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Viability and Performance of Optical Burst Switching

Christoph M. Gauger*, University of Stuttgart
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Abstract

Optical burst switching (OBS) has been proposed in the late 1990s as a novel photonic network architecture directed towards efficient transport of IP traffic. OBS aims at cost-efficient and dynamic provisioning of sub-wavelength granularity by optimally combining electronics and optics. This paper surveys work on contention resolution and node scalability performed within the TransiNet project. Both topics represent key challenges in highly dynamic optical networks and assessing their performance is critical for deciding on their viability. After a brief introduction to OBS, results of studies on the effectiveness of contention resolution in a Germany reference network scenario are presented. Then, node scalability is presented from a performance and technology point of view. Finally, conclusions are drawn regarding the performance and viability of OBS.

1 Introduction

Since its introduction as a new switching paradigm for optical transport networks [17, 18], optical burst switching has received huge attention. During the *.com* boom in the late 1990s, prototypes and even commercial products seemed only a few years ahead. While optical packet switching (OPS) research had already started in the early 1990s but still had to overcome severe technological hurdles, optical burst switching seemed to offer the dynamics and flexibility presumably needed to cope with the exploding Internet traffic with less complex technology than OPS.

Today, transport network traffic still increases by a hundred percent per year and data has surpassed voice in traffic volume. However, the downturn of the industry has shifted the focus of operators from the introduction of highly innovative network technologies to cost-efficient operation of proven network technologies. This slowdown in network evolution has moved a potential introduction of OBS networks several years into the future. Still, a detailed assessment of the principal benefits and drawbacks of OBS is essential for defining the future evolution of metro and core networks.

During the past years, definition of optical burst switching networks has become less clear due to the large number of new proposals. Still, following concepts can be regarded as defining for OBS [7]: (i) client layer data is aggregated and assembled into variable length optical bursts in edge nodes, (ii) control header packets are signaled out-of-band,

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are processed electronically in core nodes and used to set up the switch matrix before the data bursts arrive, (iii) data bursts are asynchronously switched in core nodes and stay in the optical domain until they reach their destination edge node. An additional characteristic which is part of most approaches [17, 18] (although not in all, e. g. [9]) is one-pass reservation, i. e., burst transmission is not delayed until an acknowledgment of successful end-to-end path setup is received but is initiated shortly after the burst was assembled and the control packet was sent out. One-pass reservation is assumed for the remainder of this paper.

Bandwidth granularity and switching complexity of OBS are in between those of wavelength routing (WR) and OPS networks. With respect to wavelength routing networks, OBS provides more bandwidth flexibility, i. e., it can better adapt to changes in the traffic pattern, but needs faster switching and control technology. Regarding optical packet switching, OBS requires less complex technology as it extensively uses aggregation to form larger containers and does not mandate processing of optical inband headers. Also, in contrast to several OPS architectures, there is no need for synchronization in OBS.

The key building blocks and tasks in OBS networks are burst assembly at the edge of the network, burst reservation and scheduling as well as contention resolution in core nodes. Apart from that QoS support has extensively been worked on. In [12], those building blocks and tasks are defined and recent research contributions are discussed as well as classified.

The remainder of this paper is structured as follows: Section 2 discusses principle design options for contention resolution in OBS networks and presents results of their performance evaluation in a network scenario. Methodology and results of an integrated evaluation from a technology and performance point of view is presented in Section 3. Finally, Section 4 concludes the paper regarding performance and viability of OBS.

2 Contention Resolution in OBS Networks

In an all-optical burst switch, a reservation conflict exists if the wavelength on which a burst arrived to a node is already reserved on the designated output fiber by a different burst. In order to achieve a low burst loss probability as required in transport networks, efficient contention resolution strategies in OBS core nodes have to implemented as OBS builds on one-pass reservation and statistical multiplexing.

2.1 Options for Contention Resolution

In principle, contention resolution in OBS networks can be performed in one of the three physical domains wavelength, space and time. In this paper, following basic strategies and further assumptions are considered (acronyms in parentheses):

- Wavelength domain: By means of wavelength conversion *(Conv)*, a burst can be sent on a different wavelength channel to the designated output fiber. Thus, all wavelength channels of an output fiber can be considered a single shared bundle of channels.
- Time domain: In a fiber delay line (*FDL*) buffer, a burst can be delayed until the contention situation is resolved and the wavelength becomes available. In contrast to buffers in the electronic domain, FDLs only provide a fixed delay and data bursts leave the FDL in the same order in which they entered, i.e., they do not have random access functionality. Like fiber links, FDL buffers can be operated using WDM.

- Space domain: In deflection routing (*Defl*), a burst is sent to a different output fiber of the node and consequently on a different route towards its destination node. Thus, deflection uses the entire network as a shared resource for contention resolution.

  Space domain can be exploited differently in multi-fiber networks, i. e., in networks with several parallel fibers interconnecting neighboring nodes. In this case, a burst can be transmitted on a different fiber of the designated output link without wavelength conversion. Due to the large number of wavelengths available on a fiber today, this option is no longer economical for reasonable network demands and is thus not considered in the following.

Apart from these basic strategies, also combinations of them can be applied. As the order in which these schemes are applied is essential, they are named by a concatenation of their acronyms. E. g., *ConvFDLDefl* refers to a scheme which tries conversion first, only if this fails it tries to buffer in an FDL and only if this also fails it tries deflection routing. Previous work showed that when combining full wavelength conversion with either FDL buffers or deflection routing conversion should always be used first [11, 19]. Thus, only schemes are compared which apply wavelength conversion first. Also, previous evaluations showed that for deflection routing improvements and penalties due to limitations regarding the number of deflections, the number of paths and even loops were marginal as long as a reasonable amount of flexibility was allowed. Thus, none of these extended strategies are used here.

2.2 Performance Evaluation

The optimal combination of different strategies to achieve low burst loss probabilities and to overcome the reduced flexibility of the optical layer compared to the electronic layer is investigated. Performance of the different basic and combined schemes is evaluated by event-driven simulation for a tightly dimensioned reference network of Germany (Fig. 1) with a total offered network traffic of 4 Tbps. Other network scenarios and dimensionings as well as broader and more detailed interpretations are presented in [14, 15].

Specifics of OBS are incorporated in the model, e. g., the FDL buffer and the output wavelength are both reserved according to just-enough-time (JET) *before* the burst enters the buffer which prioritizes buffered bursts over newly arriving bursts on the output wavelength—this is called *PriorRes* in [10]. Strategies for resource efficient wavelength selection in FDL buffers as proposed for optical packet switching [5] are not implemented as they target an optimization not required with *PriorRes* (a comparison is published in [6]). The delay of the single FDL buffer is $2h = 20\ \mu s$ and unless stated differently there are 8 wavelengths in this FDL.

Bursts are generated based on a Poisson process and burst length is exponentially distributed with mean 100 kbit, i. e., a mean burst duration of $h = 10\ \mu s$ for 10 Gbps line-rate. The delay for processing of a burst control packet is compensated by a short extra FDL of appropriate length at the input of the node. Thus, neither effects of offset reduction along the path nor effects of offset violation due to excessive deflections are considered.

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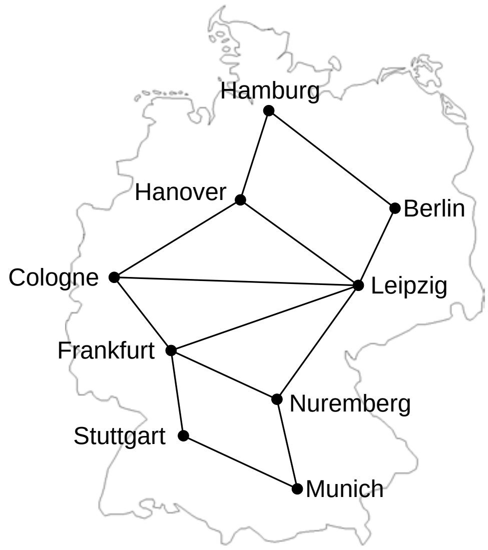

Fig. 1 Germany Network Scenario
total traffic = 4 Tbps,
mean number of λs/link = 27.15

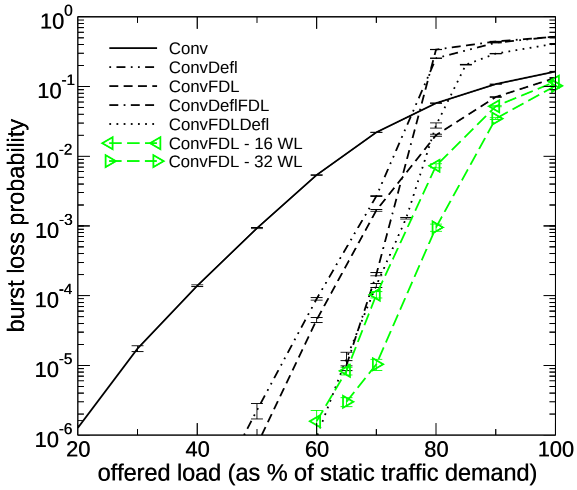

Fig. 2 Burst loss probability vs. offered load for different contention resolution schemes

Fig. 2 depicts burst loss probability versus relative offered load. For high values of load, the schemes employing deflection routing after conversion are inefficient as they produce additional load in an already highly loaded network. For low and medium values of load *ConvDefl* and *ConvFDL* yield almost identical performance and outperform *Conv* significantly due to their advanced capabilities*.* For medium values of load, it can be observed that *ConvDeflFDL* and *ConvFDLDefl* perform equally well and achieve even lower loss probabilities than the previous schemes—again due to increased flexibility.

For *ConvFDL,* Fig. 2 also depicts the impact of the number of wavelengths in the buffer FDL on burst loss probability. It can be seen that increasing this parameter from 8 to 16 and from 16 to 32 can reduce burst losses by up to an order of magnitude for medium to high load values and again make buffering significantly more efficient than deflection routing.

Concluding, the performance of contention resolution schemes is sensitive to both offered network traffic and buffer dimensioning which should be considered in their analysis. Combination of conversion with well-dimensioned FDL buffers yields lower losses than conversion with deflection routing in most cases, however at the cost of the additional buffer.

3 Node Design and Scalability

So far, relatively few work on OBS has focused on realization issues or tried to integrate realization and performance topics. However, due to the analogue operation of photonic components technological and physical constraints have to be considered assessing such new architectures and protocols. In [3, 4], a burst node architecture called Tune-and-Select (TAS) employing passive optical splitters and semiconductor optical amplifiers (SOA) as on/off gates is designed as the result of a systematic evaluation of OBS node requirements. It is also evaluated regarding physical scalability (number of fibers and number of wavelengths per fiber) as well as cascadability there.

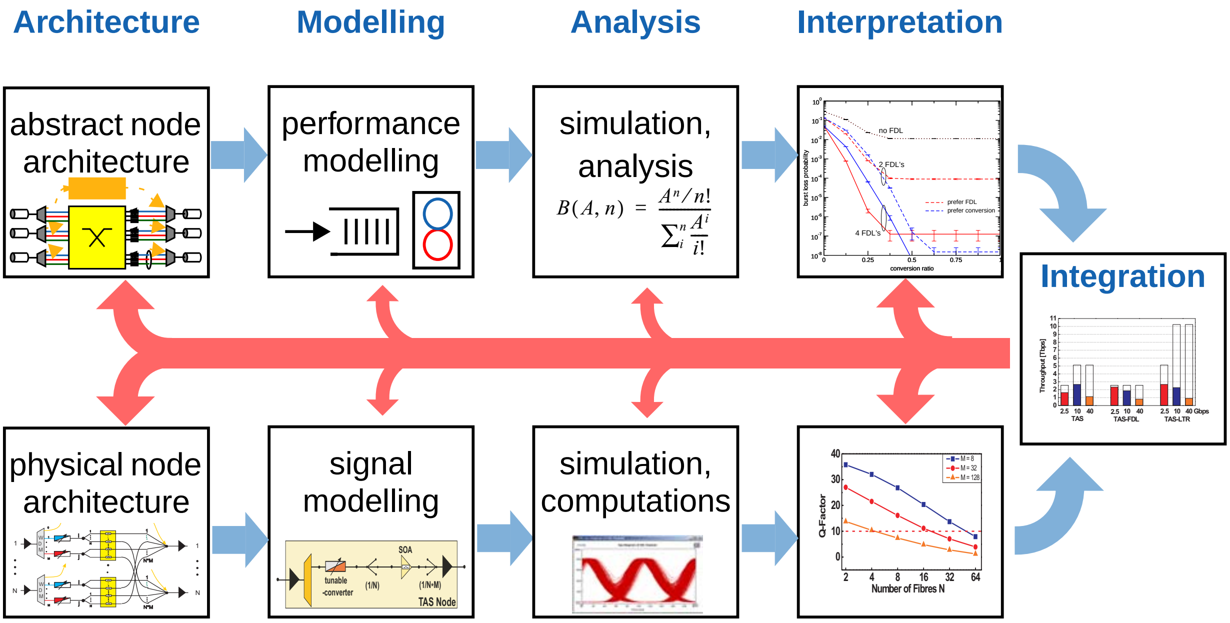

Fig. 3 Integrated performance evaluation regarding teletraffic theory (upper path) and technology (lower path)

Node scalability and thus throughput is in principle limited by several physical impairments like noise, crosstalk, amplifier saturation etc. on the signal path through a non-ideal burst switch. Specifically, in a TAS node the optical signal is broadcast towards all outputs, i. e. signal power is split by the number of outputs which makes the signal less robust against those impairments due to the reduced signal-to-noise ratio.

On the one hand, introducing additional functionality in an OBS node, e. g., an FDL buffer, requires an extension to the physical architecture similar to adding another output fiber and thus only allows for a node with a smaller number of output fibers and/or wavelengths per fiber. On the other hand, Section 2.2 shows that such advanced functionality, e. g., an FDL buffer, can effectively reduce burst loss probability which improves resource utilization.

Thus, changing the functionality and architecture of an OBS node has an impact on both the physical scalability and the traffic performance which together define the throughput performance. Consequently, an integrated analysis should be used to provide a better and more balanced view on the design and potentials of OBS nodes.

3.1 Integrated Evaluation Methodology

The methodology of the integrated evaluation approach proposed in [1, 13] is illustrated in Fig. 3 by the physical evaluation path (lower part), the traffic performance evaluation path (upper part) and the integration and feedback of their respective results.

- For a given node functionality and number of input and output fibers, signal modeling and analysis of the physical node architecture yields the maximum number of wavelengths to which the node can scale without exceeding a certain bit-error rate (BER) threshold. From this, the *maximum throughput* of the node can be calculated.

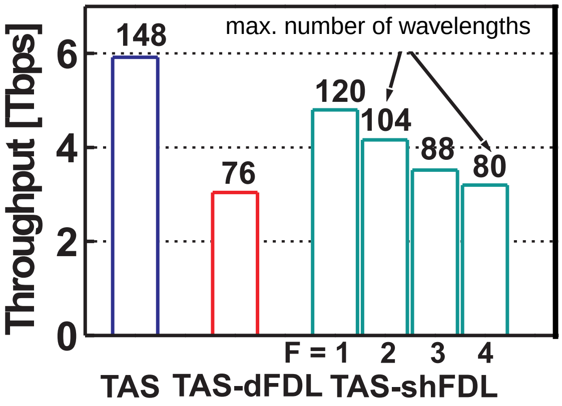

Fig. 4 Maximum and effective throughput of TAS, TAS-dFDL and TAS-shFDL

- This maximum wavelength count is used in the performance evaluation of a node with the same functionality by event-driven simulation or by teletraffic theory analysis under dynamic burst traffic. The maximum offered load is determined for which the burst loss probability stays below a certain threshold. From this, the utilization and the *effective throughput* under dynamic burst traffic can be calculated.

3.2 Integrated Evaluation

Performance evaluation is presented for an isolated node with N = 4 input and output fibers considering noise and crosstalk as physical impairments and assuming state-of-the art components [13]. The threshold for the BER is chosen to be 10^{-22} in order to have enough safety margin for impairments not considered yet, e. g. SOA dynamics [2]. The maximum acceptable burst loss probability is chosen to be 10^{-6} for this isolated node scenario as losses aggregate along a path through the network [8].

Following three TAS node configurations are considered—for a more detailed description of the architectures and a wider range of evaluations the reader is referred to [1, 13]:

- TAS: the basic architecture which only employs wavelength conversion for contention resolution.
- TAS-dFDL: this architecture assumes one single FDL buffer per output fiber in addition to full wavelength conversion.
- TAS-shFDL: this architecture assumes one FDL buffer shared among all output fibers of the node. The parameter *F* denotes the number of FDLs in the buffer.

TAS-dFDL and TAS-shFDL employ the scheme *ConvFDL*. Their basic FDL length is twice the mean burst length *2h*. In case there are several FDLs in the buffer they have increasing length $i \cdot 2h$, $i = 1, \ldots, F$ and are searched starting from the shortest FDL. Within each scenario, FDLs and output fibers have the same number of wavelengths obtained from physical analysis and indicated in Fig. 4 above the bars. Unless stated differently, all other parameters are chosen as described in Section 2.1.

Fig. 4 presents the maximum number of wavelengths, the *maximum throughput* and the *effective throughput* for the three architectures. In principle, the evaluation shows that maximum and effective throughput can be in the order of 3–6 Tbps.

As shown in Fig. 2 for a given node dimensioning, application of FDLs in an OBS node (TAS-dFDL or TAS-shFDL) can effectively reduce burst loss probability and improve utilization. However, when primarily looking at maximum/effective throughput the node dimensioning is no longer fixed but there is the direct link between node functionality and maximum node size described above.

Following observations can be made: first, the scalability analysis indicates that both options with FDL buffers reduce the node size and the maximum throughput (total height of bars) compared to the basic TAS architecture as expected. Second, although utilization, i. e., the ratio of effective and maximum throughput indicated by the relative height of the shaded bars compared to the white bars, shows the expected improvement the effective throughput values of the TAS nodes with FDLs are approx. equal to or even below the value of the basic TAS architecture. Finally, increasing the number of FDLs in the TAS-shFDL node yields lower losses and higher utilization but in absolute terms also a lower effective throughput.

4 Conclusions

This paper surveys work on contention resolution and node scalability performed within the TransiNet project. It is shown that both topics are closely linked and Section 2 and Section 3 present two different ways for approaching a viability and performance evaluation. Section 2 compares different strategies for contention resolution based on the impact of offered network traffic on burst loss probability assuming a given node and network dimensioning. It is shown that wavelength conversion only is not sufficient to operate an OBS networks efficiently with low burst loss probabilities. Deflection routing or a small FDL buffer improve performance such that an offered traffic of approx. 55 % of the static traffic demand is acceptable at an end-to-end burst loss probability of 10^{-5}. Combining both schemes or increasing the FDL buffer capacity allows the offered traffic to be raised to approx. 65–70 % of the static traffic demand.

Section 3 shows results of an integrated performance evaluation from a technology and traffic performance point of view. Regarding throughput, it identifies the most scalable among several TAS candidate node architectures with different functionality—in contrast to Section 2 a high utilization is not the primary goal here. The OBS nodes considered can scale to a maximum/effective throughput of approx. 3–6 Tbps almost independent of their functionality. This range can be regarded sufficient for a node operating at a fine granularity of 10s of kByte. Depending on the cost of transmission capacity on links vs. node resources, e. g. an FDL buffer, the most appropriate node architecture and functionality can be selected.

Based on the presented work, further evaluations of the implementation feasibility and economical attractiveness can be built. Those would have to include trends of current and future applications regarding bandwidth capacity and dynamics as well as provisioning time requirements. Also, the operational costs would have to be incorporated.

Acknowledgements

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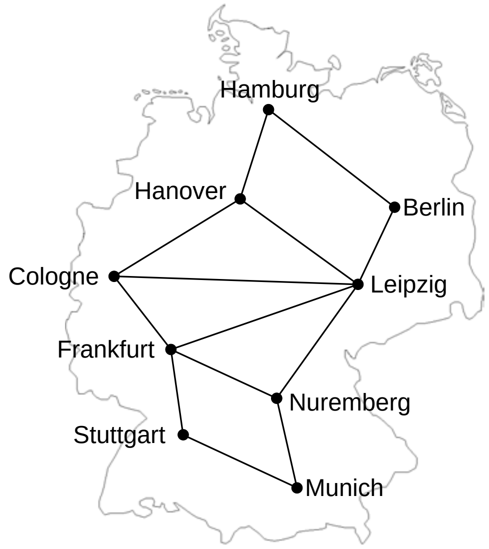

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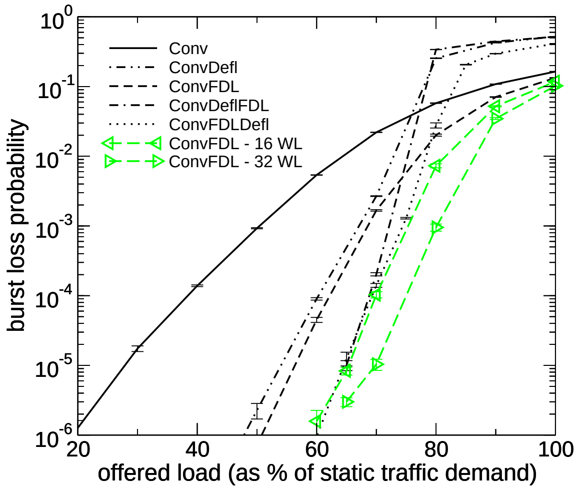

Fig. 2 Burst loss probability vs. offered load for different contention resolution schemes

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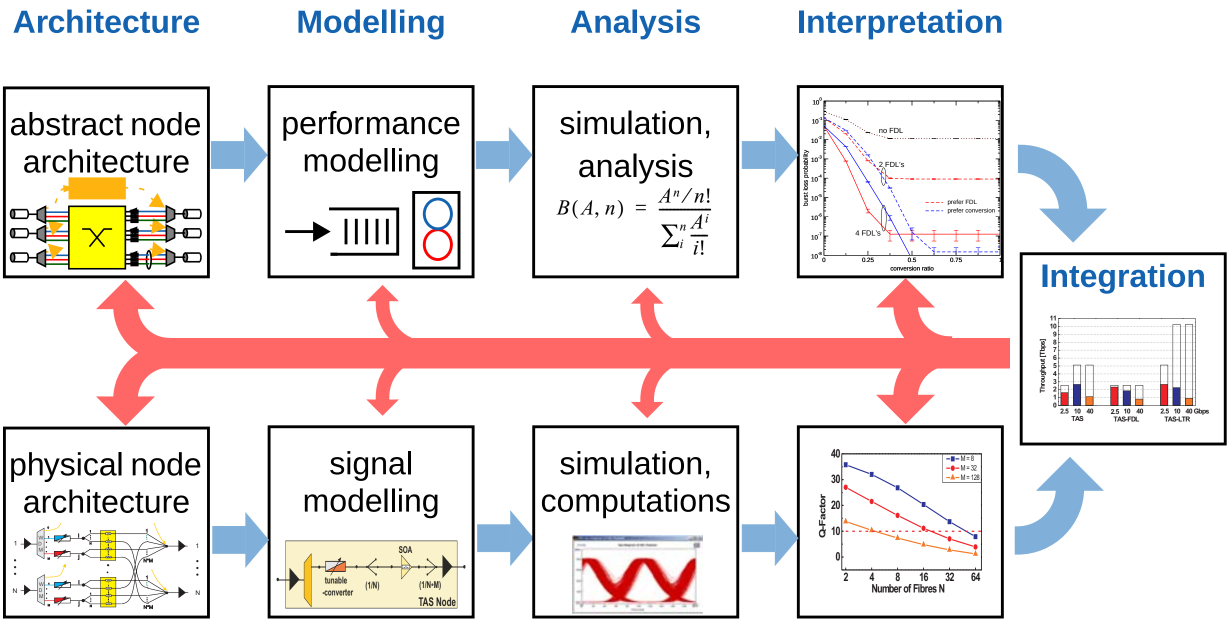

Fig. 3 Integrated performance evaluation regarding teletraffic theory (upper path) and technology (lower path)

Node scalability and thus throughput is in principle limited by several physical impairments like noise, crosstalk, amplifier saturation etc. on the signal path through a non-ideal burst switch. Specifically, in a TAS node the optical signal is broadcast towards all outputs, i. e. signal power is split by the number of outputs which makes the signal less robust against those impairments due to the reduced signal-to-noise ratio.

On the one hand, introducing additional functionality in an OBS node, e. g., an FDL buffer, requires an extension to the physical architecture similar to adding another output fiber and thus only allows for a node with a smaller number of output fibers and/or wavelengths per fiber. On the other hand, Section 2.2 shows that such advanced functionality, e. g., an FDL buffer, can effectively reduce burst loss probability which improves resource utilization.

Thus, changing the functionality and architecture of an OBS node has an impact on both the physical scalability and the traffic performance which together define the throughput performance. Consequently, an integrated analysis should be used to provide a better and more balanced view on the design and potentials of OBS nodes.

3.1 Integrated Evaluation Methodology

The methodology of the integrated evaluation approach proposed in [1, 13] is illustrated in Fig. 3 by the physical evaluation path (lower part), the traffic performance evaluation path (upper part) and the integration and feedback of their respective results.

- For a given node functionality and number of input and output fibers, signal modeling and analysis of the physical node architecture yields the maximum number of wavelengths to which the node can scale without exceeding a certain bit-error rate (BER) threshold. From this, the *maximum throughput* of the node can be calculated.

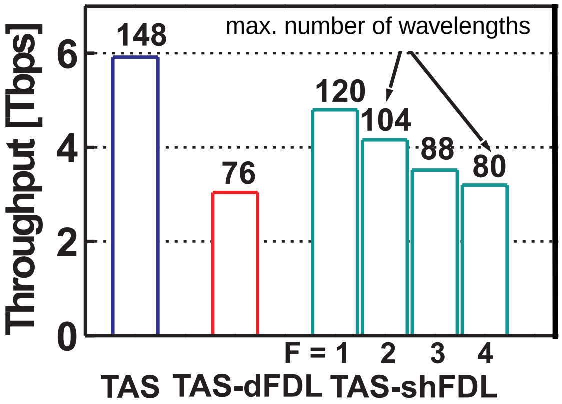

Fig. 4 Maximum and effective throughput of TAS, TAS-dFDL and TAS-shFDL

- This maximum wavelength count is used in the performance evaluation of a node with the same functionality by event-driven simulation or by teletraffic theory analysis under dynamic burst traffic. The maximum offered load is determined for which the burst loss probability stays below a certain threshold. From this, the utilization and the *effective throughput* under dynamic burst traffic can be calculated.

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- TAS-shFDL: this architecture assumes one FDL buffer shared among all output fibers of the node. The parameter *F* denotes the number of FDLs in the buffer.

TAS-dFDL and TAS-shFDL employ the scheme *ConvFDL*. Their basic FDL length is twice the mean burst length *2h*. In case there are several FDLs in the buffer they have increasing length $i \cdot 2h$, $i = 1, \ldots, F$ and are searched starting from the shortest FDL. Within each scenario, FDLs and output fibers have the same number of wavelengths obtained from physical analysis and indicated in Fig. 4 above the bars. Unless stated differently, all other parameters are chosen as described in Section 2.1.

Fig. 4 presents the maximum number of wavelengths, the *maximum throughput* and the *effective throughput* for the three architectures. In principle, the evaluation shows that maximum and effective throughput can be in the order of 3–6 Tbps.

As shown in Fig. 2 for a given node dimensioning, application of FDLs in an OBS node (TAS-dFDL or TAS-shFDL) can effectively reduce burst loss probability and improve utilization. However, when primarily looking at maximum/effective throughput the node dimensioning is no longer fixed but there is the direct link between node functionality and maximum node size described above.

Following observations can be made: first, the scalability analysis indicates that both options with FDL buffers reduce the node size and the maximum throughput (total height of bars) compared to the basic TAS architecture as expected. Second, although utilization, i. e., the ratio of effective and maximum throughput indicated by the relative height of the shaded bars compared to the white bars, shows the expected improvement the effective throughput values of the TAS nodes with FDLs are approx. equal to or even below the value of the basic TAS architecture. Finally, increasing the number of FDLs in the TAS-shFDL node yields lower losses and higher utilization but in absolute terms also a lower effective throughput.

4 Conclusions

This paper surveys work on contention resolution and node scalability performed within the TransiNet project. It is shown that both topics are closely linked and Section 2 and Section 3 present two different ways for approaching a viability and performance evaluation. Section 2 compares different strategies for contention resolution based on the impact of offered network traffic on burst loss probability assuming a given node and network dimensioning. It is shown that wavelength conversion only is not sufficient to operate an OBS networks efficiently with low burst loss probabilities. Deflection routing or a small FDL buffer improve performance such that an offered traffic of approx. 55 % of the static traffic demand is acceptable at an end-to-end burst loss probability of 10^{-5}. Combining both schemes or increasing the FDL buffer capacity allows the offered traffic to be raised to approx. 65–70 % of the static traffic demand.

Section 3 shows results of an integrated performance evaluation from a technology and traffic performance point of view. Regarding throughput, it identifies the most scalable among several TAS candidate node architectures with different functionality—in contrast to Section 2 a high utilization is not the primary goal here. The OBS nodes considered can scale to a maximum/effective throughput of approx. 3–6 Tbps almost independent of their functionality. This range can be regarded sufficient for a node operating at a fine granularity of 10s of kByte. Depending on the cost of transmission capacity on links vs. node resources, e. g. an FDL buffer, the most appropriate node architecture and functionality can be selected.

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Acknowledgements

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in Proccedings of the 9th European Conference on Networks & Optical Communications (NOC), Eindhoven/NL, June/July 2004

Viability and Performance of Optical Burst Switching

Christoph M. Gauger*, University of Stuttgart
Institute of Communication Networks and Computer Engineering (IKR)

Abstract

Optical burst switching (OBS) has been proposed in the late 1990s as a novel photonic network architecture directed towards efficient transport of IP traffic. OBS aims at cost-efficient and dynamic provisioning of sub-wavelength granularity by optimally combining electronics and optics. This paper surveys work on contention resolution and node scalability performed within the TransiNet project. Both topics represent key challenges in highly dynamic optical networks and assessing their performance is critical for deciding on their viability. After a brief introduction to OBS, results of studies on the effectiveness of contention resolution in a Germany reference network scenario are presented. Then, node scalability is presented from a performance and technology point of view. Finally, conclusions are drawn regarding the performance and viability of OBS.

1 Introduction

Since its introduction as a new switching paradigm for optical transport networks [17, 18], optical burst switching has received huge attention. During the *.com* boom in the late 1990s, prototypes and even commercial products seemed only a few years ahead. While optical packet switching (OPS) research had already started in the early 1990s but still had to overcome severe technological hurdles, optical burst switching seemed to offer the dynamics and flexibility presumably needed to cope with the exploding Internet traffic with less complex technology than OPS.

Today, transport network traffic still increases by a hundred percent per year and data has surpassed voice in traffic volume. However, the downturn of the industry has shifted the focus of operators from the introduction of highly innovative network technologies to cost-efficient operation of proven network technologies. This slowdown in network evolution has moved a potential introduction of OBS networks several years into the future. Still, a detailed assessment of the principal benefits and drawbacks of OBS is essential for defining the future evolution of metro and core networks.

During the past years, definition of optical burst switching networks has become less clear due to the large number of new proposals. Still, following concepts can be regarded as defining for OBS [7]: (i) client layer data is aggregated and assembled into variable length optical bursts in edge nodes, (ii) control header packets are signaled out-of-band,

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are processed electronically in core nodes and used to set up the switch matrix before the data bursts arrive, (iii) data bursts are asynchronously switched in core nodes and stay in the optical domain until they reach their destination edge node. An additional characteristic which is part of most approaches [17, 18] (although not in all, e. g. [9]) is one-pass reservation, i. e., burst transmission is not delayed until an acknowledgment of successful end-to-end path setup is received but is initiated shortly after the burst was assembled and the control packet was sent out. One-pass reservation is assumed for the remainder of this paper.

Bandwidth granularity and switching complexity of OBS are in between those of wavelength routing (WR) and OPS networks. With respect to wavelength routing networks, OBS provides more bandwidth flexibility, i. e., it can better adapt to changes in the traffic pattern, but needs faster switching and control technology. Regarding optical packet switching, OBS requires less complex technology as it extensively uses aggregation to form larger containers and does not mandate processing of optical inband headers. Also, in contrast to several OPS architectures, there is no need for synchronization in OBS.

The key building blocks and tasks in OBS networks are burst assembly at the edge of the network, burst reservation and scheduling as well as contention resolution in core nodes. Apart from that QoS support has extensively been worked on. In [12], those building blocks and tasks are defined and recent research contributions are discussed as well as classified.

The remainder of this paper is structured as follows: Section 2 discusses principle design options for contention resolution in OBS networks and presents results of their performance evaluation in a network scenario. Methodology and results of an integrated evaluation from a technology and performance point of view is presented in Section 3. Finally, Section 4 concludes the paper regarding performance and viability of OBS.

2 Contention Resolution in OBS Networks

In an all-optical burst switch, a reservation conflict exists if the wavelength on which a burst arrived to a node is already reserved on the designated output fiber by a different burst. In order to achieve a low burst loss probability as required in transport networks, efficient contention resolution strategies in OBS core nodes have to implemented as OBS builds on one-pass reservation and statistical multiplexing.

2.1 Options for Contention Resolution

In principle, contention resolution in OBS networks can be performed in one of the three physical domains wavelength, space and time. In this paper, following basic strategies and further assumptions are considered (acronyms in parentheses):

- Wavelength domain: By means of wavelength conversion *(Conv)*, a burst can be sent on a different wavelength channel to the designated output fiber. Thus, all wavelength channels of an output fiber can be considered a single shared bundle of channels.
- Time domain: In a fiber delay line (*FDL*) buffer, a burst can be delayed until the contention situation is resolved and the wavelength becomes available. In contrast to buffers in the electronic domain, FDLs only provide a fixed delay and data bursts leave the FDL in the same order in which they entered, i.e., they do not have random access functionality. Like fiber links, FDL buffers can be operated using WDM.

- Space domain: In deflection routing (*Defl*), a burst is sent to a different output fiber of the node and consequently on a different route towards its destination node. Thus, deflection uses the entire network as a shared resource for contention resolution.

  Space domain can be exploited differently in multi-fiber networks, i. e., in networks with several parallel fibers interconnecting neighboring nodes. In this case, a burst can be transmitted on a different fiber of the designated output link without wavelength conversion. Due to the large number of wavelengths available on a fiber today, this option is no longer economical for reasonable network demands and is thus not considered in the following.

Apart from these basic strategies, also combinations of them can be applied. As the order in which these schemes are applied is essential, they are named by a concatenation of their acronyms. E. g., *ConvFDLDefl* refers to a scheme which tries conversion first, only if this fails it tries to buffer in an FDL and only if this also fails it tries deflection routing. Previous work showed that when combining full wavelength conversion with either FDL buffers or deflection routing conversion should always be used first [11, 19]. Thus, only schemes are compared which apply wavelength conversion first. Also, previous evaluations showed that for deflection routing improvements and penalties due to limitations regarding the number of deflections, the number of paths and even loops were marginal as long as a reasonable amount of flexibility was allowed. Thus, none of these extended strategies are used here.

2.2 Performance Evaluation

The optimal combination of different strategies to achieve low burst loss probabilities and to overcome the reduced flexibility of the optical layer compared to the electronic layer is investigated. Performance of the different basic and combined schemes is evaluated by event-driven simulation for a tightly dimensioned reference network of Germany (Fig. 1) with a total offered network traffic of 4 Tbps. Other network scenarios and dimensionings as well as broader and more detailed interpretations are presented in [14, 15].

Specifics of OBS are incorporated in the model, e. g., the FDL buffer and the output wavelength are both reserved according to just-enough-time (JET) *before* the burst enters the buffer which prioritizes buffered bursts over newly arriving bursts on the output wavelength—this is called *PriorRes* in [10]. Strategies for resource efficient wavelength selection in FDL buffers as proposed for optical packet switching [5] are not implemented as they target an optimization not required with *PriorRes* (a comparison is published in [6]). The delay of the single FDL buffer is $2h = 20\ \mu s$ and unless stated differently there are 8 wavelengths in this FDL.

Bursts are generated based on a Poisson process and burst length is exponentially distributed with mean 100 kbit, i. e., a mean burst duration of $h = 10\ \mu s$ for 10 Gbps line-rate. The delay for processing of a burst control packet is compensated by a short extra FDL of appropriate length at the input of the node. Thus, neither effects of offset reduction along the path nor effects of offset violation due to excessive deflections are considered.

The number of add/drop ports in OBS nodes is not limited. Link capacities in the network are dimensioned according to a static traffic demand matrix obtained from a population model based on shortest path routing such that blocking probabilities on all links are equal in the Erlang model [16]. In order to allow for a more systematic analysis, fiber length on all links is 200 km which translates into a propagation delay of 1 ms. Thus, FDL delay is small compared to link delay which is realistic in WAN scenarios [13].

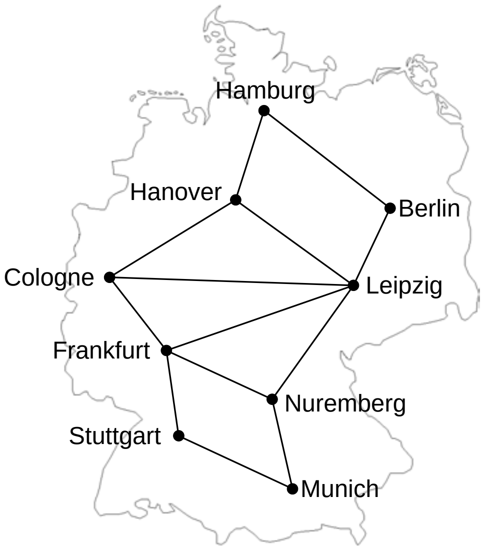

Fig. 1 Germany Network Scenario
total traffic = 4 Tbps,
mean number of λs/link = 27.15

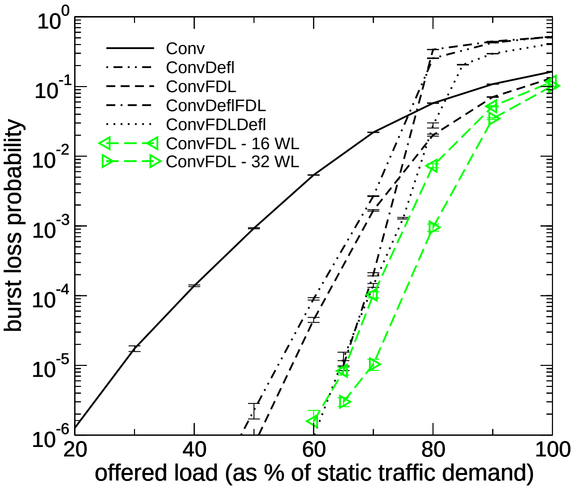

Fig. 2 Burst loss probability vs. offered load for different contention resolution schemes

Fig. 2 depicts burst loss probability versus relative offered load. For high values of load, the schemes employing deflection routing after conversion are inefficient as they produce additional load in an already highly loaded network. For low and medium values of load *ConvDefl* and *ConvFDL* yield almost identical performance and outperform *Conv* significantly due to their advanced capabilities. For medium values of load, it can be observed that *ConvDeflFDL* and *ConvFDLDefl* perform equally well and achieve even lower loss probabilities than the previous schemes—again due to increased flexibility.

For *ConvFDL,* Fig. 2 also depicts the impact of the number of wavelengths in the buffer FDL on burst loss probability. It can be seen that increasing this parameter from 8 to 16 and from 16 to 32 can reduce burst losses by up to an order of magnitude for medium to high load values and again make buffering significantly more efficient than deflection routing.

Concluding, the performance of contention resolution schemes is sensitive to both offered network traffic and buffer dimensioning which should be considered in their analysis. Combination of conversion with well-dimensioned FDL buffers yields lower losses than conversion with deflection routing in most cases, however at the cost of the additional buffer.

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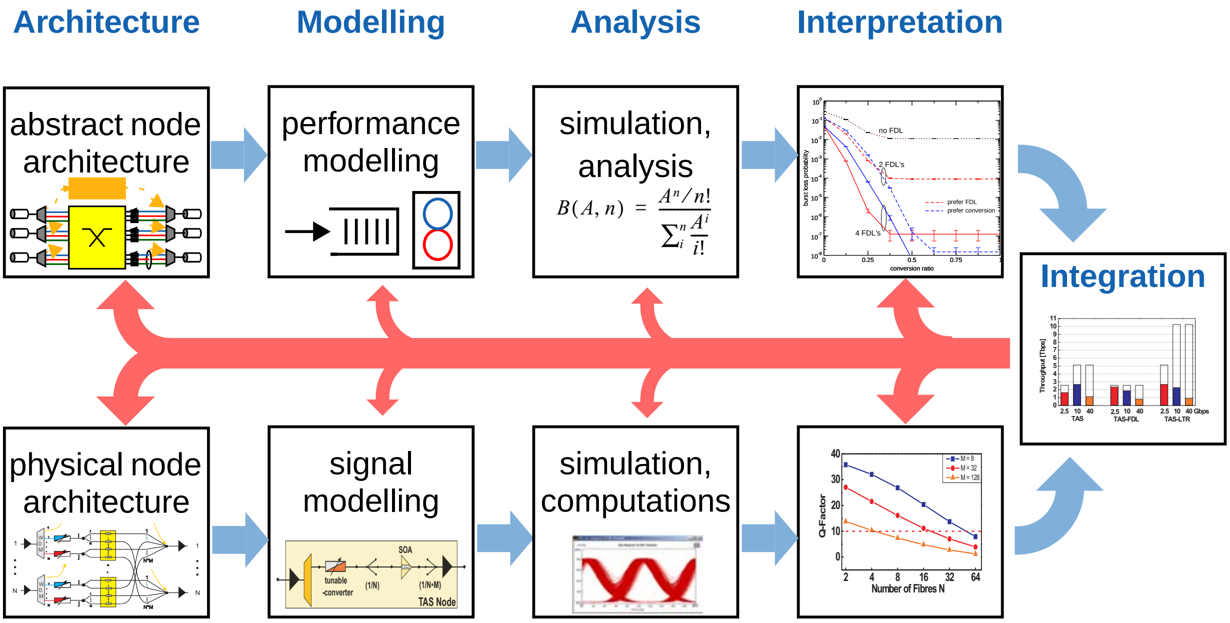

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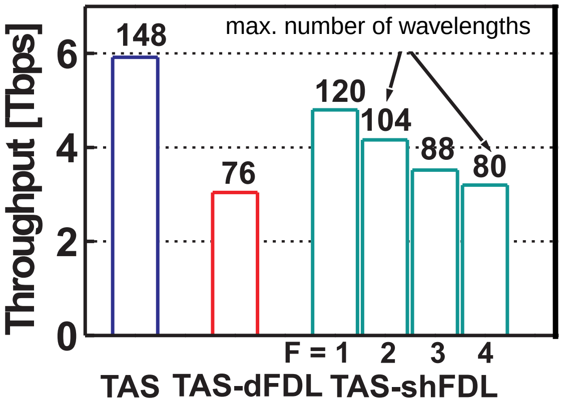

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Viability and Performance of Optical Burst Switching

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Abstract

Optical burst switching (OBS) has been proposed in the late 1990s as a novel photonic network architecture directed towards efficient transport of IP traffic. OBS aims at cost-efficient and dynamic provisioning of sub-wavelength granularity by optimally combining electronics and optics. This paper surveys work on contention resolution and node scalability performed within the TransiNet project. Both topics represent key challenges in highly dynamic optical networks and assessing their performance is critical for deciding on their viability. After a brief introduction to OBS, results of studies on the effectiveness of contention resolution in a Germany reference network scenario are presented. Then, node scalability is presented from a performance and technology point of view. Finally, conclusions are drawn regarding the performance and viability of OBS.

1 Introduction

Since its introduction as a new switching paradigm for optical transport networks [17, 18], optical burst switching has received huge attention. During the *.com* boom in the late 1990s, prototypes and even commercial products seemed only a few years ahead. While optical packet switching (OPS) research had already started in the early 1990s but still had to overcome severe technological hurdles, optical burst switching seemed to offer the dynamics and flexibility presumably needed to cope with the exploding Internet traffic with less complex technology than OPS.

Today, transport network traffic still increases by a hundred percent per year and data has surpassed voice in traffic volume. However, the downturn of the industry has shifted the focus of operators from the introduction of highly innovative network technologies to cost-efficient operation of proven network technologies. This slowdown in network evolution has moved a potential introduction of OBS networks several years into the future. Still, a detailed assessment of the principal benefits and drawbacks of OBS is essential for defining the future evolution of metro and core networks.

During the past years, definition of optical burst switching networks has become less clear due to the large number of new proposals. Still, following concepts can be regarded as defining for OBS [7]: (i) client layer data is aggregated and assembled into variable length optical bursts in edge nodes, (ii) control header packets are signaled out-of-band,

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are processed electronically in core nodes and used to set up the switch matrix before the data bursts arrive, (iii) data bursts are asynchronously switched in core nodes and stay in the optical domain until they reach their destination edge node. An additional characteristic which is part of most approaches [17, 18] (although not in all, e. g. [9]) is one-pass reservation, i. e., burst transmission is not delayed until an acknowledgment of successful end-to-end path setup is received but is initiated shortly after the burst was assembled and the control packet was sent out. One-pass reservation is assumed for the remainder of this paper.

Bandwidth granularity and switching complexity of OBS are in between those of wavelength routing (WR) and OPS networks. With respect to wavelength routing networks, OBS provides more bandwidth flexibility, i. e., it can better adapt to changes in the traffic pattern, but needs faster switching and control technology. Regarding optical packet switching, OBS requires less complex technology as it extensively uses aggregation to form larger containers and does not mandate processing of optical inband headers. Also, in contrast to several OPS architectures, there is no need for synchronization in OBS.

The key building blocks and tasks in OBS networks are burst assembly at the edge of the network, burst reservation and scheduling as well as contention resolution in core nodes. Apart from that QoS support has extensively been worked on. In [12], those building blocks and tasks are defined and recent research contributions are discussed as well as classified.

The remainder of this paper is structured as follows: Section 2 discusses principle design options for contention resolution in OBS networks and presents results of their performance evaluation in a network scenario. Methodology and results of an integrated evaluation from a technology and performance point of view is presented in Section 3. Finally, Section 4 concludes the paper regarding performance and viability of OBS.

2 Contention Resolution in OBS Networks

In an all-optical burst switch, a reservation conflict exists if the wavelength on which a burst arrived to a node is already reserved on the designated output fiber by a different burst. In order to achieve a low burst loss probability as required in transport networks, efficient contention resolution strategies in OBS core nodes have to implemented as OBS builds on one-pass reservation and statistical multiplexing.

2.1 Options for Contention Resolution

In principle, contention resolution in OBS networks can be performed in one of the three physical domains wavelength, space and time. In this paper, following basic strategies and further assumptions are considered (acronyms in parentheses):

- Wavelength domain: By means of wavelength conversion *(Conv)*, a burst can be sent on a different wavelength channel to the designated output fiber. Thus, all wavelength channels of an output fiber can be considered a single shared bundle of channels.
- Time domain: In a fiber delay line (*FDL*) buffer, a burst can be delayed until the contention situation is resolved and the wavelength becomes available. In contrast to buffers in the electronic domain, FDLs only provide a fixed delay and data bursts leave the FDL in the same order in which they entered, i.e., they do not have random access functionality. Like fiber links, FDL buffers can be operated using WDM.

- Space domain: In deflection routing (*Defl*), a burst is sent to a different output fiber of the node and consequently on a different route towards its destination node. Thus, deflection uses the entire network as a shared resource for contention resolution.

  Space domain can be exploited differently in multi-fiber networks, i. e., in networks with several parallel fibers interconnecting neighboring nodes. In this case, a burst can be transmitted on a different fiber of the designated output link without wavelength conversion. Due to the large number of wavelengths available on a fiber today, this option is no longer economical for reasonable network demands and is thus not considered in the following.

Apart from these basic strategies, also combinations of them can be applied. As the order in which these schemes are applied is essential, they are named by a concatenation of their acronyms. E. g., *ConvFDLDefl* refers to a scheme which tries conversion first, only if this fails it tries to buffer in an FDL and only if this also fails it tries deflection routing. Previous work showed that when combining full wavelength conversion with either FDL buffers or deflection routing conversion should always be used first [11, 19]. Thus, only schemes are compared which apply wavelength conversion first. Also, previous evaluations showed that for deflection routing improvements and penalties due to limitations regarding the number of deflections, the number of paths and even loops were marginal as long as a reasonable amount of flexibility was allowed. Thus, none of these extended strategies are used here.

2.2 Performance Evaluation

The optimal combination of different strategies to achieve low burst loss probabilities and to overcome the reduced flexibility of the optical layer compared to the electronic layer is investigated. Performance of the different basic and combined schemes is evaluated by event-driven simulation for a tightly dimensioned reference network of Germany (Fig. 1) with a total offered network traffic of 4 Tbps. Other network scenarios and dimensionings as well as broader and more detailed interpretations are presented in [14, 15].

Specifics of OBS are incorporated in the model, e. g., the FDL buffer and the output wavelength are both reserved according to just-enough-time (JET) *before* the burst enters the buffer which prioritizes buffered bursts over newly arriving bursts on the output wavelength—this is called *PriorRes* in [10]. Strategies for resource efficient wavelength selection in FDL buffers as proposed for optical packet switching [5] are not implemented as they target an optimization not required with *PriorRes* (a comparison is published in [6]). The delay of the single FDL buffer is $2h = 20\ \mu s$ and unless stated differently there are 8 wavelengths in this FDL.

Bursts are generated based on a Poisson process and burst length is exponentially distributed with mean 100 kbit, i. e., a mean burst duration of $h = 10\ \mu s$ for 10 Gbps linerate. The delay for processing of a burst control packet is compensated by a short extra FDL of appropriate length at the input of the node. Thus, neither effects of offset reduction along the path nor effects of offset violation due to excessive deflections are considered.

The number of add/drop ports in OBS nodes is not limited. Link capacities in the network are dimensioned according to a static traffic demand matrix obtained from a population model based on shortest path routing such that blocking probabilities on all links are equal in the Erlang model [16]. In order to allow for a more systematic analysis, fiber length on all links is 200 km which translates into a propagation delay of 1 ms. Thus, FDL delay is small compared to link delay which is realistic in WAN scenarios [13].

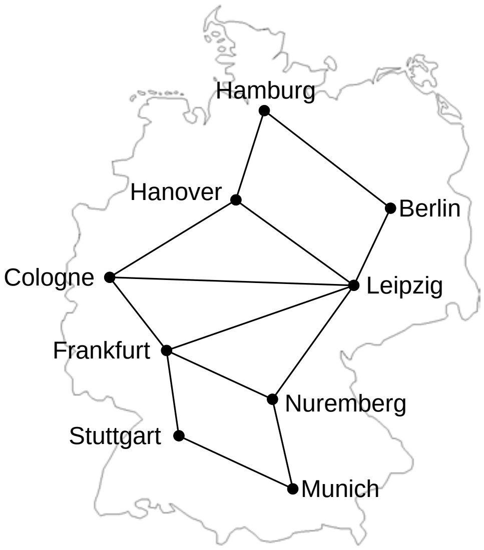

Fig. 1 Germany Network Scenario
total traffic = 4 Tbps,
mean number of λs/link = 27.15

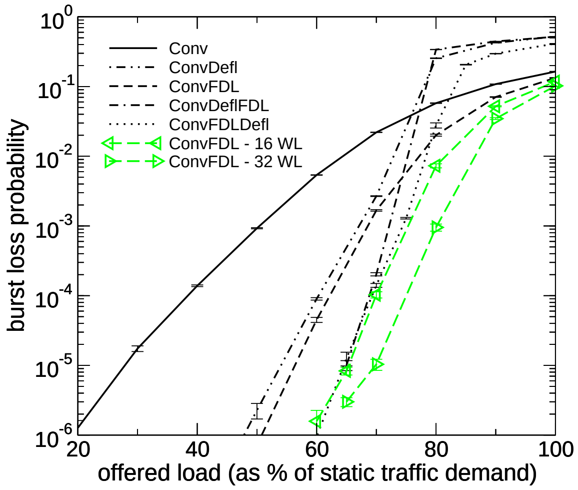

Fig. 2 Burst loss probability vs. offered load for different contention resolution schemes

Fig. 2 depicts burst loss probability versus relative offered load. For high values of load, the schemes employing deflection routing after conversion are inefficient as they produce additional load in an already highly loaded network. For low and medium values of load *ConvDefl* and *ConvFDL* yield almost identical performance and outperform *Conv* significantly due to their advanced capabilities*.* For medium values of load, it can be observed that *ConvDeflFDL* and *ConvFDLDefl* perform equally well and achieve even lower loss probabilities than the previous schemes—again due to increased flexibility.

For *ConvFDL,* Fig. 2 also depicts the impact of the number of wavelengths in the buffer FDL on burst loss probability. It can be seen that increasing this parameter from 8 to 16 and from 16 to 32 can reduce burst losses by up to an order of magnitude for medium to high load values and again make buffering significantly more efficient than deflection routing.

Concluding, the performance of contention resolution schemes is sensitive to both offered network traffic and buffer dimensioning which should be considered in their analysis. Combination of conversion with well-dimensioned FDL buffers yields lower losses than conversion with deflection routing in most cases, however at the cost of the additional buffer.

3 Node Design and Scalability

So far, relatively few work on OBS has focused on realization issues or tried to integrate realization and performance topics. However, due to the analogue operation of photonic components technological and physical constraints have to be considered assessing such new architectures and protocols. In [3, 4], a burst node architecture called Tune-and-Select (TAS) employing passive optical splitters and semiconductor optical amplifiers (SOA) as on/off gates is designed as the result of a systematic evaluation of OBS node requirements. It is also evaluated regarding physical scalability (number of fibers and number of wavelengths per fiber) as well as cascadability there.

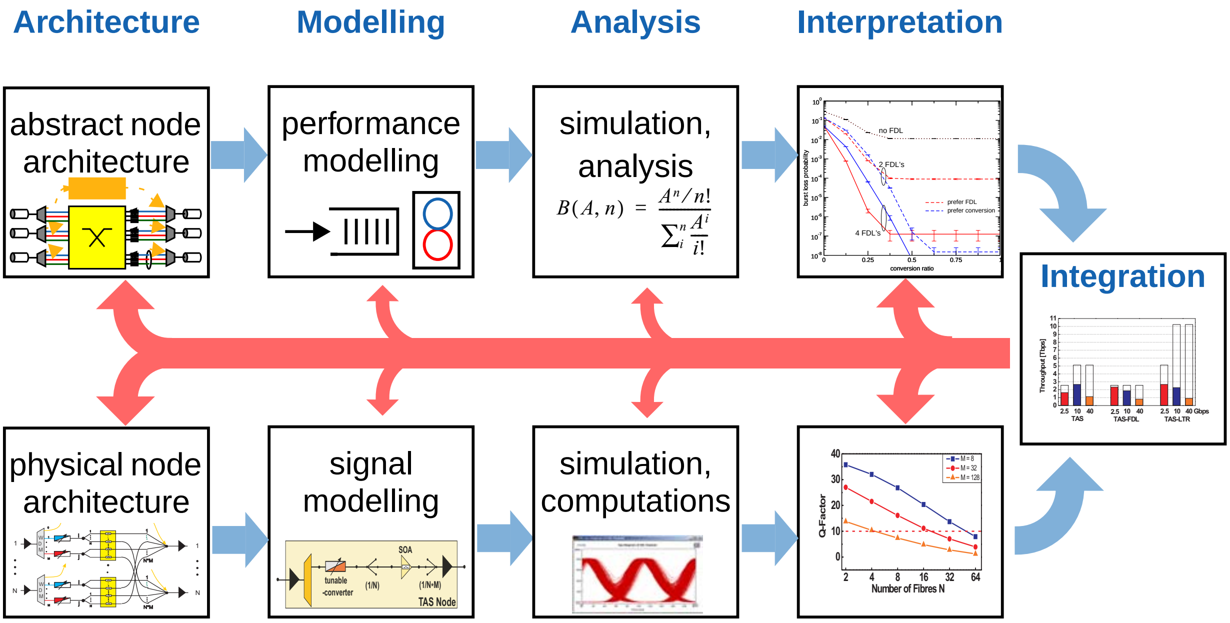

Fig. 3 Integrated performance evaluation regarding teletraffic theory (upper path) and technology (lower path)

Node scalability and thus throughput is in principle limited by several physical impairments like noise, crosstalk, amplifier saturation etc. on the signal path through a non-ideal burst switch. Specifically, in a TAS node the optical signal is broadcast towards all outputs, i. e. signal power is split by the number of outputs which makes the signal less robust against those impairments due to the reduced signal-to-noise ratio.

On the one hand, introducing additional functionality in an OBS node, e. g., an FDL buffer, requires an extension to the physical architecture similar to adding another output fiber and thus only allows for a node with a smaller number of output fibers and/or wavelengths per fiber. On the other hand, Section 2.2 shows that such advanced functionality, e. g., an FDL buffer, can effectively reduce burst loss probability which improves resource utilization.

Thus, changing the functionality and architecture of an OBS node has an impact on both the physical scalability and the traffic performance which together define the throughput performance. Consequently, an integrated analysis should be used to provide a better and more balanced view on the design and potentials of OBS nodes.

3.1 Integrated Evaluation Methodology

The methodology of the integrated evaluation approach proposed in [1, 13] is illustrated in Fig. 3 by the physical evaluation path (lower part), the traffic performance evaluation path (upper part) and the integration and feedback of their respective results.

- For a given node functionality and number of input and output fibers, signal modeling and analysis of the physical node architecture yields the maximum number of wavelengths to which the node can scale without exceeding a certain bit-error rate (BER) threshold. From this, the *maximum throughput* of the node can be calculated.

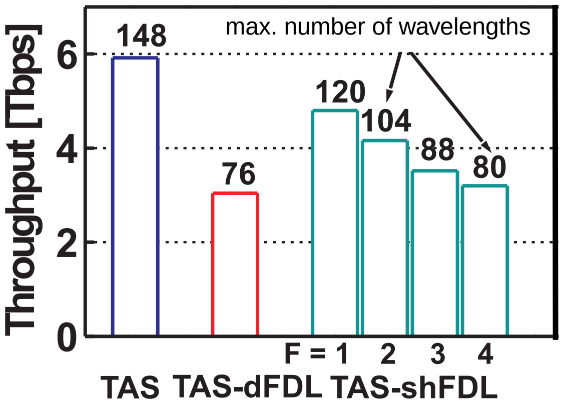

Fig. 4 Maximum and effective throughput of TAS, TAS-dFDL and TAS-shFDL

- This maximum wavelength count is used in the performance evaluation of a node with the same functionality by event-driven simulation or by teletraffic theory analysis under dynamic burst traffic. The maximum offered load is determined for which the burst loss probability stays below a certain threshold. From this, the utilization and the *effective throughput* under dynamic burst traffic can be calculated.

3.2 Integrated Evaluation

Performance evaluation is presented for an isolated node with N = 4 input and output fibers considering noise and crosstalk as physical impairments and assuming state-of-the art components [13]. The threshold for the BER is chosen to be 10^{-22} in order to have enough safety margin for impairments not considered yet, e. g. SOA dynamics [2]. The maximum acceptable burst loss probability is chosen to be 10^{-6} for this isolated node scenario as losses aggregate along a path through the network [8].

Following three TAS node configurations are considered—for a more detailed description of the architectures and a wider range of evaluations the reader is referred to [1, 13]:

- TAS: the basic architecture which only employs wavelength conversion for contention resolution.
- TAS-dFDL: this architecture assumes one single FDL buffer per output fiber in addition to full wavelength conversion.
- TAS-shFDL: this architecture assumes one FDL buffer shared among all output fibers of the node. The parameter *F* denotes the number of FDLs in the buffer.

TAS-dFDL and TAS-shFDL employ the scheme *ConvFDL*. Their basic FDL length is twice the mean burst length *2h*. In case there are several FDLs in the buffer they have increasing length $i \cdot 2h$, $i = 1, \ldots, F$ and are searched starting from the shortest FDL. Within each scenario, FDLs and output fibers have the same number of wavelengths obtained from physical analysis and indicated in Fig. 4 above the bars. Unless stated differently, all other parameters are chosen as described in Section 2.1.

Fig. 4 presents the maximum number of wavelengths, the *maximum throughput* and the *effective throughput* for the three architectures. In principle, the evaluation shows that maximum and effective throughput can be in the order of 3–6 Tbps.

As shown in Fig. 2 for a given node dimensioning, application of FDLs in an OBS node (TAS-dFDL or TAS-shFDL) can effectively reduce burst loss probability and improve utilization. However, when primarily looking at maximum/effective throughput the node dimensioning is no longer fixed but there is the direct link between node functionality and maximum node size described above.

Following observations can be made: first, the scalability analysis indicates that both options with FDL buffers reduce the node size and the maximum throughput (total height of bars) compared to the basic TAS architecture as expected. Second, although utilization, i. e., the ratio of effective and maximum throughput indicated by the relative height of the shaded bars compared to the white bars, shows the expected improvement the effective throughput values of the TAS nodes with FDLs are approx. equal to or even below the value of the basic TAS architecture. Finally, increasing the number of FDLs in the TAS-shFDL node yields lower losses and higher utilization but in absolute terms also a lower effective throughput.

4 Conclusions

This paper surveys work on contention resolution and node scalability performed within the TransiNet project. It is shown that both topics are closely linked and Section 2 and Section 3 present two different ways for approaching a viability and performance evaluation. Section 2 compares different strategies for contention resolution based on the impact of offered network traffic on burst loss probability assuming a given node and network dimensioning. It is shown that wavelength conversion only is not sufficient to operate an OBS networks efficiently with low burst loss probabilities. Deflection routing or a small FDL buffer improve performance such that an offered traffic of approx. 55 % of the static traffic demand is acceptable at an end-to-end burst loss probability of 10^{-5}. Combining both schemes or increasing the FDL buffer capacity allows the offered traffic to be raised to approx. 65–70 % of the static traffic demand.

Section 3 shows results of an integrated performance evaluation from a technology and traffic performance point of view. Regarding throughput, it identifies the most scalable among several TAS candidate node architectures with different functionality—in contrast to Section 2 a high utilization is not the primary goal here. The OBS nodes considered can scale to a maximum/effective throughput of approx. 3–6 Tbps almost independent of their functionality. This range can be regarded sufficient for a node operating at a fine granularity of 10s of kByte. Depending on the cost of transmission capacity on links vs. node resources, e. g. an FDL buffer, the most appropriate node architecture and functionality can be selected.

Based on the presented work, further evaluations of the implementation feasibility and economical attractiveness can be built. Those would have to include trends of current and future applications regarding bandwidth capacity and dynamics as well as provisioning time requirements. Also, the operational costs would have to be incorporated.

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