Optimized Combination of Converter Pools and FDL Buffers for Contention Resolution in Optical Burst Switching

Christoph M. Gauger

University of Stuttgart, Institute of Communication Networks and Computer Engineering

ABSTRACT

Optical burst switching (OBS) has attracted interest as a transport network architecture for the future optical Internet. As OBS relies on statistical multiplexing efficient contention resolution is a key issue in order to achieve a low burst loss probability. First, this paper discusses options and key design parameters for contention resolution in OBS. Then, it evaluates the performance of OBS nodes which employ shared wavelength converter pools and simple fiber delay line (FDL) buffers. Finally, optimized strategies for the order of probing a wavelength converter pool and an FDL buffer for contention resolution are presented and compared. It is shown that these strategies can be used to optimize performance for a given, e. g., minimal cost, dimensioning of the wavelength converter pool and the FDL buffer.

Keywords: WDM, Optical Burst Switching, Contention Resolution, Wavelength Conversion, Fiber Delay Lines

1. INTRODUCTION

Optical Burst Switching has been proposed as a new switching paradigm[1] for photonic networks and has emerged as a candidate for the optical transport layer of the next generation Internet. Key drivers for this evolution are increasing bandwidth requirements, e. g., due to networked business and peer-to-peer applications as well as high-speed Internet access lines, and quality of service (QoS) requirements of future Internet services, e. g., voice-over-IP (VoIP) or distributed multimedia applications. Both requirements motivate a network technology in which optical transport capacity can be provisioned on the time-scale of IP-layer dynamics.

In OBS networks (Figure 1), these dynamics can be supported by edge nodes which aggregate traffic and assemble IP packets into variable length optical bursts as well as by core nodes which asynchronously switch these bursts. A key characteristic is the hybrid approach, in which burst control packets are signaled out of band and processed electronically while data bursts stay in the optical domain until they reach their destination node. According to one-pass reservation in OBS, 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. The time between control packet and burst transmission is referred to as offset time and can be used to compensate processing times in core nodes or to allow QoS service differentiation.[2]

Bandwidth granularity and switching complexity of OBS are in between those of wavelength routing and optical packet switching (OPS) networks respectively. 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 optical header processing. Also, in contrast to several OPS architectures, there is no need for burst synchronization in OBS.

Efficient contention resolution in OBS core nodes is essential in order to achieve a low burst blocking probability despite one-pass reservation strategy and statistical multiplexing. Previous work on OBS assumed contention resolution by *full* wavelength conversion, i. e., a dedicated wavelength converter is provided for each input or output wavelength. This provides a low burst loss probability because all wavelength channels of

---

Correspondence: E-mail: gauger@ikr.uni-stuttgart.de; Web: www.ikr.uni-stuttgart.de/~gauger, Telephone: +49 711 685 7990, Fax: +49 711 685 7983, Address: University of Stuttgart, Institute of Communication Networks and Computer Engineering, Pfaffenwaldring 47, 70569 Stuttgart, Germany

an output fiber can be shared among all bursts directed towards this output fiber.[2–6] This scheme has also been complemented by providing a number of fiber delay lines in an FDL buffer. It has been shown that even FDL buffers with rather simple functionality and low technological requirements can improve OBS performance significantly.[2,7,8] As wavelength converters are technologically complex and expensive,[9] the concept of *partial* wavelength conversion, i. e., only a limited number of wavelength converters is available in the node, can be expected to yield substantial cost savings. In this scenario, tunable wavelength converters (TWC) are shared in a converter pool and are only assigned to a wavelength channel in case of contention. The goal is to minimize the number of TWCs without or without significant degradation of performance.

In optical packet switching, partial wavelength conversion was investigated for bufferless nodes[10,11] as well as in the case of slotted operation and with fixed-length packets for nodes employing FDL buffers.[12–14] Converter pools in optical cross-connects for wavelength routing optical networks, were also the focus of intensive research.[15–17] All contributions report that depending on node dimensioning, traffic model and converter assignment strategy a substantial number of converters can be saved and that the complexity of FDL buffers in OPS can be reduced compared to the case without wavelength conversion. This paper evaluates shared converter pools for OBS core nodes which asynchronously switch variable length optical bursts. For an OBS node which combines an FDL buffer and a converter pool (Figure 2), their optimal combination for contention resolution is studied in depth.

The remainder of this paper is organized as follows: In Section 2, options and key design parameters for contention resolution in OBS nodes are discussed. Section 3 describes the node model and reservation strategies used for performance evaluation. The impact of the number of available converters on burst loss probability is evaluated in Section 4.1 while Section 4.2 focuses on the combination of a converter pool and an FDL buffer. Section 5 summarizes this work and presents open questions for future research.

2. CONTENTION RESOLUTION IN OPTICAL BURST SWITCHING

2.1. Options for Contention Resolution

Optical burst switching inherently relies on statistical multiplexing in order to achieve good utilization in presence of bursty traffic. As a consequence, temporary overload situations called contention situations occur which have to be resolved. In an all-optical burst switch, a reservation conflict exists if the wavelength on which a burst arrived to he node is blocked on the designated output fiber by a different burst. Such a contention situation can be resolved in one or several of the following three domains:

- *Wavelength domain:* By means of a wavelength converter, 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 an 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.
- *Space domain:* In deflection routing, 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. neighboring nodes are connected by several parallel fibers. In this case, a burst can be transmitted on a different fiber of the designated output link without wavelength conversion.

While wavelength conversion and buffering are focused on in this paper deflection routing is not considered in the following. An investigation comparing the efficiency of different contention resolution strategies showed that deflection routing results in only limited improvement[3] in contrast to significant improvement for wavelength conversion or buffering. Also, deflection routing does not resolve contention locally in a single node but reroutes over-load traffic to neighboring nodes. Therefore, its performance depends heavily on network topology and routing strategy. Most investigations of deflection routing are related to regular topology interconnection networks, e. g., Manhattan Street (MSN) or shuffle networks.[18–20] In a Pan-European network with an irregular topology, deflection routing was investigated for a node with wavelength conversion, an FDL buffer and slotted operation.[21] Results show that deflection can mitigate losses and reduce the size of FDL buffers. However, the critical dependence on network topology mentioned above is also quantified. Compared to slotted operation, it is reported in literature that unslotted operation can lead to severe performance degradation.[19]

2.2. Key Design and Dimensioning Parameters

Performance of contention resolution in an OBS node is influenced by several parameters. The following list provides an overview of the key influencing parameters and strategies:

- *Node architecture:* In all-optical nodes, architecture and functionality are closely related to physical realization, e. g., some node architectures trade-off wavelength conversion by the number of gates in the switch matrix and vice versa.[12, 22, 23] In order to obtain fundamental results for the performance of contention resolution strategies in OBS nodes, the abstract node model described in Section 3 is chosen. Here, dimensioning parameters are the number of input and output fibers as well as the number of wavelength channels per fiber.

- *Wavelength conversion capability:* Nodes can provide no, full or partial wavelength conversion. In the latter case, converters are organized in a converter pool, for which the number of converters is an essential parameter. A technological parameter is that wavelength converters can either convert from any input wavelength to any output wavelength, within a limited conversion range[3, 24] or to a fixed output wavelength only.

- *FDL buffer:* OBS nodes can employ no buffers at all or FDL buffers of different complexity and architecture. FDL buffers are categorized in feedback and feed-forward structures and are either dedicated to an input or an output fiber or shared per node.[7, 25] They are characterized by the number and individual delays of the FDLs in the buffer as well as by the number of wavelengths per FDL.

- *Reservation strategy:* The reservation strategy for resources comprises both, the selection of resources as well as the bookkeeping of reserved bursts. In OBS, several strategies for output channel reservation were proposed and investigated.[4] Due to similar requirements, they can also be applied to wavelength converters and FDL buffer reservation. Independent of the reservation scheme, all resources occupied by a burst have to be reserved in a coordinated way with respect to wavelength and time. Regarding FDL buffers, this means that an output channel has to be reserved for the time when the burst leaves the FDL. Here, an additional degree of freedom exists: this output channel can be either reserved before the burst enters the FDL (referred to as *PreRes*) or just before it leaves the FDL (*PostRes*).[7]

2.3. Combination of Converter Pools and FDL Buffers

In an OBS node with a converter pool and an FDL buffer, both resources can be probed in different orders for contention resolution. This can be used to optimize performance for different node dimensioning scenarios, e.g., scenarios with only few converters but more FDLs or vice versa. For a burst which cannot be directly sent to the output fiber on the original wavelength three options for contention resolution and successful burst transmission exist and can be categorized as follows: a. transmission on the original wavelength after buffering, b. transmission after wavelength conversion without buffering, and c. transmission after wavelength conversion and buffering. These three options have been illustrated in Figure 3 (left) for a node which can perform wavelength conversion and which has an FDL buffer with two FDLs. The oval areas represent the output fiber ("no FDL") and the two FDLs respectively with M wavelengths each. The four sectors marked by the dashed lines represent transmission on the original wavelength or after contention resolution using one of the options a.–c. Note that within each category several possibilities for successful burst transmission exist.

Contention resolution applying buffering without conversion (option a.) and conversion without buffering (option b.) uses one resource while applying conversion plus buffering (option c.) uses two. The latter case also includes the case of conversion both before and after buffering which results in three resources in total. However, this will not be considered in the following as the focus here is on minimizing resources for contention resolution.

In case transmission on the original wavelength is blocked, several strategies for the order of probing options b.–c. can be defined. In a strategy called *minDelay*, the main goal is to minimize transfer time by preferably applying wavelength conversion. Only if there is currently no converter available or all output wavelength channels are currently busy does this strategy probe the FDL buffer starting from the minimum delay FDL and the original wavelength as indicated by the arrows in Figure 3 (center). Thus, *minDelay* applies the options for contention resolution in the sequence b., a., c. In the strategy *minConv*, the main goal is to minimize converter usage by probing the FDL buffer on the original wavelength first. Only if the burst cannot be reserved on the original wavelength using the FDL buffer, wavelength conversion is probed. In case a wavelength converter has to be used, *minConv* also seeks to minimize delay as illustrated by the arrows in Figure 3 (right). This corresponds to the sequence a., b., c. for contention resolution. Apart from *minDelay* and *minConv* several other strategies with a different order of probing can be defined optimizing for other objectives.

3. MODEL FOR PERFORMANCE EVALUATION

The abstract model of an OBS node with a converter pool and an FDL buffer is depicted in Figure 2 and used for performance evaluation. The node has a non-blocking switching matrix, N single fiber input and output links and M wavelength channels per fiber. The converter pool comprises N_C tunable wavelength converters which can be shared among all wavelength channels of this node and which can convert over the entire range of wavelengths. In order to compare performance of nodes with different dimensioning, the *conversion ratio* r_c is used: it is defined as the ratio of converters in the pool, N_C, and the total number of output wavelength channels that share this converter pool, $r_c = N_C/(N \cdot M)$.

The FDL feedback buffer has N_F fiber delay lines with basic delay b and linearly increasing FDL delays, i. e., FDL i has delay $i \cdot b$, $i = 1, \ldots, N_F$. FDLs employ WDM with M wavelength channels per FDL. In order to make results applicable to a wide range of architectures, no further architectural details of the optical switching matrix, the converter pool or the FDL buffer are included in the model.

Wavelength channels on an output fiber and in an FDL as well as converters are reserved according to the just-enough-time (JET) reservation strategy.[8, 26] It considers the exact predetermined start and end times of each burst for reservation, which allows to reserve bursts in gaps between other already reserved bursts and leads to most efficient utilization of resources. This is a key difference to most work on FDL buffers in OPS[27] as OPS does not use a flexible reservation scheme like JET.

Resources for transmission on the output fiber, for potential buffering and wavelength conversion have to be reserved in a coordinated way. It is assumed that a burst uses the same wavelength in the FDL buffer and on the output fiber, i. e., a potential wavelength conversion takes place before buffering. Also, all resources are reserved when the control packet arrives to the node, i. e., in case of an FDL buffer according to the *PreRes* strategy. Reserving the output channel for a buffered burst using *PreRes*, results in an early reservation and a priorization similar to offset-based QoS,[7] i. e., if a burst can find an idle wavelength in a buffer FDL it can also reserve an output wavelength channel with high probability.

4. PERFORMANCE EVALUATION AND RESULTS

In this section, first the simulation scenario is introduced. Then, partial wavelength conversion using a shared converter pool is evaluated in principle. Finally, the optimized combination of conversion and buffering is studied for different converter pool and FDL buffer dimensionings with respect to burst loss probability and transfer time.

Performance is evaluated by discrete event simulation of the model described above. The tool is realized in C++ and based on a simulation library[28] providing support for simulation control, traffic generation as well as statistical evaluation. In the simulation, control packets of bursts arrive in a stream according to a Poisson process. Only one service class is considered and the offset between control packet and burst is assumed to be the same for all bursts. Burst length is negative-exponentially distributed with mean 100 kbit, i. e., a mean transmission time of $h = 10\,\mu$s on a 10 Gbps line. The term *load* refers to offered load per wavelength and is given with respect to the capacity of a wavelength channel. Destination of bursts is uniformly distributed over all N output fibers. Also, selection of the wavelength on which a burst arrives to the node follows a uniform distribution. Eight wavelength channels per output fiber and per FDL are used except for Figure 5 in which there are 16 wavelengths per output fiber. Unless stated differently, graphs include 95%-confidence intervals based on the batch simulation method.

4.1. Principal Behavior of a Shared Converter Pool

Burst loss probability is shown in Figure 4 for 8 wavelengths and in Figure 5 for 16 wavelengths versus the conversion ratio $r_c = N_C/(N \cdot M)$ for different numbers of output fibers and values of load. Both, for 8 and 16 wavelength channels, loss probability decreases steadily with an increasing number of converters until it reaches a lower boundary. In case of load 0.4, this boundary is reached at conversion ratios of approximately 0.25–0.5, i. e., between 50% and 75% of the maximum number of converters can be saved. For higher values of load the lower boundary is only reached for higher conversion ratios.

Independent of load and number of wavelengths, the lower boundary is reached for a smaller conversion ratio when increasing the number of output fibers. This is due to the multiplexing gain obtained from the larger absolute number of converters in the pool. The curve for a single output fiber is included for reference and corresponds to a converter pool which is only shared per output link. Obviously, this is not a viable realization as converter saving is marginal.

When comparing respective curves for 8 and 16 wavelength channels it can be seen that the lower boundary is reached at approximately identical conversion ratios. However, loss probability reaches a much smaller lower boundary for 16 wavelength channels which is explained by the multiplexing gain of the larger wavelength bundle.

In order to quantify the dependence on the number of output fibers and to obtain values for the number of converters needed in order not to exceed a certain penalty in loss probability, an *effective conversion ratio* is introduced. It is defined as the conversion ratio which results in an only 10% higher loss probability than the case of full conversion. Figure 6 depicts the effective conversion ratio versus the number of output fibers for 8 and 16 wavelengths as well as for a load of 0.4 and 0.6. No confidence intervals are provided as data values were extracted from graphs after an interpolation step. For load 0.4, the effective conversion ratio is less than 0.5 for more than 4 output fibers and can be as low as 0.25 which results in substantial savings of wavelength converters. Increasing the number of output fibers, i. e., scaling the node size, beyond 8 fibers leads to diminishing improvements. When increasing the load, higher values of the effective conversion ratio have to be accepted while the principal behavior regarding the number of output fibers stays unchanged.

4.2. Combination of Converter Pools and FDL Buffers

In the following, the probing strategies *minDelay* and *minConv* are compared for a combination of wavelength converter pool and FDL buffer. For all graphs, a node with $N = 8$ output fibers, FDL buffers with $N_F = 2$ and 4 FDLs respectively, and $M = 8$ wavelengths per fiber and per FDL are assumed. The basic FDL delay is chosen to be $b = 20\,\mu$s, i. e., two mean burst transmission times. Note that if an FDL buffer is applied the maximum number of converters in a node is the sum of all wavelength and all FDL channels. However, in order to receive results which are comparable to those in the previous section, the conversion ratio, r_c, is still calculated with respect to $N \cdot M$, i. e. the total number of wavelength channels on output fibers. Except for Figure 9, offered load is set to 0.4.

Figure 7 depicts burst loss probability for *minDelay* and *minConv* versus the conversion ratio. The case without an FDL buffer for which both strategies are identical is included for reference. First, it can be seen that the combination of a shared converter pool and an FDL buffer has a significantly reduced burst loss probability compared to the bufferless case. Thus, a given burst loss probability can be achieved with an even smaller number of converters in the pool. For conversion ratios up to 0.3 for 2 FDLs and 0.4 for 4 FDLs, the strategy *minConv* leads to a lower loss probability than the *minDelay* strategy. In case of 4 FDLs, this improvement can be greater than an order of magnitude. However, for a large number of converters the *minDelay* strategy performs significantly better but reaches the lower boundary only for a much larger value of the conversion ratio. This can be explained by the fact that the strategy *minConv* economizes on converter usage while *minDelay* extensively uses converters.

Figure 8 analyzes the impact of the number of FDLs in the buffer and clearly shows the trade-off between number of converters, number of FDLs, and probing strategy. For conversion ratios $r_c = 12.5\%$ and 25%, *minConv* outperforms *minDelay* while for a higher conversion ratio *minConv* yields a lower loss probability. It can be clearly seen that in all cases, the difference in loss probability increases when increasing the number of FDLs.

The dependence of burst loss probability on load is depicted in Figure 9 for $r_c = 0.25$. For this conversion ratio, *minConv* has a better performance up to load 0.5. From a load of 0.5 on, the improvement of *minConv* disappears and both strategies perform equally well. As can be also seen from Figure 4, the shortage of wavelength converters is severe for load 0.6 and dominates the performance of both strategies.

The different influences of the conversion ratio on burst loss probability for the two strategies can be explained by looking at the probability that a successfully transmitted burst has used wavelength conversion and the probability that it has been buffered. Both probabilities are depicted in Figure 10 for a conversion ratio of up to 0.5 and 4 FDLs. For *minDelay*, the probability of conversion increases rapidly with increasing conversion ratio until it reaches an upper bound of almost 40%. This curve differs from the curve of a node without an FDL buffer only for small conversion ratios. For *minConv*, much fewer bursts use a wavelength converter, i. e., the strategy successfully economizes on converters. Only 6% of the bursts are converted and saturation is already reached for a conversion ratio of 12.5%. The much lower probability of conversion explains the lower blocking probability of *minConv* in case of only few converters in the pool. In contrast, the probability of buffering shows an exactly opposite dependence of the conversion ratio. For *minDelay*, it decreases when the conversion ratio is increased while it stays constant at a rather high value of almost 45% for *minConv*. This relation regarding the probability of buffering can be also seen when looking at the transfer time. The higher probability of buffering of the strategy *minConv* translates into an increased mean transfer time.

Figure 11 depicts the transfer time versus the conversion ratio for 2 and 4 FDLs. When increasing the number of converters, the transfer time stays constant for *minConv* at a value which depends on the number of FDLs. For *minDelay*, it decreases until a lower boundary is reached which is independent of the number of FDLs. In this scenario, the mean transfer time is in the order of a few tens of microseconds and can be neglected compared to propagation delay in long-haul networks, assembly delay in edge nodes or processing delay in end-user terminals. Increasing the basic delay b of the FDL buffer within physical limits can further reduce loss but also leads to increased transfer times.

5. CONCLUSION AND OUTLOOK

In this paper, options and key design parameters for contention resolution in OBS nodes are classified. For an OBS node with a shared converter pool, the influence of the number of converters is evaluated first. It is shown that depending on the number of output fibers a substantial reduction in the number of wavelength converters can be achieved. When combining a converter pool and an FDL buffer the order of probing conversion and buffering introduces an additional degree of freedom. This can be exploited to optimize performance by selecting an appropriate strategy for a given dimensioning of the converter pool and the FDL buffer. The strategies *minConv* minimizing converter usage and *minDelay* minimizing delay are evaluated and compared for several system parameters. It is shown that for a converter pool with a small number of converters, *minConv* can achieve a lower burst loss probability. The reduction is greater for a larger FDL buffer but disappears for high values of load. However, this improvement regarding loss comes at the cost of an increased but still negligible transfer time.

Further work should include the investigation of different reservation strategies for converter pools and FDL buffers. Also, an analysis which integrates realization and performance issues for different node architectures should be performed. Finally, these strategies should be evaluated in a network scenario.

ACKNOWLEDGMENTS

The author would like to thank Stefan Bodamer, Klaus Dolzer, Hao Feng, Erwin Patzak and Jürgen Saniter for invaluable discussions. This work was funded within the TransiNet project by the German Bundesministerium für Bildung und Forschung under contract No. 01AK020C (www.transinet.de).

REFERENCES

1. C. Qiao and M. Yoo, "Optical burst switching (OBS)—a new paradigm for an optical Internet," *Journal of High Speed Networks* **8**, pp. 69–84, January 1999.
2. M. Yoo and C. Qiao, "QoS performance in IP over WDM networks," *IEEE Journal of Selected Areas in Communications* **18**, pp. 2062–2071, October 2000.
3. S. Yao, B. Muhkerjee, S. J. B. Yoo, and S. Dixit, "All-optical packet-switched networks: a study of contention-resolution schemes in an irregular mesh network with variable-sized packets," in *Proceedings of SPIE OptiComm 2000*, (Dallas), October 2000.
4. K. Dolzer, C. M. Gauger, J. Späth, and S. Bodamer, "Evaluation of reservation mechanisms for optical burst switching," *AEÜ International Journal of Electronics and Communications* **55**, pp. 18–26, January 2001.
5. K. Dolzer and C. M. Gauger, "On burst assembly in optical burst switching networks—a performance evaluation of just-enough-time," in *Proceedings of the 17th International Teletraffic Congress (ITC 17)*, pp. 149–160, (Salvador, Brazil), December 2001.
6. J. S. Turner, "Terabit burst switching," *Journal of High Speed Networks* **8**, pp. 3–16, January 1999.
7. C. M. Gauger, "Dimensioning of FDL buffers for optical burst switching nodes," in *Proceedings of the 5th IFIP Optical Network Design and Modeling Conference (ONDM 2002)*, (Torino), February 2002.
8. Y. Xiong, M. Vanderhoute, and C. Cankaya, "Control architecture in optical burst-switched WDM networks," *IEEE Journal of Selected Areas in Communications* **18**, pp. 1838–1851, October 2000.
9. J. M. H. Elmirghani and H. T. Mouftah, "All-optical wavelength conversion: technologies and applications in DWDM networks," *IEEE Communications Magazine* **38**, pp. 86–92, March 2000.
10. V. Eramo and M. Listanti, "Packet loss in a bufferless optical WDM switch employing shared tunable wavelength converters," *Journal of Lightwave Technology* **18**, pp. 1818–1833, December 2000.
11. K.-C. Lee and V. O. K. Li, "Optimization of a WDM optical packet switch with wavelength converters," in *Proceedings of IEEE Infocom 95*, pp. 423–430, 1995.
12. S. L. Danielsen, B. Mikkelsen, C. Joergensen, and T. Durhuus, "WDM packet switch architectures and analysis of the influence of tuneable wavelength converters on the performance," *Journal of Lightwave Technology* **15**, pp. 219–227, February 1997.
13. S. L. Danielsen, C. Joergensen, B. Mikkelsen, and K. E. Stubkjaer, "Analysis of a WDM packet switch with improved performance under bursty traffic conditions due to tuneable wavelength converters," *Journal of Lightwave Technology* **16**, pp. 729–735, May 1998.
14. S. L. Danielsen, P. B. Hansen, and K. E. Stubkjaer, "Wavelength conversion in optical packet switching," *Journal of Lightwave Technology* **16**, pp. 2095–2108, December 1998.
15. T. Y. Chai, T. H. Cheng, G. Shen, S. K. Bose, and C. Lu, "Design and performance of optical cross-connect architectures with converter sharing," *Optical Networks Magazine* **3**, pp. 73–84, July/August 2002.
16. J. Späth and S. Bodamer, "Routing of dynamic Poisson and non-Poisson traffic in WDM networks with limited wavelength conversion," in *Proceedings of the 24th European Conference on Optical Communication (ECOC 1998)*, (Madrid), September 1998.
17. J. Späth, "Resource allocation for dynamic routing in WDM networks," in *Proceedings of the SPIE Photonics East Conference 1999*, (Boston), September 1999.
18. T. Chich, J. Cohen, and P. Fraigniaud, "Unslotted deflection routing: a practical and efficient protocol for multihop optical networks," *IEEE/ACM Transactions on Networking* **9**, pp. 47–59, February 2001.
19. F. Borgonovo, L. Fratta, and J. Bannister, "Unslotted deflection routing in all-optical networks," in *Proceedings of IEEE Globecom 93*, pp. 119–125, (Houston), November 1993.

20. F. Forghieri, A. Bononi, and P. R. Prucnal, “Analysis and comparison of hot-potato and single-buffer deflection routing in very high bit rate optical mesh networks,” *IEEE/ACM Transactions on Networking* **43**, pp. 88–98, January 1995.
21. G. Castanon, L. Tancevski, and L. Tamil, “Routing in all-optical packet switched irregular mesh networks,” in *Proceedings of IEEE Globecom 99*, pp. 1017–1022, (Rio de Janeiro), December 1999.
22. H. Feng, E. Patzak, and J. Saniter, “Size and cascadability limits of SOA based burst switching nodes,” in *Proceedings of the 28th European Conference on Optical Communication (ECOC 2002), We.8.5.5*, (Copenhagen), September 2002.
23. H. Buchta, C. M. Gauger, E. Patzak, and J. Saniter, “Limits of effective throughput of optical burst switches based on seminconductor optical amplifiers,” in *Proceedings of the Optical Fiber Communications Conference (OFC 2003)*, (Atlanta), March 2003.
24. J. Yates, J. Lacey, D. Everitt, and M. Summerfield, “Limited-range wavelength translation in all-optical networks,” in *Proceedings of IEEE Infocom 96*, pp. 954–961, (San Francisco), March 1996.
25. D. K. Hunter, M. C. Chia, and I. Andonovic, “Buffering in optical packet switches,” *IEEE Journal on Lightwave Technology* **16**, pp. 2081–2094, December 1998.
26. M. Yoo, M. Jeong, and C. Qiao, “A high speed protocol for bursty traffic in optical networks,” in *3rd SPIE Conference on All-Optical Communication Systems*, pp. 79–90, (Dallas), November 1997.
27. F. Callegati, W. Cerroni, and G. Corazza, “Optimization of wavelength allocation in WDM optical buffers,” *Optical Networks Magazine* **2**, pp. 66–72, November 2001.
28. Institute of Communication Networks and Computer Engineering, University of Stuttgart, “The IKR simulation library.” `www.ikr.uni-stuttgart.de/IKRSimLib`.

Figure 1: Network scenario for optical burst switching

Figure 2: Model of an OBS node with a shared converter pool and an feedback FDL buffer

Figure 3: Probing strategies for wavelength converters and FDLs

Figure 4: Burst loss probability vs. conversion ratio ($M = 8$)

Figure 5: Burst loss probability vs. conversion ratio ($M = 16$)

Figure 6: Effective conversion ratio vs. number of output fibers

Figure 7: Impact of conversion ratio and probing strategy for different FDL buffers

Figure 8: Impact of number of buffer FDLs and probing strategy for different conversion ratios

Figure 9: Impact of load and probing strategy for different FDL buffers ($r_c = 0.25$)

Figure 10: Probabilities for buffering and wavelength conversion (4 FDLs)

Figure 11: Impact of conversion ratio on mean transfer time

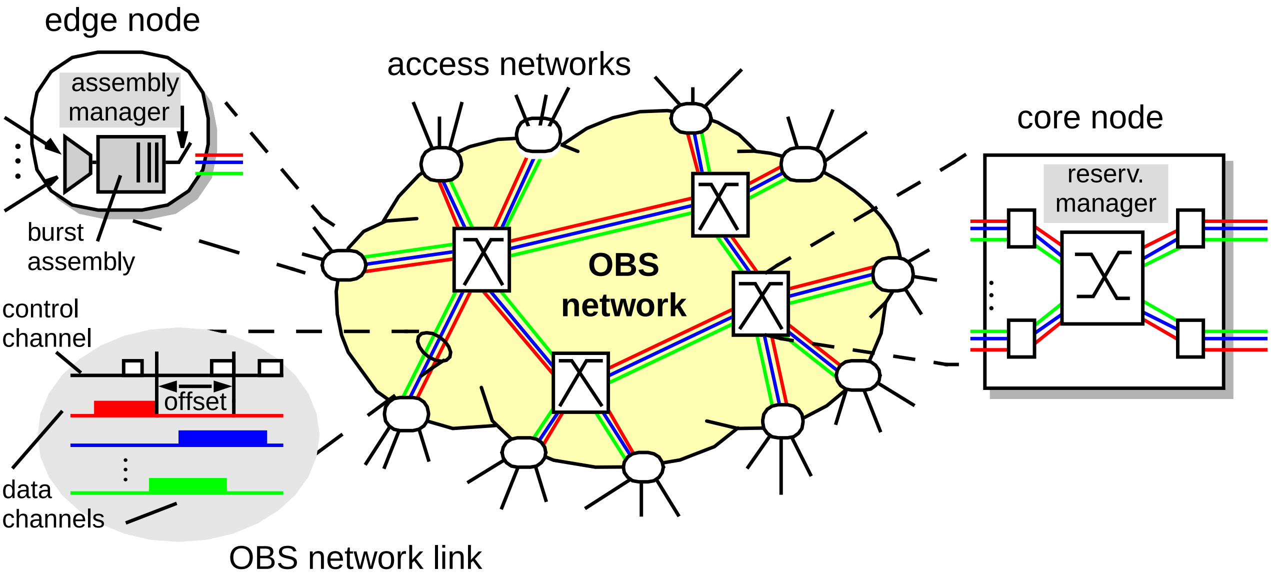

Figure 1: Network scenario for optical burst switching

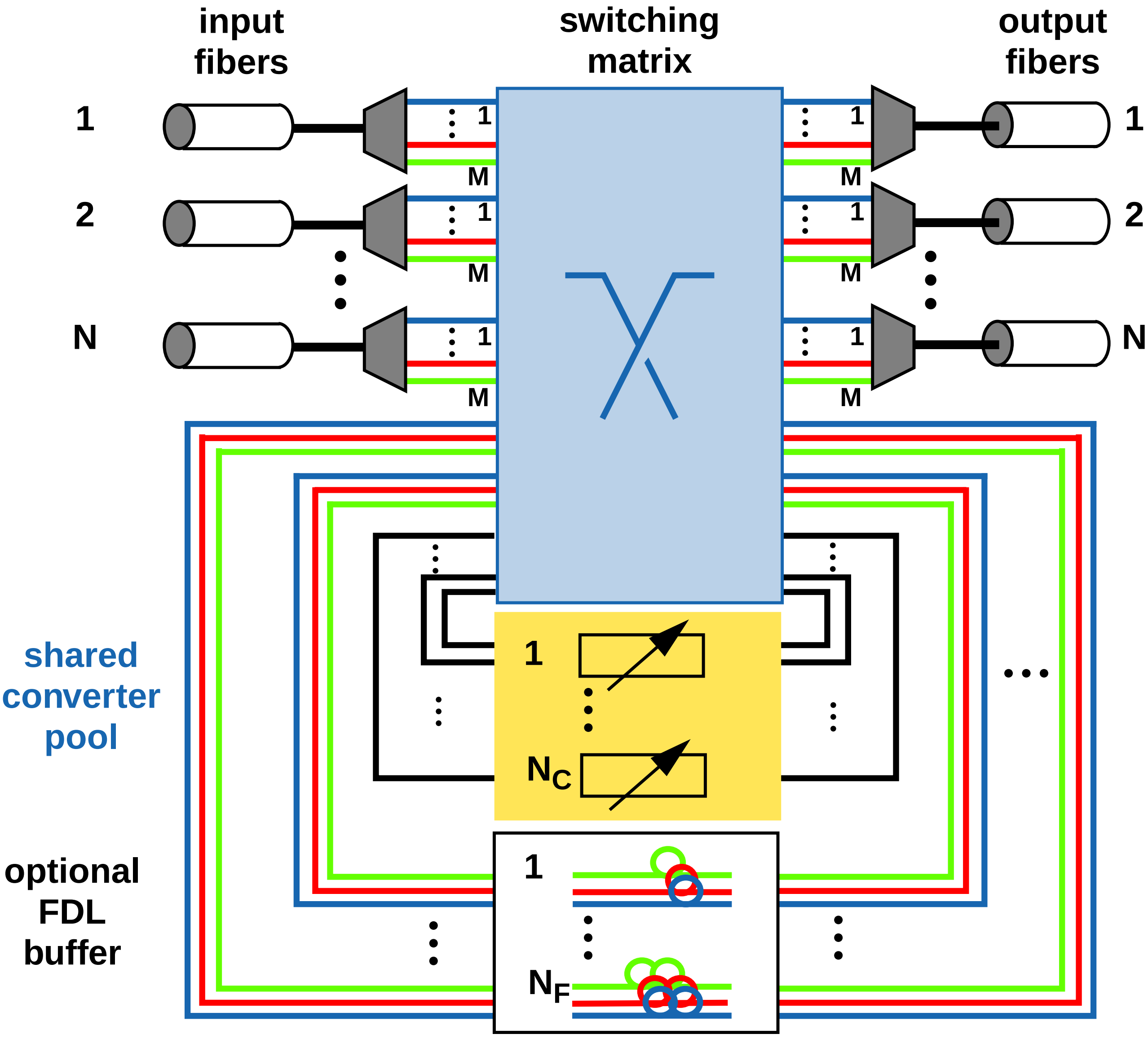

Figure 2: Model of an OBS node with a shared converter pool and an feedback FDL buffer

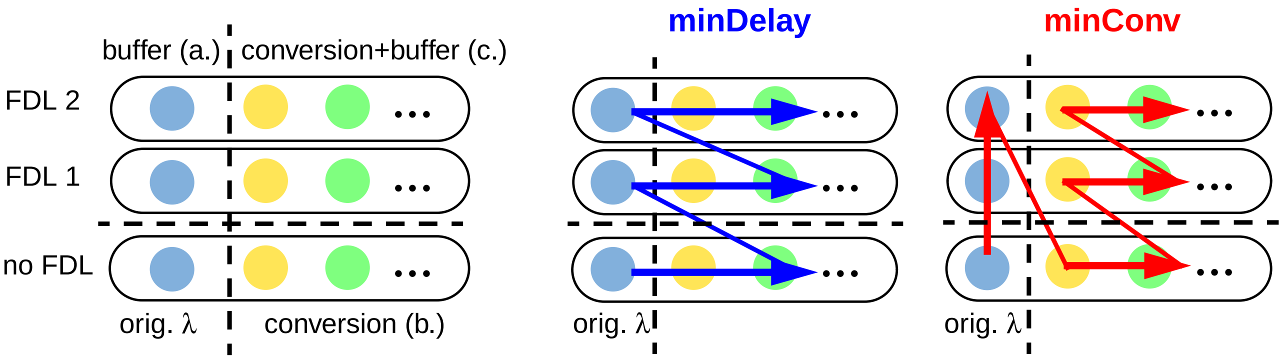

Figure 3: Probing strategies for wavelength converters and FDLs

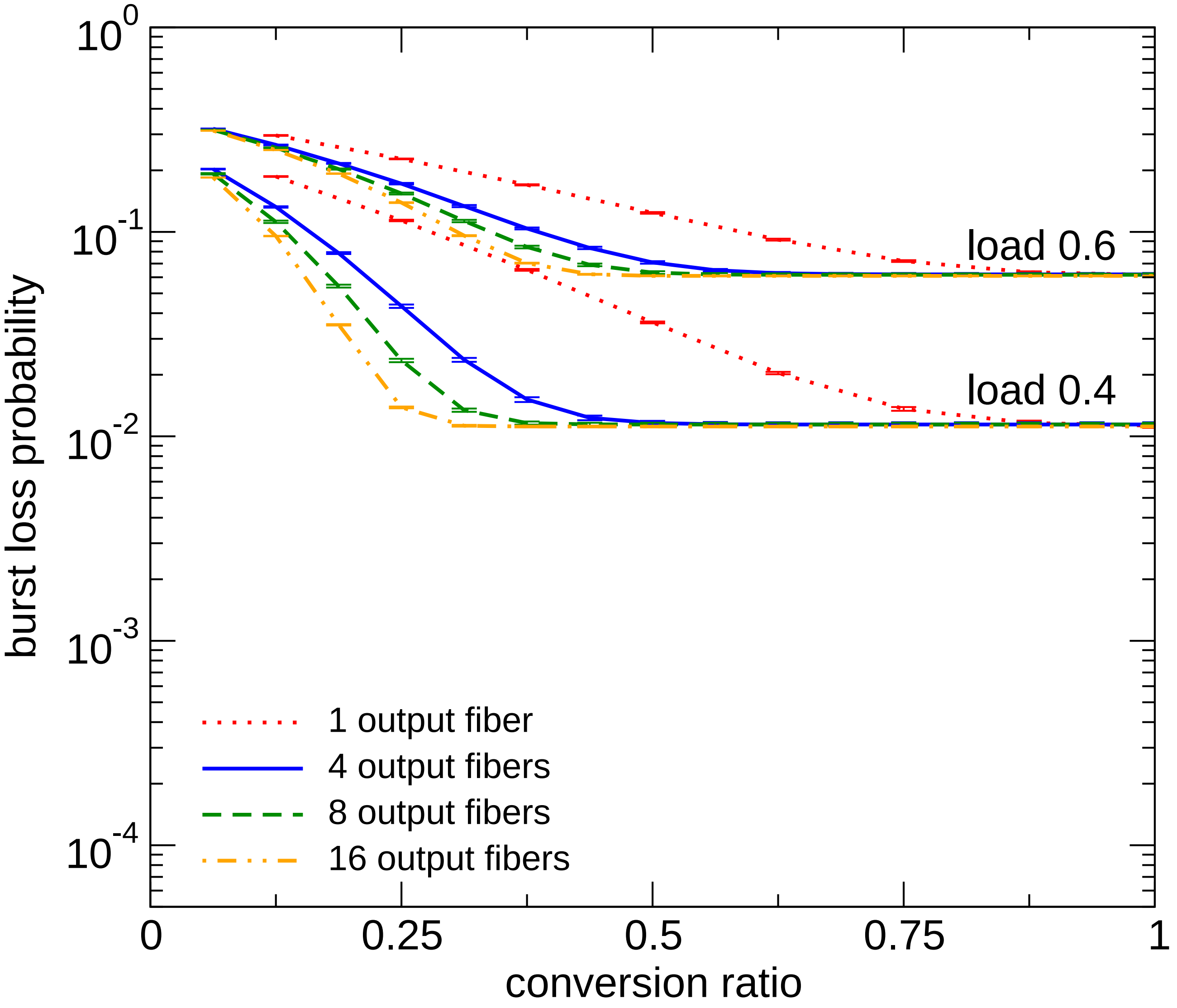

Figure 4: Burst loss probability vs. conversion ratio ($M = 8$)

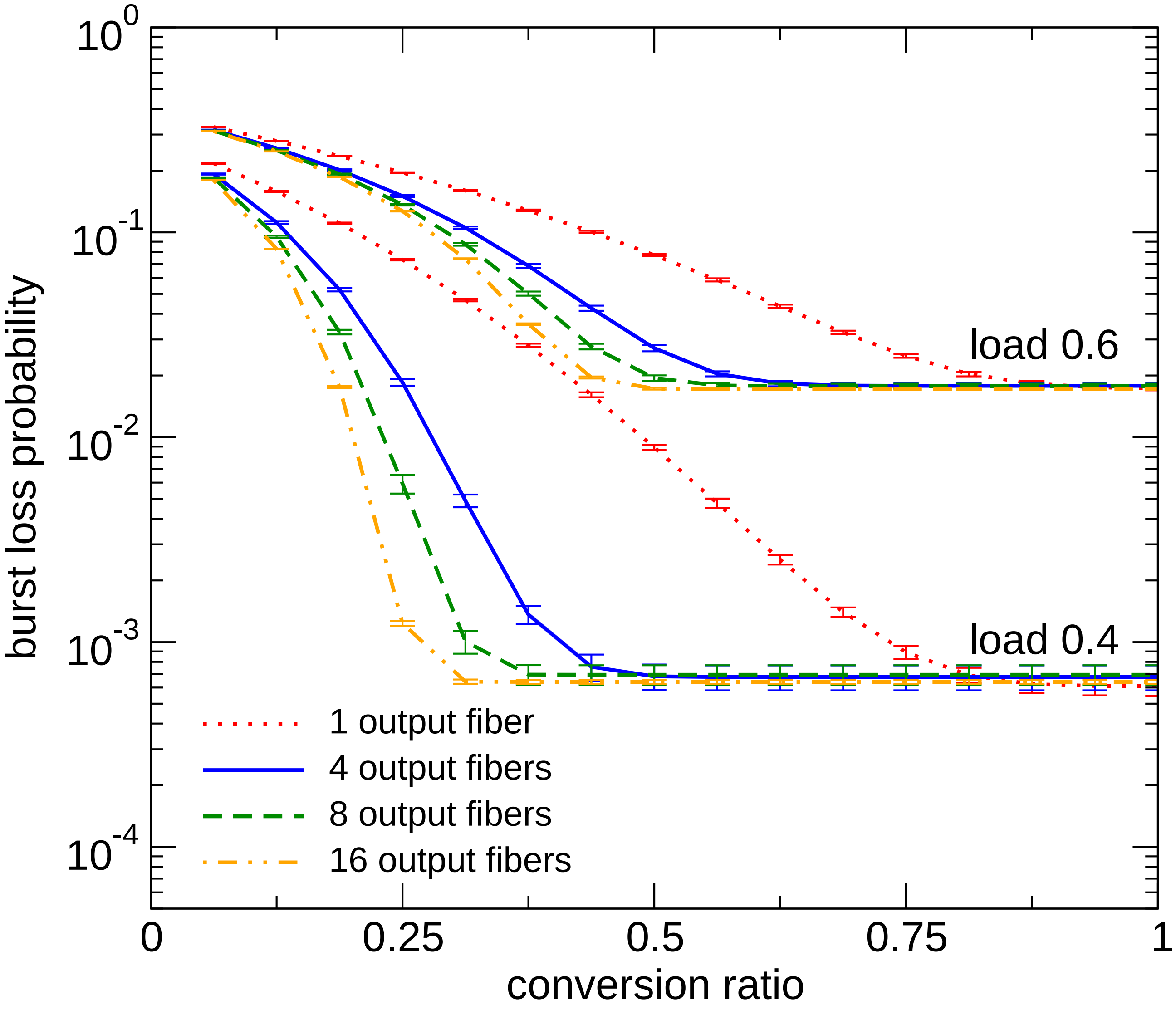

Figure 5: Burst loss probability vs. conversion ratio ($M = 16$)

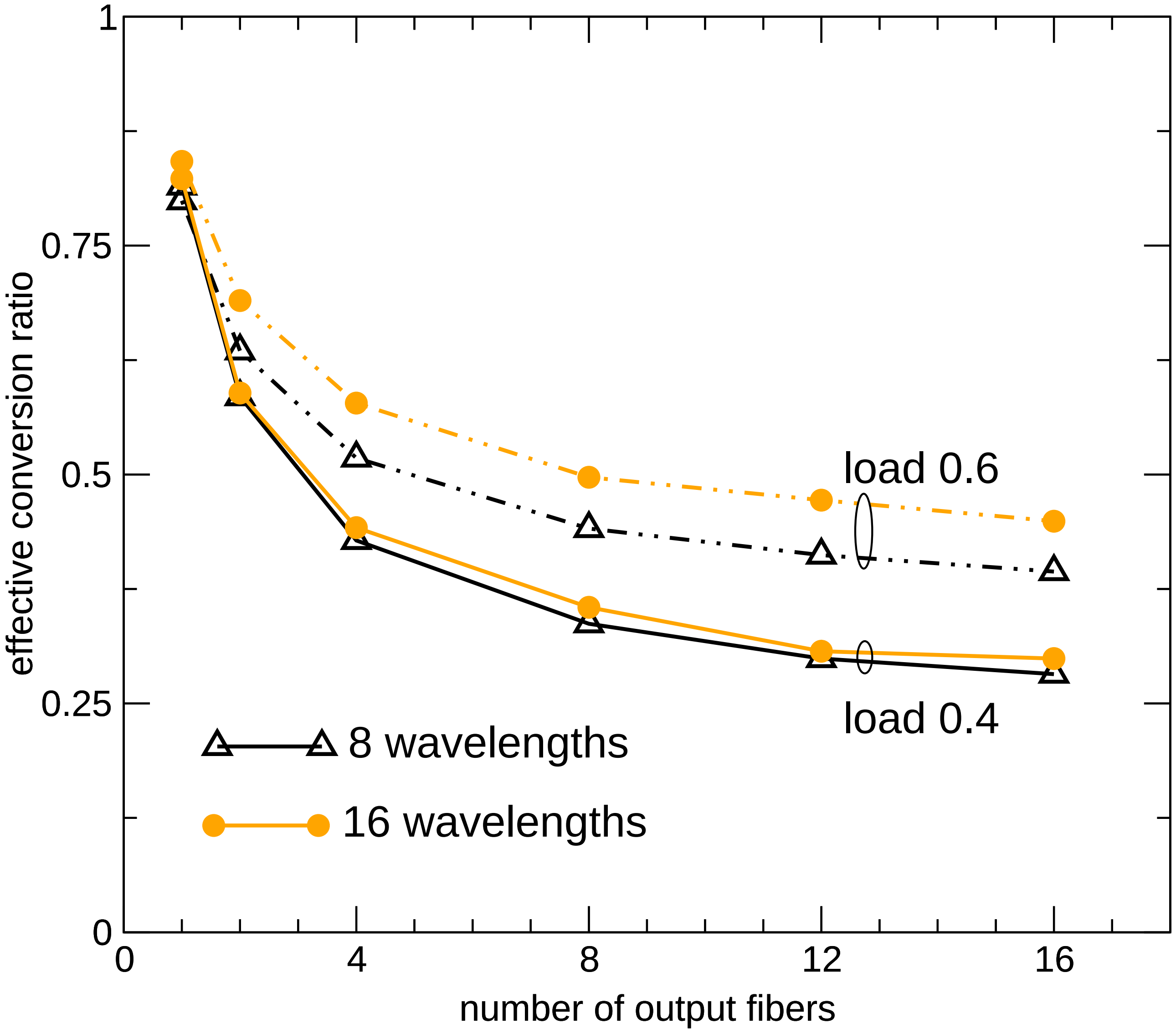

Figure 6: Effective conversion ratio vs. number of output fibers

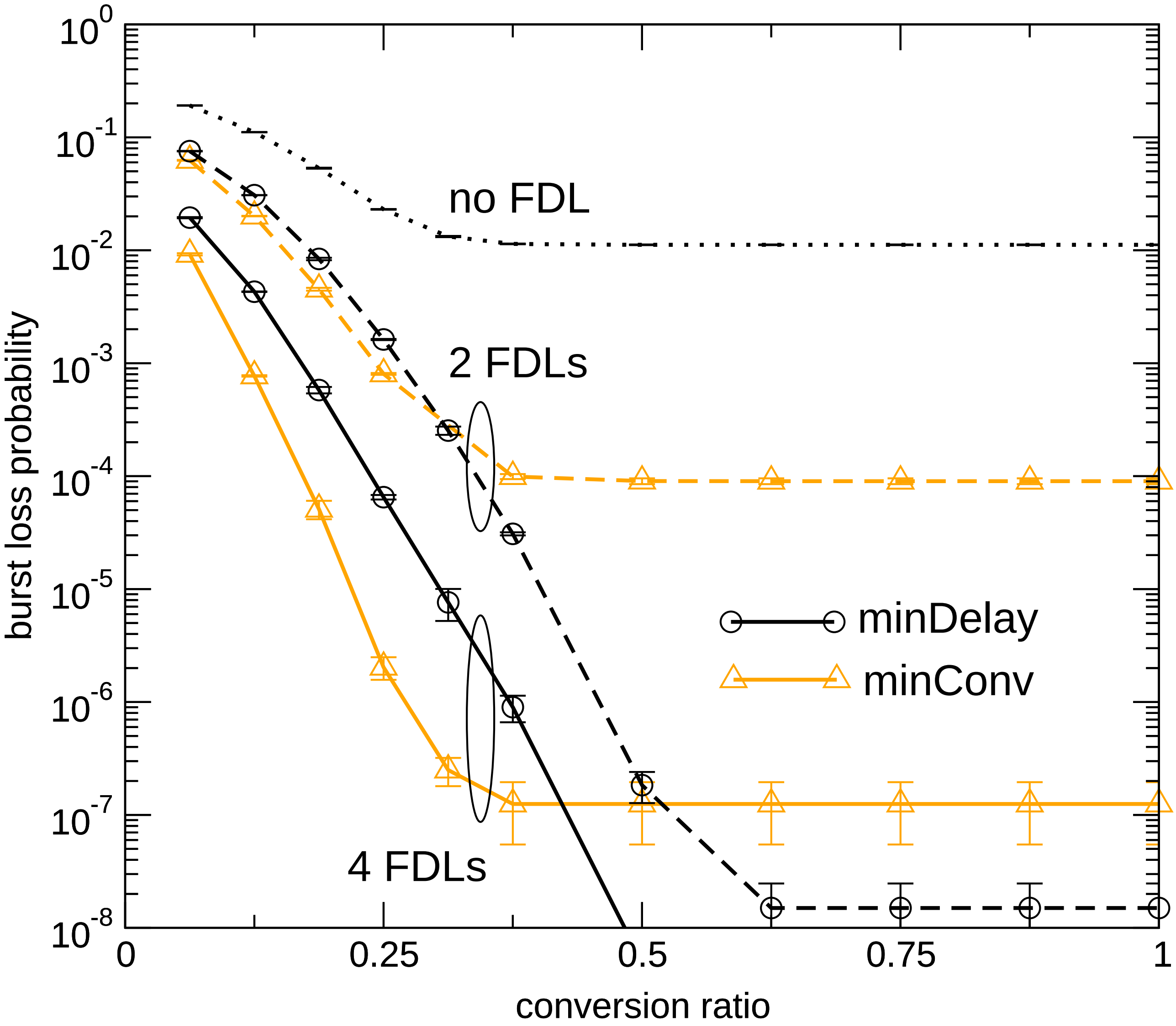

Figure 7: Impact of conversion ratio and probing strategy for different FDL buffers

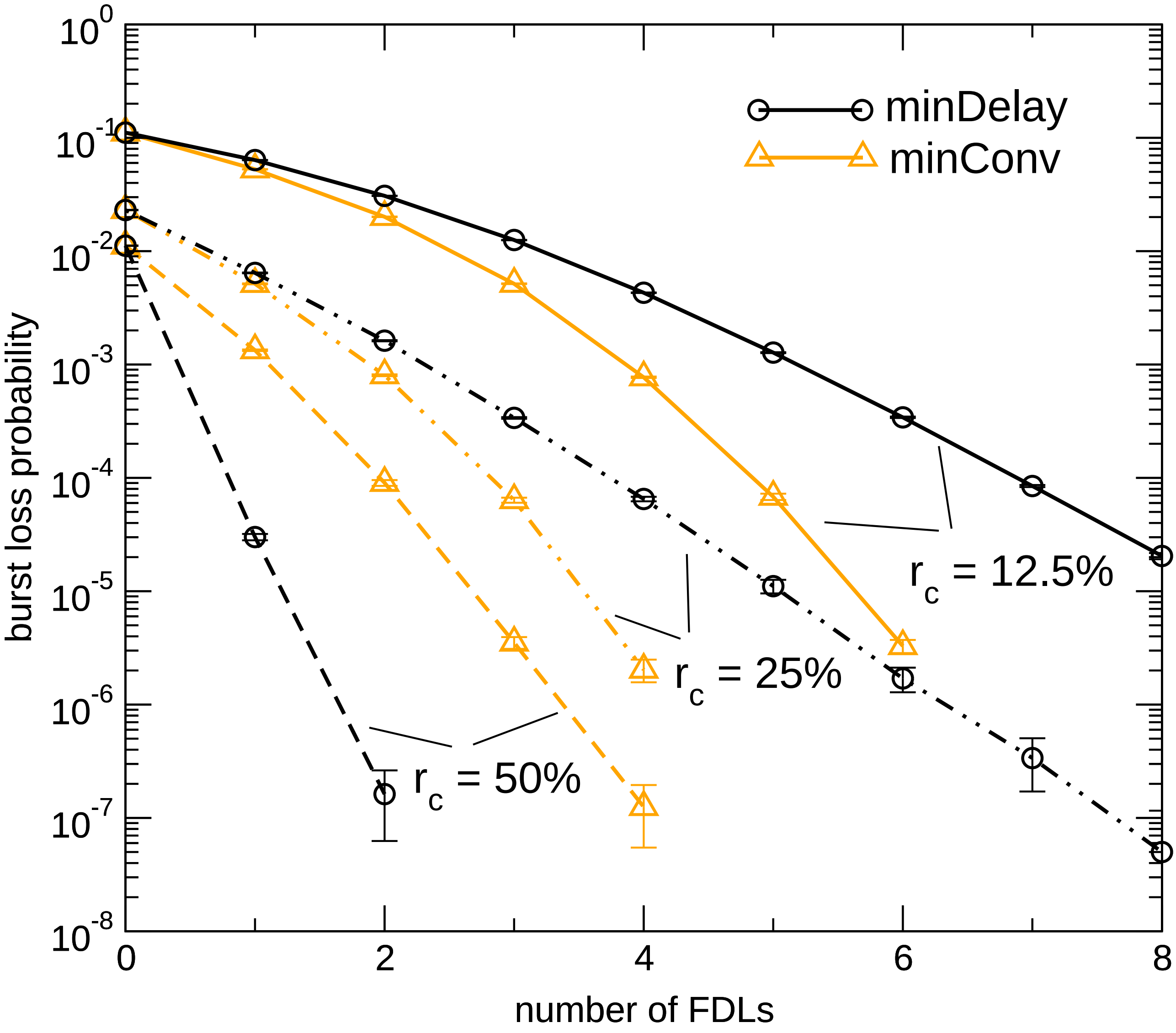

Figure 8: Impact of number of buffer FDLs and probing strategy for different conversion ratios

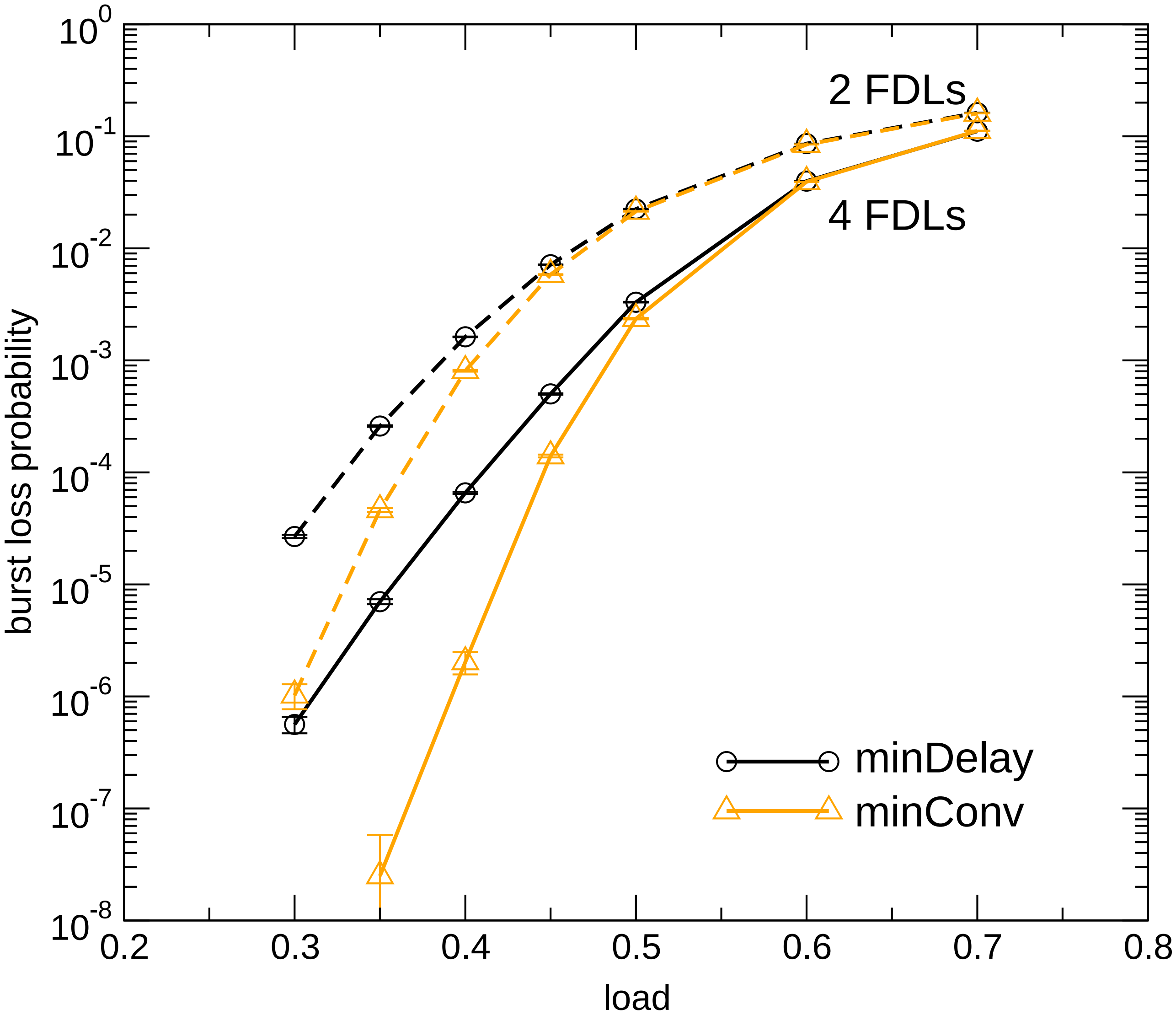

Figure 9: Impact of load and probing strategy for different FDL buffers ($r_c = 0.25$)

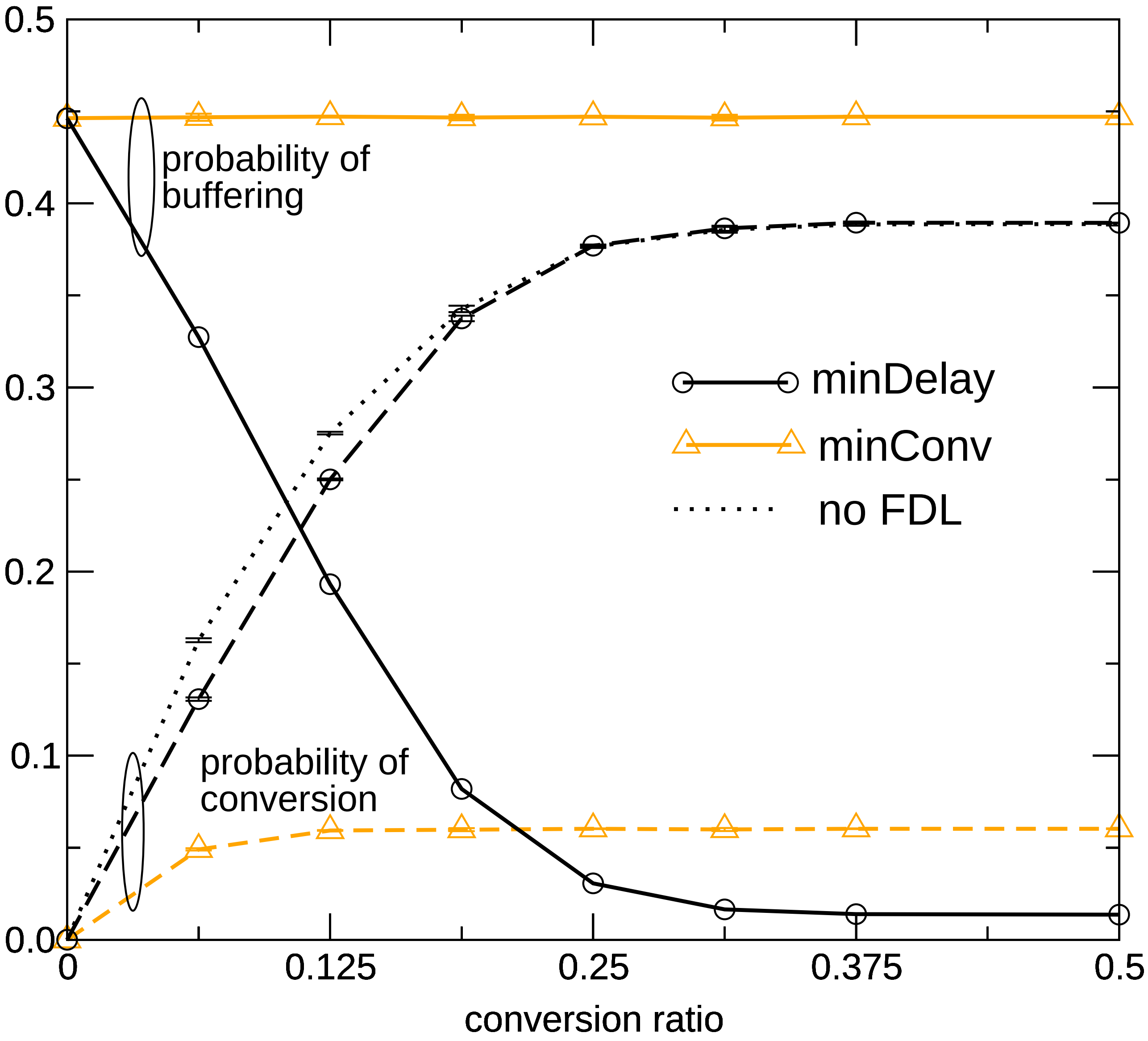

Figure 10: Probabilities for buffering and wavelength conversion (4 FDLs)

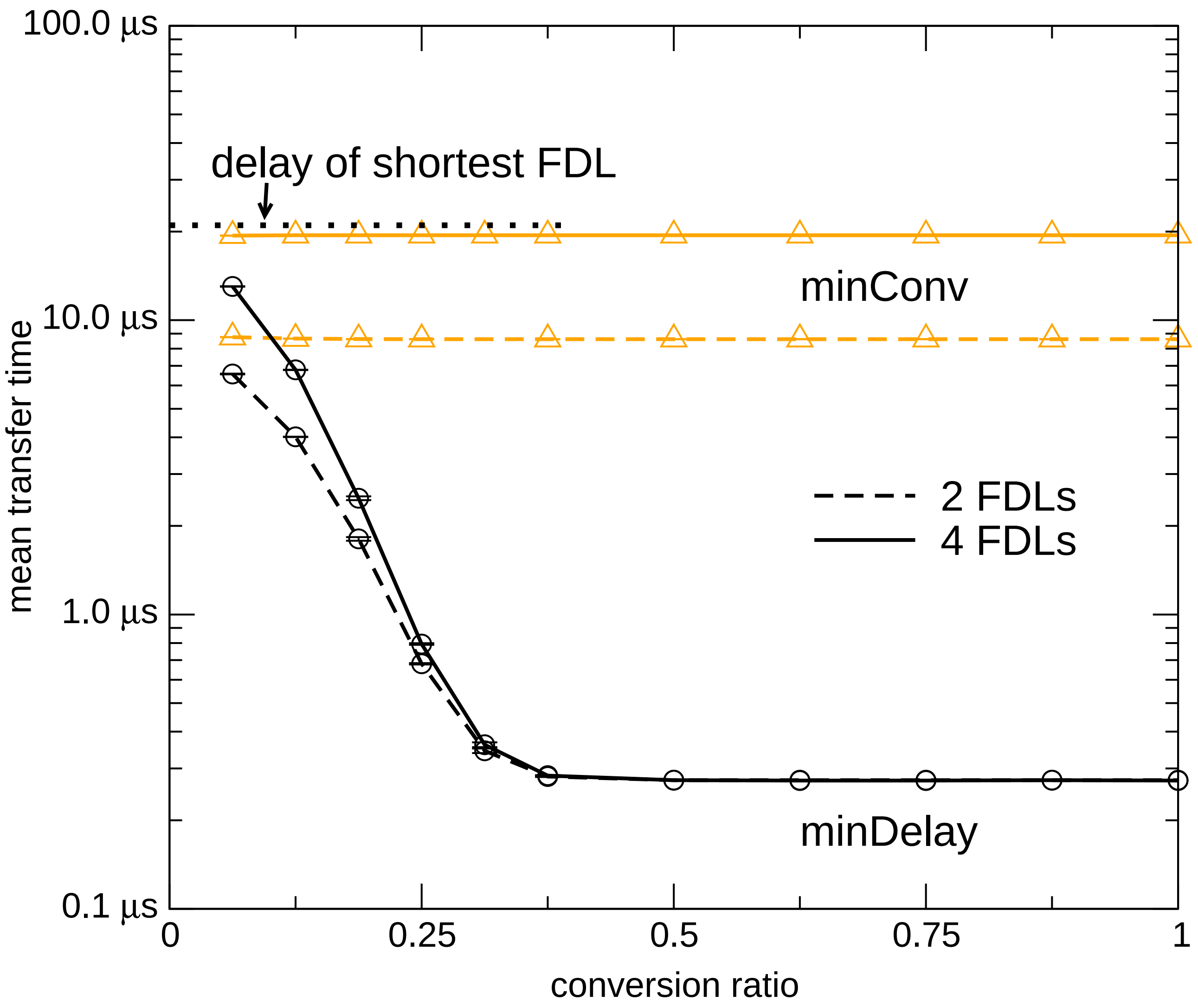

Figure 11: Impact of conversion ratio on mean transfer time