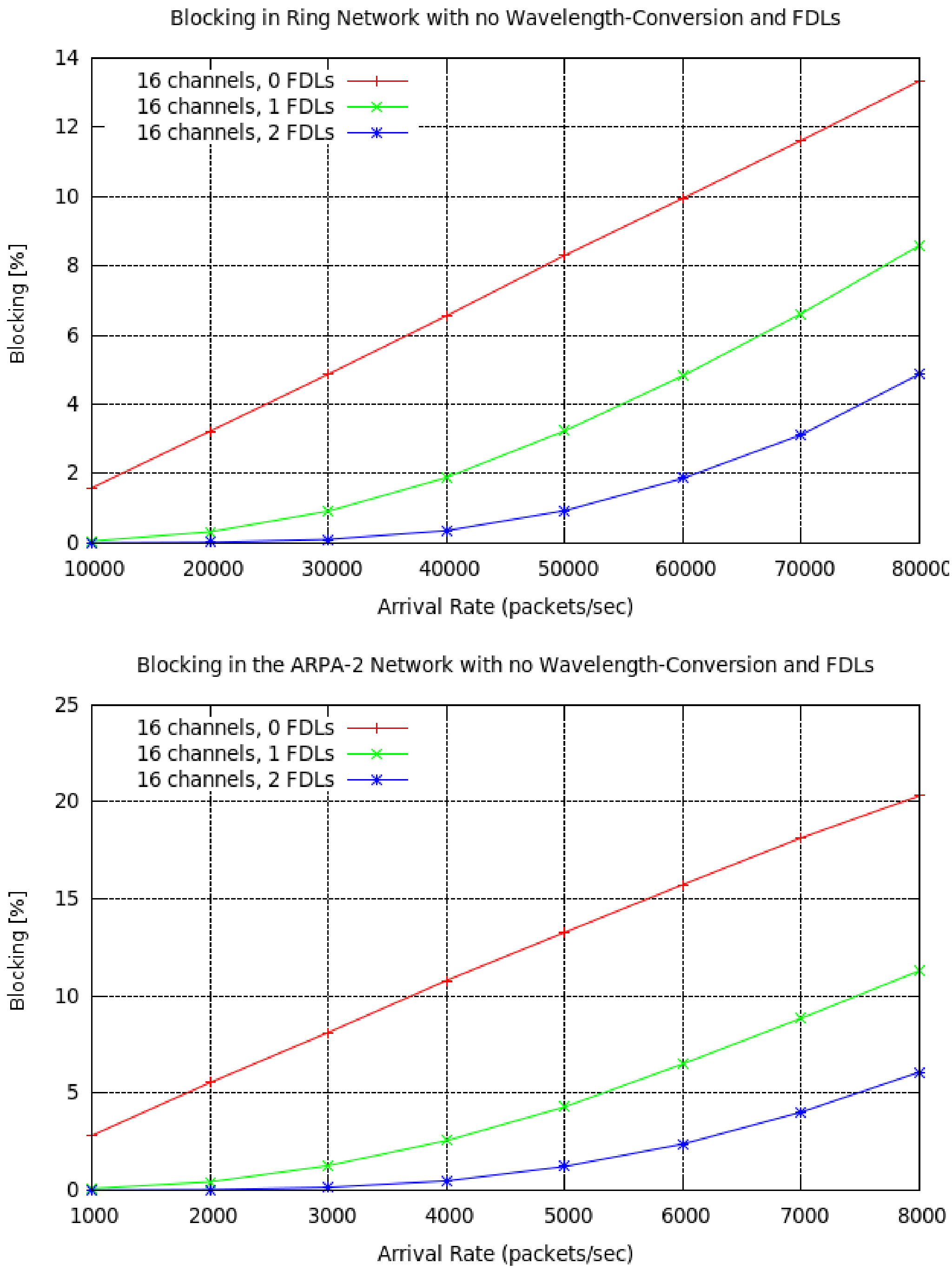


Figure 6.8: Blocking with FDLs

one FDL is available per node for all wavelengths together. The networks are simulated with 16 wavelengths and two, one and zero FDLs per node.

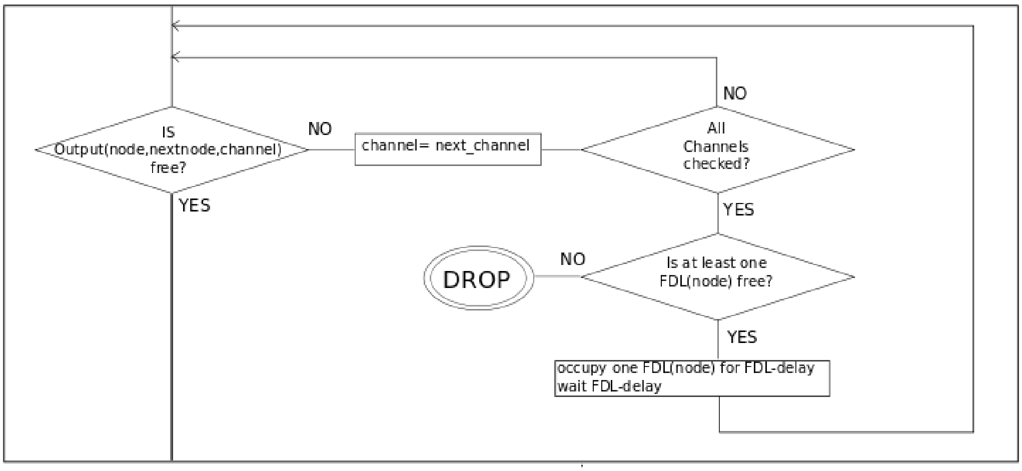
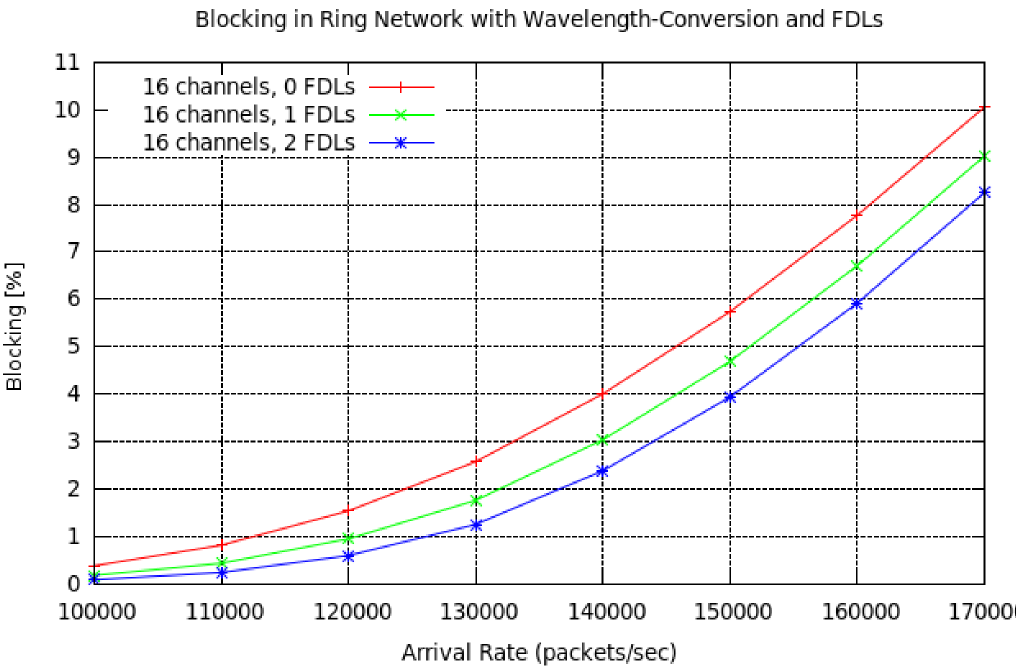


Figure 6.9: Contention resolution at each node using FDLs and wavelength conversion

At the source node a free wavelength is chosen. If no free wavelength is available, the packet is sent to an available FDL. If no FDL is free, the packet is already dropped at the source (see Fig. 6.9). Then the packet travels along its route through the network to its destination, trying to pass all links. If the wavelength is already occupied, the intermediate node searches for another free wavelength on the same output. If it succeeds, the packet is converted to the new wavelength. Otherwise the packet is sent to an FDL or, if no free FDL is available, the packet is dropped (see Fig. 6.9).
In Fig. 6.10 we see that the arrival rate at the nodes can again be very high before the blocking increases, which is because of the wavelength converters. However, adding one or two FDLs to the node does not result in a big performance boost anymore. FDLs might be added if there are already wavelength converters at every port and no more wavelength converters can be added or if specific network topology requirements call for them. It might also be cheaper at a certain point to introduce a certain number of FDLs instead of introducing another wavelength converter.

6.3.5 Compared to Each Other

Finally, all evaluated schemes are compared within one diagram to see the various benefits in blocking.
In Fig. 6.11 we compare all the evaluated schemes. We can clearly see the performance gain which can be achieved by using wavelength converters. Although the performance gain of the wavelength converters is much higher than the performance gain of FDLs, we have to keep in mind that wavelength converters are also far more expensive. Therefore, we can conclude that FDLs are a cheap way of reducing the blocking probability in a network to a certain extend but we still have the more expensive solution of wavelength conversion to achieve another big reduction in the blocking of the network.



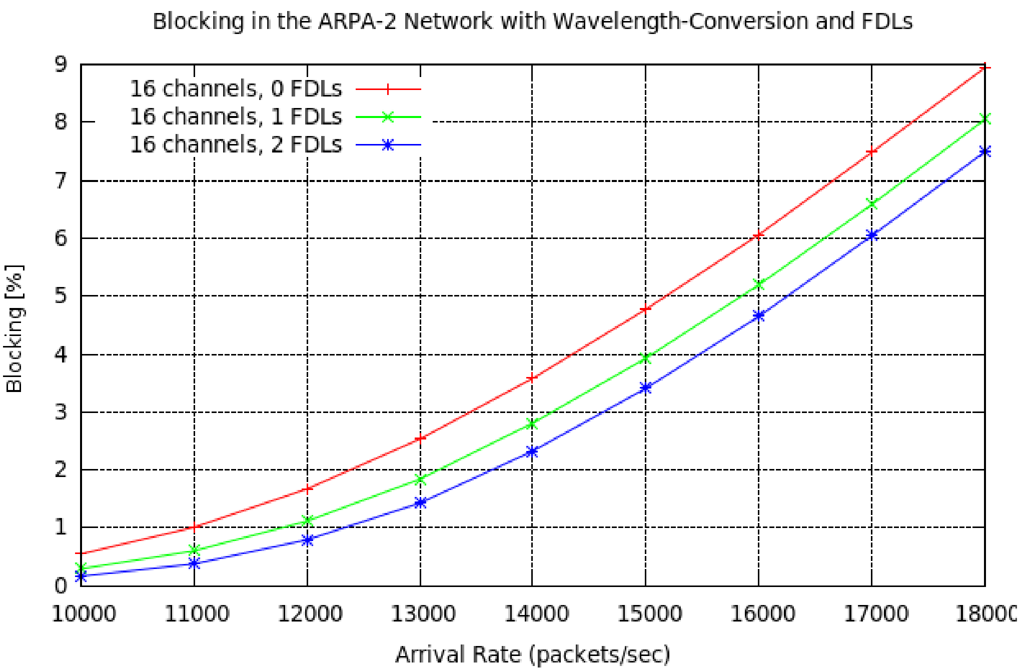
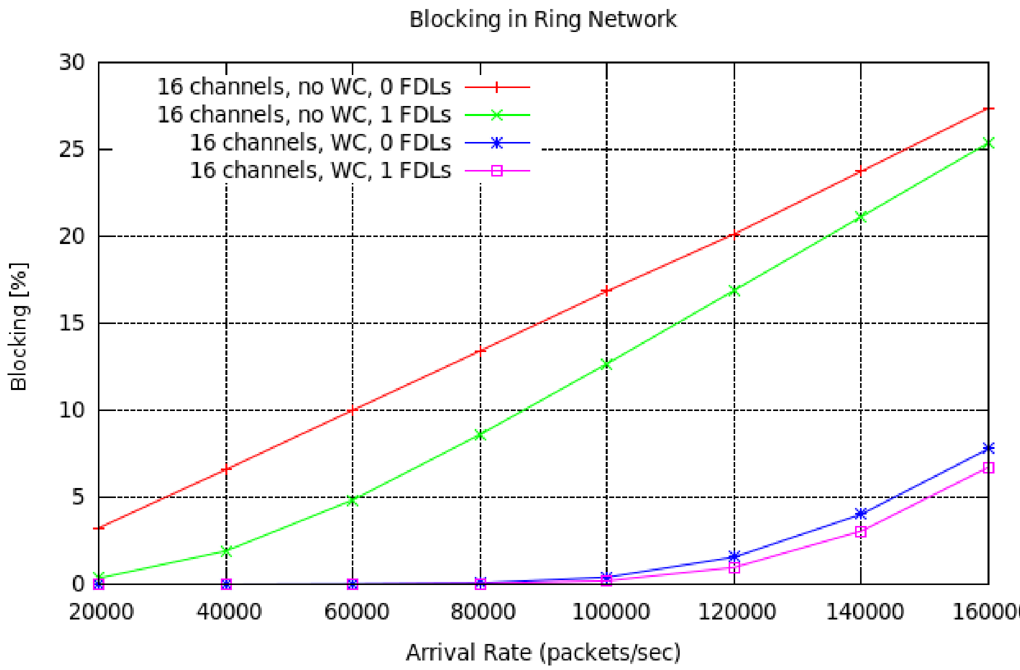


Figure 6.10: Blocking with wavelength conversion and FDLs



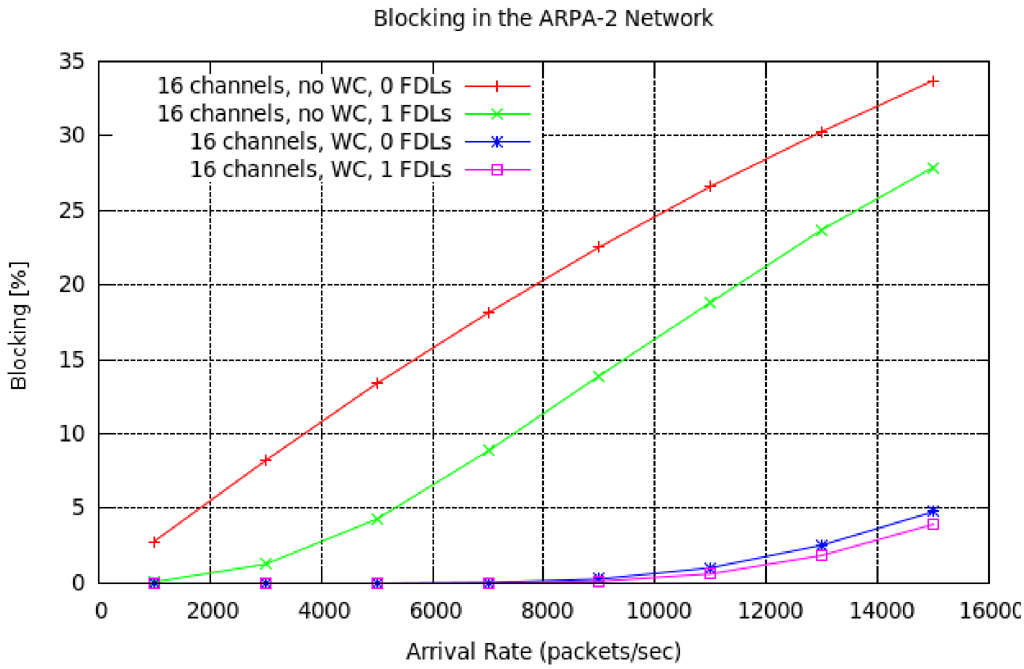


Figure 6.11: Blocking with all combinations of evaluated contention schemes applied

6.4 Quality of Service

We will evaluate two Quality of Service techniques (see section 4.5), namely the wavelength converter reservation and the fixed-dropping policies. For the evaluation we have two service classes with the same arrival rate but one class has high priority traffic and the other one has low priority traffic.

6.4.1 QoS Provided by Wavelength Converter Reservation

In the first QoS scheme we evaluate, QoS is provided by reserving some wavelength converters only for high priority traffic. This results in less wavelength converters being available for low priority traffic at each node. High priority traffic, however, can use all available wavelength converters.
In the simulation results shown in Fig. 6.12 two of the 16 wavelength converters are reserved only for high priority traffic. It can be seen that, compared to the same setup but without priorities (pink line), the total blocking increases but the blocking of high priority packets (green line) decreases. The performance gain we get for the high priority traffic has to be paid for, of course, with an increase in blocking for low priority traffic.
In the next simulation we take a closer look at the performance gain we can achieve by reserving different numbers of wavelength converters. The network still has 16 wavelengths for each direction per link and two service classes with the same arrival rate.
Fig. 6.13 demonstrates that every additional reserved converter for high priority traffic leads to a lower blocking probability. The performance gain gets even higher with higher arrival rates, which is also important because with lower arrival rates also the blocking is lower.

6.4.2 QoS Provided by Fixed Dropping

In the second evaluated QoS scheme, Quality of Service is provided by dropping a fixed percentage of packets from the low priority traffic. By dropping these packets, packets from high priority traffic have a better chance to use the available capacity. The network is still equipped with wavelength converters and has 16 wavelengths per direction for each link. We have two service classes with the same arrival rate.
As we can see in Fig. 6.14, the performance gain for high priority traffic is low compared to the blocking in the same network without priorities (pink line). However, the blocking of low priority traffic increases a lot with higher arrival rates. Moreover, the total blocking in the network increases faster.
Finally, we will take a closer look at the influence of the percentage of fixed dropped low priority packets on the performance gain of high priority traffic. To do so, we apply the scheme with a fixed dropping of zero (which means no priorities), two and four percent of low priority packets.
Fig. 6.15 shows clearly that the performance gain for high priority traffic is very small. So we can conclude that this QoS scheme is very simple but does not improve the performance of high priority traffic that much.

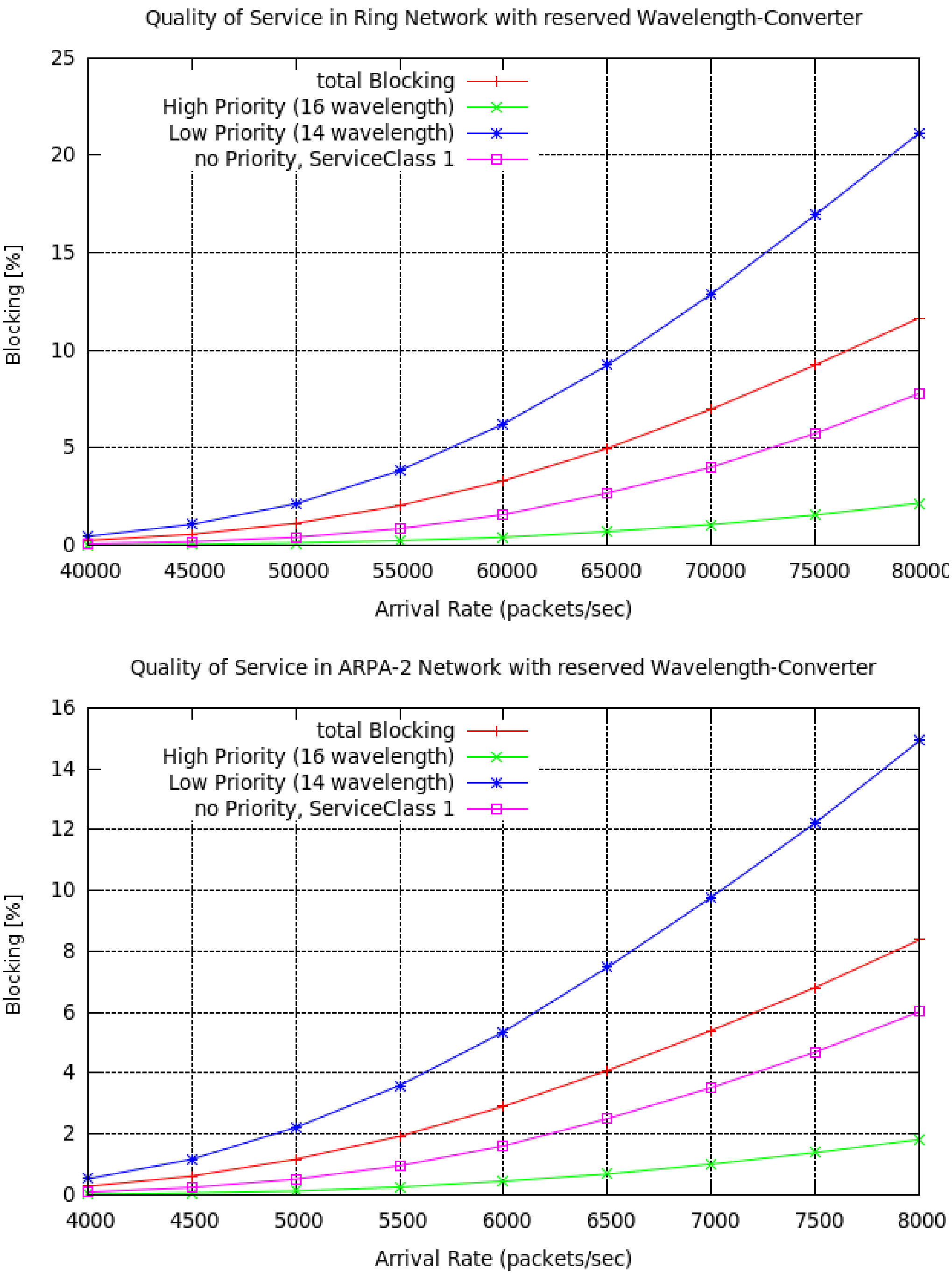
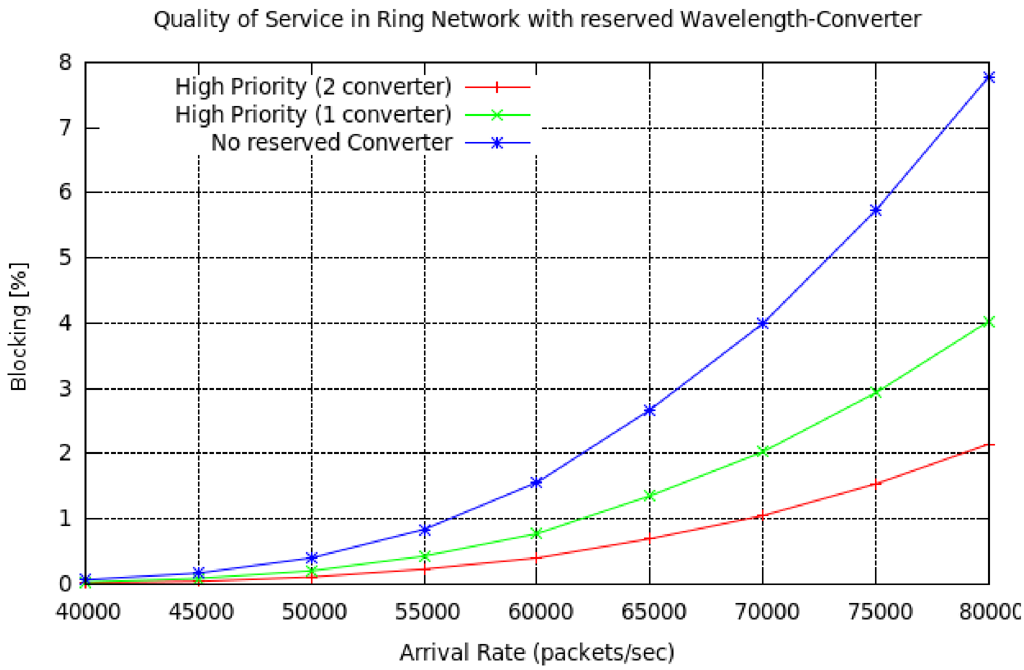


Figure 6.12: Blocking with two reserved wavelength converters for high priority service class



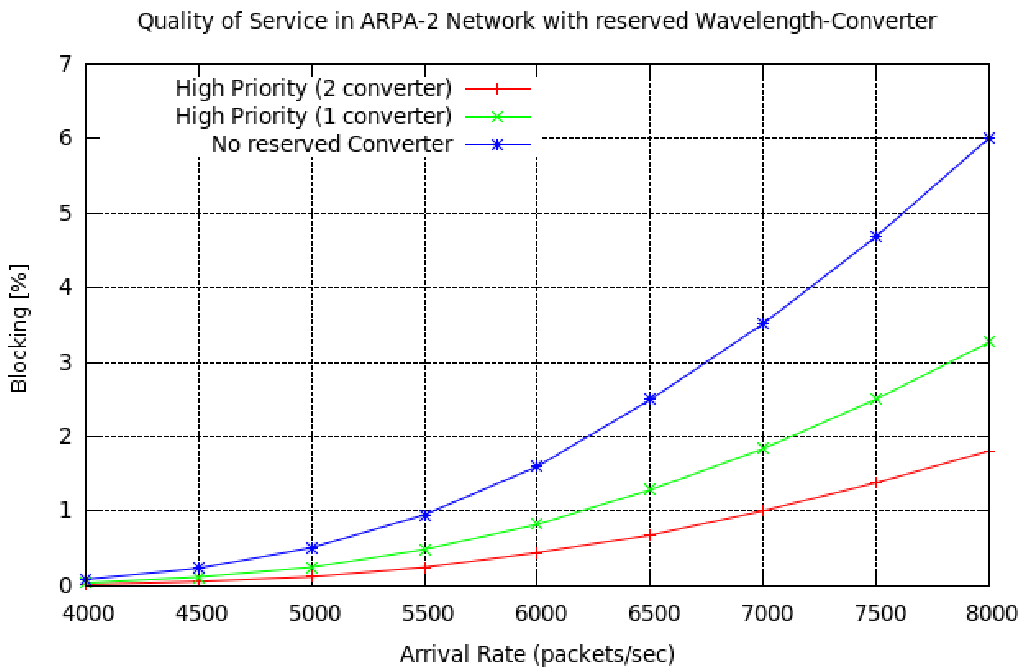
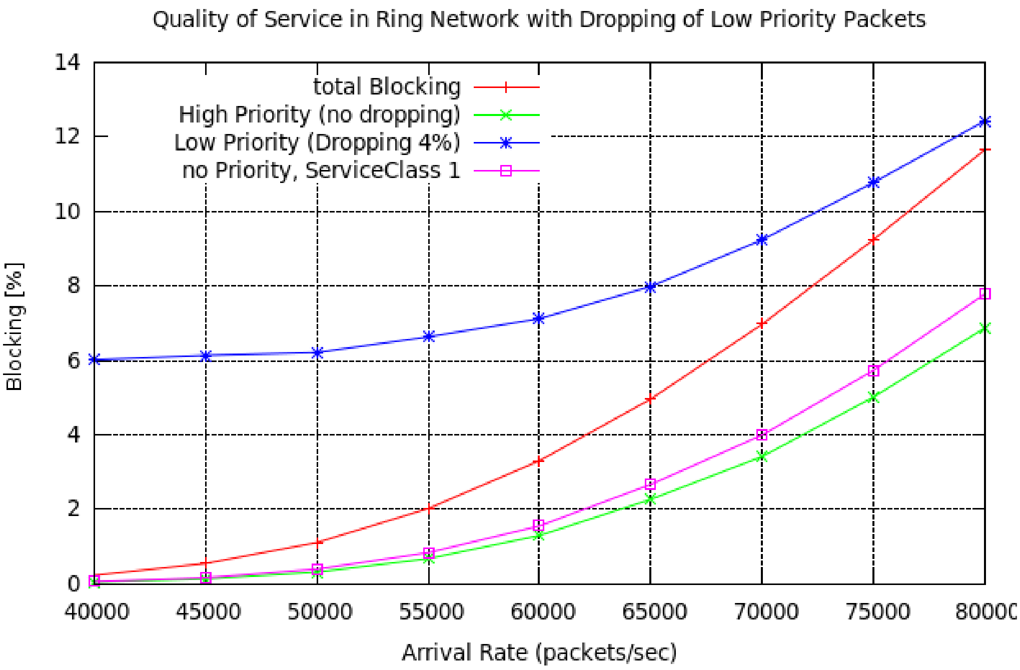


Figure 6.13: Blocking with reserved wavelength converters for high priority service class



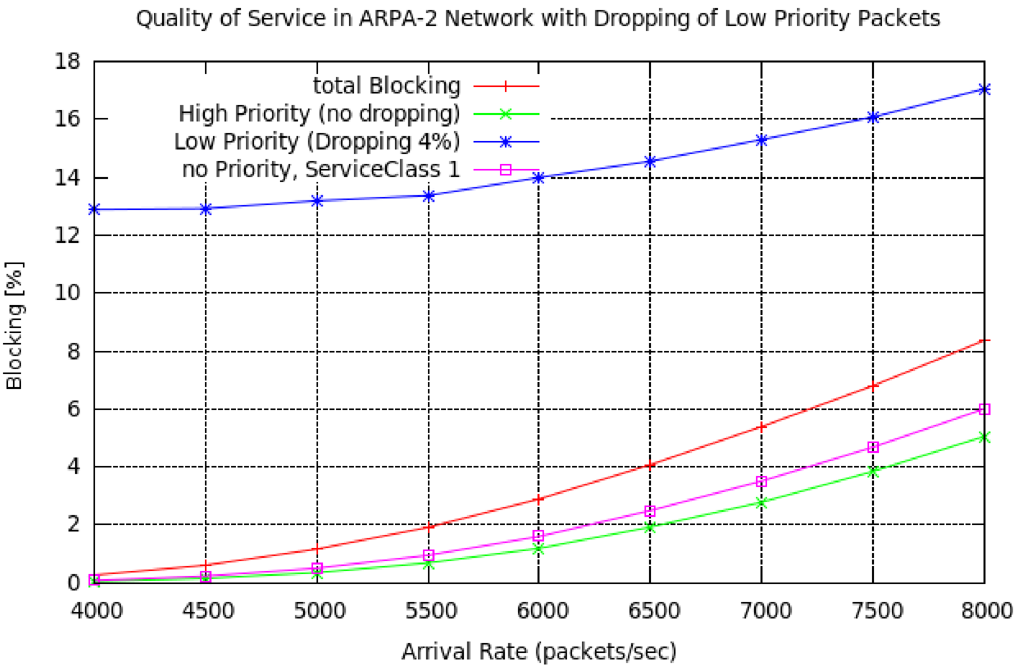
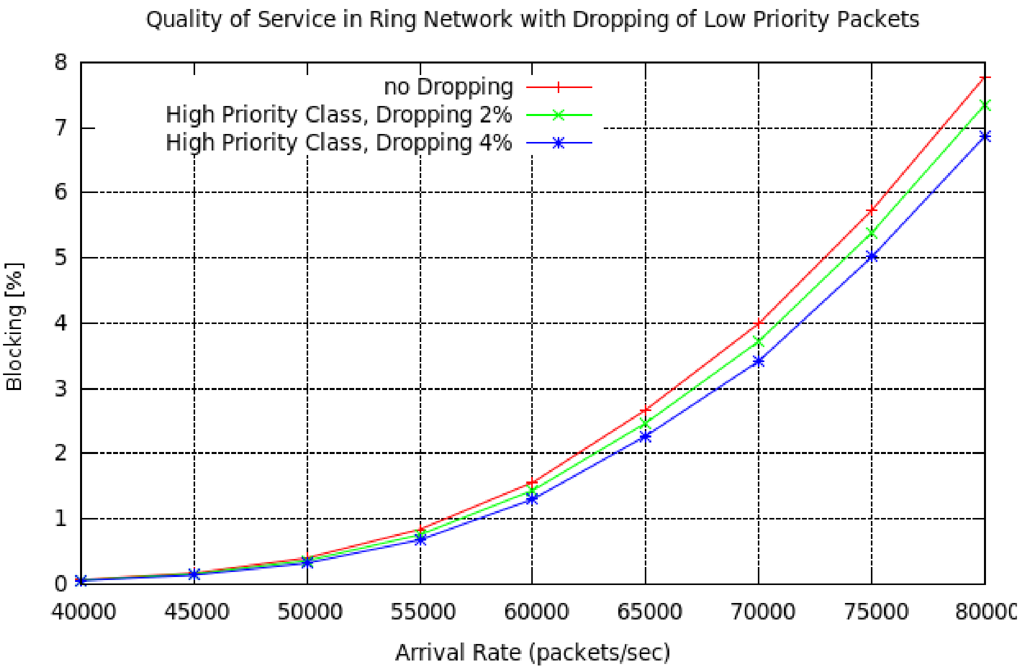


Figure 6.14: Blocking with fixed dropping of 4% of low priority packets



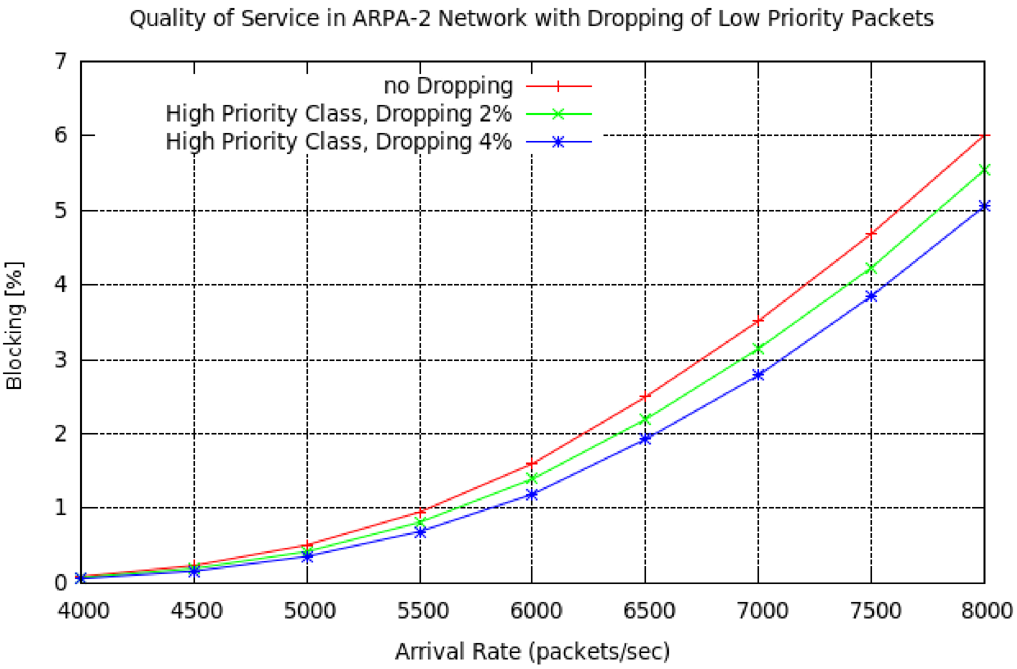


Figure 6.15: Blocking with fixed dropping of low priority packets

7 Conclusion

In chapter 1 a short introduction to optical techniques in general was given. A brief look at their history was taken and an overview of components needed in an optical network was given.

Chapter 2 took a closer look at the three generations of optical networks. Techniques which have been introduced and developed in the different generations were explained.

A closer look at the OBS technology was taken in chapter 3. First, the assembly process was explained before, and then the signaling scheme in general and some examples were presented. At the end of the chapter also OBS-specific contention resolution mechanisms were shown and a closer look at QoS signaling schemes was taken.

In chapter 4 the OPS technology was explained. At the beginning, the basics of OPS were presented and then the contention resolution schemes were introduced. Finally, it was shown how QoS can be implemented in an OPS network.

A simple analytical model to calculate the PBP in an optical packet switching network with the possibility for wavelength conversion and a fixed offset between header and payload was proposed in chapter 5. The analytical model is based on the application of the RLA method, based on the characteristics of an OPS network. The accuracy of the model was proven by comparing the results with the results gotten from simulating the same network. Furthermore, the effect of the number of available wavelengths in each link on the PBP was studied and it can be concluded that the number has a significant influence on the PBP up to a certain point. Finally, a network with wavelength converters was compared to the same network without wavelength converters and the importance of these converters for reducing the PBP was shown.

In chapter 6 the packet flow in two different networks, a simple one and a more realistic one, was simulated to evaluate the PBP using different contention schemes. The two applied contention schemes were 'wavelength-conversion' and 'FDLs'. Whereas the use of FDLs only resulted in a small decrease of the PBP, the use of wavelength converters resulted in a big performance gain. Furthermore, the FDLs introduce additional delays into the network because of the longer way the packet has to travel. However, although the wavelength converters may lead to far better results, they are also far more expensive and still in experimental stage compared to FDLs. Nevertheless, once they are available on the market and have reasonable prices, they will be a better choice than FDLs.
The other evaluation done in this chapter dealt with QoS. Two different approaches, namely 'fixed dropping' and 'wavelength converter reservation', were simulated and evaluated. Again, the solution which was using wavelength converters had the far better results. However,

the implementation of the QoS policy with 'fixed dropping' is very simple while the other approach needs a more complex control scheme and, of course, the availability of wavelength converters. So we can come to the same conclusion as with regard to the contention schemes: As long as wavelength converters are not on the market and do not have reasonable prices, 'fixed dropping' can still be an approach to implement QoS in OPS networks.

List of Abbreviations

FDL	Fiber Delay Line
LD	Laser Diode
LED	Light Emitting Diode
OBS	Optical Burst Switching
OPS	Optical Packet Switching
PBP	Packet Blocking Probability
QoS	Quality of Service
RLA	Reduced Load Approximation
WADM	Wavelength Add/Drop Multiplexer
WDM	Wavelength Division Multiplexing

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