Universität Stuttgart

INSTITUT FÜR
KOMMUNIKATIONSNETZE
UND RECHNERSYSTEME
Prof. Dr.-Ing. Dr. h. c. mult. P. J. Kühn

Interner Bericht / Internal Report Nº 48

Titel / Title

Analysis of the CSMA/CA MAC Protocol in a New Optical MAN Network Architecture

Verfasser / Author(s) Guoqiang Hu, Christoph M. Gauger, Sascha Junghans

Datum / Date 16.02.2004

Umfang / Size 12 Seiten / Pages

Quelle / Source

Schlüsselworte / Keywords MAN, MEDIA ACCESS CONTROL, CSMA, PERFORMANCE EVALUATION, PERFORMANCE ANALYSIS, SIMULATION

Beitrag der Arbeit / Achievement

This paper provides a systematical performance evaluation, by application of queueing theory and simulation, for the CSMA/CA MAC protocol in the DBORN network.

Kurzfassung / Abstract

In this paper we present a detailed performance evaluation of the carrier sense multiple access-type MAC protocol with collision avoidance in a new optical burst-mode metro network architecture. We introduce a new analytical performance model for this MAC protocol which is exact for the slotted operation mode and from which good upper and lower bound for the unslotted operation mode can be derived. Then, we validate the analytical model by simulation and discuss the principle behavior. Key design parameters like slotted/unslotted operation mode and burst size distribution are evaluated. Finally, we assess the fairness with respect to node position by looking at the node-to-hub delay.

Analysis of the CSMA/CA MAC Protocol in a New Optical MAN Network Architecture

Guoqiang Hu, Christoph M. Gauger, Sascha Junghans

Institute of Communication Networks and Computer Engineering[1]
University of Stuttgart, Germany

Abstract. In this paper we present a detailed performance evaluation of the carrier sense multiple access-type MAC protocol with collision avoidance in a new optical burst-mode metro network architecture. We introduce a new analytical performance model for this MAC protocol which is exact for the slotted operation mode and from which good upper and lower bound for the unslotted operation mode can be derived. Then, we validate the analytical model by simulation and discuss the principle behavior. Key design parameters like slotted/unslotted operation mode and burst size distribution are evaluated. Finally, we assess the fairness with respect to node position by looking at the node-to-hub delay.

1 Introduction

Due to new broadband access technologies and the increasing number of Internet users as well as due to the trend of enterprise networking, demands for higher capacity metropolitan area networks (MAN) are rising. After the fast growing networking capacity of the last years, internet providers today ask for equipment with higher bandwidth and lower costs. The demand for high bandwidth leads to optical solutions with wavelength division multiplexing (WDM) technology. As active optical switching elements are still a high cost factor, it is desired to provide an optical network architecture without active optical switching elements. The DBORN (Dual Bus Optical Ring Network) architecture satisfies these demands with a new MAN technology. It connects metro edge nodes, which do not employ any optical active switching elements, to the core network via a hub node. As this cost effective solution leads to some constraints in the area of medium access, a new medium access control (MAC) protocol and interface card design is required. In this paper, we present a detailed performance evaluation of the MAC protocol of this new network architecture.

In Section 2 we will introduce the network architecture and its MAC protocol, Section 3 describes the analytical model of the medium access protocol and Section 4

1. *Affiliation:* Institute of Communication Networks and Computer Engineering (IKR), University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany. *Tel:* +49 (711) 685.7991. *Fax:* +49 (711) 685.7983. *E-mail:* {hu, gauger, junghans}@ikr.uni-stuttgart.de

This work was funded within the MultiTeraNet programme by the German Bundesministerium für Bildung und Forschung (BMBF).

shows the results of the performance evaluation. In Section 5 conclusions are drawn and further work is outlined.

2 Network architecture and MAC protocol

DBORN is a high speed network solution for metropolitan areas [9]. On the basis of advances in the optical transmitter and receiver technology [3], the carrier sense multiple access with collision avoidance (CSMA/CA) is realized in DBORN.

2.1 Network architecture

DBORN is an optical metro ring architecture connecting several edge nodes, e. g., metro clients like enterprise, campus or local area networks (LAN), to a regional or core network. The ring consists of two parallel fibers called working and protection fiber (Figure 1 left) in order to provide resilience in case of single link failures. Each ring employs WDM and carries a set of wavelengths which are further classified into downstream and upstream wavelength channels (Figure 1 right). While downstream wavelength channels start from the transmitters in the hub, upstream wavelength channels are terminated by the receivers in the hub.

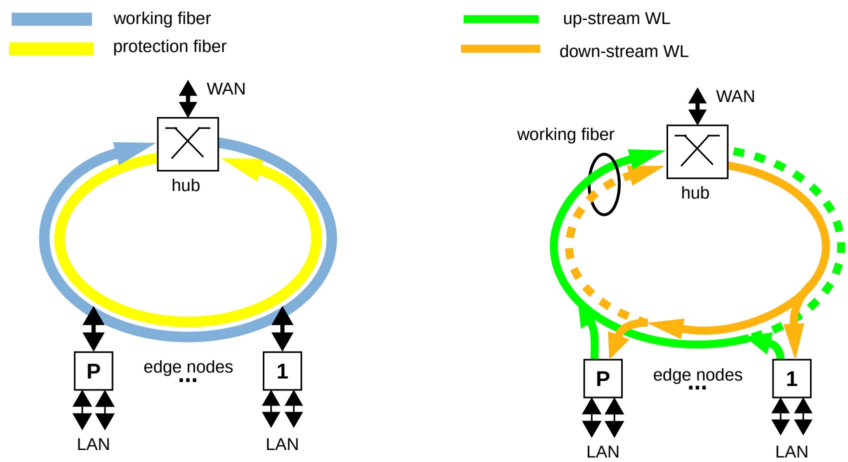

Figure 1 DBORN architecture

Several edge nodes share upstream and downstream channels respectively in asynchronous time division multiplexing. For load balancing purposes, an edge node can be attached to more than one upstream or downstream channel. In order to keep the edge node interface cards as simple as possible, all traffic—external and intra-ring—has to pass the hub. Specifically, no edge node receives or even removes traffic on upstream channels or inserts traffic on downstream channels. Thus, both upstream and downstream channels can be modelled as shared unidirectional buses .

As the hub node exclusively transmits on the downstream channel, traditional scheduling mechanisms can be applied here. However, medium access of edge nodes has to be controlled on the upstream channel which will be analysed in depth in the rest of the paper.

2.2 Burst size and burst assembly

In order to provide for safe transmitting and receiving on the ring a guard time has to be inserted between consecutive optical transmission units. A typical value of the guard time with current technologies is $50ns$ [3], which on a 10 Gbps channel corresponds to the transmission time of about 63 bytes.

DBORN targets transaction data and Internet traffic which is commonly transported over Ethernet, i. e. client layer packet sizes are in the range of 40 to 1500 bytes [12] bounded by the Ethernet maximum transmission unit (MTU). As transmission of individual client layer packets/frames would lead to a significant overhead due to guard times, all client layer traffic is assembled into larger units called *bursts* for transmission on the optical ring. A considerable amount of literature on burst assembly is available in the context of optical burst switching (e.g. [4][5][11]).

In the current version of the DBORN prototype the optical ring employs the Ethernet frame as burst format. Thus, the small MTU value only allows a limited degree of assembly gain. In future versions, this could be improved by segmentation of client layer packets [1] or by selection of a different optical layer burst format, e. g. ITU-T's G.709 frame format with a size of about 16K bytes [6]. As this paper focuses on MAC performance, we do not consider the effects of (suboptimal) burst assembly and use a maximum burst size of 16K bytes in our studies.

2.3 MAC protocol

As DBORN targets a cost efficient optical ring solution no active optical components, e. g. switches, are used on the interface cards and transmitting and receiving part are strictly separated. Figure 2 depicts a functional model of the transmitter interface, which was designed to allow a collision-free medium access.

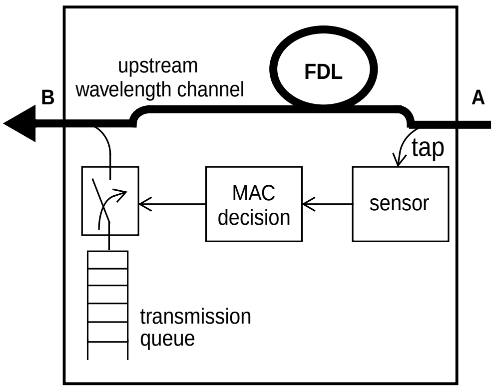

Figure 2 Functional model of transmitter interface in edge nodes

Between the input (point A) and the output (point B) of the edge node a fiber delay line (FDL) is inserted into the ring. The length of the FDL should correspond to a delay equal to or greater than the transmission time of the maximum burst size. At the input (point A) of the edge node, a simple sensor taps the upstream channel and constantly monitors the channel status—busy or idle. On the other side of the FDL a laser is coupled into the same channel and controlled by the decision unit to send bursts safely. Due to the delay introduced by the FDL, the edge node can determine the duration of voids on the channel up to the FDL delay before they pass the coupling point of the laser and thus decide on the medium access avoiding collisions.

There are two possible operation modes for DBORN: slotted and unslotted. In the slotted mode, the channel is divided into constant duration slots and the transmission is allowed if the edge node finds an idle slot on the upstream channel. On the one hand, this requires some basic synchronization between network nodes, on the other hand edge nodes only have to check whether a slot is idle or used.

In the unslotted mode, no synchronisation is required and bursts can have an arbitrary transmission time up to the FDL delay. By comparing the duration of an available void on the channel and the transmission time of the first burst in the transmission queue the edge node can decide when to transmit a burst.

3 Analysis for a single upstream channel

In this section, we present a performance model for a single upstream channel applying the CSMA/CA MAC protocol described in Section 2.3. The performance metric is the mean waiting time of an already assembled burst waiting for transmission in an edge node.

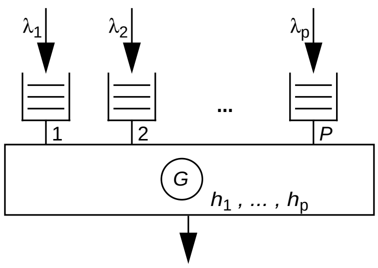

Figure 3 Priority queueing model

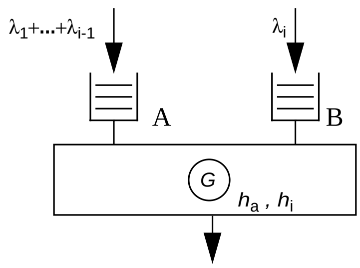

Figure 4 Approximate resulting model

In DBORN an edge node can only make use of bandwidth (voids) on the channel which was left over by other nodes located further upstream. The unfairness in the medium access, also called positional priority, can be modelled by a priority queueing system as illustrated in Figure 3 in which p queues compete for a single server and a queue is only allowed to transmit if all queues of higher priority are empty.

Each edge node is indexed in ascending order following the traffic flow direction and abstracted by its transmission queue. The class of the queue is defined by the node index i. Thus, a smaller node/queue index corresponds to a higher priority class. Note that the distance between the edge nodes only affects the propagation delay but does not impact the mean waiting time analysis in our scenario and consequently is modelled to be zero here.

For the analysis and performance studies we assume that each class injects traffic following a Poisson arrival process with rate λ_i and that traffic streams of different nodes are independent of each other. The service time of bursts is independently and identically distributed with mean h_i.

In Section 3.1, we deduce the exact mean burst waiting time for the slotted operation mode. Bounds on the mean burst waiting time are given by approximate solutions for the unslotted case in Section 3.2 and Section 3.3.

3.1 Exact analysis of mean waiting time for slotted mode

In the slotted operation mode of the DBORN MAC protocol, a fixed burst size is assumed and the slot time is equal to the burst transmission time h. Thus, an edge node which has a burst to transmit decides on medium access at the slot boundary based on whether the slot is busy or idle. In the corresponding priority system this means that the queues compete for the right of transmission only at slot boundaries, which is described by a slotted priority system without preemption.

From a mean value analysis [8] it follows that the mean value of waiting time W_i of a class-i customer equals

$$E[W_i] = \frac{h}{2} + \sum_{k=1}^{i} E[X_k]h + \sum_{k=1}^{i-1} (E[W_i]\lambda_k)h \qquad (1)$$

where X_i denotes the queue length of class i. This equation expresses that the mean waiting time experienced by a test customer[1] consists of three parts:

1. average residual lifetime of a time slot
2. workload of those customers of higher or equal priority who have been in the system upon arrival and will be served prior to the test customer
3. workload of those customers of higher priority who will arrive after the test customer and will be served prior to the test customer.

Applying Little's Theorem $E[X_i] = \lambda_i E[W_i]$ together with Equ. (1), the mean waiting time can be calculated as

$$E[W_i] = \frac{h/2}{(1-\rho_{\le i})(1-\rho_{\le i-1})} \qquad (2)$$

where $\rho_{\le i} = \sum_{k=1}^{i} \lambda_k h$ denotes the total offered traffic of classes $1, \ldots, i$.

From Equ. (2) it can be seen that the mean waiting time $E[W_i]$ is always finite as long as the $\rho_{\le i} < 1$, which conforms to the work-conserving property of the slotted operation mode.

1. Arrival customer waiting time and the outside observer waiting time are identical according to PASTA theorem.

3.2 Upper bound on mean waiting time for unslotted mode

In the unslotted operation mode of DBORN, no slot synchronization is available and bursts can have an arbitrary size up to the maximum burst size. An edge node only sends a burst if it finds a void on the channel which is large enough. As a consequence, there may be voids becoming too small to be filled, so called channel fragmentation, and burst transmission is no longer strictly in the priority order of node location but also depends on void and burst sizes.

Thus, the unslotted operation mode does not lend itself to the straightforward analysis used for the slotted mode. As indicated, arrivals of busy/idle periods on the channel observed by a downstream edge node now follow a correlated random process and thus renewal theory does not apply any more. Still, it is possible to give an upper and a lower bound on the mean waiting time by using an *preemptive repeat identical* (PRI) queueing system as alternative, approximate model.

In a PRI system, a customer belonging to a higher priority class has priority over a customer belonging to a lower priority class at any instant in time. In case a high priority customer finds the server occupied at the time of arrival by a low priority customer, the ongoing service of this customer is immediately terminated (preempted) and the server is taken by the high priority customer. The turn comes to the preempted customer again after all higher priority customers are served and service has to be carried out from the beginning which is called preemptive repeat. In each repetition a customer's required service time remains identical, i.e., there is no resampling after preemption. It can be seen that a low priority customer can only be completely served if it finds an interval long enough for its own service time without arrivals of higher-priority customers. We use $D_{i,\,\mathrm{PRI}}$ to denote the duration of the interval for a class-i customer between his arrival at the system and the beginning of his effective service period, i.e., the period in which he gets fully served without interruptions.

This is an essential analogy to the unslotted DBORN MAC protocol. The difference lies only in the fact that an edge node will not start transmission of its burst if the void is too small, so these voids can still be utilized by edge nodes located further downstream, while in the PRI system the customer occupies the server no matter whether he will be preempted or not. As the server capacity wasted by the unfinished service in case of preemption leads to a performance degradation, i. e. increased mean waiting time, for all lower priority classes, $E[D_{i,\,\mathrm{PRI}}]$ in the PRI system is an upper bound for the average burst waiting time $E[W_i]$ in DBORN:

$$E[W_i] \le E[D_{i,\,\mathrm{PRI}}] \,. \tag{3}$$

Note that in Equ. (3) the equality holds for $i = 1, 2$ because only classes with index $i \ge 3$ suffer from the performance penalty attributed to the noneffective consumption of server capacity due to the preemption.

For the derivation of $E[D_{i,\,\mathrm{PRI}}]$ several intermediate parameters are needed. Completion time C_i denotes the interval between the instant at which a class-i customer enters service for the first time and the final completion of his service. Note that we assume here that the customer leaves the queue when he first starts service, i.e., he does not return to the queue i when being preempted. In this way the completion time can be regarded as "virtual service time" of a customer. The waiting time $W_{i,\,\mathrm{PRI}}$ of a class-k customer refers only to the time he waits in the queue. Busy period B_i denotes the duration of an interval in which there is at least one customer of class i or of higher priority in the system. This corresponds to the time the server is continuously occupied by traffic of class i or of higher priority. Both completion time process and busy period process are renewal processes. $E[D_{i,\,\mathrm{PRI}}]$ can be expressed as

$$E[D_{i,\,\mathrm{PRI}}] = E[W_{i,\,\mathrm{PRI}}] + E[C_i] - h_i \tag{4}$$

The solution of $E[C_i]$ is available in [7], which will be mentioned again later. In [10] a derivation of $E[W_{i,\,\mathrm{PRI}}]$ is given by applying the transformation technology which is relative complex. In the following we offer a more intuitive but still exact derivation of $E[W_{i,\,\mathrm{PRI}}]$ by using mean value analysis method. The mean waiting time $E[W_{i,\,\mathrm{PRI}}]$ is thus further decomposed into two parts

$$E[W_{i,\,\mathrm{PRI}}] = E[X_i]E[C_i] + P_{\mathrm{busy},i}E[\Gamma_i] \tag{5}$$

where X_i denotes the queue length and the first term on the right side represents the sum of completion time of all customers in queue i which arrived earlier and have not yet started service. Γ_i represents the residual sojourn time of the class-i customer at the head of the queue before he leaves the queue. $P_{\mathrm{busy},i}$ is the probability that the server is in a busy period in terms of class-i customers

$$P_{\mathrm{busy},i} = E[B_i]/(E[B_i] + 1/\lambda_{\le i}). \tag{6}$$

Here, $\lambda_{\le i}$ denotes the total rate of traffic of class i and of higher priority and represents the termination rate of the idle period between two busy periods B_i. Note that as arrivals are Poisson and an idle period is terminated by any arrival of classes $1, \ldots, i$, its duration is negative exponetially distributed with its expected value $1/\lambda_{\le i}$.

To calculate $E[\Gamma_i]$ following situations are studied

1. With probability $\lambda_i/\lambda_{\le i}$ the current busy period B_i starts with the service of a class-i customer. In this case it can be proven[1] that presently there is definitely a class-i customer in the system who has left the queue but not yet finished his service. Therefore, $E[\Gamma_i]$ equals the residual completion time and it yields $E[\Gamma_i] = E[C_i^2]/(2E[C_i])$.
2. If the busy period B_i starts with a higher priority customer or equivalently starts with a busy period of B_{i-1}, two possibilities exist:

   2.1. With probability $E[B_{i-1}]/E[B_i]$ the present time falls in this first busy period B_{i-1} contained in the current B_i. Then Γ_i equals the residual time of the busy period B_{i-1}: $E[\Gamma_i] = E[B_{i-1}^2]/(2E[B_{i-1}])$,

   2.2. Otherwise, with the same argument as in case 1, there is $E[\Gamma_i] = E[C_i^2]/(2E[C_i])$.

---

1. A hint for the proof: The counter-example arises if and only if a busy period B_{i-1} starts exactly at the instant when a completion time C_i ends. However, this occurs with probability 0.

Therefore, $E[\Gamma_i]$ can be expressed as

$$\frac{\lambda_i}{\lambda_{\le i}} \cdot \frac{E[C_i^2]}{2E[C_i]} + \frac{\lambda_{\le i-1}}{\lambda_{\le i}} \cdot \left(\frac{E[B_{i-1}]}{E[B_i]} \cdot \frac{E[B_{i-1}^2]}{2E[B_{i-1}]} + \left(1 - \frac{E[B_{i-1}]}{E[B_i]}\right) \cdot \frac{E[C_i^2]}{2E[C_i]} \right) \quad (7)$$

The first and secondary ordinary moment of C_i and B_i can be calculated for $1 \le i \le p$ according to the iterative formulas in [7], which is presented in the Appendix. On this basis Equ. (6) and (7) can be computed consequently. Using Little's Theorem $E[X_i] = \lambda_i E[W_{i,\,\mathrm{PRI}}]$ and inserting Equ. (6) and (7) into Equ. (5) we obtain $E[W_{i,\,\mathrm{PRI}}]$. At last, the exact solution for $E[D_{i,\,\mathrm{PRI}}]$ can be derived from Equ. (4).

3.3 Lower bound on mean waiting time for unslotted mode

Based on the case of equality in Equ. (3), an alternative approximate resulting model can be built as illustrated in Figure 4. Assuming from the view of the edge node i the channel traffic generated by the $i-1$ number of upstream edge nodes is approximately the same as that generated by one upstream edge node with equal traffic intensity, the system can be abstracted by a two-class PRI system. Queue A models all upstream nodes and has a traffic arrival rate $\sum_{k=1}^{i-1} \lambda_k$. Queue B represents the observed edge node i with traffic arrival rate λ_i. The mean waiting time of a class-B customer can be computed in the same way as described in Section 3.2, standing for an approximate solution for edge node i.

However, modelling edge nodes $1, \ldots, i-1$ with one queue entirely removes the effect of channel fragmentation introduced by the MAC protocol, i. e. the fact that all edge nodes $2, \ldots, i-1$ experience an additional waiting time due to bursts arriving on the ring and too small voids in between. Thus, this approximation leads to an optimistic estimation of the performance and can be used to obtain a lower bound on mean waiting time for the unslotted operation mode.

4 Performance evaluation

In this section, the mean waiting time analysis in Section 3 will be validated using simulation. Then, slotted and unslotted mode will be compared and the impact of the burst size distribution will be evaluated. Finally, node-to-hub delay performance of DBORN are assessed.

The evaluation scenario considers 10 edge nodes attached to a single 10 Gbps upstream channel. Homogenous traffic is uniformly distributed over all edge nodes and bursts arrive according to a Poisson process. For unslotted mode both fixed burst size and variable burst size are considered while for slotted mode only the fixed size is treated. As motivated in Section 2.2 we set the burst size to 16K bytes for the fixed size case. In the variable size case, we use independent discrete uniform distributions in order to cover a broad spectrum of burst size variability in the presence of a fixed upper bound of 16K bytes. For illustration, a 16K byte burst has a transmission duration of 12.8 µs. The term load always refers to the ratio of average traffic bitrate and channel capacity. In all graphs, mean waiting time is normalized by the mean burst transmission time h.

4.1 Principle behavior and validation of the analytical models

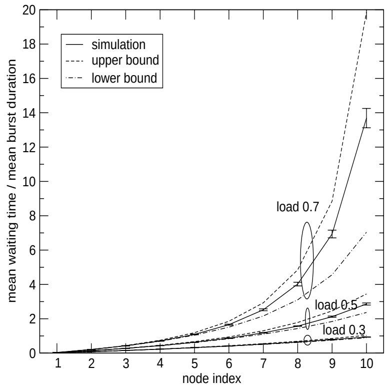

Figure 5 Mean waiting time wrt. node position for fixed burst size

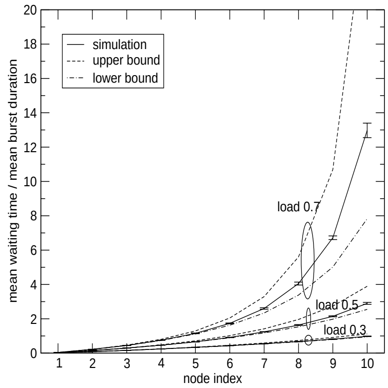

Figure 6 Mean waiting time wrt. node position for variable burst size

For the slotted mode the mean waiting time computed from Equ. (2) is exact and found to be in perfect consistency with the simulation results. For the unslotted mode, the upper bound and lower bound calculated according to Section 3.2 and Section 3.3 are drawn in Figure 5 for the fixed burst size case and in Figure 6 for the case of variable burst size with values uniformly distributed between 5058 and 16000 bytes.

It can be observed that the mean waiting time is in the order of only 1 to 20 mean burst transmission times, i. e., less than 0.25 ms, and that downstream nodes experience a larger delay due to the intrinsic priority property of the DBORN MAC protocol. However, at small and medium load levels, the unfairness between the edge nodes is not really prominent.

Also, the curves for the two approximations bound the simulation results very well in all cases. The bounds are tighter for upstream nodes and scenarios with lower load, which can be explained by the smaller channel fragmentation in both cases.

In the following sections only simulation results will be shown for clarity of graphs.

4.2 Comparison of slotted and unslotted mode

Mean waiting times for slotted and unslotted mode with fixed burst size are compared in Figure 7. In both operation modes, the principle behavior observed in the previous subsection is dominant. However, depending on load, the unslotted mode yields lower waiting times for upstream nodes up to a certain ring location. This can be explained by the residual slot lifetime at arrival. In case of high load this effect diminishes and the slotted mode has a smaller waiting time.

In Figure 8, the mean waiting time of the 10th edge node, which has the worst waiting time performance, is observed regarding different network loads. The performance gap between slotted and unslotted opens increasingly with the network load. The high sensitivity of the unslotted mode to the high load is closely related to its non-work-conserving property, i. e., the channel bandwidth is not fully utilized due to channel fragementation.

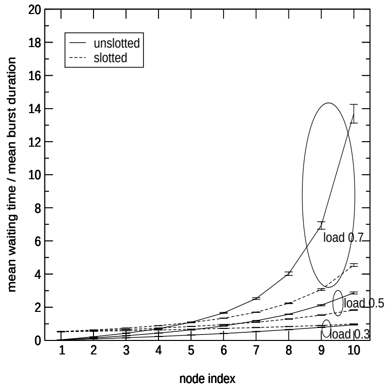

Figure 7 Mean waiting time wrt. node position

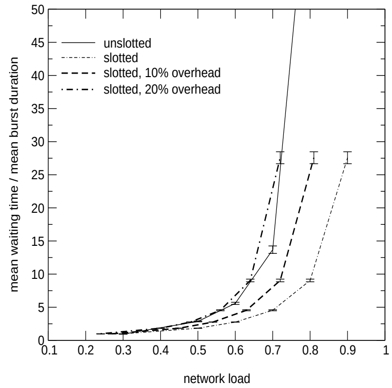

Figure 8 Mean waiting time of node #10 wrt. network load

However, slotted operation implies that not all bursts are perfectly filled (c.f. Section 2.2) which introduces an overhead to the slotted case not considered so far. To make this comparison more accurate curves with a 80 % and 90 % filling efficiency are included in Figure 8—the load is increased respectively. It can be clearly seen that the difference between unslotted operation and slotted operation with even 80 % filling efficiency is marginal. Consequently, burst assembly for fixed size bursts has to yield very high filling degrees.

4.3 Impact of burst size distribution for unslotted operation

The mean waiting time for the unslotted mode with variable burst size is drawn in Figure 9. Three discrete uniform distributions are applied with ranges for the sample values of [11276, 16000], [5058, 16000] and [1150, 16000] respectively. They are selected to systematically analyse the impact of increasing the coefficient of variation c moving from the fixed size case ($c = 0$) to $c \approx 0.1, 0.3, 0.5$. Note that as burst size is limited, so is variability.

It can be seen from the graph that a higher variability in the burst size results in an increased waiting time. However, this impact is small compared to the impact of load or node position on the ring. Thus, we restrict our following evaluations to the case with fixed burst size.

4.4 Node-to-hub delay between edge node and hub

While the MAC protocol introduces a clear unfairness with respect to mean waiting time for downstream nodes, these nodes have the advantage of a small propagation delay towards the hub. In order to consider both effects we evaluate the node-to-hub delay in the ring. It comprises the waiting time for transmission in the edge nodes as well as the propagation delay to the hub. The scenario is a reference metro ring with a total length of 120 km to which 11 equidistant nodes (10 edge nodes and 1 hub) are attached.

Figure 10 depicts the node-to-hub delay for the most upstream and most downstream node and for both slotted and unslotted mode with fixed burst size versus the load. It can be observed that the delay of edge node 1 is insensitive to the load and

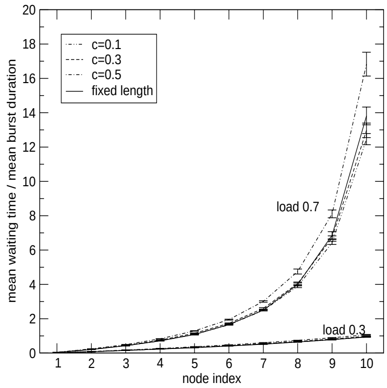

Figure 9 Impact of variable burst size

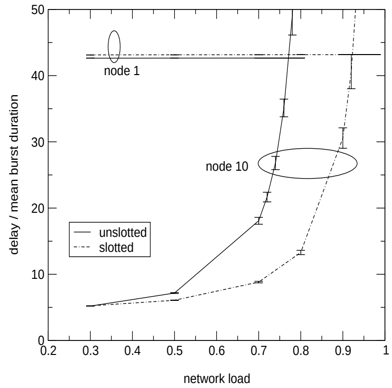

Figure 10 Node-to-hub delay

equals the constant propagation delay. In contrast, the node-to-hub delay of edge node 10 is dominated by the waiting time and thus the load. Node 1 and 10 have the same node-to-hub delay at a load greater than 0.9 for slotted mode and around 0.75 for unslotted mode. This indicates that DBORN can operate even at high load without worrying about the fairness regarding mean node-to-hub delay.

5 Conclusion and outlook

This paper accounts for the performance issues of CSMA-CA MAC protocol in DBORN. With our new analytical models for this network, we compute the exact mean waiting time for the slotted operation mode and derive the performance bounds for the unslotted operation mode. The results are verified by simulation.

The impact of key design parameters on the performance is studied. Slotted mode outperforms unslotted mode in high load situations. However, this advantages can be reduced by inefficient filling of fixed size bursts. For unslotted mode, variability in burst size shows only little influence on the mean waiting time, which is another credit for introducing variable size assembly. At last we discuss the node-to-hub delay and show that the different propagation delays of edge nodes at different positions can balance the unfairness in the mean waiting time to a large degree.

Our future work will be focused on the design and evaluation of fairness mechanisms for heavy load and overload situation with reference to the available work [2]. Also, we will study an extended system scenario including the traffic assembler, multiple channels and scheduling in edge nodes and the hub node.

6 Appendix

Iterative formulas [7] for the solutions of the first and secondary ordinary moment of the completion time C_i and busy period B_i:

$$E[C_i] = \left(\frac{1}{\lambda_{\le i-1}} + E[B_{i-1}]\right)(E[e^{\lambda_{\le i-1} T_{H,i}}] - 1) \tag{8}$$

$$E[C_i^2] = 2\left(\frac{1}{\lambda_{\le i-1}} + E[B_{i-1}]\right)^2 E[(e^{\lambda_{\le i-1} T_{H,i}} - 1)^2]$$

$$+\left(E[B_{i-1}^2] + \frac{2E[B_{i-1}]}{\lambda_{\le i-1}} + \frac{2}{\lambda_{\le i-1}^2}\right)(E[e^{\lambda_{\le i-1} T_{Hi}}] - 1)$$

$$-2\left(E[B_{i-1}] + \frac{1}{\lambda_{\le i-1}}\right)E\left[T_{Hi} e^{\lambda_{\le i-1} T_{Hi}}\right] \quad (9)$$

$$E[B_i] = \frac{\lambda_i}{\lambda_{\le i}} \cdot \frac{E[C_i]}{1 - \lambda_i E[C_i]} + \frac{\lambda_{\le i-1}}{\lambda_{\le i}} \cdot \frac{E[B_{i-1}]}{1 - \lambda_i E[C_i]} \quad (10)$$

$$E[B_i^2] = \frac{\lambda_i}{\lambda_{\le i}} \cdot \frac{E[C_i^2]}{(1 - \lambda_i E[C_i])^3} + \frac{\lambda_{\le i-1}}{\lambda_{\le i}}\left(\frac{E[B_{i-1}^2]}{(1 - \lambda_i E[C_i])^2} + \frac{\lambda_i E[B_{i-1}]E[C_i^2]}{(1 - \lambda_i E[C_i])^3}\right) \quad (11)$$

where $1 < i \le p$ and $T_{H,i}$ is the random variable for service time of the class-i customer and $E[T_{H,i}] = h_i$. For class-1 customers it is exactly a M/G/1 single queue thus there is $C_1 = h_1$, $E[B_1] = h_1/(1 - \lambda_1 h_1)$ and $E[B_1^2] = E[T_{H,i}^2]/(1 - \lambda_1 h_1)^3$ [8] which initiate the iterative computation.

7 References

[1] T. Atmaca, D. Popa: “Logical performance of the optical packet metropolitan ring architecture.” *Proceedings of 17th International Symposium on Computer and Information Sciences (ISCIS)*, Orlando, Oct. 28-30, 2002, pp. 98-102

[2] N. Bouabdallah, L. Ciavaglia, E. Dotaro, N.L. Sauze: “Matching fairness and performance by preventive traffic control in optical multiple access networks.” *Optical Networking and Communications (OptiComm 2003)*, Dallas, Oct. 13-17, 2003, pp. 424-429.

[3] G. Eilenberger, L. Dembeck, W. Lautenschläger, J. Wolde: “Optische Burst-Techniken in Metronetzen.” *ITG-Fachtagung Photonische Netze 2002*, pp. 13-18

[4] C.M. Gauger: “Trends in Optical Burst Switching.” *Proceedings of the SPIE ITCom Conference (ITCom 2003)*, Orlando/FL, September 2003

[5] G. Hu, K. Dolzer, C.M. Gauger: “Does burst assembly really reduce the self-similarity.” *Optical Fiber Communication Conference (OFC 2003)*, Atlanta, Mar. 2003, pp. 124-126.

[6] ITU-T Recommendations on the OTN Transport Plane, G.709

[7] N.K. Jaiswal: “Priority queues.” Academic Press, New York and London, 1968

[8] L. Kleinrock: “Queueing systems.” Volume I/II, John Wiley & Sons, 1975

[9] N.L. Sauze, A. Dupas, E. Dotaro, L. Ciavaglia, M.H.M Nizam, A. Ge, L. Dembeck: “A novel, low cost optical packet metropolitan ring architecture.” *European Conference on Optical Communication (ECOC 2001)*, Amsterdam, Oct. 2001.

[10] H. Takagi: “Queueing analysis." Volume I, NORTH-HOLLAND, 1991, pp. 365-373

[11] X. Yu, Y. Chen, C. Qiao: “A study of traffic statistics of assembled burst traffic in optical burst switched networks.” *Opticomm 2002*, pp. 149-159

[12] http://www.caida.org/analysis/AIX/plen_hist/