Experimental IM/DD OFDMA Transmission with Scalable Receiver Frontend for PON Scenarios

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Abstract: We propose a technique to reduce the electrical hardware effort in an OFDMA-PON by reducing the ADC and DSP complexity and therefore the costs of the ONUs and show its feasibility experimentally.

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1. Introduction

Due to the increased demand for communication bandwidth, Passive Optical Networks are regarded as a solution for access. Most PON scenarios, that use power splitting to increase the Optical Network Unit (ONU) count, have an Optical Line Terminal (OLT) with high accumulated data rate, while the average data rate of each ONU is only a fraction of it. However, in many systems the electrical frontends of the OLT and ONU are quite similar, for instance in Time Division Multiple Access (TDMA)-PON each ONU transmits and receives at the same speed as the OLT, but only in a small time window [1]. In some Orthogonal Frequency Division Multiple Access (OFDMA) systems, the ONU receives and processes the entire OFDM-spectrum, although only some subcarriers are usable [2]. In these setups the difference between the possible peak data rate (entire time window in TDMA, entire OFDM spectrum) and the actual data rate leads to hardware overhead in the electrical domain. However, it is thereby highly beneficial to use a technique known as scalable OFDM from wireless communication [3] to reduce the frontend speed of the ONUs in an OFDMA-PON to access only a part of the transmitted spectrum while decreasing the hardware requirements especially the complexity of the analog-to-digital converter (ADC) and the digital signal processing (DSP). The technique of reduced ADC sampling rate and FFT size at the ONU [4] and frequency shifting in digital domain [5] were already shown, but to the best of our knowledge this is the first time that a reduced ONU frontend is analyzed experimentally in optical communication together with analog IQ down-mixing. Through experimental investigation we evaluate various real world issues in this context like synchronization and equalizer (EQ) training with reduced ONU frontends and required accuracy for the local oscillators (LO).

2. OFDMA-PON with reduced ONU frontend

The downstream part of a typical PON is shown in Fig. 1. In the OLT, a complex OFDM signal is generated, which contains subcarriers for different ONUs. Due to the high accumulated data rate, the IFFT size $N_{\mathrm{IFFT,Tx}}$ and the sampling rate of the DAC $f_{\mathrm{s,Tx}}$ are relatively high. By up-conversion onto an intermediate frequency $f_{\mathrm{LO,Tx}}$ by using an electrical IQ modulator a real valued OFDM signal is achieved. This signal is used to drive the intensity modulator (IM). The optical signal is transmitted over a single mode fiber (SMF) and split up to reach several ONUs. After direct detection, the received spectrum shows some intermodulation distortions mainly within the frequency gap. The desired subcarriers for each ONU are down-converted with LO frequencies $f_{\mathrm{LO,Rx}}$, which can differ from the LO of the OLT. In the common case where the average received data rate of a specific ONU is much

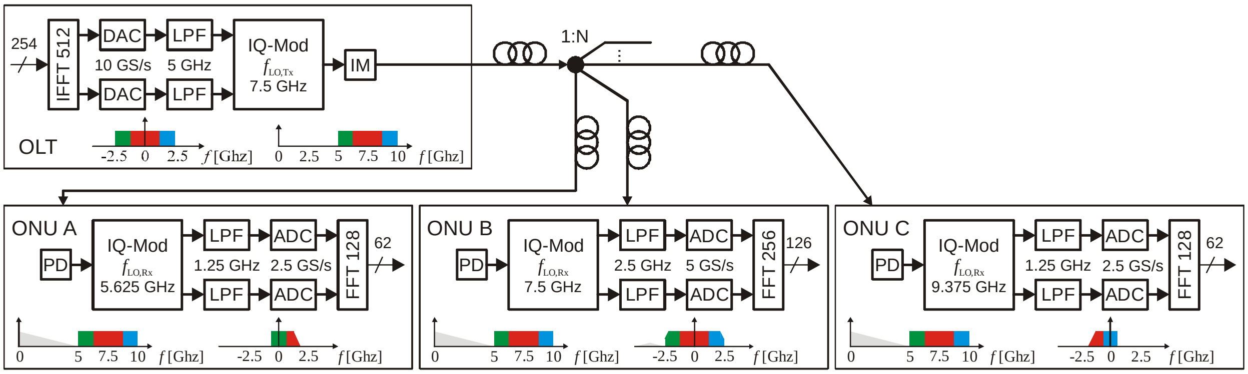

Fig.1: Schematic diagram of an OFDMA-PON downstream part with different kinds of reduced ONUs regarding the ADC and DSP complexity compared to the OLT.

smaller than the accumulated data rate of the OLT a reduced frontend with a slower ADC with the sampling rate $f_{\mathrm{s,Rx}}$ and smaller FFT size $N_{\mathrm{FFT,Rx}}$ can be used to decrease costs. This is possible if the subcarrier grid of the transmitter (Tx) and the receiver (Rx) agree and the sampling theorem is maintained. The first condition is satisfied if the frequency spacing between the subcarriers Δf is kept constant

$$\frac{f_{\mathrm{s,Rx}}}{N_{\mathrm{FFT,Rx}}} = \Delta f_{\mathrm{Rx}} \overset{!}{=} \Delta f_{\mathrm{Tx}} = \frac{f_{\mathrm{s,Tx}}}{N_{\mathrm{IFFT,Tx}}}, \qquad (1)$$

and the frequency difference of LOs of Tx and Rx is an integer multiple n of this spacing:

$$f_{\mathrm{LO,Rx}} - f_{\mathrm{LO,Tx}} = n \cdot \Delta f_{\mathrm{Tx}}\,. \qquad (2)$$

The required frequency accuracy of some 10 kHz is provided by most commercial available LOs. The sampling theorem can be fulfilled by an adequate low pass filtering (LPF) before the ADC. Thus, the sampling frequency, the FFT size, the cyclic prefix length N_{CP} and the cut off frequency of the anti-aliasing-filter have to be reduced by the same factor $r = N_{\mathrm{IFFT,Tx}} / N_{\mathrm{FFT,Rx}}$. If the RF up-conversion at Tx and the RF down-conversion at Rx are done with the same LO-frequency, the receiver has access to the subcarriers in the middle of the transmitted spectrum. To access a different subcarrier interval the Rx-LO can be tuned to higher or lower frequencies to down-convert the desired subcarriers to the ADC bandwidth. At the ONUs the DC subcarrier after down-conversion cannot be used for data reception. Thus the total number of received subcarriers is smaller than the total number of transmitted subcarriers. However, in a larger PON other ONUs with overlapping reception intervals but different LO frequencies could receive these subcarriers.

In a typical OFDM system, the channel response is estimated by using training symbols and is used to equalize the OFDM symbols in the frequency domain. Here, with different LO frequencies at OLT and ONU the shift of n subcarriers for the estimation of the channel response and an additional phase shift from symbol to symbol has to be taken into account. The phase shift between two neighboring OFDM symbols is determined by ($f_{\mathrm{LO,Rx}} - f_{\mathrm{LO,Tx}}$) and the OFDM symbol duration T_{OFDM}:

$$\Delta\varphi = 2\pi \cdot \left(f_{\mathrm{LO,Rx}} - f_{\mathrm{LO,Tx}} \right) T_{\mathrm{OFDM}} = 2\pi \cdot \frac{n}{N_{\mathrm{FFT,Rx}}} \cdot f_{\mathrm{s,Rx}} \cdot \frac{N_{\mathrm{FFT,Rx}} + N_{\mathrm{CP,Rx}}}{f_{\mathrm{s,Rx}}} = 2\pi \cdot n + 2\pi \frac{n \cdot N_{\mathrm{CP,Rx}}}{N_{\mathrm{FFT,Rx}}}\,. \qquad (3)$$

If the second term is an integer multiple of 2π, the communication works without further adjustments, otherwise the increasing phase shift must be corrected for successful transmission. This phase shift must also be taken into account in some synchronization schemes. In addition, if the subcarriers are shifted by an odd number n, the synchronization with even symmetry in time domain at the transmitter turns into odd symmetry at the receiver which has to be remembered for inter-symbol correlation like the Schmidl and Cox synchronization algorithm [6].

3. Experiment

The experimental setup is shown in Fig. 2. The OFDM signal with 8-QAM symbol mapping, IFFT of size 512, of which 254 subcarriers are used for data transmission, is calculated offline. A cyclic prefix and cyclic postfix of 4

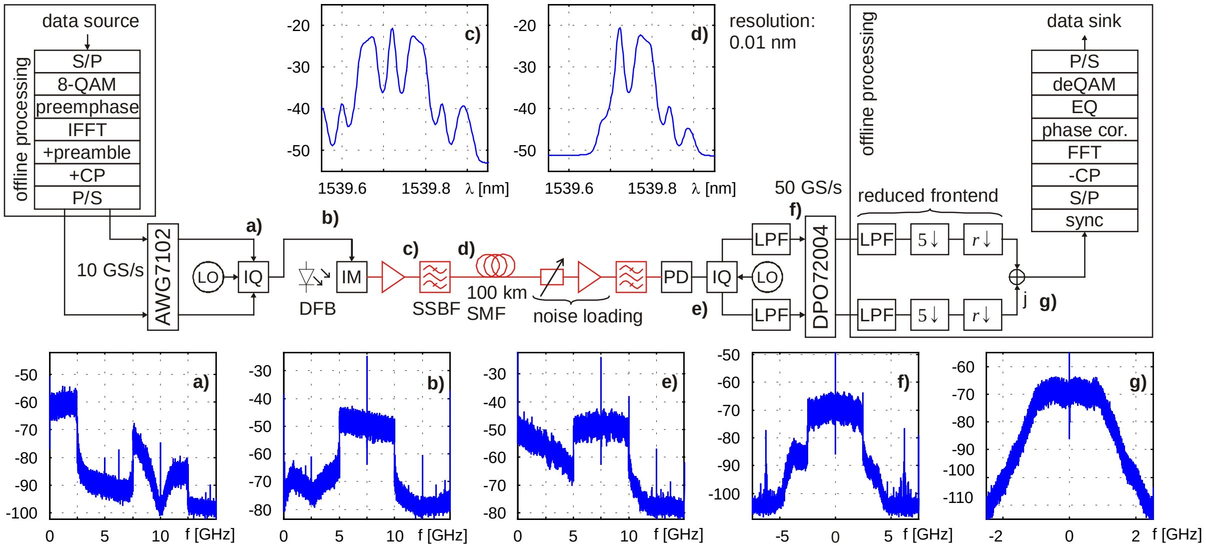

Fig.2: Experimental setup with one OLT and one ONU with digitally reduced sample rate and reduced DSP complexity by a factor of *r*

samples each is added to the signal, which is loaded into the 10 GS/s Tektronix AWG7102. Each OFDM frame composed of 32 data symbols and 4 training symbols for synchronization and equalization purposes. The net data rate is 12.173 Gb/s after removing the overheads of CP, FEC=7% and preamble. The AWG outputs (Fig. 2a) are up-converted with a balanced IQ-mixer with a LO frequency of 7.5 GHz. This signal (Fig. 2b) is used to drive a Mach-Zehnder-Modulator (MZM) for IM of a DFB laser at 1539.71 nm (Fig. 2c). After amplification and single sideband filtering (SSBF) with 0.15 nm optical filter bandwidth (Fig. 2d), the signal is launched into 100 km SMF. At the receiver, an attenuator and EDFA are used for noise loading and OSNR measurements. After an optical filter with 0.2 nm bandwidth, the signal is directly detected with a 12 GHz PIN photodiode (PD) (Fig. 2e). The electrical OFDM signal is then amplified, down-converted with IQ-mixer at LO frequency $f_{\mathrm{LO,Rx}}$ (Fig. 2f) and sampled with the real-time oscilloscope DPO72004 with a sampling rate of 50GS/s. To pretend a low speed frontend, the signal is filtered and down-sampled by a factor of 5 and r in digital domain (Fig. 2g) to a sampling frequency of $f_{\mathrm{s,Rx}} = 10/r$ GS/s, where r is the reduction factor of the receiver frontend. We chose $r \in \{1, 2, 4\}$ to receive with full (ONU 1), half (ONU 2a-c) and quarter bandwidth (ONU 4a-e). With reduced frontend, different LO frequencies (a: lowest, c/e: highest) according to Table 1 are chosen to receive different parts of the OFDM spectrum. The received signal is processed offline and the bit error ratio (BER) is retrieved.

Table 1: Setup of the measured ONUs

Name	ONU 1	ONU 2a	ONU 2b	ONU 2c	ONU 4a	ONU 4b	ONU 4c	ONU 4d	ONU 4e
$N_{\mathrm{FFT,Rx}}$, $N_{\mathrm{SC,Rx}}$, $N_{\mathrm{CP,Rx}}$	512, 254, 8	256, 126, 4			128, 62, 2				
$f_{\mathrm{s,Rx}}$ [GS/s]	10	5			2.5				
$f_{\mathrm{LO,Rx}}$ [GHz]	7.5	6.25	7.5	8.25	5.625	6.875	7.5	8.125	9.325
max. data rate [Gb/s]	12.17	6.04			2.97				

4. Results

Depicted in Fig. 3 are the results of the BER measurements depending on the OSNR. It can be seen, that the required OSNR @ BER=10^{-3} for the whole bandwidth (ONU 1) is approximately the same as the average OSNR needed for the different parts of the spectrum (average ONU 2/4). The difference in the depicted OSNR curves can be explained by the different channel response of the system, where the higher frequencies will suffer a higher attenuation from optical and electrical filtering. Here, ONU 4a with subcarriers nearest to DC has the best performance and ONU 4e the worst performance. In a PON the subcarrier at high frequencies could be used for ONU closer to the OLT and vice versa.

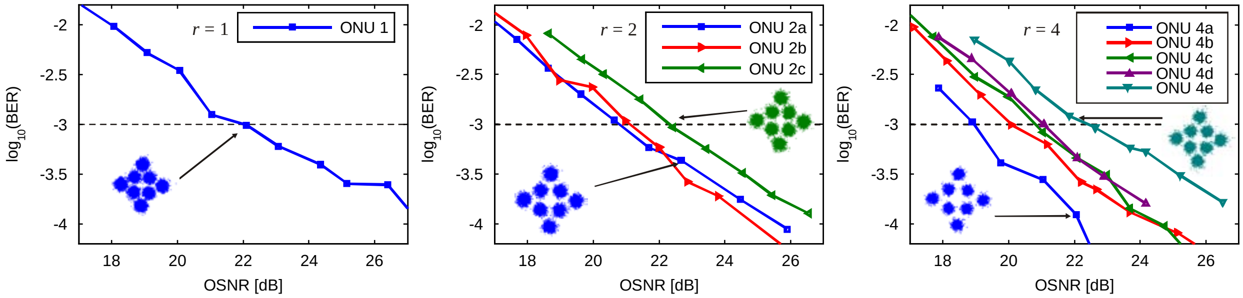

Fig.3: BER curves for ONUs with full frontend (a), half frontend (b) and quarter frontend (c) with different receiver LO frequencies (b,c)

5. Conclusion

In this paper we demonstrated the feasibility of a scalable OFDMA-PON to reduce the hardware requirements for the ONU regarding sampling speed of the signal converter and the DSP complexity. We showed that the OFDM-signal can be received with different receiver frontends, meaning that different ONU types could coexist in an OFDMA-PON. The reduction factor r can be increased even higher as long as all ONUs have integer FFT and CP lengths.

6. References

[1] D.P Shea et al., "A 10-Gb/s 1024-Way-Split 100-km Long-Reach Optical-Access Network," JTL, vol.25, no.3, pp.685-693, March 2007
[2] M.-F. Huang et al., OFC 2009, paper OMV5, 2009.
[3] Z. Abichar et al. , "WiMax: The Emergence of Wireless Broadband," *IT Professional* , vol.8, no.4, pp.44-48, July-Aug. 2006
[4] L. Cheng, et al., "Channel characteristic division OFDM-PON for next generation optical access," in Opt. Express **19**, 19129-19134, 2011.
[5] N. Cvijetic, et al., OFC 2011 , paper PDPD7, 2011.
[6] T.M.Schmidl et al., "Robust frequency and timing synchronization for OFDM," *IEEE Transaction on Communications.*, vol.45, no.12, pp.1613-1621, Dec 1997