

# Architectures for Resource Reservation Modules for Optical Burst Switching Core Nodes<sup>\*</sup>

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## Abstract

Optical Burst Switching (OBS) is a promising candidate for a more dynamic optical network layer. One central task is the reservation of resources in the core nodes. Reservation modules in the output ports of OBS nodes will perform this reservation task. As these modules should not limit the performance of the node, reservation must be performed in very short time intervals. This paper surveys reservation schemes in OBS and discusses relevant scenarios with respect to offset values. Then, two architectures for reservation modules supporting the just-enough-time (JET) reservation scheme are presented. Finally, their implementation complexity and their scalability are analyzed.

## 1 Introduction

Optical burst switching seems to be a promising candidate to bring more dynamic into the optical layer of transport networks [2]. It can be regarded as an intermediate solution on the evolution path towards all optical packet switching networks. As technological limitations do not allow switching of individual IP packets, several packets with the same route through the network are assembled into bursts and switched through the network all optically. For the control of data burst switching an out-of-band signaling scheme is used. A control packet is sent through the network and initiates the reservation of optical resources for the corresponding burst.

The control system of each output port of a node processes all control packets for the connected link and reserves wavelengths (WL) for the requested burst transmission intervals. For successful reservations new control packets must be generated and sent to the next node. The reservation module has to find idle wavelengths for the bursts and, after the assignment of a burst to a wavelength, the module has to take care, that no other burst will be assigned to the same wavelength at the same time.

In this paper we introduce first approaches for designing reservation modules for OBS nodes and analyze their implementation complexity and scalability.

The remainder of this paper is structured as follows: In Section 2 OBS and different reservation schemes are introduced. Section 3 presents two architectures for reservation modules which support the JET reservation scheme and in Section 4 results for the scalability of the reservation modules are shown.

## 2 Reservation schemes in optical bursts switching

### 2.1 Introduction of OBS

As transmission speed on optical links grows much faster than the electrical processing speed, optical burst switching represents an ideal solution for closing the gap between optical circuit switching and optical packet switching. It allows a finer granularity than circuit switching and leads to more flexibility in the optical domain but does not require the high complexity of the control part for optical packet switching systems.

Two types of nodes can be found in an OBS network: In the edge nodes, the incoming traffic from access or metro networks is collected, stored in electrical buffers and assigned to larger data units, called bursts. The core nodes serve as transit nodes. They switch the incoming bursts directly in the optical domain to the appropriate output without electrical buffering or complex data processing.

For the switching of the data bursts, a control packet is generated and sent separately from its corresponding data burst. This control packet must be converted back into the electrical domain in each core node in order to extract the information necessary for switching the burst. A reservation module in the corresponding output port of the node must search a wavelength which will be free during the transmission time of the burst.

As the control packet is processed in each node, it propagates slower through the network than the burst itself. Therefore suitable precautions must be taken. A common way in OBS scenarios is the introduction of an offset time.

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The control packet is sent out a certain time (the offset time) before the data burst itself. A core node uses the offset interval for processing the control packet, setting up the switching matrix and generating a new control packet to inform the next nodes on the path.

A key concept of OBS is one-pass reservation, i.e. a burst is not delayed until an acknowledgement of successful reservation of an end-to-end path is received but is sent out as soon as the burst is assembled. Several algorithms for the reservation of wavelengths were introduced in literature [2, 6]. The JET (just enough time) algorithm [1] promises a good utilization of the links and enables the usage of quality of service (QoS) mechanisms by the introduction of additional QoS offsets between burst and control packet [3, 7]. In order for the control packet not to get caught by the burst, processing of burst reservation and setting up the switching matrix has to be very fast.

Although there is no unique definition of OBS, the separation of control information and data in time and space seems to be widely agreed. Also, the length of the bursts is not limited, thus we assume variable length bursts.

Several approaches for offset sizes are introduced in literature. At the edge nodes, a specific offset is determined for the bursts. On their way through the network, this offset can be reduced by core nodes. In the following sections we categorize different approaches in edge and core node and identify scenarios for more detailed studies about the realization of the according reservation modules in core nodes.

## 2.2 Determination of offsets at the edge

When a fully assembled burst in an edge node is ready for transmission, the respective control packet must be generated and transmitted. The offset interval between control packet and data burst can be determined in three ways:

E1 No offset is used.

Control packet and data burst are transmitted in parallel on two different channels. In this case no additional complexity for delaying the data burst at the edge or predicting burst properties for sending the control packet in advance would be necessary. Of course, the processing time of the control packet in the core nodes must be compensated differently by the core nodes, i. e. by adding a fibre delay line (FDL) for delaying the data bursts.

E2 The offset could be proportional to the hop count.

For each core node, the burst will pass, the edge node adds an offset for compensating the processing time of the control packets in the core node. This offset for compensation processing delays is called basic offset.

E3 The support of Quality of Service (QoS) mechanisms can be provided by using different offsets for different service classes. The earlier a reservation is performed, the higher is the probability of getting the desired resources. Thus, high priority bursts are sent with greater offsets than low priority bursts. The offset for differentiating service classes is called QoS-offset.

The combination of the two offset based mechanisms E2 and E3 is possible but can easily lead to unexpected interaction and unfairness among bursts in the same service class [7].

## 2.3 Offset adaptation by core nodes

The control packets arriving at a core node must be converted into the electrical domain, forwarded to the corresponding processing modules and finally processed. The last processing stage must generate a new control packet and send it to the next node on the path. All these steps lead to a statistical delay of the control packet flow which is not experienced by the data bursts. The core nodes can influence the offset length in several ways:

C1 The offset length can be kept constant.

As the electrical processing will always take time, the data burst must be delayed in this scenario. Fibre delay lines (FDL) can be applied to delay the optical signals for a constant period. Control packets must be processed in a deterministic time in order to keep the offset constant. If processing takes variable time with an upper limit which corresponds to the FDL length, the new control packets must be sent out precisely so that the original offset is reached. This scenario also copes with an offset time of zero, which means that data burst and control packet are sent at the same time.

C2 Offset reduction by a constant value.

Like before, the processing time of control packets must be limited by an upper bound and the control packet is sent out after a fixed period of time after its arrival time.

C3 Offset reduction by a variable value.

The core node sends the control packet to the next node immediately after processing it. As processing time can vary from packet to packet, the offsets are decreased just as much as necessary.

## 2.4 Offsets in network scenarios

The scenarios for determination of offset times in edge nodes and the influence on the offset adaptation in core nodes described in the previous two sections can be combined in several ways. Of course, not all combinations are useful or even functioning. But a large number of them is

considered in literature and some more could be imagined. From the point of view of reservation modules for core nodes, the combinations can be classified in three groups, determined by the property of the offset time distribution.

### Unique, network wide offset value

If all offset times should be kept constant in the network, the core nodes must not change the offset times and need a possibility to delay the data bursts for the processing time of the control packets (C1). All edge nodes send control packets with a network wide constant offset (E1), which can also be zero, towards the core nodes. Data bursts pass the node in the same order as the corresponding control packets.

Each control packet arrival time is deterministically correlated to the start time of burst transmission. The reservation module must check the status of the wavelengths to this point in time. As all offsets are the same, it is impossible that bursts have been already reserved and start transmission later than this burst. This fact leads to quite simple solutions for the resource reservation [4]. As QoS-classes cannot be differentiated by their offsets, other mechanisms for QoS are needed. One approach with few additional complexity is an admission control scheme to the reservation process [8].

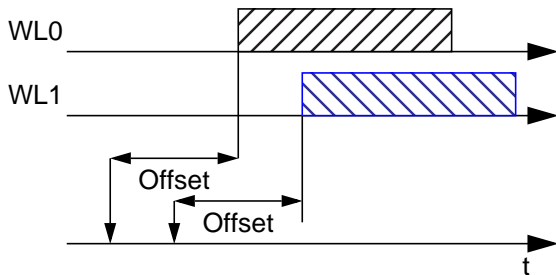


Fig. 1 Reservation with network wide constant offsets

### Few discrete offset values in the network

The introduction of discrete offset values could be useful from several points of view.

It would be possible to add a specific offset  $\Delta_O$  for each node to be passed in the network. In this scenario, the edge node must know the number of hops for each burst and calculate a basic offset time for the burst.

Another scenario for discrete offset length distributions could be the introduction of offset-based QoS support. The longer the offset of a burst, the higher the probability to get a successful resource reservation. In this case, the core node should not change the offset of passing bursts but compensate the processing delay.

As the order of control packets does not represent the order of data bursts, the resource reservation becomes more complex. Not only a single start time of the burst

transmission but the entire transmission interval must be checked. Therefore, the reservation module could determine the status of the wavelengths at all possible offset times intersecting with the burst transmission interval (marked with bold lines in Fig. 2). All points on the time line at which bursts could start are determined by the actual system time and the possible offsets. The status information at these points on the time line could be pre-calculated by the reservation module for getting a shorter searching period.

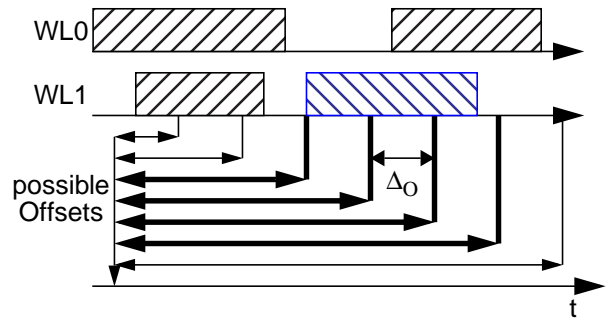


Fig. 2 Reservation with discrete offset distribution

Which scenarios would lead to discrete burst length distributions? The main premises are, that edge nodes only generate offsets as multiples of  $\Delta_O$  (E1, E2, E3) and core nodes only change offsets by multiples of  $\Delta_O$  (C2).

The generation of different offsets for compensating processing time in core nodes and for supporting offset based QoS could only be used in parallel, when the QoS offsets  $\Delta_{QoS}$  are much larger than the offsets for processing time compensation  $\Delta_{Comp}$ . This would lead to a spreading of offset times around multiples of  $\Delta_{QoS}$ . This results to accumulations of offset lengths which could probably be used by a reservation module by caching some precalculated information about the wavelength status. But the more core nodes are in the network, the more the offsets will be spread which results in a continuous offset time distribution which is described next.

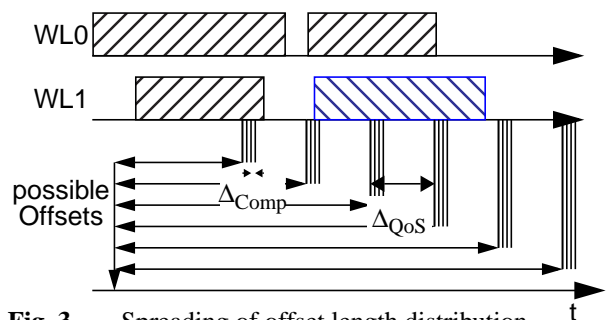


Fig. 3 Spreading of offset length distribution

## Continuous offset values in the network

The continuous offset time distribution is the most general case. All scenarios in which core nodes reduce offset lengths by variable amounts (C3) or scenarios with generation of variable offset lengths in edge nodes need this flexibility. Of course, realization complexity for a reservation module for continuous offset distribution is the highest, too. A reservation module which can cope with continuously distributed offset times can be used in all scenarios, even if these scenarios do not need this generality.

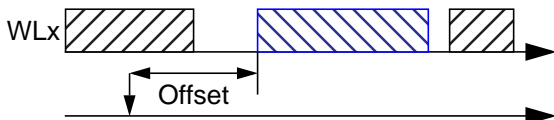
The original introduction of OBS by Qiao [2] includes an offset based QoS support with variable offsets. The reservation mechanism called just-enough-time (JET) reserves wavelengths just for the actual transmission interval and allows the use of gaps between bursts.

### 2.5 The JET reservation scheme

The reservation algorithm JET is a very general algorithm. JET is a so-called RFD-algorithm (reserve-a-fixed-duration). This means, that the arrival time of the burst at the node and the duration of the transmission is well known at the node. The wavelength is reserved exactly for the time, the burst really needs the transmission link, but not longer and not earlier (Aside from some guard times at beginning and end of the burst for compensating jitter and switching time of the optical cross connect.).

When a control packet arrives, the reservation module searches for a free wavelength for the burst in the desired time interval. As wavelength converters are expensive components, it would be desirable to assign the burst to the same wavelength on the output link like on the input link. If the wavelength is already busy, other wavelengths are checked for their status in the time interval of transmission. If one or more wavelengths are not occupied to the allocated time one of them is selected and reserved for the belonging burst. Special orders for selecting one among the free wavelengths are not proposed by Qiao and not considered in this paper.

Fig. 4 shows a reservation procedure. A control packet for a burst arrives. WLx provides a gap in its time line and the new burst fits in this gap. The wavelength is reserved for the corresponding burst.



**Fig. 4** Reservation with JET

## 3 Realization of JET reservation modules

As JET is the most flexible of the introduced reservation mechanisms, we decided to study the realization of suitable reservation modules. Other reservation algorithms with less complexity could also use this reservation module. As processing of the control packets has to be performed very fast, hardware based solutions are needed. Section 4 will discuss the requirements of processing time and the performance of the proposed architectures.

In this section, we introduce two possible architectures for reservation modules. One is based on the idea to represent the status of all wavelengths like a timetable. Each column in the table represents a specific small time interval and each row contains the status of one wavelength. This table is implemented as embedded memory in a Field Programmable Gate Array (FPGA). The second architecture works as a combinatorial circuit. For each burst, a specific entity is used, which stores start and end time in registers and uses comparators to determine, whether a new burst would intersect with the burst reservation represented by this module.

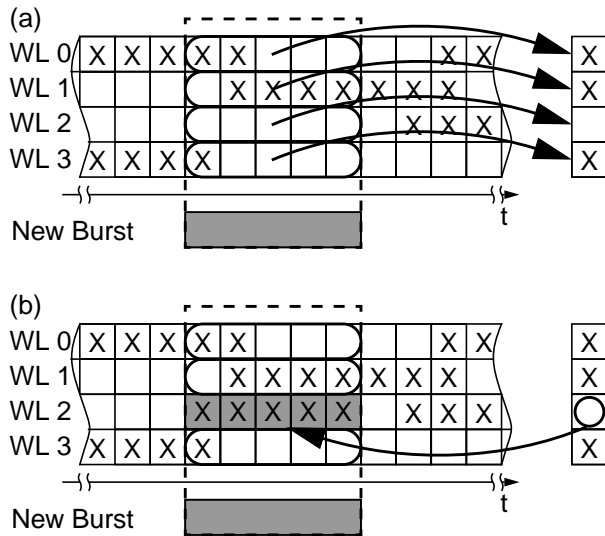
### 3.1 Memory-based solution of a JET reservation module

As explained in Section 2.5 the JET reservation scheme needs information about start and end time of a burst. Even when we assume an unslotted media with continuous distribution of burst arrivals, a real system will always work with discrete times. For the realization of the reservation module we introduce an architecture, which divides the continuous time scale into discrete slots. As we will show in Section 4 a minimum resolution in time of two percent of the mean burst length does not limit the performance of the system significantly. In the context of the control packets the offset and length of the burst can be measured with a high resolution in time, the allocation of wavelengths in the reservation module is realized with a slotted structure with lower resolution in time.

The status of wavelengths is stored in a table. Each column represents a time slot, each row represents one wavelength of the system.

**Fig. 5** shows an example of a table for four wavelengths. An empty square represents free slots, an 'X' in the square shows that a slot is already reserved for a burst. With the arrival of a control packet the slots with start and end time of the burst and all intermediate slots are identified and free wavelengths for the specified slots are searched (a). A free wavelength will then be selected for the burst and marked as reserved (b). After the identification of the new

wavelength a new control packet for the next node is generated and a request with all switching informations for the optical cross connect is sent to its controller.



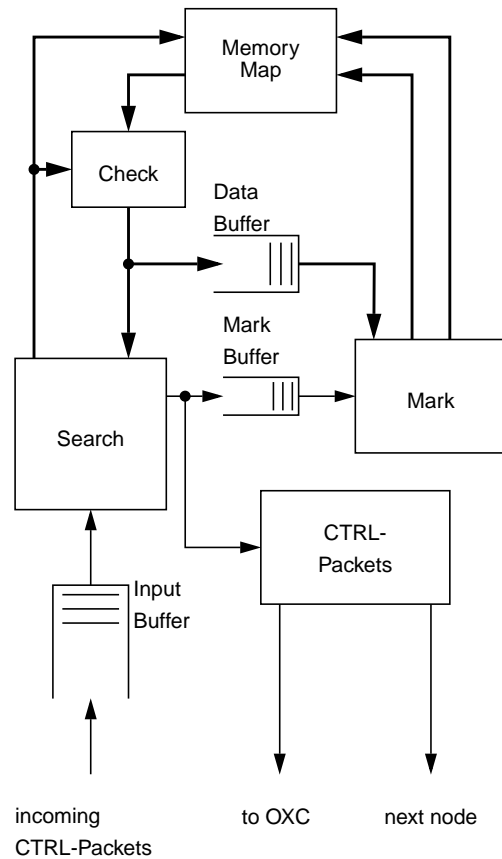
**Fig. 5** Reservation table and determination of free wavelengths

As all control packets in the system must be switched to their corresponding output port and be processed there one by one, they must be buffered on their way through the system. As the control packets will experience a delay which is not constant but varies in a relatively wide range, the offset information in the packets wouldn't be exact anymore. A central system clock will provide a unique time information for all system components. At the arrival of a control packet a timestamp is assigned to it. The timestamp, the offset and the length information in the packet enable the system to compute absolute values for start and end time of the burst. These absolute values are used in the reservation module for a unique addressing of the reservation table. When a new control packet for the next OBS node is generated, the offset is recalculated as difference between absolute burst arrival time and actual system time.

As reservation requests will cover a finite time interval from the actual system time to a maximum offset plus a maximum burst length the reservation table needs to buffer only this time interval. As informations about the past are not relevant for the reservation anymore all entries which are older than the actual time could be reused for entries in the future. So the reservation map can be realized as a classical ring buffer where the actual system time is the earliest point in time. We call the time interval from actual time to the last possible entry in the table the reservation horizon.

## Architecture of the memory-based solution

**Fig. 6** shows the basic architecture of the memory-based version of the reservation module.



**Fig. 6** Memory-based reservation module

All incoming control packets are buffered in a FIFO-queue Input buffer and processed one after another. The search module reads the memory content of the respective time interval and checks for free wavelengths. In parallel, the memory data is stored in a FIFO queue data buffer. The read module selects one of the free wavelengths for the bursts and forwards the data to the mark buffer and to the generator for new control packets.

The data buffer is needed, because normal memory devices do not allow writing single bits. A read-modify-write-cycle would be necessary for setting the bits in the memory. As the memory data is already read by the search module, it buffers these data in the data buffer.

As the search module does only read the memory and the mark module does only write to it, these modules can work in parallel if dual ported memory is used. The mark module reads the information of assigned bursts from the mark buffer, combines them with the informations from the data buffer and writes these data sets back to the memory map.

The check module is necessary for data consistency. Bursts which are assigned to wavelengths but still in the mark buffer must be considered by the search module. The check module monitors the addresses of the search module and overrides the memory bits for the bursts in the mark buffer.

The reservation of a burst is split in two phases: Searching of a wavelength and marking of the reserved wavelength in memory. Both phases are performed in sequence. As these phases are nearly independent, the reservation module is realized as a two stage pipeline. During the marking of one burst, free wavelengths for other bursts can already be searched. As the bursts occupy several slots in the memory map, both stages need a processing time proportional to the burst length, one clock cycle per slot.

As platform for the implementation of the reservation module we used Field Programmable Gate Arrays (FPGA) of the APEX 20KC family from Altera. They have large numbers of logic elements for realizing register banks and state machines and provide internal memory blocks for the reservation table. The memory blocks can be used in several operating modes and can be combined together for getting wider or deeper memory. Like all digital systems the reservation module works with a central clock. Each calculation or memory access is performed within one clock cycle of 10 ns which results in an operation frequency of 100 MHz.

The design needs about 1800 logic elements and 17 embedded memory blocks for a reservation module which supports 64 wavelengths. These values correspond to 11% of logic elements and 16% of memory blocks of an APEX20KC400.

The performance of this architecture will be discussed in Section 4.

### 3.2 Combinatorial Solution

The processing time of a control packet for reserving a burst should be as short as possible. The memory-based solution from the previous section needs a number of clock cycles proportional to the burst time. In this section a solution with a constant and deterministic processing time is introduced. It is based on a large combinatorial network which performs a lot of comparisons of time informations for determining free wavelengths and reserving one for the corresponding burst.

All informations about the status of wavelengths are represented in a decentralized fashion in dedicated logical burst reservation entities BRes. Each of these entities stores information for one reserved burst, i. e. start and end time of the burst transmission. The architecture of the reservation module is shown in Fig. 7.

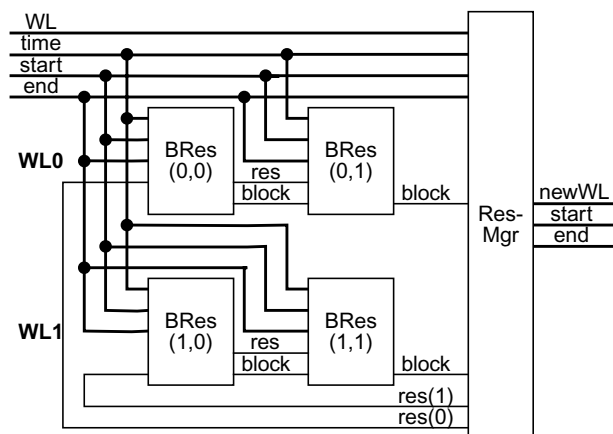


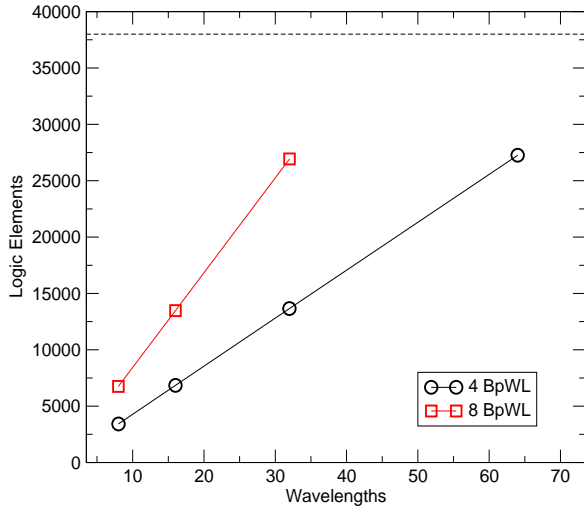
Fig. 7 Architecture of the combinatorial reservation module

In Fig. 7 two wavelengths are used and two reservations per wavelength can be stored simultaneously. There are several dedicated reservation entities BRes per wavelength which are arranged in one row in the figure. As simulation results show, the probability of having more than eight bursts reserved for one wavelength is very small even for high load. So we assume four to eight entities of BRes per wavelength for the synthesis of the reservation module.

The data of the new burst and the system time are indicated to all entities. Each entity carrying a valid reservations compares its reservation data with the data of the newly indicated burst. When the bursts overlap, the entity sets the block signal. All block signals of one wavelength are logically combined. The reservation manager ResMgr analyses the block signals of all wavelengths and determines one free wavelength for storing the reservation of the new burst. It sets the reserve signal for the determined wavelength. All entities of a wavelength are daisy chained. The reserve signal is forwarded if the reservation entity is already storing a valid reservation itself. The first free BRes entity in the chain buffers the reservation informations.

The actual system time is provided to all reservation entities. With this time information the entity checks, if the stored reservation is still valid or outdated. In the latter case the information is deleted and a new reservation can be stored in the entity. An additional combinatorial network signals, if all entities of a wavelength are in use. In this case it is not possible to buffer an additional burst, even when the wavelength is not used during the transmission interval of the new burst.

The complete procedure is performed in one clock cycle. With the following clock edge all reservation information is stored and the next comparison can be done. With this design it would be possible to reserve a burst within each clock cycle. With growing number of wavelengths and BRes entities per wavelength the size of the combinatorial



**Fig. 8** Usage of Logic Elements

networks increase and the critical paths get longer. So the maximum clock frequency of the reservation module decreases with increasing number of reservation entities.

### 3.2.1 Logic resources of the reservation module

The reservation module was modeled and described in VHDL and synthesized for a Field Programmable Gate Array (FPGA). The APEX 20KC family from Altera was selected as target platform. The synthesis was made for different numbers of wavelengths and for four and eight reservable bursts per wavelength. The time information was represented as 20 bit words which cover a time range of 1 ms with a resolution of 1 ns.

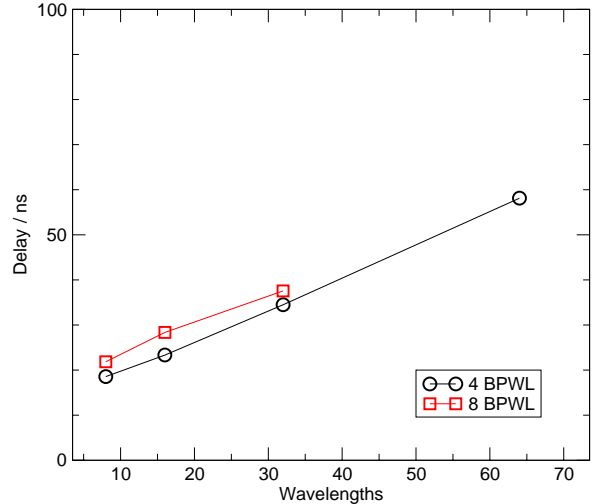
**Fig. 8** shows the number of used logic elements in the APEX device. The devices provide a maximum capacity of 38400 logic elements, which is represented by the dashed line in the graph.

**Fig. 9** shows the combinatorial delays which limit the maximum operation frequency of the reservation system. The reservation takes several tens of nanoseconds.

## 4 Scalability analysis

### 4.1 Model of the reservation module

In a reservation module control packets for bursts directed to all wavelengths of this output fiber have to be processed. While several data bursts are transmitted on the fiber in parallel using WDM, all control packets are processed by a single module.



**Fig. 9** Combinatorial Delays

The single server queue with Poisson arrivals and generally distributed service time (M/G/1) can be used as a simple model for analyzing performance and scalability of reservation modules.

In case the waiting and processing time of control packets exceeds the offset time or the delay of the FDL the corresponding burst is lost. In a well dimensioned system, burst loss probability due to violation of control packet time constraints has to be much smaller than the loss probability due to output contention. Here, we assume that it should be less than 1% of the burst loss probability caused by contention of the optical resources.

While burst loss probability can be calculated according to the well-known Erlang B formula [6], the probability for exceeding a certain value of the waiting time is described by the complementary waiting time distribution.

The arrival rate of the M/G/1 queue depends on the number of wavelengths  $w$ , the load per wavelength  $\rho_\lambda$  and the mean burst length  $E[T_{burst}]$ :

$$\lambda_{res} = (w\rho_\lambda)/(E[T_{burst}])$$

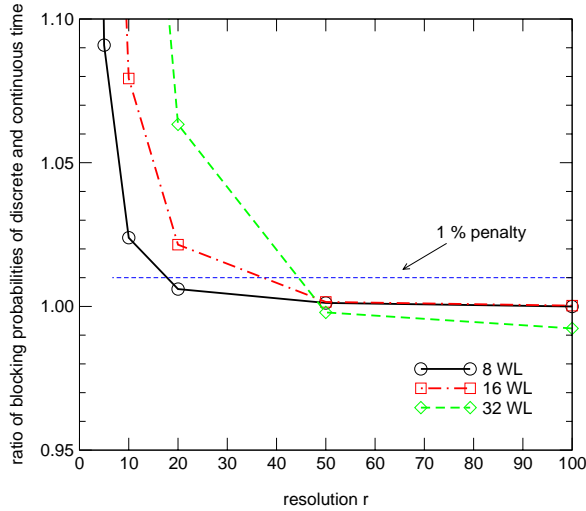
In all evaluations, bursts arrive according to a Poisson process and burst length is negative-exponentially distributed.

### 4.2 Memory-based solution

In case of the memory-based reservation module, the time for reservation is proportional to the burst length and depends on the time resolution of the memory map. The resolution  $r$  is defined as the number of slots which comprise an average burst.

**Fig. 10** shows the impact of different resolutions of the memory map on burst loss probability for load  $\rho_\lambda = 0.5$ . It can be seen that the ratio of the blocking probabilities for discrete and continuous time operation, i. e. operation with and without slots, decreases with increasing resolu-





**Fig. 10** Impact of resolution of the memory map

tion. Depending on the number of wavelengths, it can be seen that a resolution of 10–50 slots per average burst is necessary in order to limit the penalty to approximately 1%.

In order to assess the scalability of the memory-based solution, the minimum offset time per node is defined: For the minimum offset time the probability of a control packet to wait longer than this offset equals 1% of the burst loss probability.

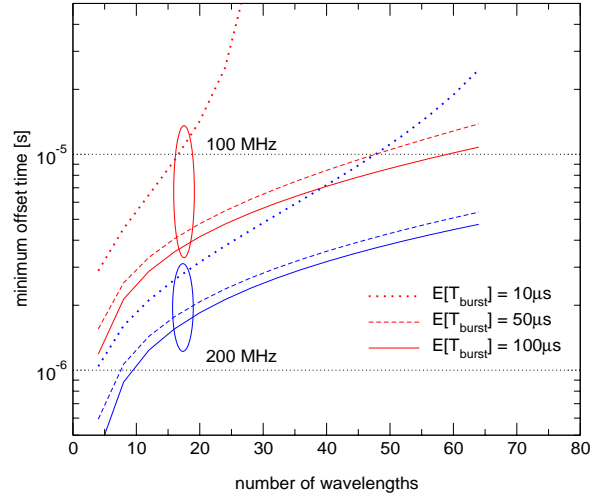
As described above, for the memory-based solution, reservation time is proportional to the burst length and calculated as

$$E[T_{r1}] = \frac{r}{f_{\text{clock}}}$$

where  $f_{\text{clock}}$  is the clock rate of the chip. In order to simplify the analysis, reservation time  $T_{r1}$  is assumed to also be negative-exponentially distributed, i. e. the complementary distribution function of the waiting time is calculated for the M/M/1 queue.

**Fig. 11** shows the impact of the number of wavelengths on the minimum offset time for resolution 50 and load  $\rho_\lambda = 0.5$ .

It can be seen that the minimum offset increases with increasing number of wavelengths and decreasing mean burst length. The memory-based solution only leads to minimum offsets which are well below the mean burst duration for a mean burst duration in the range from 50  $\mu\text{s}$  to 100  $\mu\text{s}$ . In these cases, up to 60 wavelengths can be supported. For a mean burst length of 10  $\mu\text{s}$ , the memory-based solution can manage a very small number of wavelengths.

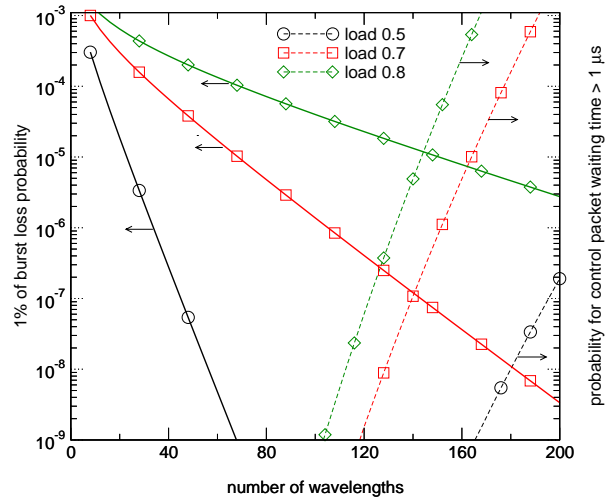


**Fig. 11** Scalability of the memory-based solution

### 4.3 Combinatorial solution

From a performance point of view, the combinatorial solution differs from the memory-based solution by having a reservation time which is constant and independent of the burst duration. Therefore, the complementary distribution function of the waiting time is calculated for the M/D/1 queue with a mean reservation time  $T_{r2} = 60$  ns. [9]

In **Fig. 12**, the probability that the waiting time of a control packet exceeds 1  $\mu\text{s}$  is plotted versus the number of wavelength for different values of load (right). Curves representing 1% of the burst loss probability are also included (left). It can be seen that almost independent of the load respective curves intersect for a wavelength count greater than 120. For a smaller wavelength count the blocking probability due to contention in the optical domain domi-



**Fig. 12** Scalability of the combinatorial solution



nates. Summarizing, this solution provides very low probabilities for violating control packet time constraints even for a large number of wavelengths and high load.

## 5 Conclusion

Two architectures for reservation modules have been proposed and evaluated with respect to realization, performance and scalability. The architectures were modeled and described in VHDL and synthesized for determination of the needs of hardware resources.

The memory-based solution needs only few resources of today's available FPGA devices but is limited in the number of wavelengths. Even for faster next generation FPGA families the number of supported wavelengths will remain rather limited. The usability of this architecture depends on the size of offset times or the length of fibre delay lines at the inputs, respectively.

The combinatorial solution needs much higher hardware resources. However, as the processing time for the reservation of one burst is much faster, this architecture scales much better. Even with today's devices and without additional optimization up to 100 wavelengths can be realized. With next generation FPGAs allowing lower delays with higher complexity, the wavelength count will increase without any additional optimization.

In general, both solutions could be used for higher numbers of wavelengths if several instances of the modules are used in parallel. Several wavelength bands could be defined and for each of them, one reservation module is used. Only if no reservation in the same band is possible, the request is forwarded to other reservation modules. This approach suits ideally to wavelength converters with limited conversion range.

As the actual realization of the combinatorial solution is a very large combinatorial net, the segmentation in several pipeline stages could increase the maximum frequency and performance of the system. With a higher throughput of control packets the maximum number of wavelengths per output port is increased.

From our point of view, the use of JET in core nodes is possible and won't limit the network performance. So, in principle the JET reservation protocol is not prohibitively complex.

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