An ultra-high speed OFDMA system for optical access networks

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***Abstract*—In this paper we present an FPGA based, ultra-high speed OFDMA system which is intended to be used as a bandwidth efficient, advanced modulation format in optical access networks like fiber-to-the-home. The aggregate bandwidth of the network reaches up to 50 GBit/s while handling hundreds of different subscribers, sharing the same optical bandwidth. Compared to other domains using OFDM like e.g. wireless communication, data rates in the multi GBit/s range require very high performance signal processing components at a central office and at the subscribers. With modern FPGA technologies like the Xilinx Virtex-6 family and massive parallelization of the algorithms the necessary processing power can be provided. Besides the OFDMA processing blocks themselves also their connections to a suitable analog front end as well as to data sources and sinks have to be considered. The presented system uses digital-to-analogue (DAC) and analogue-to-digital (ADC) converters with up to 25 GSa/s at the central office and up to 3.125 GSa/s at the subscribers. The connection to data sources and sinks is realized via 10G Ethernet links. The whole system is therefore transparent for Ethernet packets making its integration into existing infrastructure very easy.**

***Index Terms*—FPGA; Virtex-6; OFDM; Fiber; High Speed;**

I. Introduction

In most modern societies, communication plays a key role. Besides traditional telephone services also access to the internet gets more and more important for many applications. Due to video streaming platforms, IP-TV and other bandwidth demanding services the amount of data exchanged worldwide rises continuously [1]. Providing a fast and stable access to the internet for a large amount of people is a challenging task for telecommunication companies.

Currently, copper based technologies like DSL are widely used and continuous enhancements like e.g. vectoring [2] provide bandwidths up to 200 MBit/s per subscriber. However, it is foreseeable that sooner of later optical access networks like fiber-to-the-home (FTTH) will replace current technologies in the access network sector due to their considerably greater bandwidth compared to any other currently known technology.

Typically, providers favour a point to multipoint (P2MP) architecture of their FTTH networks where multiple customers share a common feeder fiber from a central office. This approach is possible due to the extremely high bandwidth of a glass fiber. It saves costs and the network equipment requires less room in the central office. State of the art communication protocols for shared optical access networks like e.g. Gigabit Passive Optical Network (GPON) typically use some sort of Time Division Multiple Access (TDMA) for the separation of multiple users. Considering the very high aggregate data rate in a shared optical access network, a TDMA approach has a serious drawback: The optical network unit (ONU) at each subscriber has to operate at the full network bandwidth while it is only interested in a small fraction of the total data rate. Consequently the optical and also many electrical components of the ONU need to be designed for very high frequencies which makes them very costly.

A different approach was investigated by the European Project ”ACCORDANCE”. Instead of TDMA, Orthogonal Frequency Division Multiple Access (OFDMA) is used. This modulation scheme, already widely used in wireless communication, uses multiple small subcarriers with relatively low symbol rates instead of a single carrier with a high symbol rate. When designed appropriately, each ONU needs to process only a fraction of the aggregate network bandwidth containing the data it is interested in. Hence, the usage of components operating at much lower frequencies compared to a TDMA approach is possible which saves costs. A drawback of an OFDMA solution is a higher computation complexity. However, when optical access networks get widely deployed it is expected that ONUs become a mass product and even very complex signal processing solutions become relatively cheap in high volumes (compare e.g. modern wireless LAN solutions).

The objective of the ACCORDANCE project is the prototypical realization of a complete OFDMA based optical access network. One of the complexities of this task lies in the very high processing power required to handle the large bandwidth used in the communication system. This paper describes the realization of the digital signal processing part of the implemented system using Xilinx Virtex-6 FPGAs. To reach the required processing speed, all computation intensive processing blocks required by the OFDM transceivers where specially designed and optimized for their particular task. The analogue electrical and optical front ends of the ONU and its correspondent counterpart at the central office, the optical line termination (OLT), are described in depth in [3]. [4] gives in overview of the whole ACCORDANCE network.

The remaining part of this paper is organized as follows: Section II gives a short overview of related work. In Section

III the parameters of the implemented OFDMA system are presented. Section VI covers the FPGA realization of the OFDM core systems at the OLT and the ONU. In section V simulation and preliminary test results are presented and the last section concludes the paper.

II. Preliminary Work

Due to the very high bandwidth of glass fibers, very simple modulation schemes like e.g. On-Off-Keying (OOK) where sufficient for optical networks for a long time. Quite recently the sensibility to efficient bandwidth usage also reached the optical community and the usage of OFDM(A) gained some interest due to its successful establishment in the wireless domain. However, most publications solely deal with an efficient transmission of the signal via a glass fiber and its generation by relatively simple OFDM transmitters [5]. The received signal is typically recorded by an oscilloscope and evaluated subsequently via offline processing. Although several real time receivers where published (e.g. [6] and [7]), most realizations omit or simplify the complex task of time and frequency synchronization in a way making them unusable outside of the laboratory. The protection of data transmitted via an OFDM based system by e.g. a Forward-Error-Correction (FEC) is another topic typically ignored by experiments in optical communication systems.

However, for a complete commercial communication system synchronization and data protection are mandatory. To our knowledge no OFDM(A) system fulfilling all of these requirements at a speed comparable to state of the art TDMA based optical networks was demonstrated so far. The ACCORDANCE project aims to realize such a system containing all required components to transfer real time Ethernet packets at a speed of multiple GBit/s. Besides other components especially the OFDM parts of the system presented in this paper had to be designed very carefully to reach this goal.

III. OFDMA System Parameter

Before the implementation of the OFDM processing modules could start, it was very important to define the frequency and time domain structure of the system and to define the way data is transferred by the different subcarriers. Good realizability on FPGAs at high speed and support for the transmission of real data was particularly considered while the design of the system. In this section the structure of the ACCORDANCE OFDMA system is presented and discussed in detail.

Due to limitations of available digital-to-analogue (DAC) and analogue-to-digital (ADC) converters as well as available processing power, the sample rate at the OLT was fixed to 25 GSa/s at the very beginning. The converters have a resolution of six bits only which is especially for OFDM(A) systems an issue due to their high Peak-to-Average-Power-Ratio (PAPR). Special care must be taken to avoid clipping of pilot tones and reference symbols at the OLT.

As the analogue downstream and upstream signals at the OLT are available as complex base band signals composed of an in-phase and a quadrature part, two DAC or rather ADCs are required, respectively. Thus, the full network bandwidth also equals to 25 GHz. The calculation of the Fast-Fourier-Transformation (FFT) is typically the most computational part in an OFDM system, hence its size has to be considered very well. On one hand, the FFT size should be as low as possible to save resources while on the other hand a larger number of points allow a finer subcarrier granularity and thus smaller minimal bandwidth windows used by the subscribers. Additionally, FFTs with sizes being a power of four (e.g. 64, 256, 1024) can be implemented especially resource efficient based on a Radix-4 butterfly algorithm. While the selection of the FFT size for the ACCORDANCE network, it was important to allow every subscriber to operate having access to solely a fraction of the total bandwidth and also to ensure that every ONU still has access to enough subcarriers. The latter part is important because some subcarriers can not be used for data transmission and thus having only few subcarriers available per ONU would radically reduce the network performance. As a compromise between high computational effort and high subcarrier granularity an FFT size of 256 points providing 256 subcarriers was chosen.

The time and frequency parameters presented below are valid for downstream and upstream. The downstream is sent continuously, i.e. if a frame is complete, the next one follows immediately, while the presence of some parts of the upstream depends on the activity of the ONUs.

A. Frequency domain parameters

A fundamental requirement of the ACCORDANCE OFDMA concept is to provide an ONU access to the network while processing only a fraction of the aggregate bandwidth. Such a fraction is called a spectral group. Each group consists of 16 subcarriers resulting in a total of 16 groups at an overall number of 256 subcarriers. A spectral view of the accordance OFDMA system with a focus on spectral groups is shown in figure 1.

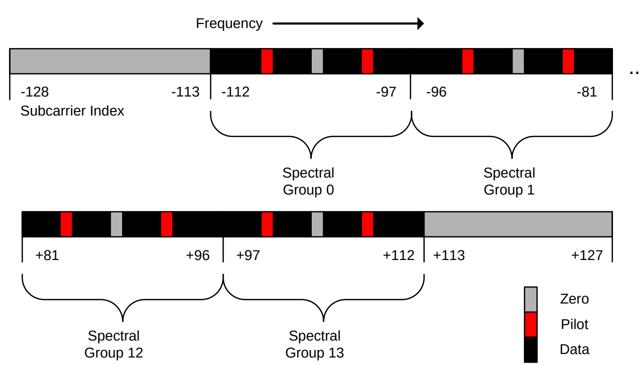

Fig. 1. Spectral view

Both groups at the outer sides of the spectrum must remain unused due to excessive phase noise. Hence only 14 groups are available for data transmission. Each group consists of 13 subcarriers which can be used for data, two pilot tones carrying a constant value of 1+0i and an unmodulated subcarrier in the middle. Every ONU connected to the network chooses one of the spectral groups to work on by adjusting the frequency of its local oscillator in the analog front end appropriately. The pilot tones are used by a phase tracking algorithm in the receiver to determine local and sampling oscillator frequency offsets. The unmodulated carrier in the middle of the group is seen as a DC value by the ONU and therefore needs to remain unmodulated to suppress extensive clipping.

As an ONU processes only a single spectral group, its operation bandwidth could theoretically be as low as the bandwidth of one group. Containing only $\frac{1}{16}$ of the total number of subcarriers in the network, the bandwidth calculates to 1.5625 GHz. Using a complex base band signal at the ONU, the sampling rate of the ADCs and DACs theoretically could also be as low as 1.5625 GHz. However, the spectral groups are attached directly next to each other in the spectrum and a suitable anti aliasing filter would be extremely hard or even impossible to design. Instead a sampling rate of 3.125 GHz is chosen at the ONU and an FFT size of 32 points is required to obtain the same subcarrier spacing compared with the OLT. Of course only the inner 16 subcarriers are part of the selected spectral group and will be regarded by the further signal processing of the ONU.

B. Time domain parameters

Having defined the spectral composition of the ACCORDANCE OFDMA system, the frame structure could be developed. Due to implementation reasons [8] a cyclic suffix with a length of $\frac{1}{4}$ of the FFT size (= 64 samples) is used. Consequently the duration of a complete symbol is 12.8 ns, equalling to 320 samples at the OLT and 40 samples at the ONU. The complete frame structure in time domain is shown in figure 2.

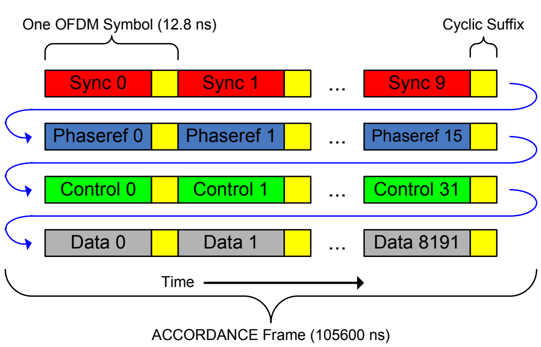

Fig. 2. Timing view

Typically a receiver in an OFDM system uses some sort of autocorrelation to find a characteristic sequence indicating the beginning of a frame. Such a synchronization sequence is formed by the first ten symbols of an ACCORDANCE OFDMA frame. It is composed by two identical beacon signals embedded in pause symbols containing only zero values. That way it is very easy to detect the sequence via an autocorrelation at the receiver. Additionally using two identical beacon signals allows an estimation of the local oscillator offset [9].

The following sequence of 16 symbols is used as a phase reference for the receiver. Each data subcarrier and both pilot tones of a spectral group gets modulated consecutively for the duration of one symbol with a value of 1+0i. This relatively long and inefficient sequence was chosen to avoid clipping at the OLT due to its low DAC resolution of only 6 bits.

The next sequence consists of 32 symbols and forms a control block carrying configuration data. To ensure that every ONU connected to the network receives all control messages independently of the group it is currently operating on, the configuration data in the downstream is sent identically in each spectral group by the OLT. Answers to control messages sent by ONUs in the upstream must be coordinated to avoid a collision of several messages from different ONUs operating on the same spectral group.

Following the control sequence, a data sequence consisting of 8192 symbols is sent. Here the actual payload data is transmitted. The modulation format of every subcarrier can be configured individually to BPSK, 4-QAM, 8-PSK or 16-QAM or it can be switched off when unused. Further granularity can be obtained by configuring a start and an end symbol within the transmission of the data sequence. Thus several ONUs can use the same subcarriers at different time slots, effectively implementing an underlying form of TDMA. Figure 3 shows an example for the possible two dimensional subcarrier allocation space.

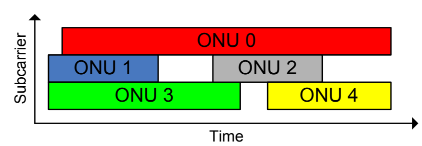

Fig. 3. Subcarrier allocation space

C. Synchronization

In every OFDM(A) system, exact synchronization of the local and sampling oscillators is very crucial for the OLT and ONU. To ensure that the combination of the upstream signals from different ONUs works smoothly, the oscillators at the ONUs and the OLT ideally have to be phase locked.

In a first step the downlink is established. Therefore the local and sampling oscillators at the ONU have to be synchronized to the downstream continuously sent from the OLT. While the initial synchronization process, the oscillator frequency offsets are obtained from the synchronization sequence at the beginning of a downlink frame. When the ONU is in normal operation state, the pilot tones are used for frequency offset estimation. The correction values determined by the ONU downstream receiver can also be used by the upstream transmitter, because the channel characteristics of the glass fibre change very slowly. The only task remaining for a successful upstream synchronization is the correct adjustment of the start time of the frame sent by the ONU.

It is absolutely necessary that all frames created by different ONUs arrive at the OLT at exactly the same time. Only in this case a joint processing of all spectral groups is possible with a single 256 point FFT. The shifting of the start time of an upstream frame sent by an ONU can be requested easily by the OLT with the help of a control message sent via the already established downlink.

More details on the synchronization concept used in the ACCORDANCE network can be found in ref [9].

D. Data representation

The control sequence included in every ACCORDANCE frame uses all available subcarriers per spectral group. Each subcarrier is modulated with a fixed BPSK modulation scheme to ensure a reliable data transfer. Additionally the control data is protected by a Reed Solomon Forward Error Correction (FEC) with a code rate of $\frac{1}{2}$. Thus, after subtracting the FEC overhead 26 Bytes are available in each frame which are organized as follows:

The first byte contains synchronization flags used by the physical layer. Here e.g. the start time of the uplink frame sent by the ONU can be adjusted to compensate for slow propagation delay changes in the network. The next byte contains the type of the control message and a six bit wide frame counter which is continuously increased until it wraps over. The message type identifies a packet as a control message for the physical layer (e.g. pre equalization values for the uplink transmitter) or for other data processing blocks (e.g. a MAC layer). The remaining 24 bytes contain the message and a 16 bit CRC. Figure 4 illustrates the format of a control message.

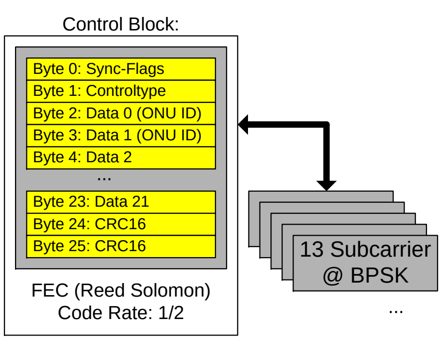

Fig. 4. Control Block

The payload data sent within the data sequence of the ACCORDANCE frame is packed in so called ”virtual channel packets”. Each such packet can carry up to 64 Kbytes of payload data and is organized as follows:

The first four bytes contain a fixed value of 0x453DCD28, called magic number. Its purpose is the identification of the beginning of a packet in an unsynchronized data stream. Following the length of the packet, its type and a continuously increased packet number is transmitted. The packet type allows a differentiation between various types of payload data like e.g. Ethernet packets and CPRI data. The remaining bytes of the packet contain the actual payload data.

The virtual channel packets are transmitted over a virtual transmission pipe which is created in the following way: Depending on the required bandwidth a number of subcarriers with a particular modulation scheme and sequence of data symbols is allocated for a particular ONU. These allocated channel resources form the pipe which continuously carries data bytes at the selected rate. If no virtual channel packet is ready for transmission, the pipe is padded with zero bytes. As soon as payload data is available a virtual channel packet is created and inserted into the pipe. A virtual channel packet can easily cross the boundaries of an ACCORDANCE frame, because the pipe formed by the allocated resources behaves like a FIFO for data bytes. Before the virtual channel packets are actually processed by the OFDM cores, a $\frac{223}{255}$ code rate Reed Solomon FEC is used to protect them against transmission errors. Figure 5 shows the structure of the described virtual channel.

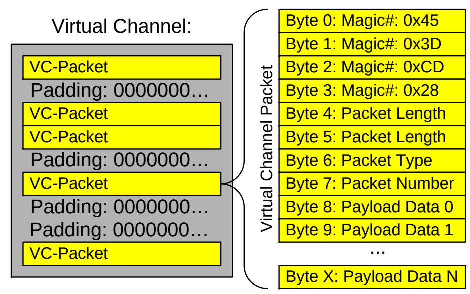

Fig. 5. Data Block

IV. OFDMA Transceiver Implementation

The OFDM transceivers of OLT and ONU are a very crucial part of the system. Due to the very high required bandwidth, their implementation has to be as efficient as possible. Especially the 256 point FFTs of transmitter and receiver at the OLT requires lots of FPGA resources. Details on its implementation can be found in [8]. To relieve the OLT from as much further tasks as possible, most of the synchronization and channel equalization parts for down- and uplink where transferred to the ONU side.

A. OLT Transmitter

A detailed view of the OLT OFDMA transmitter can be found in figure 6.

Synchronization and phase reference sequences as well as control and payload data are sent via a multiplexer to the inverse 256 point FFT of the OLT. The iFFT processes 64 samples per clock cycle at a resolution of six bits at the input and 14 bits at the output. Its output is scaled and rounded to eight bits and subsequently clipped to a six bit resolution as required by the DACs. The last block inserts a cyclic suffix by storing the first 64 samples of a symbol and appending them at its end. A total of five clock cycles are required per symbol resulting in an operation frequency of 390.625 MHz.

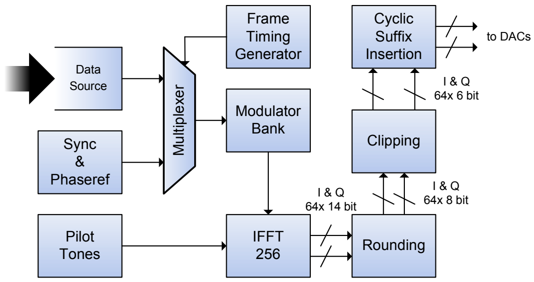

Fig. 6. OLT Transmitter

To reach such a high frequency special care had to be taken while the implementation of the FFT and other blocks present in the data path (e.g. a lot of pipelining stages and specially designed multipliers).

B. ONU Receiver

The input stream from the ADCs first passes a local oscillator frequency correction stage. The compensation frequency is generated by a numerically controlled oscillator (NCO) and multiplied with the incoming sample stream. Following the frequency correction the "SYNC" module searches for the synchronization sequence in the downstream and provides the exact start position of the frame. This information is used to configure the "Delay & Cut" module which prepares the incoming sample stream for the processing by the 32 point FFT. Here the sample stream is aligned correctly and the redundant part of the symbol added by the cyclic suffix is removed. Following the FFT the phase reference sequence in the downstream is analyzed by the "Phase Reference Calculator" which provides correction values for the channel equalizer. Near the end of the signal processing chain the pilot tones are used to determine the common and differential phase errors which are used to control frequency correction modules via PID controllers. The remaining subcarriers carrying data are finally decoded by the demodulators. Figure 7 shows a picture of the ONU receiver part.

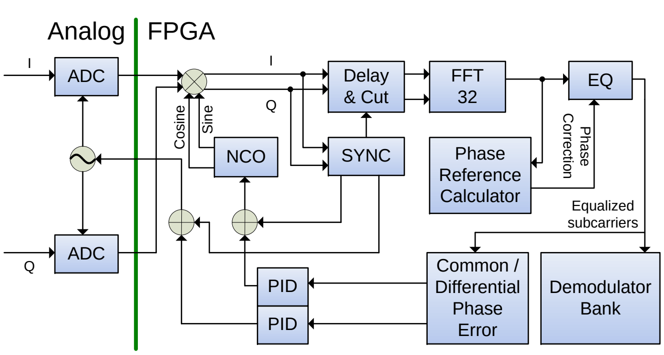

Fig. 7. ONU Receiver

C. ONU Transmitter

In the ONU transmitter the synchronization and phase reference sequences used by the OLT while uplink synchronization are generated and inserted into the control and payload data stream. All subcarriers transmitted are pre-equalized by set values received from the OLT via a control message. To allow the OLT the synchronization of multiple ONUs the synchronization and phase reference sequences as well as the pilot tones may be masked. The "Frame Time Delay" module controls the exact start position of the frame sent by the ONU on a sample base. This feature is used by the OLT to align the transmission of all ONUs to its own local frame timing. A block diagram of the ONU transmitter is shown in figure 8.

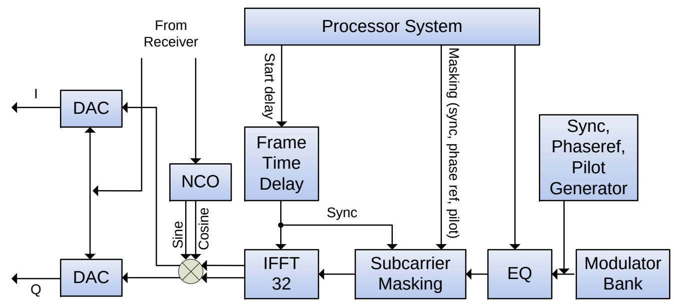

Fig. 8. ONU Transmitter

D. OLT Receiver

As shown in figure 9, the incoming sample stream at the OLT receiver can be processed directly by the FFT and is decoded without any special subcarrier equalization. This simple receiver structure is possible because the ONUs already perform any necessary frame delay and subcarrier equalization as explained in the last section. The "SYNC" and "Phase Reference Recording" modules allow the OLT processor system to observe the received synchronization and phase reference sequences sent by an ONU. The obtained data is the base for the calculation of correction values sent to the ONUs. The "Sync Recording" and "Phase Reference Recording" modules can be implemented using only a small amount of FPGA resources compared to their corresponding counterparts in the ONUs.

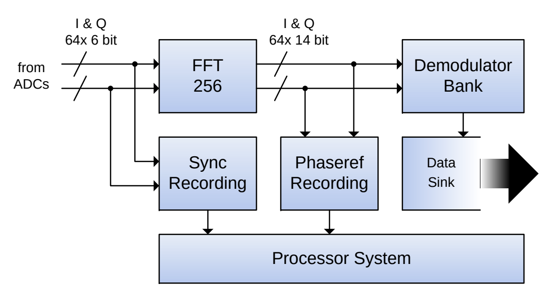

Fig. 9. OLT Receiver

V. Results

The first verification step was a complete simulation of the overall system. OLT and ONU where connected to each other via a Modelsim test bench allowing a frequency conversion of transmitted and received signal to a carrier frequency. Additional blocks adding noise and frequency offsets and jitter as well as different transmission delays allowed extensive tests of the OFDM(A) cores. A block diagram of the test bench part realizing the downlink can be found in figure 10.

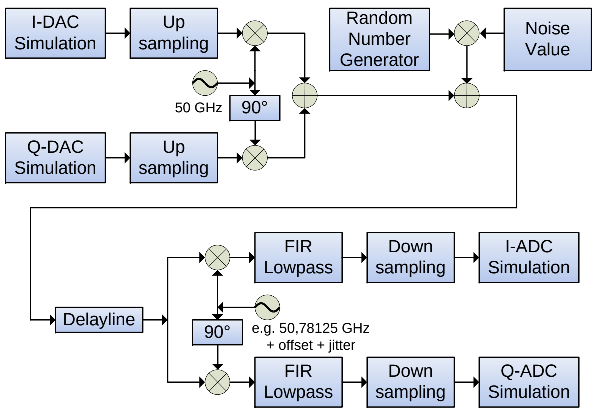

Fig. 10. Channel Simulation

After a successful completion of all simulations, tests with a real transmission system could be started. Besides the OFDM cores also the interfaces to the DACs and ADCs as well as a 10G Ethernet interface and the FEC processing where included into the FPGA design realizing the complete system able to transfer ordinary Ethernet traffic. Due to a delay in the production of the FPGA hardware platform specially designed for the ACCORDANCE system, only the ONU receiver part could be tested in hardware so far. However, this block is the most complex and crucial part of the system as it performs most of the synchronization tasks.

The downstream signal for this test was generated by Modelsim using the OLT transmitter VHDL design. It contains twelve ACCORDANCE frames including several control messages and Ethernet packets in their payload data sections. The signal was transmitted using an arbitrary waveform generator (AWG7102 from Tektronix) providing the OLT in-phase and quadrature signal at 10 GSa/s. Similarly to the test bench, the I and Q signals are subsequently mixed up to a carrier frequency of 10 GHz and mixed down to the base band at the ONU according to the selected spectral group. Of course sampling and local oscillator frequencies at the ONU need to be adjusted to the reduced OLT sampling rate (10 vs. 25 GSa/s). Tests showed that all data included in the downstream could be received correctly and was sent out via the 10G Ethernet port of the ONU after passing the FEC decoder.

Tests including also the optical components are difficult to perform at an OLT sample rate of only 10 GSa/s due to a variant spectrum of the generated signal. However, at least the synchronization sequence could already be generated at 25 GSa/s, transmitted via the optical network and successfully received at the ONU.

VI. Conclusion and Future Work

We have shown an implementation of an ultra-high speed OFDMA system transferring data at an aggregate speed of more than 50 GBit/s. The system includes real time transmitters and receivers able to synchronize to each other without further assistance. Furthermore real data in form of 10G Ethernet was transmitted instead of PRBS test sequences requiring additional components like an FEC. The design of the system is fully completed and simulated. Also place and route for the target FPGAs in OLT and ONU was successful and the correct functionality of the ONU receiver has been verified in hardware already.

Future work of course includes the hardware tests of the remaining transmitter and receiver of OLT and ONU and the real time transmission of 10G Ethernet packets. Also in the design of the OFDMA parameters some enhancements are possible by e.g. reducing the number of pilot tones via a joint usage by adjacent spectral groups.

VII. Acknowledgements

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