Performance of MAC Layer and Fairness Protocol for the Dual Bus Optical Ring Network (DBORN)

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***Abstract*–DBORN (Dual Bus Optical Ring Network) is a network architecture for wavelength division multiplexing metropolitan area networks. In DBORN, metro clients like enterprise networks are connected to the optical metro-ring by edge nodes which share the wavelength channels on the ring. In order to allow for a high-speed optical interface on the upstream wavelengths while avoiding active optical switching components, a carrier sense multiple access/collision avoidance (CSMA/CA) medium access control (MAC) protocol is realized. A Fairness protocol so-called TCARD was proposed [2] to tackle with the positional priority problem and provide guaranteed QoS.**

In this paper, the MAC protocol and the closely related transmitter interface are described first. Then, the performance of the MAC protocol is evaluated with respect to important system parameters like slotted/unslotted operation mode, burst size distribution and node position in terms of the mean waiting time as well as the node-to-hub delay. The performance of TCARD is inspected through simulations with respect to different parameter settings. Based on the original TCARD protocol in asynchronous unslotted operation mode, we also introduce slotted TCARD for the slotted operation mode and obtain outstanding performance gains.

***Index Terms*–Optical MAN, Media Access Control, Fairness, Performance Evaluation, Simulation**

I. 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 [12] satisfies these demands in 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. A novel medium access control (MAC) protocol was designed to operate on the basis of passive detection of the optical power level on the wavelength channel [4]. In spite of its conceptual simplicity and cost effective implementation, the fair sharing of bandwidth between the network nodes cannot be assured by applying well-known solutions in bus/ring networks such as DQDB or MetaRing [3]. In [2] a protocol TCARD (Traffic Control Architecture using Remote Descriptors) was proposed to mitigate the positional priority and provide QoS guarantee in DBORN networks. In this paper, we will present a detailed performance evaluation of the MAC protocol and TCARD fairness protocol.

In Section II, we will describe the network architecture, its MAC protocol and the TCARD mechanism. Section III and Section IV present the results of the performance evaluation of the MAC protocol and TCARD respectively. In Section V conclusions are drawn and further work is outlined.

II. NETWORK ARCHITECTURE AND MAC PROTOCOL

DBORN is a high speed network solution for metropolitan areas [12]. On the basis of advances in the optical transmitter and receiver technology [4], carrier sense multiple access with collision avoidance (CSMA/CA) could be realized in DBORN.

A. 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 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 (Fig. 1). While downstream wavelength channels start from the transmitters in the hub, upstream wavelength channels are terminated by the receivers

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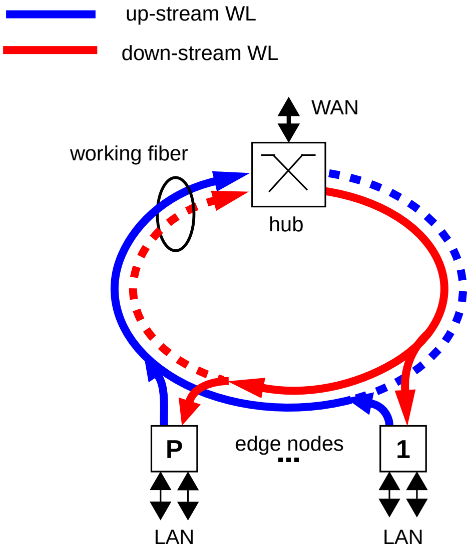

Fig. 1: DBORN architecture

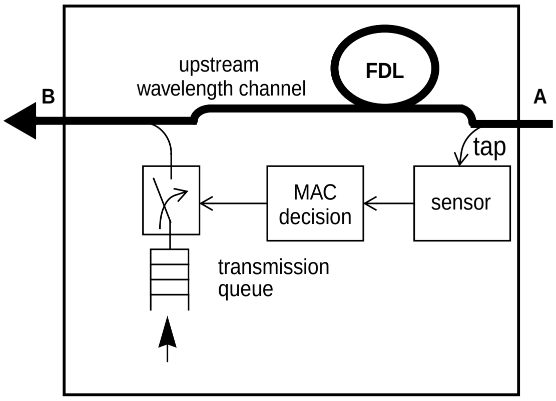

Fig. 2: Functional model of transmitter interface in edge nodes

in the hub. In a typical scenario, the metro ring has a bitrate 2.5 Gbps or 10 Gbps per wavelength.

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 introduced and inspected in the following sections.

B. 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 $50ns$ [4], which on a 10Gbps 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 [14] 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. [5][6][9][11][13]).

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, efficiency 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 [8]. As this paper focuses on MAC performance, we use a maximum burst size of 16K bytes in our studies and only consider the effects of (suboptimal) burst assembly by varying the filling efficiency in one specific scenario.

C. 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. Fig. 2 depicts a functional model of the transmitter interface, which was designed to allow a collision-free medium access.

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 without collision. 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 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 busy.

In the unslotted mode, no synchronization 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.

In the context, an edge node B is defined as the downstream node of another edge node A if node B is located closer to the tail of the upstream bus (cf. Fig. 1) than node A. Correspondingly, node A is called the upstream node of node B. With the CSMA/CA MAC protocol an edge node can only utilize the void on the upstream channel for transmission of its local bursts. Since the by-passing traffic seen by the upstream nodes is always more intensive than that seen by the downstream nodes, the downstream nodes can be discriminated in the channel access. In the extreme case, upstream nodes can monopoly the whole channel bandwidth and the downstream nodes are simply throttled.

Since on the upstream channel each node only detects the optical power level but does not inspect the content of channel signals, there is no information exchange between the edge nodes on the time-scale of node-to-node propagation delays. Thus, it is not practical to apply the traditional fairness mechanisms that are based on reservation bits or explicit signaling between the nodes. Possible solution may be the introduction of a distributed flow control in each edge node to constrain the channel access, especially for the upstream nodes. Here the well-known traffic regulator like GCRA (Generic Cell Rate Algorithm) and token bucket algorithm can be considered. These algorithms are originally designed for the cases that the packet/cell sizes are constant. So they are not directly applicable in case the burst length is variable. The algorithms generally have two parameters, one for restricting the mean rate of the departure traffic (first moment statistic), the other for tuning the burstiness of the departure traffic (second moment statistic). Our simulation research showed that although in overloaded case the fairness can be well assured by these algorithms, in underloaded cases it is in general required to press strong restriction on the burstiness of departure traffic in order to achieve fairness. This can lead to significant increase in the access delay.

D. Fairness Protocol (TCARD)

TCARD [2] is proposed for unslotted operation mode of DBORN not only to mitigate the fairness problem, but also to provide QoS guarantee for the high priority traffic. It takes advantages of a so-called anti-token mechanism to constrain the channel access of upstream nodes and reserve bandwidth for downstream nodes. The principle is similar to the token-bucket. However, in contrast to token-bucket in which each token is a grant for sending a packet/cell, each anti-token stands for the necessity to leave bandwidth idle for the transmission of a maximum length burst at one of the downstream nodes. In practice, an edge node abstains from transmitting in a void whose length is equal to or greater than the maximum burst length as long as the token bucket is not empty.

The rate of anti-token and the size of the anti-token bucket are two parameters directly related to the TCARD algorithm. The token rate $R_{\text{token},\,i}$ at Node i corresponds to the total amount of transmission capacity to be reserved for its downstream nodes and can be calculated according to the following formula:

$$R_{\text{token},\,i} = \frac{C \cdot \sum_{j=i+1}^{N} \rho_j}{L_{max}} . \tag{1}$$

Here C denotes the wavelength channel capacity, ρ_j is portion of the channel capacity reserved for Node j, and L_{max} is the maximal burst size in bit. N is the number of edge nodes.

The relevance of the size of anti-token bucket is not mentioned in [2]. We carried out experiments in different network scenarios in the condition of infinite bucket size. It was found that there are only very small backlog in the bucket. For example, in the overloaded case of unslotted operation mode and with 10 edge nodes on the ring, the maximal number of anti-tokens in the bucket amounts to only 3. Therefore, we concluded that the size of the anti-token bucket does not serve as an essential system parameter for TCARD since the anti-token is seldom backlogged. In the following evaluations, the bucket size is simply taken to be infinity.

III. PERFORMANCE EVALUATION OF THE MAC PROTOCOL

In this section, performance evaluation will be concentrated on the MAC protocol on the upstream channel. 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 system model for the upstream channel is illustrated in Fig. 3. Two scenarios are considered: a system with 10 edge nodes attached to a single 10 Gbps upstream channel and a system with 5 edge nodes on a 2.5 Gbps channel. Since the results are quite similar in these two cases, only the results from the former scenario are presented here. Homogenous

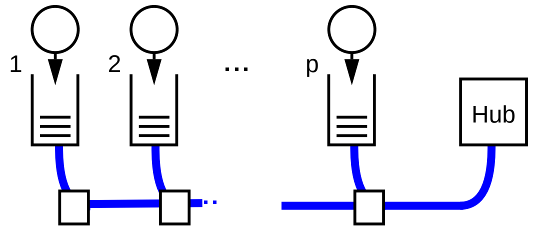

Fig. 3: System model of MAC protocol

traffic is uniformly distributed over all edge nodes. As for the traffic model, although the data traffic was verified to possess self-similarity (or long range dependence), latest research showed that within a specific small time scale the Internet traffic still shows Poisson property [10], which can be more relevant for system performance than the self-similar property in the large time scale [7]. In [11] a traffic aggregation scheme is suggested to assure the output burst traffic to be Poisson traffic. Therefore, we use Poisson process to model the burst arrivals in each edge node. 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 II, 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 systematically 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.

A. Comparison of Slotted and Unslotted Mode

Mean waiting times for slotted and unslotted mode with fixed burst size are compared in Fig. 4. It can be observed that in both operation modes the mean waiting time is in the order of only 1 to 20 mean burst transmission times, i. e., less than 0.25 ms. Also, downstream nodes experience a larger delay due to the intrinsic priority property of the DBORN MAC protocol, i. e. , an edge node can only make use of bandwidth (voids) on the channel which was left over by other nodes located further upstream. However, at small and medium load levels, the unfairness between the edge nodes is not really prominent. 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 outperforms the unslotted mode. Because in unslotted mode the edge nodes send asynchronously, there may be voids becoming too small to be filled by any of the bursts, so called channel fragmentation. This leads to significant performance degradation at high load level.

In Fig. 5, 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 fragmentation.

However, in practice slotted operation implies that not all bursts are perfectly filled (c.f. Section B) which introduces an overhead to the slotted case not considered so far. To make this comparison more accurate curves with a 80 % and 90 %

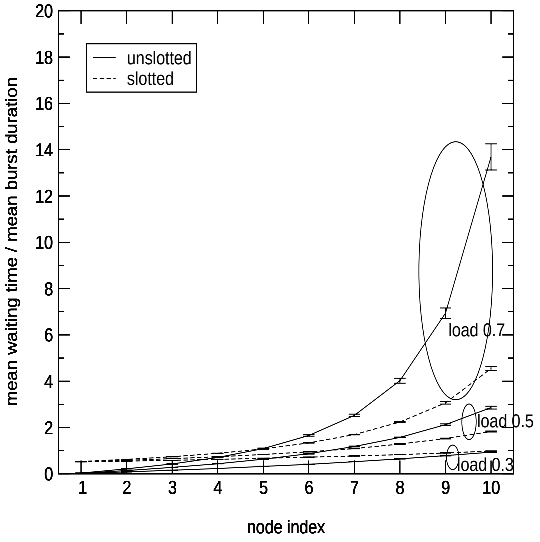

Fig. 4: Mean waiting time wrt. node position

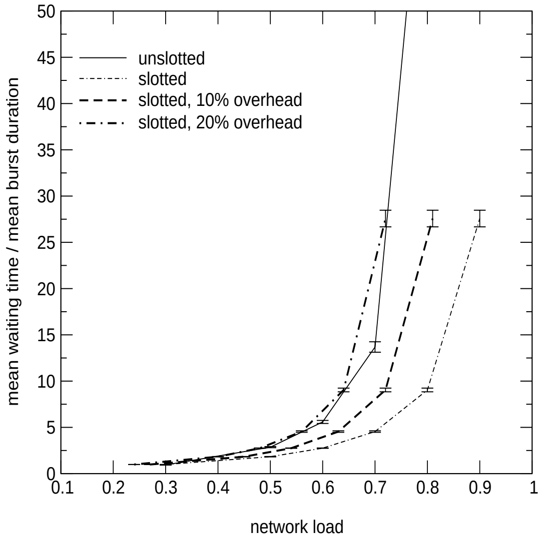

Fig. 5: Mean waiting time in node #10 wrt. network load

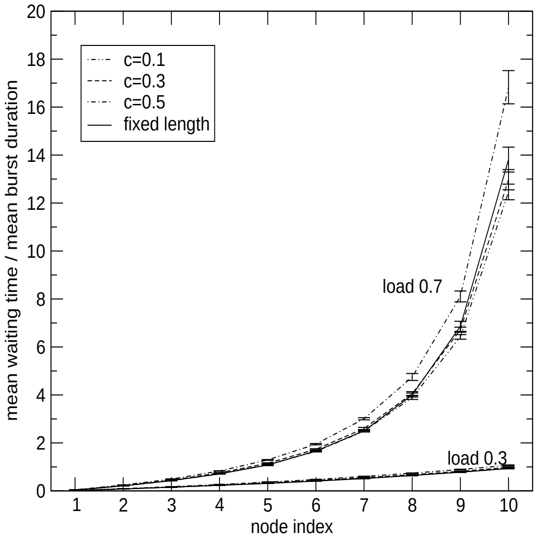

Fig. 6: Impact of variable burst sizep

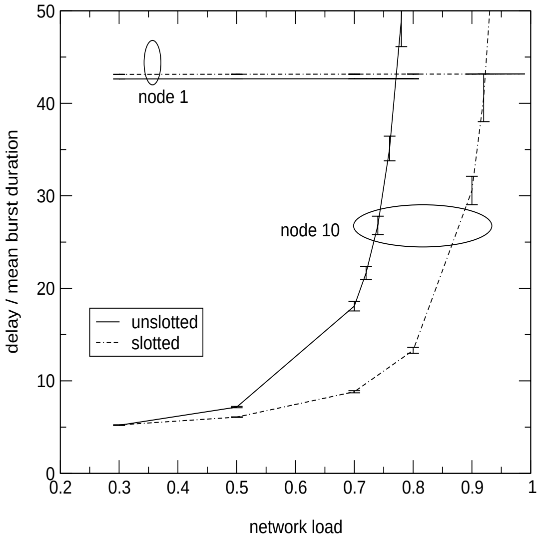

Fig. 7: Node-to-hub delay

filling efficiency are included in Fig. 5—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 to reach better performance than unslotted operation.

B. Impact of Burst Size Distribution for Unslotted Operation

The mean waiting time for the unslotted mode with variable burst size is drawn in Fig. 6. 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 its 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.

C. 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.

Fig. 7 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 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 in a large metro-ring, the unfairness problem can be largely alleviated.

IV. PERFORMANCE OF TCARD

The determination of parameter ρ_j in Equ. (1) is relative straightforward in bandwidth reservation for high priority services. They generally requires guaranteed high QoS and are also subject to the call admission control and usage parameter control. Thus, the states (traffic volume, traffic profile) of these services are inherently available so that amount of necessary bandwidth can be calculated and reserved dynamically. For example, in [2] ρ_j is calculated from the admitted peak rate of the high-priority traffic in Node j .

In the worst case, the operator can predict the bandwidth requirement of the high priority services and statically over-allocate a certain amount of capacity for them. This can be the case, in which no information regarding the current network states is available, or it is not possible to dynamically tune the bandwidth allocation according to the network status. The point here is, high priority service today accounts for a small portion of the total network traffic but means high revenues for the network operator. So it is practical and profitable to over-allocate bandwidth for high priority traffic of each edge node at the cost of more discrimination on the low priority traffic, i.e., best effort traffic.

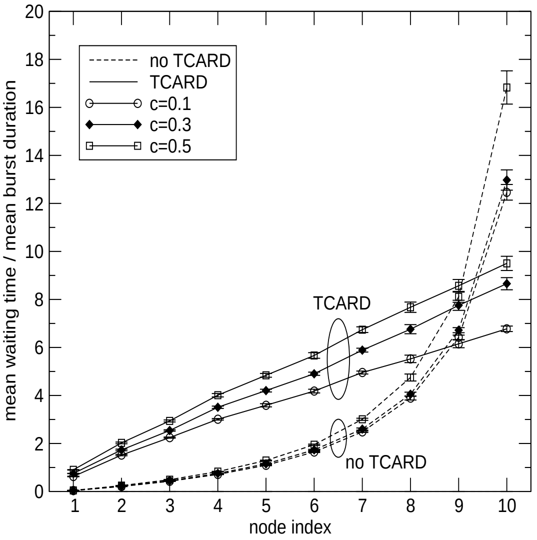

Fig. 8: Mean waiting time wrt. node position for variable burst size in unslotted operation mode at load 0.7 (alpha=1)

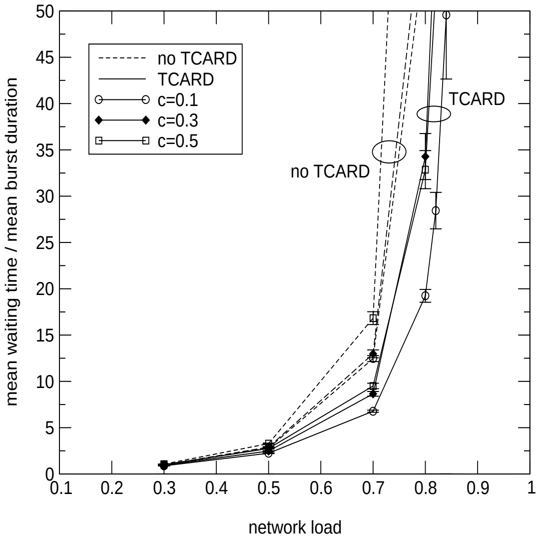

Fig. 9: Mean waiting time wrt. total network load for variable burst size in unslotted operation mode (alpha=1)

For best effort service, since there are no specific QoS requirements, ρ_j is decided only to provide fairness between different edge nodes [1]. In [2], ρ_j is calculated according to the mean traffic rate. However, the best effort traffic is stateless, so the determination of its mean rate must depend on online or off-line measurement, both of which is subject to the measurement accuracy. Besides, due to the lack of a admission control scheme, best effort traffic is generally quite bursty and dynamic. The influence of inaccurate setting of the anti-token rate should be considered. Even if the traffic rate can be accurately estimated, the application of Equ. (1) is still questionable with respect to the concept of fairness. If the fairness means that each node is allocated with a certain amount of network capacity, Equ. (1) is quite natural. This is the case when the network is overloaded. However, when the network is not overloaded, in principle each node can enjoy the amount of bandwidth that is no less than its offered traffic. The fairness issue is then more focused on the delay performance of each node. Thus, Equ. (1) does not necessarily represent the best parameter setting with respect to the mean waiting time of bursts in the edge node.

Therefore, the influences of different settings of the anti-token rate on the fairness performance should be closely inspected for the best effort traffic. To do this, we apply a more general formula to determine the anti-token rate:

$$R_{\text{token},\,i} = \frac{C \cdot \sum_{j=i+1}^{N} \rho_j}{L_{max}} \alpha \qquad (2)$$

ρ_j is the offered traffic load of Node j and α is an additional factor inserted to adjust the anti-token rate. If $\alpha = 1$, Equ. (2) becomes equivalent to Equ. (1).

In this section, we will first verify the fairness performance of TCARD with its parameter setting according to Equ. (1). Then the performance behavior of different settings of the anti-token rate according to Equ. (2) will be studied. Both are in unslotted operation mode. Based on the anti-token mechanism, *slotted TCARD* will be proposed for the slotted operation mode and its performance will be shown. Finally, the fairness with respect to the bandwidth share in the overloaded situation is inspected. The traffic model and system parameters are the same to those applied in Section III.

A. *Fairness wrt. Access Delay ($\alpha = 1$)*

In Fig. 8 the mean burst waiting time of different edge nodes is plotted for unslotted operation mode at network load of 0.7 with and without TCARD. Uniform distributions of [11276, 16000], [5058, 16000] and [1150, 16000] are again taken to model the variable burst size. The correspondent coefficient of variation c amounts to 0.1, 0.3 and 0.5. It can be observed that for all three cases, the access delay of the last downstream node is significantly reduced due to the introduction of TCARD, of course at the cost of the increased access delay in the upstream nodes. The mean waiting time increases almost linearly with the node index, in comparison to the convex form of the original curve, meaning the last several edge nodes are now not so strongly discriminated. An obvious improvement in the fairness.

In Fig. 9 the mean waiting time in the last edge node is plotted with respect to the network load. At small network loads, it is not surprising that all scenario show just small access delay and there is little difference in the curves. With the

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[1] For study, it is assumed here that all the network traffic is best effort traffic. So, only the fairness issue is involved.

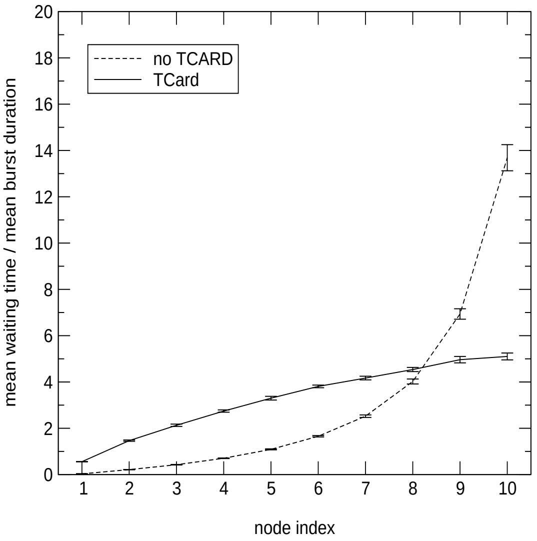

Fig. 10: Mean waiting time wrt. node position for fixed burst size at load 0.7 in unslotted operation mode (alpha=1)

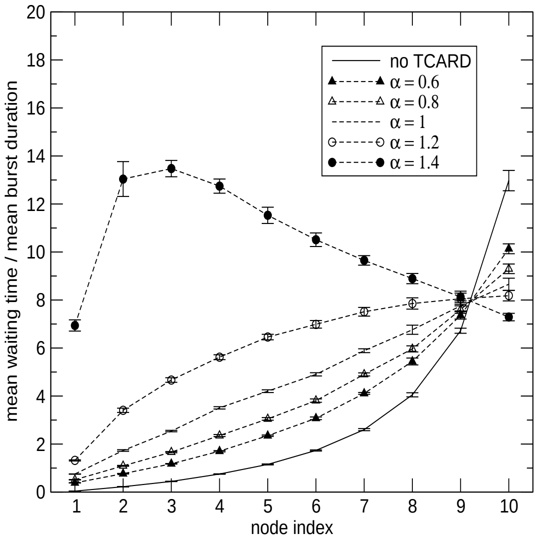

Fig. 11: Mean waiting time wrt. node position for variable burst size at load 0.7 in unslotted operation mode (different values of alpha)

increasing network load, the difference between the schemes with/without TCARD becomes more and more prominent. At large network loads, three TCARD curves fall far below the curves without TCARD, indicating a large reduction in the access delay.

The mean burst waiting time wrt. the node index for constant burst size of 16 KBytes is plotted in Fig. 10 . Similar to cases of variable burst size, TCARD brings large performance improvement. Especially noticeable in Fig. 10 is the slower increase of access delay with the increase of edge node in the deployment of TCARD. The curve becomes concave and shows even better fairness characteristic than the linear increase of mean waiting time in Fig. 8.

In general, it can be concluded that TCARD can provide significant improvement in the fairness and system performance.

B. *Fairness wrt. Access Delay (Different Values of α)*

In this section, we focus on the influences of different settings of anti-token rate by tuning the value of α in Equ. (2) for unslotted operation mode. Since similar results and conclusions can be drawn for fixed and variable burst size, only the results for variable burst size uniformly distributed between 5058 and 16000 bytes with $c = 0.3$ are presented.

For $\alpha = 0.6, 0.8, 1.0, 1.2, 1.4$, the mean waiting time in each edge node is sketched in Fig. 11 for network load of 0.7.

In case $\alpha < 1$, it can be seen that the curves locate between the one for unslotted MAC protocol without TCARD and the one for the application of TCard with $\alpha = 1$. Since small values of α mean less access control in the edge node, the curves behave more like the unslotted MAC protocol. For cases with $\alpha > 1$ the phenomenon is not straightforward to be understood. With $\alpha = 1.2$ the mean waiting time grows fast in the beginning and then tends to be constant or even decrease. This indeed implies a better fairness than the case of $\alpha = 1$. With $\alpha = 1.4$ the curve rises first and then sinks, which goes again to unfairness with discrimination pressed on the upstream nodes. Such behaviors can be attributed to two aspects: the amount of free bandwidth “seen” by an edge node and the bandwidth fragmentation.

Based on the setting of the token rate, the following relation can be derived for the available bandwidth $C_{\mathrm{idle},i}$ for Node i on the upstream channel:

$$C_{\mathrm{idle},i} = C\left(1 - \alpha \cdot \sum_{j=i+1}^{N} \rho_j - \sum_{k=1}^{i-1} \rho_k\right) \qquad (3)$$

It is simply the total channel bandwidth subtracted by the bandwidth utilized by upstream nodes and the bandwidth reserved for the downstream nodes through the anti-token mechanism. If $\alpha = 1$ or $\alpha < 1$, $C_{\mathrm{idle},i}$ remains constant or decreases with the increase of node index. Additionally, the downstream nodes suffer even more from the bandwidth fragmentation. Therefore, the mean waiting time increases monotonically with the nodes index. When $\alpha > 1$, $C_{\mathrm{idle},i}$ increases with the node index. The downstream node has larger free bandwidth, but it also meets with more bandwidth fragmentation. So the behavior of the curves is subject to the interaction between these two effects. For $\alpha = 1.2$, the step-wise increase of $C_{\mathrm{idle},i}$ equals $0.014C$ and is not large enough to balance the bandwidth fragmentation, so the mean waiting time still continuously grows. For $\alpha = 1.4$, the step-wise increase of $C_{\mathrm{idle},i}$ amounts to $0.028C$ and begins to suppress the effect of bandwidth fragmentation in the 3rd node.

Therefore, it is clear that by proper setting the anti-token rate (in this case $\alpha = 1.2$), better fairness performance can be achieved. Too small anti-token rate ($\alpha < 1$ here) results in

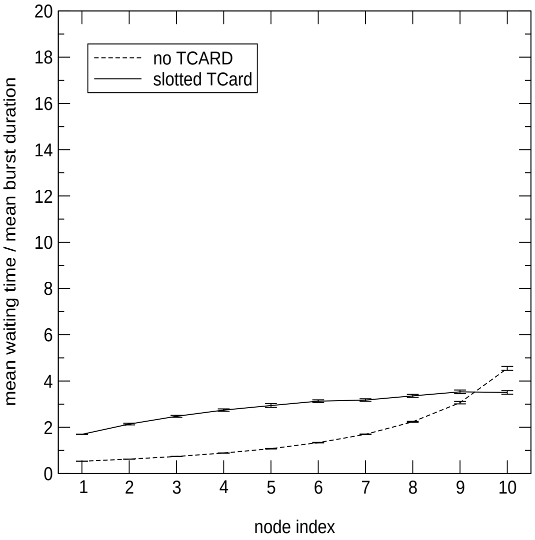

Fig. 12: Mean waiting time wrt. node position at load 0.7 in slotted operation mode

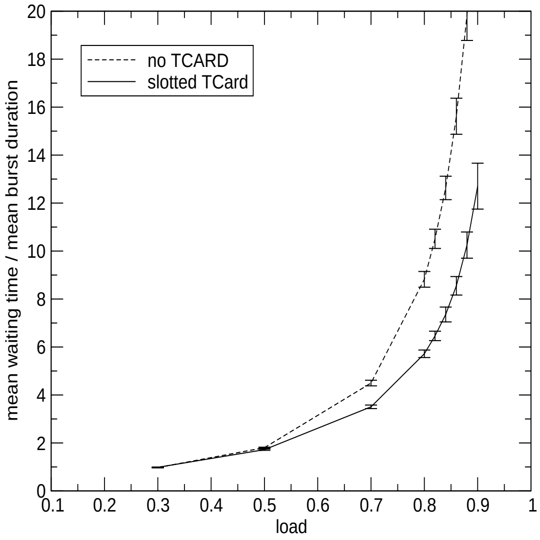

Fig. 13: Mean waiting time wrt. load in slotted operation mode

less effectiveness of the control mechanism and the performance degrades towards unslotted operation mode without TCARD. However, too large anti-token rate ($\alpha = 1.4$ here) just pushes the weight of access priority to another side and can cause even more dramatic unfairness. In practice, great care shall be taken to set the anti-token rate to reach an optimal fairness performance.

C. Access Delay of Slotted TCARD

In Section III it is observed that in slotted operation mode the fairness is much better than the unslotted mode at the same network load. However, at very high load it still has the problem of unfairness. The anti-token mechanism of TCARD can be also applied to the slotted mode to cope with it: for each by-passing idle slot the anti-token has always the higher priority than a local burst. We refer to this fairness protocol as slotted TCARD.

For a brief presentation of the basic system behaviors of slotted TCARD, Equ. (1) is applied to determine the rate of anti-token. Simulation results are plotted in Fig. 12 for the mean waiting time with respect to node index at a load of 0.7. The burst size is fixed to 16K bytes. A quite flat curve is obtained with slotted TCARD. In Fig. 13, the mean waiting time of the 10th edge node is depicted with respect to the network load. The curve for slotted TCARD lies beneath the curve without slotted TCARD at high loads. The performance gain is very obvious.

D. Fairness wrt. Bandwidth

For unslotted operation mode, throughput of each node is shown in Fig. 14 when the network is overloaded (network load greater than 1). So the bandwidth allocated to each node is 1/10 of the channel capacity and the anti-token rate in each node is calculated according to Equ. (1). Fixed burst size and variable burst size are inspected respectively. For variable burst size, the three uniform distributions are again used. It can be figured out that perfect bandwidth fairness is achieved with TCARD in case the burst size is fixed, because the voids reserved in the unit of constant burst size by anti-tokens can be completely utilized by the downstream nodes. When the burst size is variable, the result is not so ideal. The first node always gets its complete share of bandwidth, i.e., carried traffic equal to 0.1, because the first node can take fully advantages of the channel bandwidth except those reserved for the downstream nodes. On the second node, however, there is an abrupt drop in its throughput since the available bandwidth,

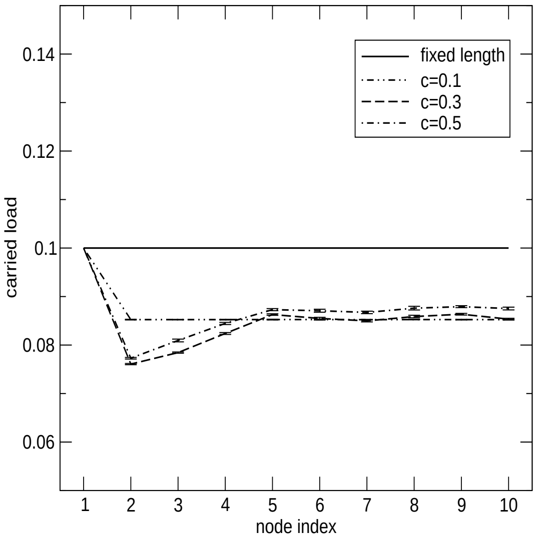

Fig. 14: Throughput of nodes when network is overloaded in unslotted operation mode

which is reserved by the first node in the unit of maximal transmission time of one burst, cannot be completely utilized due to the bandwidth fragmentation problem. After the second node, the throughput can grow again for the distributions of [5058, 16000] ($c = 0.3$) and [1150, 16000] ($c = 0.5$). This is due to two aspects. On the one hand their individual available bandwidth share is guaranteed by the anti-token mechanism of the TCARD although they also suffer from bandwidth fragmentation. This means their throughput should be at least comparable to the throughput of the second edge node. On the other hand, these downstream nodes have additional probability to consume the fragmented bandwidth, referring to the small voids that could not be used by the upstream nodes. Therefore, they can achieve a larger throughput than the upstream nodes. For distribution [11276, 16000] ($c = 0.1$), however, the nodes after the second node have the same throughput as Node 2, because the small bandwidth fragments caused by the upstream node are too small to be utilized again by the downstream nodes. For instance, a void of length 16000 bytes is occupied by a smallest burst of 11276 bytes. The bandwidth fragment amounts to $16000 - 11276 = 4724$ bytes, which is no more suitable for any burst.

Because the bandwidth fragmentation cannot be completely avoided for variable burst size, 100% utilization of the channel capacity is impossible. In this regard, the bandwidth fairness realized through TCARD is quite acceptable.

In slotted operation mode with slotted TCARD and fixed burst size, each edge node has an ideal throughput share, i.e., 1/10 of the total channel capacity, not considering the padding overhead in the burst assembly procedure. The curve is similar to the fixed burst size case in Fig. 14.

V. CONCLUSION AND OUTLOOK

This paper analyses the performance issues of the CSMA-CA MAC protocol in DBORN. The impact of key design parameters on the performance is studied. Slotted mode outperforms unslotted mode in high load situations. However, inefficient filling of fixed size bursts might reduce this advantage. 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. We also 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 in a large metro-ring.

Also, the fairness protocol TCARD proposed for unslotted operation mode is evaluated in details. It is shown that with appropriate setting of the anti-token rate, satisfying fairness can be assured with respect to the access delay of each edge node. However, the performance is sensitive to the setting of anti-token rate and special care shall be used for an optimal solution. We also show that the slotted TCARD in slotted operation mode can bring significant performance gain as well. At last, the fairness is inspected with respect to the throughput when the network is overloaded. In unslotted operation mode, with fixed burst size the ideal bandwidth share can be achieved by TCARD; with variable burst size, although the obtainable throughput of each edge node is below the ideal one except for the first edge node, the degree of fairness is still acceptable.

The parameter setting of TCARD in any case relies on the information regarding the offered traffic load in downstream nodes. In real network operation, due to the traffic dynamics it is not always easy to predict the best effort traffic load of other edge node precisely and collect the information together for the parameter setting of a local edge node. The setting of the anti-token rate based on inaccurate network load information may lead to unexpected performance degradation. This remains to be an issue for further study.

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] L. Ciavaglia, N. Bouabdallah, 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] M. Conti, E. Gregori, and L. Lenzini: “Metropolitan area networks.” Springer-Verlag London, 1997

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

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

[6] 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.

[7] G. Hu: “Impact of Access Bandwidth on Aggregated Traffic Behavior and Queueing Performance.” *Proceedings of the 12th GI/ITG Conference on Measuring, Modelling and Evaluation of Computer and Communication Systems/3rd Polish-German Teletraffic Symposium,* Dresden, Sept. 12-15, 2004

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

[9] M. Izal, J. Aracil: “On the influence of self-similarity on optical burst switching traffic.” *Proceedings of IEEE GLOBECOM 2002,* Taipei, Nov. 2002

[10] T. Karagiannis, M. Molle, M. Faloutsos, A. Broido: “A nonstationary Poisson view of Internet traffic.” *Proceedings of IEEE INFOCOM 2004,* Hong Kong, March 7-11, 2004.

[11] M. de Vega Rodrigo, J. Götz: “An analytical study of optical burst switching aggregation strategies.” *The Third International Workshop on Optical Burst Switching,* San Jose, Oct. 25, 2004

[12] 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.

[13] X. Yu, Y. Chen, C. Qiao: “A study of traffic statistics of assembled burst traffic in optical burst switched networks.” *Optical Networking and Communications Conference (Opticomm 2002),* Boston, Jul. 29 - Aug. 1, 2002, pp. 149-159

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