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Evaluation of Reservation Mechanisms for Optical Burst Switching

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Dedicated to Professor Paul J. Kühn on the occasion of his 60th birthday

Abstract **In this paper, we give an overview and classification of optical burst switching schemes and present burst reservation concepts. The performance of various basic reservation mechanisms proposed in literature is compared. Furthermore, a new analysis is introduced that allows to calculate the loss probabilities of a two-class system based on the reservation mechanism just-enough-time (JET) for arbitrary offsets. Finally, a variety of new results is presented including the dependence of burst loss probabilities on offset, burst length distribution, and interarrival distribution.**

Keywords **Optical burst switching, reservation mechanisms, performance analysis, quality of service, IP over WDM.**

1. Introduction

At the beginning of the new millenium several trends can be observed in the field of communication networks. First, bandwidth requirement in networks seems to grow without limits. Internet protocol (IP) based data networks play a central role. This is not only due to the fact that data traffic has surpassed voice traffic but even more due to the exponential growth rate of IP traffic volumes. Second, more and more users and applications request quality of service (QoS) mechanisms from today's communication networks. Third, optical technology continues to provide an exponential growth in fiber transmission capacities at higher rate than IP traffic growth.

In this paper, we will elaborate on these trends and show how they motivate *optical burst switching* (OBS) as a new switching paradigm for future transport networks. The remaining sections of this paper will describe and evaluate OBS mechanisms in detail.

1.1 Photonic network evolution

In the late 70s, the first fiber based optical transmission systems were installed. Today, most wide area traffic in communication networks is carried via fibers. Until a few years ago, most systems used a single high-speed optical channel and all multiplexing was done in the electrical domain. In 1995, a new technology entered the market in the USA: *wavelength division multiplexing* (WDM) [1]. This optical multiplexing technique allows better exploration of fiber capacity by simultaneously transmitting multiple high-speed channels on different frequencies (wavelengths) [2, 3, 4].

Fig. 1 shows a possible evolution scenario for photonic networks based on WDM. It spans from today's point-to-point transport links over add/drop multiplexers (ADM) and cross-connects (CC) for ring and mesh networks, respectively, to networks with higher reconfiguration speeds [5]. In the long term, optical packet switching seems to be a promising technology, but due to its complexity it is expected to remain a research topic for some more years.

Recently, OBS was proposed as a new switching paradigm for optical networks requiring less complex technology than packet switching. OBS is based on concepts developed several years ago for electronic burst switching networks. At that time, burst switching essentially was an extension of fast packet switching with variable and arbitrary length packets employing decentralized shared buffer switches [6, 7]. OBS has some more specific features and will be described in detail in Section 2.

Another hot topic is extending multi protocol label switching (MPLS) concepts [8] to optical transport networks (so-called MPλS) [9, 10]. For MPλS, the core idea is to use wavelength channels as labels and to establish appropriate routing paths in the network. Such paths allow fast switching of data without requiring complex routing processes along the path. Label switching concepts can be easily integrated with burst switching concepts [11].

Label switching as well as burst switching concepts serve a more efficient integration of IP and WDM than allowed by today's multi protocol stacks. Both concepts can be combined to a comprehensive and efficient "IP over WDM" framework [12, 11].

1.2 IP network evolution

The Internet is a packet oriented network based on IP, a connectionless networking protocol. The Internet has been designed to offer best effort services and for a long time this was sufficient. But recent years have seen an increasing demand for QoS mechanisms mainly due to new applications, an increasing number of users and traffic volume, and growing commercial interest in network services.

On the one hand, this lead to the development of new network technologies like asynchronous transfer mode (ATM) which allow a broad spectrum of service guarantees. On the other hand, there is significant effort to include QoS mechanisms into the Internet. These mechanisms can be classified as providing either *absolute* or *relative* guarantees represented by IntServ [13] and DiffServ [14] approaches, respectively.

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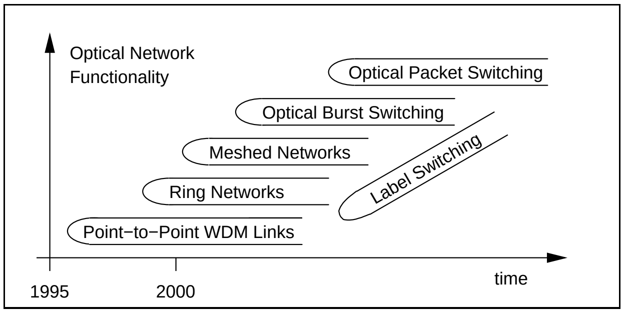

Fig. 1. Evolution of photonic transport networks

It is a key feature of the Internet that it can be run basically on top of any transport technology. This independence of the physical layer strongly contributed to the wide spread use of Internet technologies. Nowadays, Internet traffic is the dominant part in many networks. Therefore, more and more networks are designed in an "IP centric" way. This includes a transport layer offering most efficient support for IP traffic. OBS is one proposal of how to realise such a transport network.

1.3 A short comparison of switching paradigms

The basic switching concepts are circuit switching (CS) and packet switching (PS). For application in optical transport networks, their pros and cons can be characterized as follows.

Circuit switching (of wavelength channels) is relatively simple to realise but requires a certain amount of time for channel establishment and release independent of the connection holding time. This overhead, mainly determined by the end-to-end signalling time, leads to poor channel usage if connection holding times are very short. For long holding times, CS is very efficient from a signalling overhead point of view. However, that case leads to a reduced ability to adapt to traffic dynamics. This is especially true if IP traffic with its bursty behaviour is carried over such circuit switched wavelength networks.

PS in the optical domain allows a good adaptation to the dynamics of any higher layer. However, there are several other drawbacks. The first is concerned with realisation aspects. If the realisation is based on opto/electrical conversion, it can be done with technology available today. But this approach suffers from the fact that the development of electronics cannot keep pace with the rapid growth of optical transmission speed. This could be improved by all-optical PS technology (including signal processing). Such all-optical approaches will be difficult to realise in the foreseeable future e.g. due to their highly complex technology and lack of optical buffers.

Another basic restriction stems from the fact that packets have to be of limited size due to several reasons (buffering requirement in each node, increasing delay if store-and-forward is used). Moreover, each switching process needs a finite non-zero time. This leads to reduced efficiency for large data blocks which have to be transmitted using multiple packets.

As a new paradigm, OBS tries to combine the advantages of both, CS and PS while avoiding the main drawbacks described above.

1.4 Main achievements of this paper

In this paper, we first describe the principle and basic design parameters of OBS. Section 3 elaborates on a central mechanism of OBS, namely resource reservation. It contains for the first time a qualitative and quantitative comparison of various basic mechanisms described in literature so far. Section 4 contains a new analysis to determine losses in an OBS system supporting two service classes. In Section 5 we present several results including a comparison of analysis and simulation, and an investigation of the influence of several system parameters on the performance of high and low priority classes. Also, we evaluate the impact of low priority traffic characteristics on system performance. Finally, Section 6 summarizes our work and presents some open questions.

2. Optical Burst Switching (OBS)

2.1 Definition and motivation

As mentioned above, OBS is in some way a combination of optical PS and CS. Although there is no unique definition of OBS in literature, it is widely agreed that the following list describes its main characteristics.

- OBS granularity is between CS and PS.
- There is a separation between control information (header) and data. Header and data are usually carried on different channels with a strong separation in time (see example OBS network link in Fig. 2).
- Resources are allocated without explicit two-way end-to-end signalling, instead so-called one-pass reservation is applied.
- Bursts may have variable lengths.
- Burst switching does not require buffering.

Note that not all of these features must be satisfied and "smooth" transitions to PS and to (fast) CS are possible. Although the concept of burst switching has been already known since the 1980s, it has never been a big success in electrical networks. The main reason is that its complexity and realisation requirements are comparable to that of more flexible electronic PS techniques (e.g. ATM). However, with the introduction of very high speed optical transmission techniques this has changed. Now, there is an even increasing discrepancy between optical transmission speed and electronic switching capability. Moreover, due to cost and complexity aspects, it is advantageous to keep data in the optical domain and to avoid opto/electronic conversion. On the other hand, all-optical PS is still too complex to perform all processing in the optical domain.

Therefore, a hybrid approach like burst switching seems very promising: it keeps data in the optical domain but separates control information which allows sophisticated electronic processing of this control data. Fig. 2 shows some of the main characteristics of an OBS network. There are two types of nodes. In edge nodes, traffic is

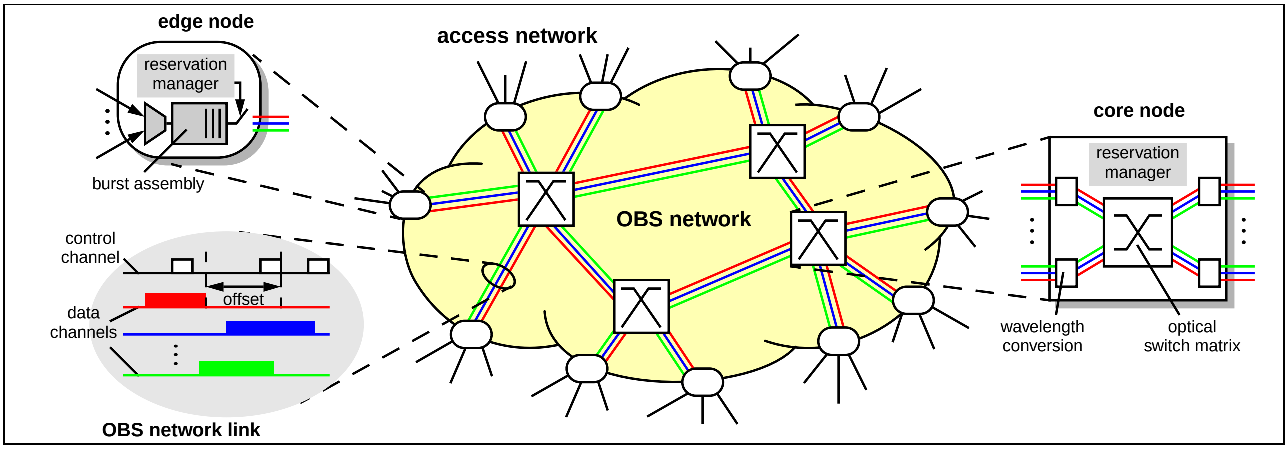

Fig. 2. Node and network architecture for optical burst switching

collected from access networks and assembled into larger data units, so-called bursts. Core nodes serve as transit nodes in the core network. Their main task is switching bursts without extensive processing. To achieve this, some control information containing reservation requests is necessary ahead of every burst's transmission time.

There are several possibilities how to perform reservation of data channel bandwidth. Our paper concentrates on the evaluation of what we call SCDT schemes (*separate control, delayed transmission*). These reservation concepts are based on a strong separation of control information and data. A reservation request is sent in a separate control packet on a different channel while the actual transmission of the data burst is delayed by a certain basic offset (see Fig. 2). This basic offset enables the intermediate nodes to process control information and set up the switching matrix. In contrast to systems with immediate transmission[1], which send control information together with the burst, the network can do without buffering the data burst in each node along the path.

SCDT schemes use one-pass reservation, i.e. the sender of a burst does not wait for an acknowledgement of its reservation request. This approach is in contrast to two-pass reservation as typically applied during connection setup in circuit switched optical networks. The advantage of a one-pass reservation is higher efficiency as there is no overhead caused by propagation delay. An example may illustrate this. The transmission time of a 100 KB burst on a 10 Gbps link is 80 μs while the propagation delay over a distance of 200 km (which is not long in a backbone network) is typically about 1 ms.

2.2 OBS design parameters for SCDT schemes

The following list describes the most important design parameters for OBS and includes examples from literature.

[1] Non-SCDT schemes with data immediately attached to control information could be imagined, but are very similar to either fast packet or fast circuit switching.

- *Buffers for data bursts at intermediate nodes.* Many proposals avoid buffers or use only simple delay lines to keep the system significantly less complex than a PS system [15, 16, 17], other work includes sophisticated buffering concepts [18].
- *Resource reservation mechanism.* Key system resources which have to be reserved are channels and possibly buffers. There are several proposals in literature which are classified and compared in Section 3.
- *QoS support.* First proposals for OBS only considered one class of bursts [16, 17]. Due to the increasing importance of QoS support, recent proposals extended the OBS concept to multiple service classes [18, 19].
- *Protocol aspects.* Designing a protocol for OBS strongly depends on the reservation mechanism and QoS support to be realised but still offers many degrees of freedom. Even for the one-pass reservation scheme we focus on, "one-way" [15] or "two-way" [17] protocols are possible. In the latter case, blocking events or successful channel reservations are reported back. Note that even with two-way protocols in an SCDT scheme burst transmission starts before any confirmation message is received at the initiating node.
- *Node architecture and technology.* Depending on the design choices for the parameters listed above, there are many realisation possibilities for a burst switching node. Basic building blocks are I/O interfaces, control information processing units such as a reservation manager, and switching systems for control and user data possibly including buffers (see Fig. 2). [16] gives a very detailed description of an example node architecture, [18] describes various delay line concepts.
- *WDM technology.* All OBS proposals using WDM as transmission technology require full wavelength conversion in a core node such that each burst can be switched to any of the output channels. Therefore, there is a trade-off between performance benefits due to higher number of wavelength channels and higher cost due to more wavelength converters [5, 20].

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3. Comparison of reservation concepts

3.1 Reservation mechanisms

Recently, several SCDT-based reservation mechanisms have been proposed. They can be distinguished based on their way of indicating the end of a burst and the time when allocation of a WDM channel starts.

A rather simple approach is to indicate the end of a burst by an additional trailing control packet[2] or using an *in-band terminator* (IBT). In both cases there is no information about burst length when the heading control packet containing the reservation request arrives. A mechanism that follows that principle is *just-in-time* (JIT) reservation [17]. Upon arrival of the reservation request a wavelength channel is immediately allocated if available. Otherwise, the request is rejected and the corresponding data burst is discarded. The wavelength remains allocated until burst transmission has finished. The only information that has to be kept record of in network nodes is whether a wavelength is currently available or not. This makes JIT a light weight approach with low complexity in both edge and core nodes. The drawback of JIT is, however, its reduced efficiency as losses also occur in cases without any transmission conflict between different bursts on the same wavelength (case 1 in Fig. 3).

An improvement to schemes like JIT can be achieved by using RLD (*reserve-a-limited-duration*). Mechanisms based on RLD require the sender to signal the burst length in the control packet. A wavelength is only allocated for a limited duration so that subsequent burst transmission requests with a start time greater than the finishing time of an allocated burst may be accepted (case 1 in Fig. 3). That means the offset interval of a burst may overlap the transmission phase of a previously accepted burst. In an IBT approach, a new burst is lost because the end of the previous (accepted) burst is unknown at the instant when the control packet arrives. In contrast, the end is known with RLD and hence the new burst can be accepted (see scenario depicted in case 1 in Fig. 3).

The *Horizon* mechanism proposed by Turner in [16] is an RLD-based mechanism. Wavelength channel state information is enhanced by the so-called reservation horizon, i.e. the time until which the wavelength is allocated. When a new request arrives Horizon looks for the wavelength with the largest reservation horizon less than the start time of the new burst. Like in JIT, reservation starts immediately upon arrival of the control packet and lasts until the expected end of burst transmission, which is the new reservation horizon of this wavelength.

If both the start and finishing times of accepted bursts are considered during reservation an even higher efficiency may be achieved, because a new burst can reserve in a free gap if it fits in. This approach is called RFD (*reserve-a-fixed-duration*) as the channel is allocated for a fixed duration corresponding to the burst transmission time. One proposal of an RFD-based mechanism is *just-enough-time* (JET) developed by Qiao and Yoo [11, 15]. State information in JET comprises both, the starting and finishing times of all accepted bursts, which makes the system rather complex. On the other hand and in contrast to Horizon, JET is able to detect situations where no transmission conflict occurs although the start time of a new burst is earlier than the finishing time of the already accepted burst 2 (case 2 in Fig. 3), i.e. a burst can be transmitted in between two already reserved bursts. Hence, bursts can be accepted with a higher probability than in Horizon especially for large offset time variations.

[2] Qiao and Yoo denote this as TAG (tell-and-go) [11, 21]

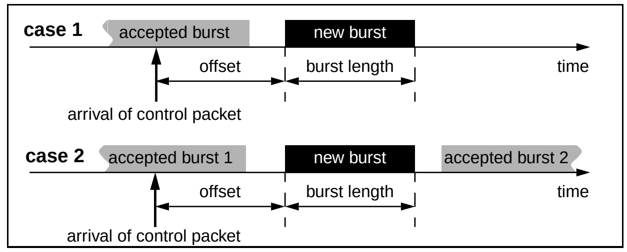

Fig. 3. Reservation scenarios

Qiao and Yoo take advantage of that property and extend this mechanism in order to support different service classes [19]. In this case, the offset of a data burst consists of a base component (*basic offset*) representing the sum of processing times for the control packet and an extra component (*QoS offset*) specific to a service class. As bursts with larger offsets experience lower blocking larger offset values are assigned to high priority classes. We will come back to this extension later in this paper.

3.2 Performance analysis

The performance of the different reservation mechanisms presented in the previous section can be expressed in terms of the burst loss probability. If we restrict evaluation to a single node case with fixed offsets δ for all bursts the loss probability may be obtained analytically. In the case of JET this also means that only a single service class is considered. Under the assumption that control packets (and in consequence data bursts) arrive in a Poisson stream with rate λ we can use Erlang's well-known B formula for the loss probability of an M/G/n loss system:

$$B(A,n) = \frac{A^n/n!}{\sum_{i=0}^{n} A^i/i!}\,. \qquad (1)$$

In this formula n represents the number of servers in a loss system which in this context corresponds to the number of wavelengths on a link. The offered load A relevant for loss computation depends on the reservation mechanism. For Horizon and JET the offered load is simply the product of arrival rate and mean transmission time h of a data burst. So the loss probability of a burst is given by

$$P_{\text{Loss,Horizon}} = P_{\text{Loss,JET}} = B(\lambda h, n). \qquad (2)$$

Note that Horizon and JET have the same performance under the given assumptions as the second scenario shown in Fig. 3 does not occur in the single node case with constant δ. For JIT, the system behaves like a loss system with increased offered load, resulting in the loss probability:

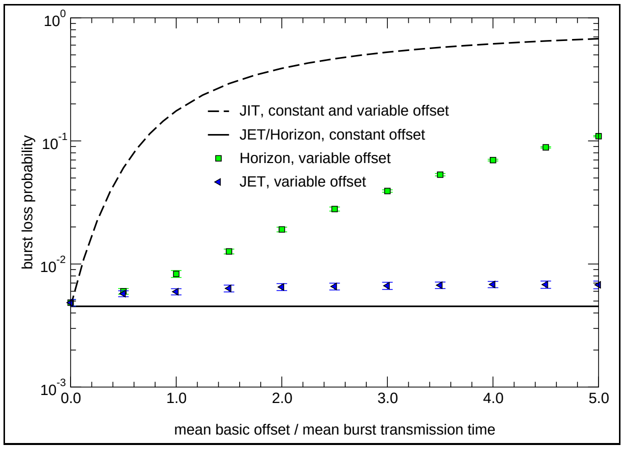

Fig. 4. Dependence of the burst loss probability on the offset

$$P_{\text{Loss,JIT}} = B(\lambda(h+\delta), n). \tag{3}$$

The reason for this is that each request blocks a channel for an interval which length is the sum of basic offset and burst transmission time. The increased load leads to a higher loss probability of JIT compared to Horizon and JET especially for large δ as demonstrated by the lines in Fig. 4. Therein as well as in several following graphs, we depict the burst loss probabilities against the mean offset normalized by the mean burst transmission time, i.e. δ/h, in order to ease interpretation.

In a network scenario, the offset values occurring in a node will not be constant. Therefore, we also investigated the influence of randomly varying δ by simulations as our analysis does not cover varying offsets (Fig. 4). All variable offset results are obtained for negative-exponentially distributed δ and burst length. For JIT this has no effect, i.e. the loss probability can still be determined using eq. (3). In the case of JET and Horizon, however, we found by simulation that this variation leads to higher losses. While this effect is minor for JET, loss probability significantly increases for a larger mean offset when Horizon is applied. The conclusion is that the higher complexity of JET as compared to Horizon results in better performance for varying offsets.

4. Analysis for a two-class OBS node

In this section, we present an analysis of the loss probabilities in a JET OBS node that distinguishes two classes—a high priority class denoted by index H and a low priority class denoted by index L. According to the debate in the Internet community to only support two classes—stream and elastic—and to recent results indicating that this QoS support might be sufficient [22], we restrict our evaluation to two classes. Unlike the single class case where all bursts have the same fixed basic offset to compensate switching times we follow—as mentioned in Section 3.2—Qiao's and Yoo's suggestion [19] to introduce an additional offset, called *QoS offset*, that provides service class differentiation. For our analysis, we assume the basic offset to be much shorter than the QoS offset and thus be negligible. Furthermore, we choose the low priority QoS offset $\delta_{\text{L}} = 0$ in order to achieve a small QoS offset of the high priority class and consequently a small overall delay.

The overall burst loss probability $P_{\text{Loss,O}}$ in a multi-class OBS node can be obtained from Erlang's loss formula eq. (1) in case of Poisson arrivals for an overall offered load A_{O} and bundle size n as

$$P_{\text{Loss,O}} = B(A_{\text{O}}, n). \tag{4}$$

In order to calculate the burst loss probability of the high priority class $P_{\text{Loss,H}}$, not only the offered load A_{H} of the high priority class has to be considered but also a fraction of the carried traffic of the low priority class. This traffic $Y_{\text{L}}(\delta_{\text{H}})$ represents bursts which started prior to the arrival of the high priority control packet and are still being served when the high priority burst starts, i.e. δ_{H} after the high priority control packet arrived. This additional traffic stems from the fact that in this system, high priority traffic is not totally isolated from low priority traffic. Thus, $P_{\text{Loss,H}}$ is approximated by

$$P_{\text{Loss,H}} = B(A_{\text{H}} + Y_{\text{L}}(\delta_{\text{H}}), n). \tag{5}$$

The burst loss probability of the low priority class $P_{\text{Loss,L}}$ can be obtained according to the conservation law[3] solving

$$A_{\text{O}}\, P_{\text{Loss,O}} = A_{\text{H}}\, P_{\text{Loss,H}} + A_{\text{L}}\, P_{\text{Loss,L}} \tag{6}$$

with the offered load A_{L} of the low priority class. For the carried traffic $Y_{\text{L}}(\delta_{\text{H}})$ we have

$$Y_{\text{L}}(\delta_{\text{H}}) = A_{\text{L}}\,(1 - P_{\text{Loss,L}})\,(1 - F_{\text{L}}^{\text{f}}(\delta_{\text{H}})) \tag{7}$$

where $A_{\text{L}}\,(1 - P_{\text{Loss,L}})$ is the carried traffic of the low priority class at the time when the high priority control packet arrives. $(1 - F_{\text{L}}^{\text{f}}(\delta_{\text{H}}))$ is the complementary distribution function of the forward recurrence time of the burst transmission time at time δ_{H}. It describes the probability that a low priority burst that has already started transmission prior to some random observation time τ (the time when the control packet of the high priority burst arrived) and has not finished transmission within the period $[\tau, \tau + \delta_{\text{H}}]$. Eq. (7) is an approximation because in reality, longer bursts are discarded with a higher probability, see also Section 5.2.

Furthermore, it can be concluded that $P_{\text{Loss,H}}$ is dependent on the burst length distribution of the low priority class whereas it is independent of the burst length distribution of its own class. Section 5.2 will elaborate on the impact of low priority burst length characteristics on high priority burst loss probability.

According to eq. (5), (6), and (7), there is a mutual dependency between $P_{\text{Loss,H}}$ and $P_{\text{Loss,L}}$. Therefore, we suggest an iterative solution for above formulæ.

We initialize the iteration with estimates for the loss probabilities of the high and low priority classes, $P^{(0)}_{\text{Loss,H}}$

[3] If the conservation law holds, the overall loss probability is not dependent e.g. on the number of classes. In [19] it has been shown by simulation that the conservation law is satisfied for an OBS system as considered here.

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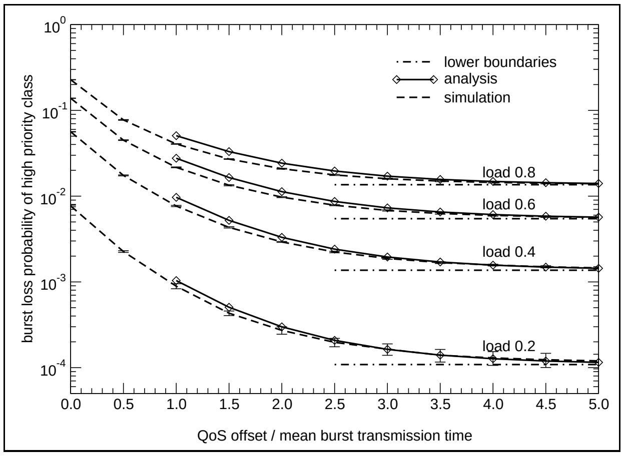

Fig. 5. Comparison of analysis and simulation for $n = 4$

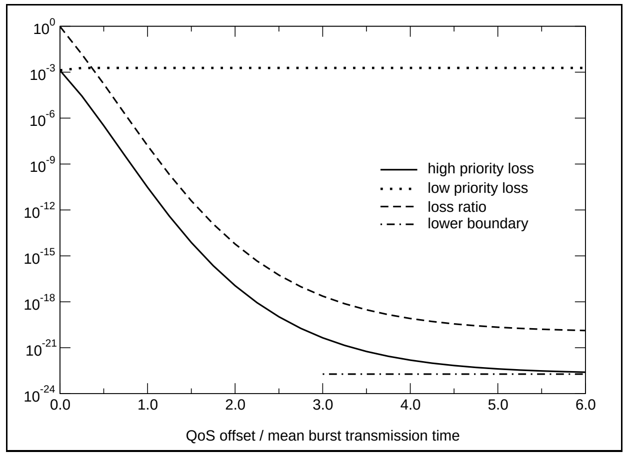

Fig. 6. Burst loss probability for 64 wavelengths and load 0.7

and $P^{(0)}_{\text{Loss,L}}$, respectively. These zero order estimates are given in eq. (8) and can be derived from eq. (4)–(6) by decoupling the high priority class from the low priority class which is equivalent to neglecting $Y_\text{L}(\delta_\text{H})$:

$$P^{(0)}_{\text{Loss,H}} = B(A_\text{H}, n) \tag{8a}$$

$$P^{(0)}_{\text{Loss,L}} = 1/A_\text{L}\,(A_\text{O} P_{\text{Loss,O}} - A_\text{H} P^{(0)}_{\text{Loss,H}}) \tag{8b}$$

These formulæ are also published by Qiao and Yoo [19] and yield lower boundaries for our analysis if the QoS offset is very large (Fig. 5, see below).

The distribution function of the forward recurrence time of the burst transmission time is given by

$$F^\text{f}_\text{L}(t) = 1/h_\text{L} \int_{u=0}^{t} (1 - F_\text{L}(u))\,\mathrm{d}u \tag{9}$$

where h_L and $F_\text{L}(u)$ represent the mean and the distribution function of the burst transmission time, respectively.

Finally, the amount of carried low priority traffic is determined by eq. (7) using eq. (8) and (9) as

$$Y^{(0)}_\text{L}(\delta_\text{H}) = A_\text{L}\,(1 - P^{(0)}_{\text{Loss,L}})\,(1 - F^\text{f}_\text{L}(\delta_\text{H})) \tag{10}$$

and can be inserted in eq. (5) yielding a first order result for the loss probability of the high priority class, $P^{(1)}_{\text{Loss,H}}$. The first order result $P^{(1)}_{\text{Loss,L}}$ is obtained from the conservation law, eq. (6), and $P^{(1)}_{\text{Loss,H}}$. Iteration until some precision criterion is satisfied leads to $P_{\text{Loss,H}}$ and $P_{\text{Loss,L}}$.

5. Results for a two-class OBS node

In the following, we use a high priority traffic share of 30 % of total load, a mean burst length of 12.5 KB and a bundle of either 4 or 64 wavelengths operating at 2.5 Gbps each (mean burst transmission time 40 μs). Load stands for total load per wavelength comprising high and low priority traffic. Unless stated differently, interarrival time and burst length are negative-exponentially distributed.

5.1 Impact of QoS offset

Assuming a given traffic scenario, δ_H is the only parameter that influences the service experienced by both classes. As our analysis is valid for arbitrary non-zero offsets, the point of sufficient service isolation can be precisely obtained.

Fig. 5 shows $P_{\text{Loss,H}}$ as a function of the ratio of δ_H and mean burst transmission time. It can be seen that analysis and simulation match very well. The analysis slightly overestimates $P_{\text{Loss,H}}$ for smaller δ_H because it assumes a loss probability independent of actual burst length within each class which is not exactly true—as described in more detail below. The horizontal lines in Fig. 5 are lower boundaries in case the influence of the low priority class is neglected. This case corresponds to the start of our proposed iteration eq. (8) and the solution proposed in [19].

In Fig. 6, $P_{\text{Loss,H}}$, $P_{\text{Loss,L}}$ as well as the ratio $P_{\text{Loss,H}}/P_{\text{Loss,L}}$ are depicted for 64 wavelengths and a load of 0.7. In a scenario like this, $P_{\text{Loss,L}}$ is rather independent of the QoS offset. In contrast, $P_{\text{Loss,H}}$ and thus $P_{\text{Loss,H}}/P_{\text{Loss,L}}$ decrease over many orders of magnitude for increasing δ_H before they approach their lower boundaries. This type of graph can be used to find the balance between perfect isolation of the high priority class but longer deterministic delay and very short delay but higher losses (which might still be comfortable within a target burst loss probability range). For example, if 10^{-10} is the target loss probability of the high priority class, a QoS offset of one mean burst transmission time is sufficient. Furthermore, comparison of Fig. 5 and Fig. 6 demonstrates the positive impact of a large number of wavelengths on loss probabilities.

Another effect arising with offset based reservation mechanisms may make smaller QoS offsets even more preferable: Fig. 7 depicts the burst loss probability of the low priority class conditioned on the actual burst length (*conditional*). For comparison, we also show the burst loss probability of all low priority bursts (*class*). It demonstrates for a system with different offsets that the loss probability of a low priority burst depends on the actual length of the burst. This behaviour is inherent to a system

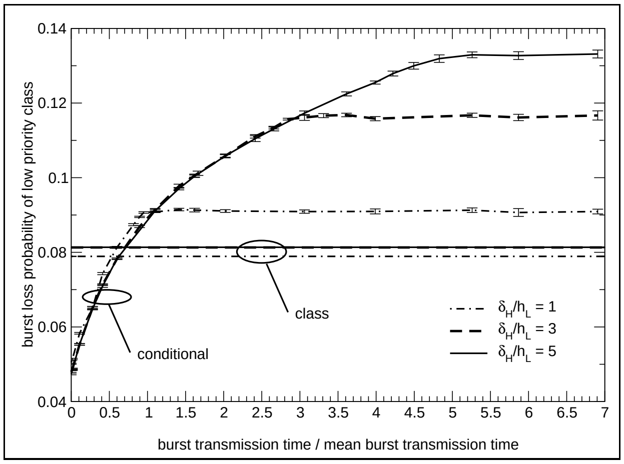

Fig. 7. Low priority losses against burst length for $n = 4$

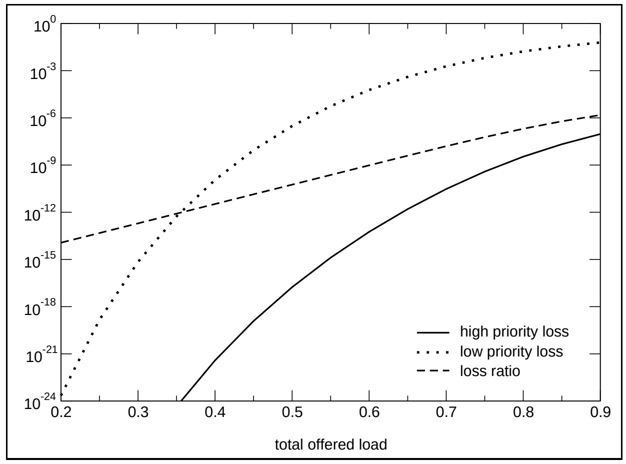

Fig. 8. Burst loss probability against load ($\delta_{\mathrm{H}}/h_{\mathrm{L}} = 1$, $n = 64$)

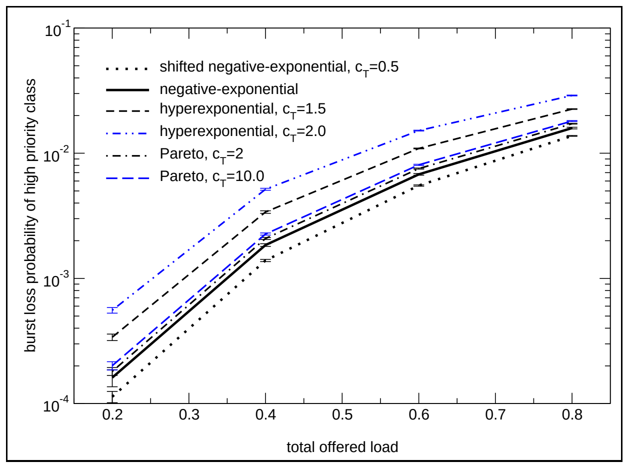

Fig. 9. Impact of burst length distributions ($\delta_{\mathrm{H}}/h_{\mathrm{L}} = 3$, $n = 4$)

in which low priority bursts tend to occupy wavelengths in between already reserved high priority bursts (see also Fig. 3 case 2). Thus, the probability to find a gap of appropriate length is higher for bursts that are shorter than δ_{H}. It can be seen that the conditional low priority burst loss probability increases until the respective burst transmission time is as long as δ_{H} and stays constant from there on. The longer the offset time, i.e. the greater the isolation, the larger is the difference between the burst loss probabilities of a short burst and a very long burst. For the scenario of a QoS offset of five times the mean burst transmission time, $P_{\mathrm{Loss,L}}$ more than doubles for long bursts. A solution to this problem could be to bound burst lengths within a short interval. However, this has the disadvantage that several short bursts produce much more overhead concerning connection management, which is especially undesirable for the low priority class.

The class loss probabilities depicted in Fig. 7 are used as values of $P_{\mathrm{Loss,L}}$ for our analysis in Section 4. The fact that the analysis overestimates the loss probability can be explained by the offered load, which is lower in simulations as long bursts are discarded with higher probability.

5.2 Impact of traffic characteristics

An important feature of a system that distinguishes different classes is the isolation between them. Fig. 8 depicts $P_{\mathrm{Loss,H}}$, $P_{\mathrm{Loss,L}}$ and the ratio $P_{\mathrm{Loss,H}}/P_{\mathrm{Loss,L}}$ against the load, which is equally increased for both classes. Here, like in Fig. 6, we used 64 wavelengths. The offset δ_{H} was set equal to the mean burst transmission time, which yielded $P_{\mathrm{Loss,H}} \approx 10^{-10}$ at a total load of 0.7 according to our example related to Fig. 6. Although $P_{\mathrm{Loss,H}}/P_{\mathrm{Loss,L}}$ increases steadily with increasing load, a good grade of isolation is maintained even for high loads.

The distribution of the burst length is not an OBS system parameter, but can be influenced by the strategy of aggregating IP packets into bursts. As discussed in Section 4, $P_{\mathrm{Loss,H}}$ is influenced only by the burst length distribution of the low priority class but not by that of its own class. Therefore, we stay with a negative-exponential distribution for the high priority burst length. In order to only change the coefficient of variation c_T of the burst length distribution of the low priority class and keep its mean value unchanged, we chose either a shifted negative-exponential ($c_T < 1$) or a second order hyperexponential[4] ($c_T > 1$) distribution. For these distributions, Fig. 9 shows the expected result that $P_{\mathrm{Loss,H}}$ increases for growing c_T of the low priority class. Surprisingly, in case of Pareto distributed low priority burst length with the same mean value, $P_{\mathrm{Loss,H}}$ stays nearly unaffected, even for large c_T.

Finally, the influence of the distribution of the interarrival time of the low priority class on $P_{\mathrm{Loss,H}}$ was investigated. Left out due to space restrictions, our results show that $P_{\mathrm{Loss,H}}$ is hardly affected. Therefore, our assumption of negative-exponentially distributed interarrival times yields reasonable results [23].

[4] The hyperexponential distribution satisfies the symmetry condition $ph_1 = (1-p)h_2$ where p is the branch probability and h_1 and h_2 are the mean values of the respective phases.

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6. Conclusions and outlook

Based on a discussion of various switching paradigms as well as network evolution scenarios, we could show in this paper that OBS promises many benefits for future QoS supporting high speed transport networks. Then, we gave a detailed overview of characteristics and design parameters of OBS. A classification of different reservation mechanisms proposed in literature as well as a performance comparison for a single OBS node was presented.

In single-class OBS, we found that JET and Horizon perform equally well and much better than JIT for constant offsets. Varying offsets have only minor impact on JET but significantly degrade the performance of Horizon.

For the multi-class capable reservation mechanism JET, a new analysis was introduced which allows to exactly determine the point of sufficient isolation between classes for arbitrary QoS offsets. Based on this analysis and extensive simulations, several results related to both, the QoS offset and traffic characteristics, were obtained. For the two-class case we proved that even small QoS offsets, which do not completely decouple high and low priority traffic while keeping end-to-end delay to a minimum, still yield a very low loss probability of the high priority class. Moreover, smaller QoS offsets lead to a more uniform low priority loss characteristic over the burst length.

Future work could improve the presented evaluation by also considering higher layer protocols such as TCP. Another key questions is how IP traffic should be best aggregated into bursts. Finally, studies for an entire OBS network are necessary in order to assess the impact of routing strategies and traffic management on system performance.

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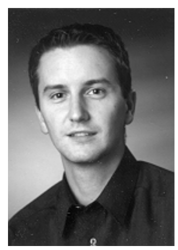

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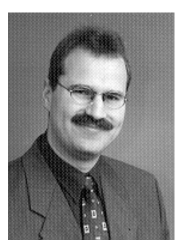

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