Passive Optical Networks based on OFDM: Perspectives and Experimental Verifications

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ABSTRACT
We investigate the different requirements for OFDMA-PON in downstream and upstream direction. We show an approach to reduce the DSP effort at the ONUs and demonstrate the OFDMA upstream transmission with four individually modulated ONUs with central distribution of the optical carrier and coherent reception at the OLT.
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1. INTRODUCTION

It is agreed that passive optical networks (PON) are the only long-term solution to deal with the steadily increasing demand for communication bandwidth. To further increase bandwidth and subscriber count different approaches are currently investigated [1]. Most promising are combinations of wavelength division multiplexing (WDM) with multiple access techniques per wavelength including time division multiple access (TDMA) and frequency division multiple access (FDMA). A major advantage of FDMA is the ability to access a part of the total bandwidth in a WDM-channel with reduced electrical effort [2, 3] in contrast to TDMA where the total bandwidth has to be accessed in short intervals. With the concept of orthogonal frequency division multiple access (OFDMA) the individual subscriber signals could be packed much closer in frequency domain due to the rectangular-like spectra [4,5]. This paper aims to compare the different challenges for the downstream (DS) and the upstream (US) part within the OFDM-PON. Although all setups are supposed to use WDM to increase the total number of subscribers and aggregated data rate, we focus on the techniques in each WDM channel. The discussed systems, supporting several users with a single wavelength pair (DS/US) or even a single wavelength for both directions are claimed to be scalable with WDM techniques.

2. OFDM-SYSTEM

In any PON the optical network unit (ONU) must be as cost efficient as possible, since its cost arise at any subscriber. Therefore most setups propose direct detection and relative simple optical modulation at the ONU. For efficient handling and logistics in the field using WDM techniques the ONU also should be “colorless”, meaning that any ONU device should work on any possible WDM channel in the PON. This requires either the absence of optical filters and sources or their tuneability. On the other hand more effort can be tolerated at the optical line terminal (OLT), where the costs can be shared among several users. Complex optical modulation, special filtering and coherent detection are more likely to be used at the OLT than at the ONU. This means that for the DS part more effort is spend on the optical modulation to allow detection with simple optics and for the US more effort is spend on the detection of a signal with simple optical modulation. In the case of (O)FDMA on each WDM channel a second difference of DS and US is present. FDMA is very sensitive to frequency mismatch of the individual signals, which might result into crosstalk. In the case of OFDMA also synchronization in time domain among the subchannels might be required. For the DS this can be easily assured, since all subsignals are generated at a single location (OLT) and modulated together on a single optical source with the DS wavelength λ_{DS}. In US the subsignal generation within one WDM-channel is distributed in the PON. Since the required frequency accuracy cannot be provided by low-cost tuneable optical sources in each ONU, only a common optical source for all ONUs in one WDM channel could be used. This common optical source could be either a unmodulated carrier for distributed from a central location (e.g. OLT) to the ONU [4, 5] or the modulated DS carrier that is remodulated by each ONU [2, 6]. Early approaches using individual wavelength for each ONU in US direction [7] are neglected here, since these concepts can hardly be further scaled with WDM.
Fig. 1 shows a possible setup for the WDM-OFDMA-PON. At the OLT the combined OFDM-signal for multiple users per wavelength is generated and optically modulated onto the DS carrier with wavelength λ_{DS}. Single sideband (SSB) transmission is applied by complex SSB-modulation, optical filtering or special aligning with AWG. In addition, the corresponding US carrier λ_{US} is generated at the OLT as well and distributed to the ONUs. If remodulation of the DS signal is applied, this is not required. WDM with arrayed waveguide gratings (AWG) is used to further increase the number of subscribers. In the remote node the DS signal is split by an AWG and by power splitters. At the ONU a band splitter (BS) is used to separate the DS signal and the US carrier. With DS remodulation a single power divided can be used here. The DS signal is directly detected on a photodiode (PD) and demodulated. Since the assigned signal bandwidth of each ONU is smaller than the aggregated bandwidth, the conversion effort can be significantly lower than at the OLT. For the US each ONU

transmits an OFDM signal, which is spectrally non-overlapping with the other US signals. With this electrical signals either the US carrier is modulated or the DS signal is remodulated. In the remote node these different optical signals are combined and transmitted over the same fiber. At the OLT the WDM channels are separated again. Although the various US signals per WDM channel have a common optical carrier frequency, the optical phases and polarizations are typically uncorrelated due to different transmission paths. Thus, dual polarization coherent optical reception (CO-Rx) is required at the OLT to detect the signals robustly. For demodulation of the individual OFDM signals with one single FFT, all US signals need to reach the receiver synchronously [6]. This could be achieved by synchronizing all ONUs to the DS clock and using additional information about the channel delays. This requires a complex control loop to estimate the delays and maintain the synchronization, which is considered as a main challenge in OFDMA-PONs. Alternatively the signal is processed with separate OFDM-processors, each matched to its corresponding ONU [5]. Here, accurate synchronization is not required as lack of synchronization leads to some small amount of ICI only. However, the signal is still detectable. Because each receiver only processes a part of the whole spectrum, a reduction of the complexity of each OFDM-processor in terms of sampling rate and FFT-length is possible [8]. Thus, the total DSP complexity of this approach is only slightly increased compared to a single FFT, but does not require a synchronization of all ONUs, which greatly simplifies the network layout.

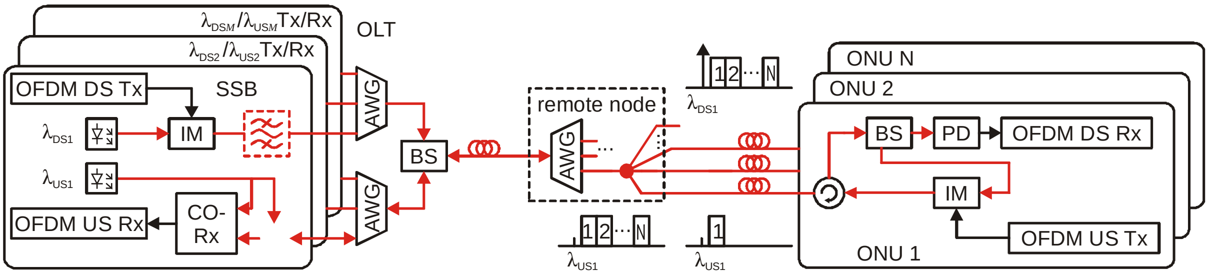

Fig. 1. Proposed architecture of the OFDMA-PON (US=upstream, DS=downstream, BS=band splitter, IM=intensity modulator).

3. DOWNSTREAM-EXPERIMENT

An experimental setup investigating the ONU simplification in DS direction is shown in Fig. 2. At the transmitter, corresponding to the OLT, a broad OFDM signal with 5 GHz bandwidth and a net data rate of 12.2 Gb/s is calculated offline and is loaded into the 10 GS/s Tektronix AWG7102. System details are given in [8]. The waveform generator (WG) outputs are up-converted with a balanced IQ-mixer with a LO frequency of $f_{LO,Tx}$=7.5 GHz. This signal is used to drive a Mach-Zehnder-Modulator (MZM) for IM of a DFB laser (Fig. 2a).

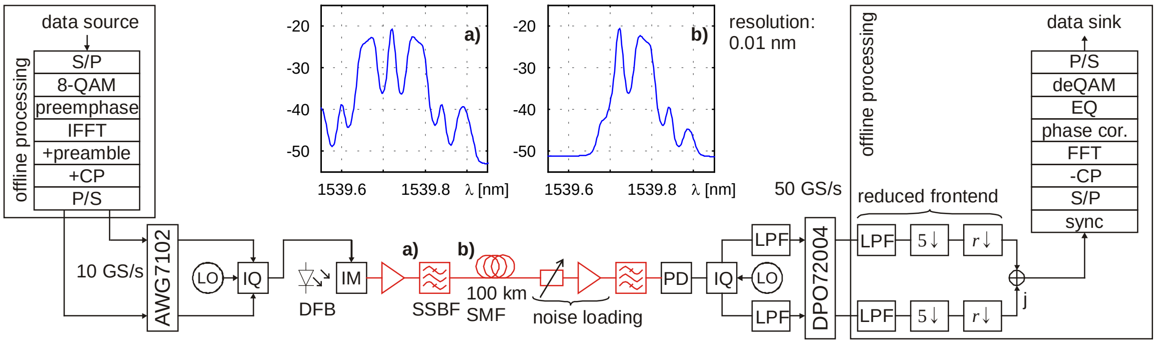

Fig.2: Experimental DS setup with one OLT and one ONU with digitally reduced sample rate and reduced DSP complexity by a factor of *r*

After amplification and single sideband filtering (SSBF, Fig. 2b), 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 filtering, the signal is directly detected with a PIN photodiode (PD). The intermodulation products generated by the PD are located within the frequency gap and do not distort the signal. The electrical OFDM signal is then down-converted with IQ-mixer at LO frequency which can differ from $f_{LO,Tx}$ and sampled with the real-time oscilloscope DPO72004 with a sampling rate of 50 GS/s. To pretend a low speed frontend, the signal is filtered and down-sampled by a factor of 5 and r in digital domain to a sampling frequency of $f_{s,Rx}$ = 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, up to 12.7 Gb/s), half (ONU 2a-c, up to 6.04 GB/s) and quarter bandwidth (ONU 4a-e, up to 2.97 GB/s). With reduced frontend, different LO frequencies (a: lowest, c/e: highest) are chosen to receive different parts of the OFDM spectrum. The received signal is processed offline and the bit error ratio (BER) is retrieved (Fig. 3). 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. This experiment showed the feasibility of an OFDM transmission with different sampling rates and DSP complexities at transmitter and receiver to efficiently decrease ONU cost when only receiving a part of the whole signal.

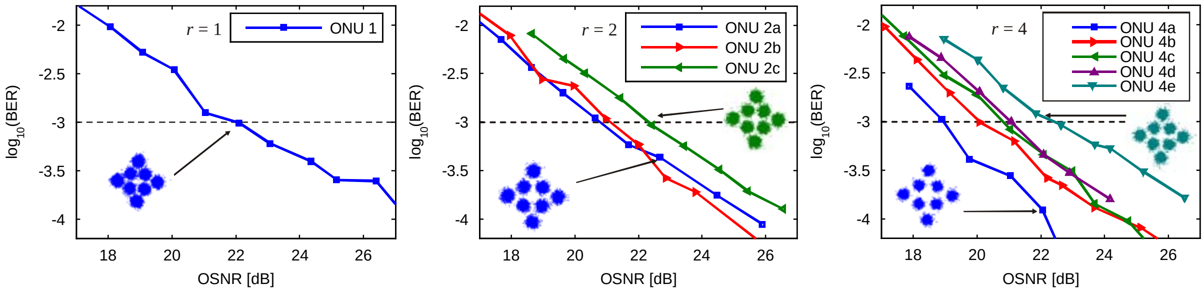

Fig.3: BER curves for ONUs with full frontend (a), half frontend (b) and quarter frontend (c) with different receiver LO frequencies (b,c)

4. UPSTREAM-EXPERIMENT

For the DS direction a point-to-point transmission experiment is helpful to investigate the system, since for each ONU it doesn't matter, if other ONUs receive the remaining parts of the total signal or not. On the other hand realistic investigations for the US direction require the presence of different ONU transmitters to observe the interaction of the individual US parts. In the past, some experiments avoid this, by modulating the whole US signal onto the optical carrier at a single location, which is useful to investigate WDM performance but it neglects some problems arising with distributed signal modulation. Fig. 2 shows the experimental setup of the US from 4 ONUs to the OLT. For each ONU US signal 46 out of 512 subcarriers are filled with QPSK data symbols. The subcarrier at DC is unused. After transformation into time domain by IFFT a cyclic prefix (CP) with 16 samples is appended to each OFDM-symbol. The complex valued OFDM time signal (in baseband) is spectrally shifted such that for each ONU a non-overlapping frequency band (with double sidebands and thus real valued) around a carrier frequency corresponding to the frequency of subcarrier no. 30, 78, 126 and 174 is assigned. The signals of the four ONUs are loaded to two WG with two channels each. Thus, for each ONU one 10 GS/s DAC channel is used. With these parameters, each ONU transmits a nominal bit rate of 1.79 Gb/s. Excluding the overhead of CP, TS and 7% for FEC the net bit rate is 1.53 Gb/s. Note, that the same electrical signals could be realized using analog IQ-mixers and two DACs with reduced sampling rate, similar to [3]. Each analog signal drives a Mach-Zehnder-modulator, biased at V_π for carrier suppression. The optical carrier with a linewidth of less than 100 kHz is amplified by an EDFA and is distributed via a 1:4 splitter to the ONUs. After optical intensity modulation (IM), signal 1 and signal 3 are transmitted over 25 km SSMF before all signals are combined using an optical 4:1 coupler. Signal 2 and signal 4 are attenuated by 5 dB to maintain similar power levels. After the 4:1 coupler the combined signal is transmitted over another 25 km SSMF. Due to different transmission lengths and free running DAC clocks all four US signals are fully asynchronous. A variable optical attenuator allows analyzing the receiver sensitivity. Finally the signal is detected at the OLT using a dual polarization coherent receiver. The four electrical output signals of the coherent receiver (two polarizations with two quadrature parts) are sampled with sampling rate 50 GS/s. The digital signals are then processed offline. First, a downsampling by factor 5 is done to simulate a slower electrical frontend. Then, with the 4 OFDM processors we downconvert the signal of the matched ONU (1...4) into baseband (demodulation). The frequency selection is supported by FIR-low pass filter to suppress the neighboring spectra. Further downsampling by a factor of r=8 is applied to simplify the numerical effort of the following OFDM-DSP. Note, that now a FFT-size of 64 and CP length of 2 is sufficient. After synchronization and CP removal the signal is transferred to the frequency domain by FFT. The TS are used to estimate the channel transfer function in both polarizations and to equalize the following OFDM data symbols. A mean phase offset of each OFDM symbol is estimated and compensated for to handle the decorrelated laser phase noise. Finally the symbols are demapped and the BER is calculated for each US signal. Note, that no optical amplification is applied in the US part of the network. By using low-cost SOA [6] the EDFA used in the experiments may be removed, too. Another simplification in our experiment is the use of an extra fiber for the distribution of the optical US carrier. A single fiber could be used in a real system together with circulators as shown in Fig. 1 or [2,6]. In our experiment the polarization was relative steady, but since the polarization sensitive equalizer is trained every OFDM-frame (3.7 µs), slow variation of the polarization could be handled. For BER measurements OFDM frames are loaded into the four channels of 2 WG. Both devices are free-running and thus not synchronized. Note that the timing offset between ONU 1 and ONU 2 and between ONU 3 and ONU 4 is fixed and determined by the path difference. However, these fixed delays were measured to be each non-integer multiple of an OFDM-symbol duration which

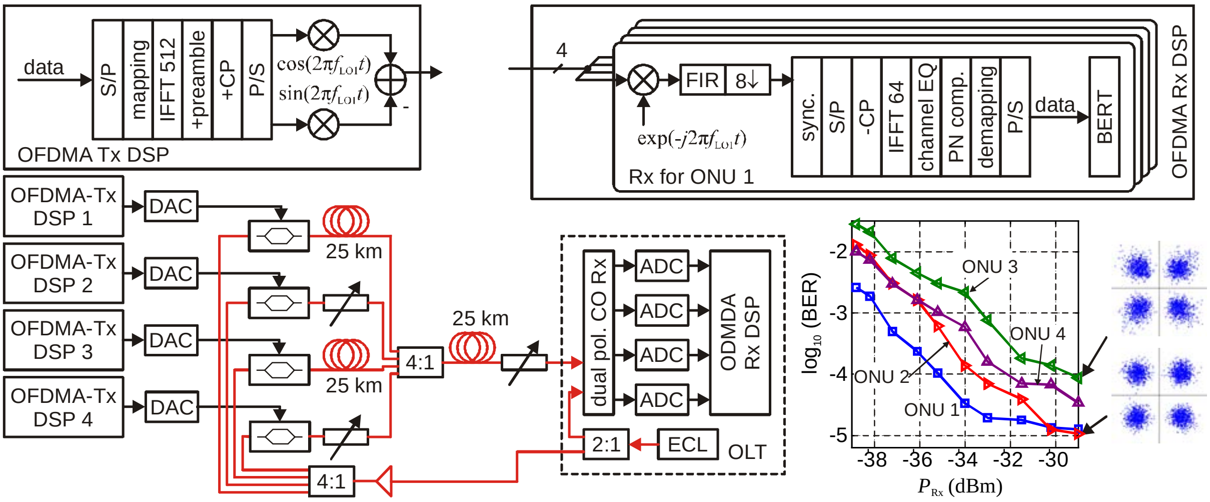

Fig. 4. Experimental US setup with four transmitting ONUs and coherently receiving OLT.

corresponds to non-ideal case in terms of ICI. Thus, the whole set of US signals can be regarded as asynchronious and the feasibility of this asynchronious US concept with OFDMA could be demonstrated.. The measured BER vs. the received power into the OLT-Rx are shown in Fig. 4. With a received power of P_{Rx}=-29 dBm all signals achieve a BER of better then 10^{-4}. The results show, that the higher frequency signals (ONU 3 and 4) have worse performance than the lower frequency signals (ONU 1 and 2) which results from bandwidth limitations of the used components. In addition, it can be noticed, that the signals at the spectrum edge (ONU1 and ONU4) have better performance because they only interfere with one neighbor, while ONU 2 and ONU 3 both have two neighbors. This could be used in a network with different path lengths to assign the spectra with highest frequency to the links with shortest distance. The results show, that crosstalk and electrical bandwidth limitations are the dominating impairments in this US system.

5. CONCLUSIONS

In this paper we investigate some approaches in OFDMA-PON. We showed that different cost constraints at the ONU and at the OLT result in very different subsystems for the DS and US part of the connection. While the DS part is similar to point-to-point OFDM transmission with direct detection, where the effort at the ONU could be reduced, the US direction is typically more challenging due to the distributed signal generation and optical modulation. Here, feasibility of a simple setup is shown, but further investigation is still required. Since the proposed techniques for DS and US are limited to one or two wavelengths, they should be scalable with WDM.

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REFERENCES

[1] P. Vetter: Next generation optical access technologies, *in Proc. ECOC 2012*, Amsterdam, Netherlands, Sep. 2012, paper Tu.3.G.1

[2] C. Kottke, *et al.*: Coherent subcarrier-WDM-PON system with SSB modulation and wavelength reuse, *in Proc. OFC 2013*, Anaheim, USA, March 2013, paper OM2A.3

[3] L. Anet Neto, et al. : On the limitations of IM/DD WDM-FDMA-OFDM PON with single photodiode for upstream transmission, *in Proc. OFC 2012*, Los Angeles, USA, March 2012, paper OM4B.1

[4] N. Cvijetic, *et al.*: Terabit optical access networks based on WDM-OFDMA-PON, *J. Lightwave Technol*, vol. 30, no. 4, 2012

[5] J. von Hoyningen-Huene, et al.: Experimental demonstration of OFDMA-PON uplink-transmission with four individual ONUs, *in Proc. OFC 2013*, Anaheim, USA, March 2013, paper OTh3A.2

[6] A. Agmon *et al.*: Bi-directional ultra-dense polarization-diverse OFDM/WDM PON with laserless colorless 1Gb/s ONUs based on Si PICs and <417 MHz mixed-signal ICs, *in Proc. OFC 2013*, Anaheim, USA, March 2013, paper OTh3A.6

[7] D. Qian, *et al.*: Optical OFDM transmission in metro/access networks, *in Proc. OFC 2009*, San Diego, USA, March 2009, paper OMV1

[8] J. von Hoyningen-Huene, *et al.*: Experimental IM/DD OFDM transmission with scalable Rx frontend for PON scenarios, *in Proc. OFC 2012*, Los Angeles, USA, March 2012, paper OW4B.6