Evaluation of Dynamic Bandwidth Allocation Algorithms for G-PON Systems using a reconfigurable Hardware Testbed

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Abstract

The capabilities of passive optical networks (PONs) are strongly influenced by the quality of the used dynamic bandwidth allocation (DBA) algorithm. DBA algorithms control the assignment of available upstream bandwidth to the users connected to the PON. In an oversubscribed environment, that poses a challenge regarding the selection of an appropriate DBA algorithm. Therefore, DBA algorithms are subject of continuous research. To support efficient development and realistic evaluation of DBA algorithms, an FPGA-based hardware evaluation platform is presented. It supports fast implementation and evaluation of both hardware- and software-based algorithms. The evaluation process is featured by software tools, which are used to control stimulus creation. Furthermore, the results of changes in simulated user traffic can be analyzed on a connected workstation.

1 Introduction

Gigabit-capable Passive Optical Networks (GPONs) are the future of access networks. In Asia, North- and South America access networks based on FTTx technologies are widely in service already today [1]. In Europe, customers are mostly connected by digital subscriber line (DSL) technology, which is copper-based. This situation will probably change in the near future in favor of growing share of FTTx technology.

One important part of FTTx-based networks is the optical access network (OAN). It is always terminated by two components. Towards the provider network the termination is carried out by an optical line termination (OLT). Towards the home network, optical network units (ONUs) terminate the fiber network. FTTx-technologies are differentiated by the place, where the optical fiber is terminated. That can be in the areas of the cabinet (Fiber-to-the-Cabinet—FTTC), the building (Fiber-to-the-Building—FTTB), or the flat (Fiber-to-the-Home—FTTH) of the connected users. Figure 1 clarifies these differences. ONUs convert the optical signals coming from the OLT into electrical signals forwarded via copper cable to the customers and vice versa. If the ONU is located at the customers flat, it performs the network termination as well.

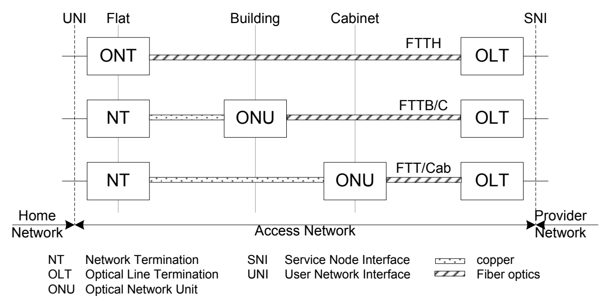

Figure 1. FTTx network architectures

The optical distribution network (ODN) is positioned between ONU and OLT. When using PON technology, up to 64 ONUs are connected to one OLT by a shared fiber. The fiber sharing is performed by a passive beam splitter. That results in special features for traffic distribution. In downstream, from network to customer, any information is simply broadcasted and reaches every connected ONU. In upstream data transmission is performed by applying time division multiplex (TDM). The control of time slots, whereby each is dedicated to one ONU, occurs dynamically by a so called *bandwidth map*. To optimize the bandwidth map a DBA algorithm is required. The algorithm's quality determines the efficiency of bandwidth use and thus the Quality-of-Experience for connected customers. ”A well-defined DBA algorithm can significantly improve network performance, provide means of flexibly tailoring network responsiveness and enable providers to generate more revenue from their FTTH networks without boosting raw bandwidth

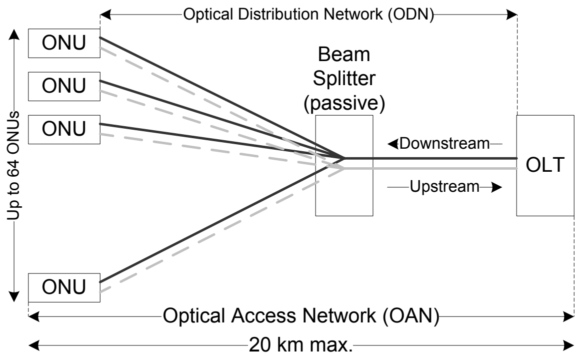

Figure 2. Passive optical network—PON

by increasing the percentage of acceptable oversubscription" [2]. Hence, a lot of attention has to be paid to the development of high performance DBA algorithms. Therefore, an evaluation testbed has been designed, which supports fast development of DBA algorithms both as soft- and hardware implementations.

The remainder of the paper is organized as follows: Section 2 explains GPON technology, as basis of the developed evaluation platform. The DBA algorithms that are to be evaluated and the resulting bandwidth map are introduced in Section 3. Sections 4 and 5 deal with architecture and functionality of the evaluation platform. Section 6 concludes the paper.

2 GPON Technology

As implied in the introduction, PONs are mostly employed in access networks. The reason for applying PONs is the lower price compared to direct fiber or active optical networks (AONs). In contrast to AONs, PONs do not have active switches, which are complex opto-electrical hardware. Instead, a passive optical beam splitter is connected to the OLT on one side and to all ONUs on the other side (see Figure 2). Besides savings in monetary costs that results in important technical implications for traffic distribution.

There is a physical point-to-multi point connection between OLT and ONUs. Thus, in downstream OLT broadcasts all data coming from the core network to all connected ONUs. Each ONU extracts only the parts of data that refer to it. The data for the connected user is then forwarded to the customer premise equipment. The ONUs terminate the broadcast in downstream. As stated before, many ONUs have to share the fiber between splitter and OLT in upstream. To avoid collisions on the fiber, TDM is used. Each ONU sends data in a certain time slot, in which no other ONU is allowed to send. Hence, all streams overlay each other without interfering. That results in a single virtual data stream reaching the OLT. ITU-T and IEEE defined many standards and references for PON systems (APON, BPON, EPON, GPON, GEPON, 10 GEPON) regarding the speed/technology used. All of them show the same functional principle, as described above.

The proposed solution is based on the Gigabit-capable PON (GPON) specification [3]. GPON describes a flexible optical network based on PON, which supports both wide- and narrow band services for connected clients. Principally, GPON equals the already described PON system. Gigabit-capable refers to the reachable data rates. The rate is at maximum at 2.48832 Gbit/s both in up- and downstream. However, asymmetric variants, e.g., 0.15552 Gbit/s upstream and 2.48832 Gbit/s downstream, exist as well.

2.1 GPON Transmission Convergence

Data transfer via optical fiber is performed by the GPON Transmission Convergence (GTC). It is implemented both on ONUs and OLT. The task of GTC is to adapt standard services of clients and providers to the transmission convergence (TC) layer of the GPON by performing framing operations. Compared to standard Ethernet frames, GTC frames are very large. The transmission of a GTC frame via the ODN takes exactly 125 µs. Frames are transmitted continuously without any inter frame gap. That is done both in up- and downstream direction, independent of the existence of user data. Dependent of the line speed, frames reach sizes of up to $19,440$ bytes.

In downstream, all user data is encapsulated in a GTC frame (Figure 3). The payload consists of the data for all connected ONUs (broadcast). Each ONU is addressed by a single GPON Encapsulation Method (GEM) frame. The GEM header consists of information to address the destination ONU. Thus, ONUs are capable of extracting the correct parts of data from the whole GTC frame. Using a header (physical control block downstream -PCBd) control data is transferred together with user data to the ONUs. Amongst others, it contains the TDM information for the upstream in form of a bandwidth map.

In upstream, the GTC frame is a virtual frame. It is composed of all signals coming from the ONUs within an interval of 125 µs (Figure 4). It consists of N time slots to implement TDM. N denotes the number of connected ONUs in the PON system. In each time slot one ONU is permitted to transfer GEM frames to the OLT. The size of the time slots is variable. It is defined in the bandwidth map, which is transferred within the header of the downstream GTC frames. By variations of the bandwidth map, the size of each time slot can be altered at runtime. The DBA algorithm is responsible for the creation of the bandwidth map and computes the size of each time slot, depending on the demands of the ONUs.

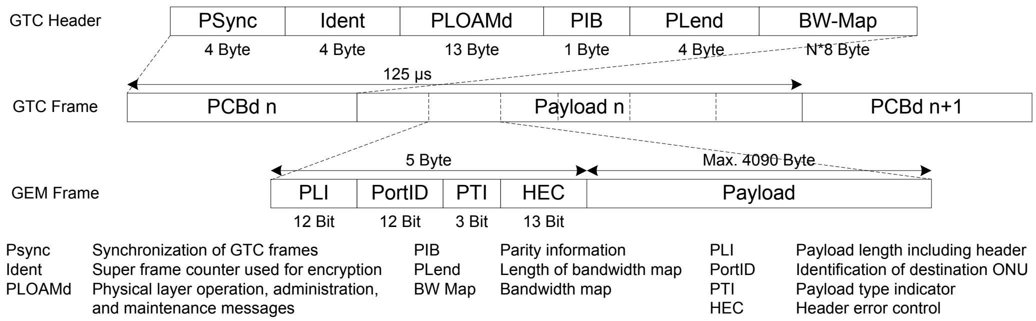

Figure 3. Frame structure of a downstream GTC frame

3 DBA and Bandwidth Map

By modifying the bandwidth map at runtime, an ISP is able to react dynamically to varying bandwidth demands of its customers. Depending on the assigned time slot each ONU has to send GEM frames to fill its slot completely. The bandwidth map (see the structure in Figure 5) defines start and end of all time slots. It contains an 8 Byte wide field for each ONU with a start (SStart) and a stop (SStop) position. As GTC downstream frames reach all ONUs by broadcast, bandwidth information is always available to each ONU. When sending data in upstream all ONUs are synchronized. Thus, each ONU transmits its data, when it is its turn. If there is not enough user data to fill the granted time slot, unused capacities are filled with idle frames. Idle frames are GEM frames, which do not contain any payload. Consequently, an idle frame consists only of the header (PLOu) and has a length of 5 Byte.

With every new downstream GTC frame a new bandwidth map is transferred and the size of the time slots may change. The ONUs adjust their transmission behavior according to the new information from the map. Computation of the bandwidth map is performed in the OLT. The ITU does not define a standard algorithm to compute the values for the bandwidth map. Thus, each manufacturer of GPON systems and ISP can apply its own DBA algorithm to optimize upstream data transfer. Fundamentally, DBA algorithms are based on two kinds of information: Status Reporting and Non Status Reporting.

3.1 Status Reporting

When applying status reporting, the OLT requests information about the status of each ONU. That information is used to determine the actual bandwidth demands of the ONUs. In the simplest case this information is about the fill level of the ONU's transmission buffers [4]. Together with the payload that information is transmitted to the OLT. Based on the information of all ONUs the DBA algorithm computes the bandwidth map for the next downstream GTC frame. In [5] the OLT requests status reports about the class of the traffic each ONU generates. The bandwidth is granted depending on the traffic's content. That way, multimedia services are supported by the DBA algorithm.

3.2 Non Status Reporting - NSR

When applying non status reporting, the OLT determines the bandwidth demands indirectly. Each ONU sends Idle GEM Frames to fill its whole time slot, if there is not enough user data to be transmitted. Thus, by counting the number of sent idle frames, the OLT gets information about the actual bandwidth utilization. With this information the OLTs DBA algorithm can compute an adequate bandwidth map. The fewer the number of idle frames, the higher the bandwidth demand is. Dependent on the actual DBA algorithm, the computation is more or less accurate and meets the actual demands. The authors in [6] use a different approach. A distributed DBA algorithms is presented, which is computed in the ONUs. Basis of the computation is the power required to send upstream data. If no power is detected, no data is sent and other ONUs can use the time for sending data.

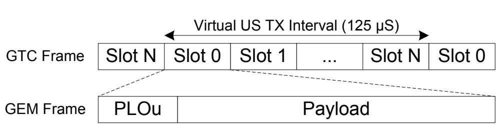

Figure 4. GTC upstream frame

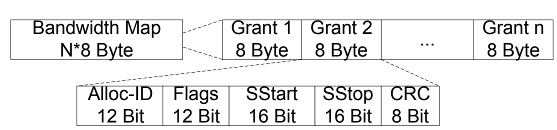

Figure 5. Structure of the bandwidth map

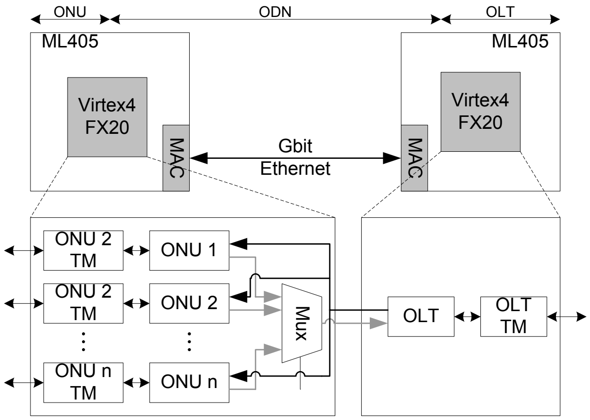

Figure 6. Prototype architecture of the evaluation platform

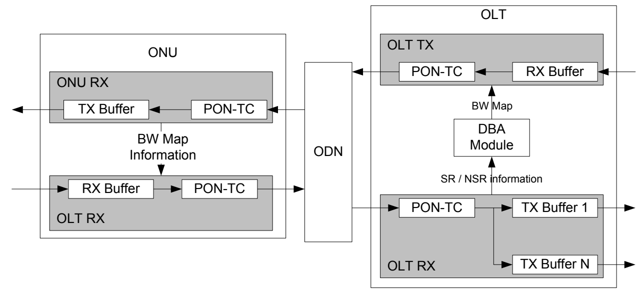

Figure 7. OLT and ONU Architecture

4 PLATFORM ARCHITECTURE

A high performance DBA algorithm optimizes upstream bandwidth. It is though a decisive factor in an environment, which is characterized by overprovisioning. It is most important to offer customers good Quality-of-Service and Quality-of-Experience. The better the DBA algorithm performs, the more satisfied the customers are. From an ISPs point of view, it can be stated, the better the DBA algorithm, the more customers can be connected to a single OLT without falling short of certain service levels. To support the evaluation of different DBA algorithms an FPGA-based evaluation platform was developed. With that platform it is possible to perform evaluation tasks without the need of optical elements or long evaluation times through software models.

The hardware model of a complete PON-System with OLT, ODN, and ONUs was developed to function on two Xilinx ML405 development boards. The goal is to model the PON system with sufficient accuracy and to be able to draw conclusions from the performance of the implemented DBA algorithms. The system is partitioned into two parts, one for the OLT and one for the ONUs. Each of them is implemented on one development board. Figure 6 depicts the block diagram of the system. The OLT-part is implemented together with a traffic module (TM), which is responsible for generating traffic in downstream. Both ONUs and a model of the beam splitter are implemented on the other FPGA. To each ONU one TM is assigned as well.

4.1 ODN

Both parts, OLT and ONUs are connected via a Gbit Ethernet connection. The transmission medium is not an optical fiber. As there is no noteworthy distance between OLT and ONUs, functionalities of layer one as ranging and synchronization do not need to be implemented into the model. To enable frames that require $125\ \mu\text{s}$ for transmission, Jumbo Ethernet frames are used. The size of each Ethernet frame is $16,625\ \text{byte}$. Each frame encapsulates correct GTC frames, as described in Section 2, both in upstream and downstream direction.

It is not possible to model a continuous data transmission as Ethernet requires an inter fame gap and a preamble in front of each frame. In downstream, broadcast is utilized. Modeling that is not problematic. All downstream GTC frames are simply transferred to every ONU. In upstream, a Round-Robin algorithm is used. Collision free TDM is provided by using a multiplexer. The upstream data of the ONUs forms the input of the multiplexer. Its output forms upstream GTC frames. The multiplexer is controlled basing on the data derived from the bandwidth map, which is included in each downstream GTC frame.

4.2 OLT and ONU

The OLT is divided into three parts (Figure 7). A transmission module (OLT-TX), a receive module (OLT-RX), and a DBA module. The TX module implements a buffer, which stores every frame coming from the OLT TM completely. The PON-TC module, which reads from the buffer, is responsible for GTC framing. Therefore, each Ethernet frame from the buffer is encapsulated into a GEM frame. Multiple GEM frames form the GTC frame. As the size for the GTC frame is defined, OLT-TX is capable of fragmenting frames in order to comply with the frame size. To insert a correct bandwidth map, proper information is presented by the DBA module to the TX module. In upstream the TC module extracts all Ethernet frames coming from the ONUs from the virtual GTC frame. Date of each ONU is assigned to an adequate buffer. There are as many buffers as ONUs. The NSR information is extracted as well. For each ONU it is sent to the DBA module.

The ONUs comprise of a TX and RX part as well. The TC modules differ in functionality. In downstream each ONU checks the destination of all encapsulated GEM frames and extracts only those Ethernet frames that are addressed to it. Furthermore, the GTC header is checked, and bandwidth map information is extracted and presented to the own TX part, which uses the information to time its sending interval correctly. The sending interval must be utilized completely for sending data, which is encapsulated in GEM frames. As stated before, if no data is existent, idle frames are sent containing only the header.

4.3 Evaluation Support

TMs are connected to each ONU and OLT module. These modules have the purpose to create traffic both at customer and ISP side. Thus, the system's behavior and performance can be evaluated under different traffic conditions by setting the TMs accordingly. Therefore, TMs can create Ethernet frames. Adaptable parameters are:

- *Frame size* It is possible to send frames of a defined size, of random size, and to send more realistic traffic. According to [7], realistic Internet traffic consists of 35% minimal frames, 10% intermediate frames, 11% maximum frames, and 44% random frames.
- *Inter frame gap (IFG)* It is possible to have a constant IFG or a random IFG with defined mean value. Randomization is implemented by a linear feedback shift register.

All TMs are controllable by software. The properties of the traffic are set by software at runtime. It is thus possible to emulate for example changing user behaviors during a day. All TMs can be accessed individually, meaning traffic parameters can be set for every TM. Hence, it is possible to create complex traffic patterns. Traffic patterns as used in [8] to evaluate different DBA algorithms can be modeled as well. Performing the whole traffic generation completely externally could be regarded as an option. It would save hardware resources and simplify programming. It is though difficult to create stable data rates of $1\ \mathrm{Gbit/s}$ with a typical workstation. Task switches and other unforeseen behavior reduce the reliability of traffic generation. Furthermore, it has to be considered that all implemented ONUs have to be accessed separately. Additional measures to demultiplex the data stream from the PC would be inevitable.

The outputs of OLT and ONUs are monitored on the hardware system. Statistics and information about the composition of traffic are gathered and transferred to another software system. Additionally, all information from the bandwidth map is extracted from the GTC frame, in order to control the correct behavior and reactions of the implemented DBA algorithm.

Individual testing scenarios can simply be implemented by the system described above. The TMs are easy to configure. Thus, different stimulus can be created by software

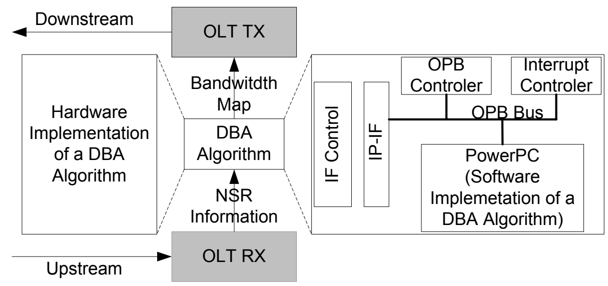

Figure 8. Hard- and software DBA algorithm implementation

without being forced to change and resynthesize the hardware platform. However, to adapt the output information to user's needs changes to soft- and hardware are necessary. Hence, a new hardware synthesis of the evaluation platform is necessary in that case.

5 DBA Implementation

DBA algorithms to be evaluated can be implemented both as hardware and software. The actual system supports the examination of NSR-based algorithms. Therefore, between RX- and TX-part of the OLT a DBA module is implemented. The module receives all incoming information about the number of idle frames received in each time slot from the RX-part. With this information an appropriate algorithm computes the bandwidth map. The map is presented to the TX-part of the OLT, which includes it into the next GTC frames to adapt the time slot size of each ONU. Figure 8 shows the OLT with two different alternatives for a DBA algorithm—hardware- and software implementation. Both implementations have the same interfaces to OTL RX and OLT TX to be exchangeable. For both variants a sample DBA algorithm of low complexity, based on NSR has been developed. The algorithm counts all idle frames for each ONU. The ONU with the most and the one with the least idle frames are determined. The one with the least idle frames is granted an extra amount of time for transmission, which is subtracted from the time amount of the ONU with the most idle frames. All other time slots remain unchanged.

5.1 Hardware DBA Algorithm

Implementing a new algorithm in hardware is straight forward. The existing module for the reference design just needs to be exchanged by a new implementation. There is only one constraint. The module must have the same interfaces and external behavior as the reference implementation. If status reporting shall be implemented further changes in the designs of ONU and OLT need to be performed.

5.2 Software DBA Algorithm

For evaluation of software implementations the same platform can be used as for the software reference. Only the hardware DBA algorithm module has to be exchanged by an interface module, which integrates a PowerPC into the system. The Virtex4-FX20 contains a hard coded PowerPC. The interface module can access the PowerPC by using a controller for the on-chip peripheral bus (OPB) and an interrupt controller. Idle information is gathered by the interface and transferred interrupt controlled to the software DBA algorithm. The algorithm is running on the PowerPC. The processor executes the necessary computations and the bandwidth map is transferred back to the interface module. From there it reaches the OLT TX module. Implementation of a software algorithm is as simple as for a hardware version. The new algorithm has to have the same function prototype and external behavior as the reference only.

5.3 Implementation Results and Performance

Considered as Black Box both hardware and software implementation show the same behavior. To verify the functionality the example algorithm was implemented both in VHDL and in C. The platform reached a system speed of $125\ \mathrm{MHz}$, which is necessary to cope with a link speed of $1\ \mathrm{Gbit/s}$. The hardware costs of the OLT depend on the selected DBA algorithm version. For the hardware implementation of the sample algorithm the resource consumption was at 4228 logic elements, which equals 50% of the available resources. The software implementation was with 4460 logic elements slightly more expensive. The reason for that is the need of extra logic to interface the PowerPC. More complex algorithms will have higher costs, when implemented in hardware. Complexity of software algorithms does not interfere with hardware costs.

The hardware cost for ONU implementations together with the ODN model was at about 6770 slices for 8 ONU modules. That equals a utilization of 79%. For the FX20 the number is thus limited to a maximum of 12. If more ONUs are necessary, a different FPGA must be used.

6 Conclusion

We presented an FPGA-based Hardware system, which models GPON systems. The whole system in implemented onto two FPGA evaluation boards, of which one acts as OLT while the other one models ONUs and parts of the ODN.

The proposed testbed allows the evaluation of DBA algorithms, which can be implemented either as VHDL-described hardware or as a C implementation. Both versions can be integrated easily into the evaluation platform. For evaluation support, different and variable traffic patterns can be generated for each implemented ONU and the OLT. The pattern generation is done in hardware to achieve sufficient data rates but controlled by software to ease the usage of the system. The bandwidth map and traffic statistics are gathered on the boards and transferred to an external workstation, where it can be analyzed by software.

Future work will include the integration of status reporting into the the testbed and the integration of RocktetIO interfaces, which support higher bandwidths than $1\ \mathrm{Gbit/s}$ for data exchange.

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