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Delay improved Media Access Control for Passive Optical Networks

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***Abstract*—Passive Optical Networks (PONs) are a promising technology for replacing today's access networks and to combine them with metropolitan area networks, because they offer high bandwidth and cover wide distances. However, the large distances between the endpoints introduce the problem of a relatively large propagation delay. Traditional Media Access Control (MAC) protocols applied in today's PONs are not able to handle these propagation delays efficiently. We present a new MAC mechanism specifically tailored for operation in Orthogonal Frequency Division Multiplexing (OFDM) based long-reach PONs. Our approach combines classical polling and random access to join the benefits of both MAC principles to reduce transmission delays. We perform an analytical evaluation of the combined MAC mechanism as well as simulation studies. The simulation studies show that the new MAC approach is able to reduce the minimal transmission delay by up to 63%.**

I. Introduction

A. Motivation

Future Internet access networks have to provide higher bandwidth than available today to fulfill the requirements of upcoming applications. Passive Optical Networks (PONs) are a suitable replacement of current access networks, as they can offer bandwidth up to $100\,\text{Gbit/s}$ [1]. Besides the bandwidth, the delay of the access network is also a restricting factor of the network performance. Especially in the case of long-reach PONs, where the distance between the endpoints of the access network can be as large as $100\,\text{km}$, the propagation delay alone adds up to $500\,\mu\text{s}$ [2]. Applications like document processing on hosted applications in the cloud (e. g., Google Docs or Microsoft Office Web Apps) require short transmission delays in order to provide a good user experience. Other applications like streaming video games require high bandwidth, but also small delays.

In access networks with a shared medium, transmissions from the head-end to the subscribers can be performed without much effort, if the network is centrally coordinated by the head-end, i. e., a variant of Coordinated Access (CA) is applied. All downlink data have to pass the head-end where available resources of the shared medium can be assigned to transmit the data. Uplink transmissions are more challenging, because the medium access of the subscribers has to be coordinated to avoid collisions. Therefore the focus of this paper is on an appropriate Media Access Control (MAC) protocol for uplink transmissions.

Current standardized MAC protocols for PONs are designed to offer a high utilization of the medium, but the delay has only a lower priority. For this reason we present in this paper a new MAC protocol offering high utilization and short transmission delays. This is achieved by the combination of classical CA and Random Access (RA).

B. Related Work

Standardized PON systems, like Gigabit-PON (GPON) [3], Ethernet-PON (EPON) [4] and their successors, use polling for uplink transmissions. This method requires the exchange of status messages between the endpoints of the PON. To gain more flexibility in assigning the available bandwidth to the subscribers, Dynamic Bandwidth Allocation (DBA) algorithms are applied. In [5] the authors compared different DBA algorithms for EPONs with respect to their throughput and delay behavior. To reduce the delay in long-reach PONs, several improvements for classical polling have been introduced. Interleaved Polling with Adaptive Cycle Time (IPACT) was one of the first improved polling variants for EPONs [6]. In contrast to classical polling, with IPACT it is not necessary to wait until all subscribers have reported their resource requirements to the head-end before resources can be allocated. Instead, resources for one subscriber can be allocated directly after the report of this subscriber is received. Another concept is multithread polling [7], which introduces multiple concurrently executed polling threads to reduce the time between the exchange of status messages. Another improved variant is real-time polling. This variant requires an additional uplink control channel to report status changes from the subscribers of the PON immediately. A comparison between polling variants showed that both multithread polling and real-time polling lead to smaller delays compared to IPACT and classical polling [2].

The scope of the EU-funded project ACCORDANCE was to evaluate all parts of Orthogonal Frequency Division Multiplexing (OFDM) based PONs, including

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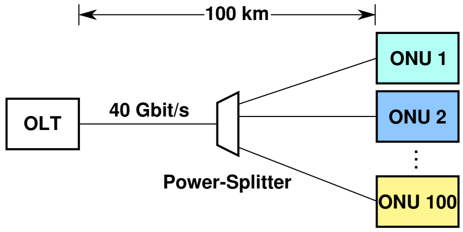

Figure 1. Topology of the PON

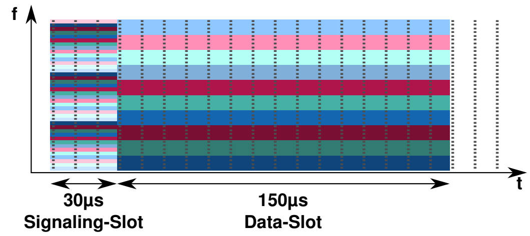

Figure 2. OFDM frequency time diagram with Codeblocks

the MAC layer. Their outcome is to reuse existing MAC protocols from EPON and GPON [9]. Because the protocols for EPON and GPON are designed for a Time Division Multiplexing (TDM) operation of the PON, they have to be extended to support the additional frequency component of OFDM. The additional degree of OFDM-PONs and their advantage compared to TDM-PONs have been presented [10]. Also a MAC protocol tailored for OFDM PONs has been developed [11]. The protocol is designed as an addition to Multi Point Control Protocol (MPCP) used in EPON. Delay reduction is achieved by applying DBA and taking Quality of Service requirements into account.

In contrast to centralized polling approaches, decentralized media access (RA) offers shorter transmission delays at the expense of possible collisions. A MAC protocol for long-reach PONs was proposed that is designed to reduce the delay by a RA scheme [12]. One drawback of the proposal is the requirement of direct communication between all subscribers.

The idea of combining CA and RA to reduce the delay and joining the advantages of both principles was already introduced in [13] and [14]. Both publications present wireless networks where traffic with different requirements is transmitted. Based on the requirements of the traffic, the appropriate MAC approach is used. RA is applied for applications requiring short delays and CA is used if higher delays can be tolerated but more data has to be transferred.

Summarizing the related work it can be said that the problem of high delays in long-reach PONs has been identified and also solutions to reduce the delay have been proposed. But the proposals still suffer from high propagation delays. Also the benefits of decentralized MAC protocols have been identified. However, the combination of CA and RA to join the benefits of both principles is a new approach for the operation of PONs.

The remainder of the paper is organized as follows. Section II introduces the scenario where the presented MAC protocol is applied. Section III gives an overview of CA variants. Section IV presents the proposed MAC protocol. The results of a performance evaluation of the proposed MAC protocol are presented in Section V. Finally, Section VI concludes the paper.

II. Scenario

The presented MAC protocol is designed for an OFDM based PON with the topology shown in Fig. 1. The PON consists of one Optical Line Termination (OLT) in the central office, up to 100 Optical Network Units (ONUs) at the subscriber side and at least one optical power-splitter to connect the ONUs with the OLT. We consider a long-reach PON which means that the distance between OLT and ONUs can be up to $100\,\text{km}$. The result of the long distance is a propagation delay τ of approximately $500\,\mu\text{s}$. We assume that the distances between each ONU and the OLT are similar, so that the difference of the propagation delay can be neglected. One reason for this assumption is that the length of the drop-fiber (the fiber connecting an ONU with the power splitter) is much shorter than the length of the feeder-fiber (the fiber between OLT and power splitter). The PON is dimensioned to carry $40\,\text{Gbit/s}$ of traffic in both directions in full-duplex mode. Direct communication between ONUs is not possible, which also means that they can not use techniques like carrier sensing to detect if they are allowed to send.

The PON is based on OFDM which offers a high flexibility for resource allocation, because it is possible to allocate resources in the two dimensions frequency and time. The smallest possible resource types are Codeblocks (CBs) of fixed sizes, which are composed out of multiple subcarriers and OFDM symbols.

The transmission of data inside the CBs is protected with the help of a Forward Error Correction (FEC) code. We assume that it is possible to perfectly decode the data inside a CB if no collision occurs. A collision occurs if two or more ONUs send on the same subcarriers at the same time. To simplify the operation of the PON a slotted transmission scheme of the CBs is utilized. This means that transmissions of CBs may only be started at the beginning of discrete timeslots.

Here we assume two different types of CBs:

- CBs with a size of $75\,000$bytes. This type is used for the normal data transmission and is called Data-Codeblock (DCB).
- Smaller CBs with a size of 1500bytes. They are used for signaling information and are called Signaling-Codeblocks (SCBs).

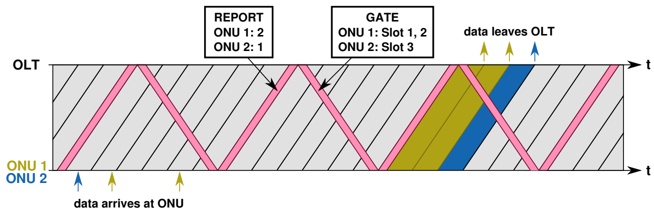

Figure 3. Principle of polling

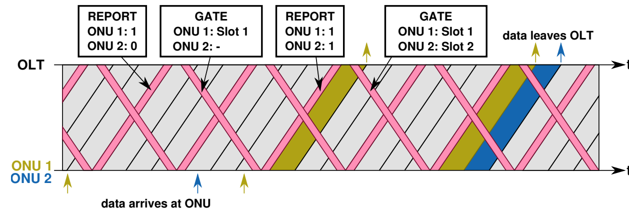

Figure 4. Principle of multithread polling

The exact sizes of the CBs are not important for the general idea to combine CA and RA. The presented MAC protocol only depends on transport mechanisms for data and signaling information.

The CBs are transmitted in parallel, i. e., the frequency domain is used to transmit 10 DCBs simultaneously. We call this a data-slot. The choice of 10 parallel DCBs is a tradeoff between good usage of available OFDM subcarriers and guard intervals in the time domain. With the given bandwidth of the PON this leads to transmission durations of $T_{DS} = 150\,\mu s$ (see Fig. 2). To support 100 subscribers, 100 SCBs are transmitted in parallel. This is called signaling-slot. The duration for the transmission is therefore $T_{SS} = 30\,\mu s$. To support higher numbers of subscribers more than 100 SCBs are required, which can be achieved by concatenating several signaling-slots. As we use the frequency domain of OFDM only to transmit several CBs in parallel, it would be also possible to apply the presented MAC protocol to other PON technologies like TDM-PONs.

Another important aspect for the design of MAC protocols for PONs is the traffic that has to be transmitted. Measurements of traffic characteristics in existing access networks show that the carried traffic is highly bursty and fluctuating [15], [16]. We assume similar characteristics of the traffic in the PON. Therefore we design the MAC protocol to be able to handle bursty traffic efficiently. Especially a full buffer or greedy source scenario, where all subscribers of the PON want to send as much data as possible all the time is not the common situation.

III. Coordinated Access

One classical operation mode for shared media networks is CA. A central station controls the medium access of all other stations. Often this is achieved with an implementation of polling, but a token passing mechanism is also a form of CA. The advantages of CA are the good resource utilization and the lack of collisions. Depending on the actual variant of CA, the waiting time until a station is allowed to send can increase drastically with increasing number of stations.

A. Polling

Polling is the typical operation mode of today's standardized PONs [3], [4]. In general the OLT queries the amount of buffered data waiting for uplink transmission inside the ONUs periodically. The ONUs answer the query by reporting the current buffer level in *REPORT* messages. If possible, the OLT will then grant sufficient resources to the ONUs. Query and grant can be combined into one *GATE* message. *GATE* and *REPORT* messages are both transferred in SCBs. Transmission of payload data is performed in *DATA* messages in DCBs.

Note that the polling mechanism used in the standardized PONs differs from the polling mechanism shown in this paper. One reason is the slotted OFDM operation in contrast to TDM in EPON and GPON.

Fig. 3 shows the used polling mechanism that is suitable for a slotted system with a constant polling cycle length. In the figure signaling-slots are colored in red and data-slots used by ONUs 1 and 2 in yellow and blue, respectively. Unused data-slots and data-slots used by other ONUs are colored in gray. The principle shown in the figure is not true to scale to the assumed durations of data- and signaling-slots. Data-slots are transferred between consecutive *REPORT* messages. The depicted *REPORT* and *GATE* messages contain one *REPORT* and one *GATE* for every connected ONU. To identify the DCBs during a polling cycle, we apply an index starting from 0 up to the number of available DCBs. This index is also used by the OLT to assign DCBs to ONUs.

The components in the PON have to perform the following operations in order to transmit data in the uplink direction.

- *S1* Data arrives at the ONU and is stored in a local buffer.
- *S2* The ONU reports the amount of stored data towards the OLT in the next signaling-slot.
- *S3* The OLT grants the number of needed DCBs to the ONU and sends a *GATE* message. (Fig. 3 shows the assignment of whole data-slots for a more descriptive illustration.)
- *S4* The ONU sends the buffered data in the assigned DCBs.
- *S5* The OLT receives the data

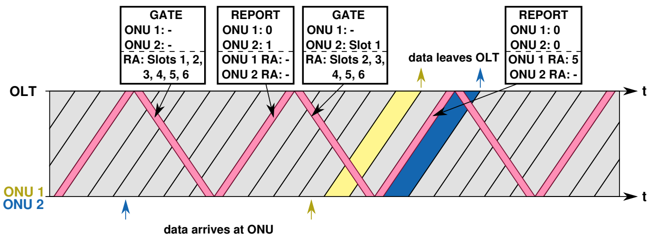

Figure 5. Principle of the combination of RA and CA

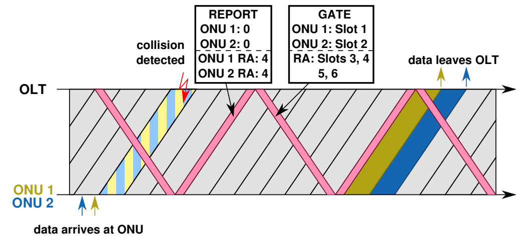

Figure 6. Reaction to collisions

This leads to the following delay components for uplink transmissions. In case of overload, the overall delay increases because of necessary queuing. However, we do not consider the case of overload in the following.

T_1 A variable duration until the ONU can send the next *REPORT* message (duration from *S1* to *S2*).

T_2 The constant duration until the next *GATE* message arrives from the OLT (*S2* to *S3*). This duration mainly consists of the propagation delay.

T_3 A variable duration until the ONU is allowed to send (*S3* to *S4*).

T_4 The constant transmission duration of a DCB (*S4* to *S5*).

The duration of a polling cycle, which is defined as the time between the transmissions of two consecutive *GATE* messages, should be as small as possible to offer short delays. For optimal utilization of the medium the following equation should hold:

$$nT_{DS} + T_{SS} \geq 2\tau$$

Where n denotes the number of data-slots per polling cycle. If $nT_{DS} + T_{SS}$ is smaller than 2τ, slack times occur where the ONUs are idle and waiting for arriving *GATE* messages. On the other hand $nT_{DS}+T_{SS}$ should not be much larger than 2τ, because otherwise the delay would increase. Under these aspects n can be calculated as follows:

$$n = \left\lceil \frac{2\tau - T_{SS}}{T_{DS}} \right\rceil = \left\lceil \frac{1000\,\mu s - 30\,\mu s}{150\,\mu s} \right\rceil = 7$$

B. Multithread Polling

An interesting candidate to reduce the delay especially in long-reach PONs is multithread polling. If multithread polling is used, then multiple polling threads are active concurrently (see Fig. 4). This reduces the waiting time until an ONU can report the buffer level to the OLT.

Again the overall delay consists of the same four parts described in the previous section. But the difference is that both variable parts (T_1 and T_3) are reduced due to the fact that there is the possibility to send signaling-slots more often. In the following we use the extreme case ($n = 1$), where uplink signaling-slots and data-slots alternate. The drawback of the increased number of exchanged signaling-slots is more signaling overhead and therefore a degraded maximum utilization of the PON.

IV. Combination of Coordinated Access and Random Access

This section introduces the main contribution of this paper, namely the delay improved MAC mechanism. First we introduce the principle, then we present a way how collisions can be handled efficiently.

A. Principle

The principle of the presented MAC procedure is to transfer data in unused resources in a RA fashion. Unused resources are DCBs which are left free in the CA operation, called RA area. Every ONU reports the buffer level as it would do in a pure CA system. Additionally each ONU adds information about the indices of DCBs it tried to send a *DATA* message in the RA area during the previous polling cycle. The OLT operates in the same way as it would in the CA case, but additionally it marks unused DCBs as RA area. Both information is sent towards the ONUs in extended *GATE* messages. It is possible to combine RA with normal polling (Random-Access + Polling (RAPo)) or to combine RA with multithread polling (Random-Access + Multithread Polling (RAPoMT)).

During normal operation ONUs always send newly arriving data as soon as possible in the RA area (transmission of ONU 1 in Fig. 5). If there is no DCB marked for RA, which is the case if all DCBs are used for CA, the ONU falls back to the normal polling mechanism (transmission of ONU 2 in Fig. 5).

To reduce the possibility of collisions in the RA area, ONUs are not allowed to perform RA attempts if they already received a grant in the current polling cycle. However, ONUs are allowed to report data to the OLT and sending data in the RA area in the same polling-cycle.

B. Handling Collisions

The combination of CA and RA leads to several challenges, caused by possible collisions between ONUs.

The OLT detects collisions, if it is not able to decode the received *DATA* messages. The OLT resolves collisions by assigning an additional DCB to the involved

ONUs in the next *GATE* message. It knows about the involved ONUs by comparing the index of the DCB where the collision has happened with the information about RA attempts from the *REPORT* messages.

In the example of Fig. 6 the collision happened in slot 4 and ONU 1 as well as ONU 2 report that they tried to send a *DATA* message in slot 4. So the OLT knows that a collision between ONU 1 and ONU 2 has to be resolved. It adds an additional DCB to both ONUs in the next *GATE* message. Also the OLT has to notify the ONUs about the collision so that they can send the collided *DATA* messages again. For this notification we utilize an ACK mechanism, where each *GATE* message contains an ACK for every correctly received *DATA* message. If there is no ACK for a previously send *DATA* message in the next *GATE* message, the ONU has to repeat this *DATA* message.

A special case of a collision happens, if ONU 1 wants to send data, but there is no RA area before the next *REPORT*. Therefore it reports the current buffer size (here assumed to correspond to one DCB) to the OLT and sends the data during the next polling cycle in the RA area. In the next cycle ONU 2 transmits a *DATA* message in the same DCB in the RA area and a collision is detected by the OLT. If the OLT would react by assigning two DCBs to ONU 1 (one for the requested DCB from the *REPORT* message and one for the detected collision) and one DCB to ONU 2, it would assign one unnecessary DCB to ONU 1.

To solve the problem, the ONU not only reports the amount of data in the first *REPORT* message, but also adds the indices of the DCBs where it is going to send the *DATA* message in the RA area. This is possible because the information about the RA area is already available from the previous *GATE* message. The OLT can use the information about the planned RA attempts to avoid double grants.

If the first RA attempt of ONU 1 would be successful, then ONU 1 would receive an unneeded grant. Compared to a pure CA scenario, this behavior is no waste of resources, because the ONU would need a grant, too. Additionally the unneeded grant can be used to transmit data that has arrived in the meantime.

If an ONU is sending multiple *DATA* messages in the RA area it could happen that not all of them arrive at the OLT, due to collisions. Then the data is not in order anymore and the OLT should not forward it. Reordering can be resolved by assigning sequence numbers to every *DATA* messages and buffering. But even with the involved buffering delay the total delay is not larger than in the pure CA case.

V. Evaluation

In this section we compare polling, multithread polling, RAPo and RAPoMT. As the design goal of the combined MAC approaches is a minimal delay, the evaluation is mainly focused on the delay improvements. The evaluation is split into two parts. In the first part maximum and minimum values of relevant metrics are derived analytically. The second part is based on a system level simulation, to gain a deeper insight in the behavior of the MAC protocols. For both parts two assumptions hold. First, OLT and ONUs are ideal devices, which means that they do not introduce any processing delays. The second assumption is that there is no loss in the fiber. Therefore collisons are the only cause for losses.

A. Analytical Evaluation

In this subsection we present bounds for the achievable utilization and minimum and maximum limits of the delay for the evaluated MAC mechanisms.

1) Polling: During a polling cycle there is the possibility to transmit $n = 7$ data-slots and one signaling-slot. The maximum utilization can be calculated as follows:

$$\rho_P = \frac{nT_{DS}}{T_{SS} + nT_{DS}} = \frac{1050\,\mu s}{1080\,\mu s} = 97.2\%$$

We derive delay bounds by considering the four components introduced in Section III-A. The minimum possible delay is achieved if both variable parts (T_1 and T_3) vanish. Then the transmission delay is:

$$T_{P,min} = T_{SS} + nT_{DS} + T_{SS} + T_{DS} + \tau = 1760\,\mu s$$

The maximum delay omitting queuing delay is obtained if T_1 and T_3 reach their maximum possible value and can be calculated as follows:

$$\begin{aligned} T_{P,max} &= nT_{DS} + T_{SS} + nT_{DS} + T_{SS} + nT_{DS} + \tau \\ &= 2T_{SS} + 3nT_{DS} + \tau = 3710\,\mu s \end{aligned}$$

2) Multithread Polling: Multithread polling introduces an increased exchange of signaling-slots. Therefore the maximum achievable utilization is reduced to:

$$\rho_{Pm} = \frac{T_{DS}}{T_{SS} + nT_{DS}} = \frac{150\,\mu s}{180\,\mu s} = 83.3\%$$

The minimum possible delay is in the case of multithread polling the same as for normal polling:

$$T_{Pm,min} = m(T_{SS} + nT_{DS}) + T_{SS} + T_{DS} + \tau = 1760\,\mu s$$

m is necessary to take the slotted operation of multiple polling threads into account. The duration between an ONU sends a *REPORT* and receives the corresponding *GATE* cannot be shorter than $2\tau + 2T_{SS}$. Due to the slotted structure consisting of one signaling-slot and $n = 1$ data-slots, the duration between a *REPORT* and *GATE* has to be an integer multiple of $T_{DS} + nT_{DS}$. Therefore m can be calculated as follows:

$$m = \left\lceil \frac{2\tau + 2T_{SS}}{T_{SS} + nT_{DS}} \right\rceil = 6$$

Due to the multiple polling threads, T_1 equals in the worst case the duration of one data-slot and one signaling-slot. The maximum delay is therefore much shorter than for the normal polling variant.

$$\begin{aligned} T_{Pm,max} &= T_{SS} + T_{DS} + m(T_{SS} + nT_{DS}) + T_{SS} + T_{DS} + \tau \\ &= T_{SS} + T_{DS} + T_{Pm,min} = 1940\,\mu\text{s} \end{aligned}$$

3) RAPo and RAPoMT: For the combined MAC mechanisms the maximum utilization is the same as for the underlying polling variant. In the case of RAPo with $n = 7$ the utilization is $\rho_C = 97.2\%$. For RAPoMT ($n = 1$) the maximum utilization is $\rho_{Cm} = 83.3\%$.

The minimum delay occurs if data arrives shortly before the RA area and is transmitted immediately:

$$T_{C,min} = T_{Cm,min} = T_{DS} + \tau = 150\,\mu\text{s} + 500\,\mu\text{s} = 650\,\mu\text{s}$$

The maximum duration for the transmission of a *DATA* message is given by the maximum delay of the underlying polling mechanism, because in any case data can be transmitted via CA and the access scheme guarantees that data in CA slots is not harmed by collisions.

B. Simulation Studies

For the system level simulation a model of the PON was implemented with the help of the event driven simulation library IKR SimLib [17]. The model represents the PON in Fig. 1. We considered 100 ONUs, each transmitting data corresponding to the size of one DCB after a negative exponentially distributed Inter Arrival Time (IAT). The mean value of the IAT is adjusted so that the offered load of the PON can be regulated. 100% offered load means that the full capacity of the PON is used for data transmissions, which is due to the necessary exchange of signaling information not achievable. In contrast to the analytical considerations, the delay in the simulation is measured including queueing delays.

Fig. 7 shows the median of the delay (straight line) as well as the minimal delay (dotted) and the 95% quantile (dashed) of the delay over the offered load for the evaluated methods. Additionally the maximum utilization of the MAC variants is illustrated by two vertical lines at 83.3% and 97.2% offered load. The minimal delays in the case of polling agree with the analytical findings. The 95% quantiles of the delay stay slightly below the analytical upper bounds. If the load of the PON increases to the maximum utilization, the delay also increases, because of short overload situations. The results for multithread polling also correspond to the analytical results.

In contrast to both variants of polling, RAPo and RAPoMT offer a much lower minimum delay. Even for higher traffic loads it is still possible to reach the minimal possible delay, whereas the delay median converges to the values of the corresponding polling counterparts. The same holds for the 95% quantile of the delay, which is always smaller than that of the corresponding polling counterparts. The median of the delay for RAPo significantly increases for an offered load larger than 58%, whereas the delay of RAPoMT increases at higher offered loads. The reason is that the chance for an successful transmission directly in the next data-slot in the RA area is decreased for both variants, as more and more DCBs are used for CA transmissions. But because of the shorter duration of the polling cycle and the more frequent exchange of signaling messages in the case of RAPoMT, the overall delay is smaller than that of RAPo.

Figures 8 and 9 show the CDF of the delay for 40% and 75% offered load, respectively. As can be seen in Fig. 8 the delay for more than 80% of all transmissions of RAPo is smaller than in the case of multithread polling. RAPo achieves in comparison to RAPoMT for almost 70% of all transmissions very similar delays. However, RAPoMT achieves shorter delays for all transmissions. The CDF reveals also that up to 65% of all transmissions have a delay smaller than $800\,\mu\text{s}$, if RAPo is used. This means that up to 65% of all transmissions can be transferred successfully in the next available DCB (at maximum T_{DS} waiting time until the next data-slot starts, T_{DS} to transmit the DCB and the propagation delay τ). For RAPoMT even more transmission can be done in the next DCB.

For an offered load of 75% (see Fig. 9), RAPo achieves only in almost 50% of all transmissions a shorter delay than multithread polling, but stays still below the delays of polling. RAPoMT offers with a probability of 60% significant smaller delays than the multithread polling counterpart. But the delay is always smaller than achieved by multithread polling. With RAPo only 12% of the transmissions can be transferred in the next available DCB, whereas RAPoMT can transfer 15% of all transmissions within the next DCB.

VI. Conclusion

We have presented a new approach for MAC protocols tailored for the characteristics of long-reach PONs. We overcome the delay restrictions of classical MAC protocols by combining polling with random access. The combination allows to use previously unused resources to decrease the transmission delay. The evaluation of the mechanism showed in simulation studies as well as in analytical calculations, that the minimal delay can be reduced by 63% compared to traditional polling mechanisms. The median of the delay can be reduced by 73% in comparison to polling in typical load situations. In contrast to MAC protocols based completely on RA, upper bounds for the delay can be guaranteed, because regular polling is used as a fallback in case of collisions during RA transmissions.

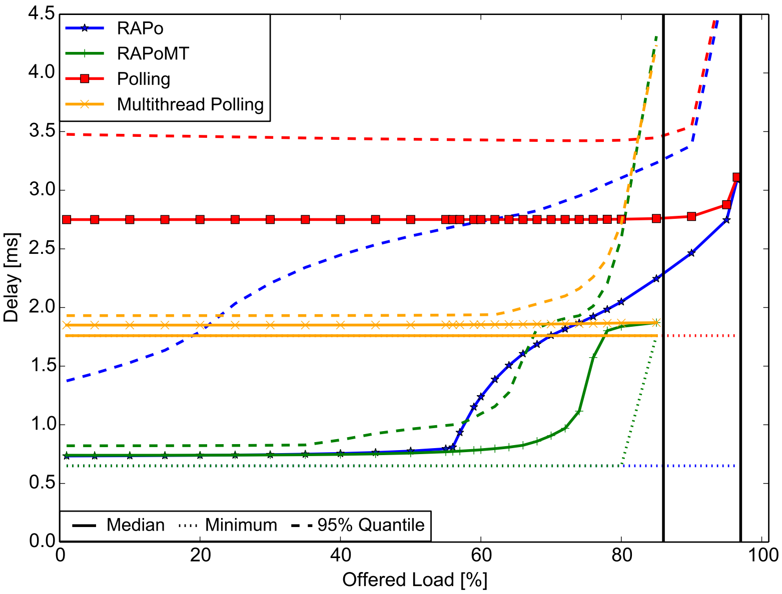

Figure 7. Simulation results for the transmission delay

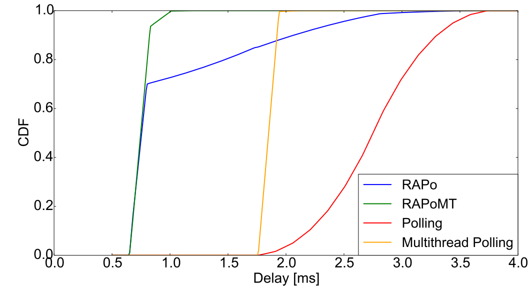

Figure 8. CDF of the delay, 40% offered load

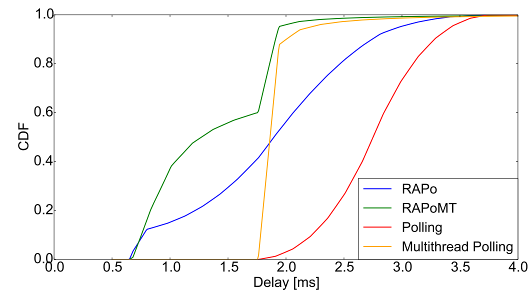

Figure 9. CDF of the delay, 75% offered load

RA collisions may lead to reordering, which can also occur with MAC protocols based on pure CA, where reordering can happen due to losses in the fiber. Both sources of reordering can be easily treated by sequence numbers and buffering in the OLT.

Future steps include further optimization of the proposed MAC protocol and a performance evaluation with more realistic traffic models.

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