# Experimental Demonstration of OFDMA-PON Uplink-Transmission with Four Individual ONUs

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**Abstract:** We demonstrate the first OFDMA uplink transmission with four individually modulated ONUs with central distribution of the optical carrier and coherent reception at the OLT, showing that OFDMA-PON is viable.

**OCIS codes:** (060.2330) Fiber optics communications; (060.4080) Modulation

## 1. Introduction

Since the demand of internet traffic is steadily increasing, various schemes for optical access are investigated. In order to increase the number of subscribers, combinations of wavelength division multiplexing (WDM) and multiple access per wavelength like time division (TDMA) or frequency division (FDMA) are desired. The concept of orthogonal frequency division multiple access (OFDMA) has advantages regarding the spectral efficiency and the flexibility to choose the modulation format and the bandwidth allocation for each subscriber [1]. Much work has been done concerning the downlink part of the bidirectional connection [2, 3]. However, in an OFDMA-PON the uplink part is typically more challenging. While for the downlink the whole multiplex signal is generated at once, the uplink signals are generated and modulated at different locations and have to be combined without distorting each other. For error free transmission these signals need to be orthogonal in frequency domain. Some work has been done to analyze the uplink. However most experiments are still simplified, because the whole uplink signal is generated at a single location [4] or the different optical network units (ONU) are transmitting on different wavelength, which on one hand avoids spectral overlapping but on the other hand reduces the number of WDM channels for further scaling of the system [5, 6]. In this paper we experimentally demonstrate the transmission of four individually modulated uplink signals and the combined reception at the optical line terminal (OLT).

## 2. OFDMA-PON

Since the optical spectrum is shared among different users (ONUs) transmitting at the same time, the individual transmitters have to have the same optical carrier frequency reference in order to prevent the uplink signals from overlapping. Fig. 1 shows the proposed setup for the OFDMA-PON. At the OLT the combined OFDM-signal for multiple users per wavelength is generated and optically modulated onto the downlink carrier with wavelength $\lambda_{DL}$. In addition, the corresponding uplink carrier $\lambda_{UL}$ is generated at the OLT as well and distributed to the ONUs. WDM with arrayed waveguide gratings (AWG) is applied to further increase the number of subscribers. In the remote node the downlink signal is split by an AWG and by power splitters. At the ONU a band splitter (BS) is used to separate the downlink signal, which is directly detected on a photodiode (PD), and the uplink carrier, whose intensity is modulated by the ONU transmitter. For the uplink each ONU transmits an OFDM signal, which is spectrally non-overlapping with the other uplink signals. In the remote node these different uplink signals are combined and transmitted over the same fiber. At the OLT the uplink WDM channels are separated again. Although the various uplink 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 uplink signals with one single FFT, all uplink signals need to reach the receiver synchronously. This could be achieved by

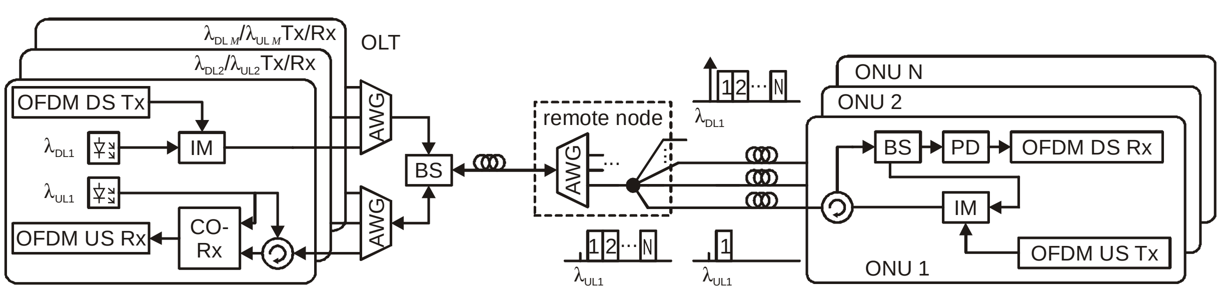


Fig. 1. Proposed architecture of the OFDMA-PON (UL=uplink, DL=downlink).

synchronizing all ONUs to the downlink 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 in our proposed approach, the signal is processed with separate OFDM-processors, each matched to its corresponding ONU. 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 [2, 3]. 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.

## 3. Experimental Setup

Fig. 2 shows the experimental setup of the uplink from 4 ONUs to the OLT. For each ONU uplink 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. For every 64 data-OFDM-symbols 4 special OFDM training symbols (TS) for synchronization and channel estimation (TS) are inserted to form an OFDM frame. 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 arbitrary waveform generators (AWG) 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 $V_\pi$ for carrier suppression. The optical carrier is provided by an ECL with a linewidth of less than 100 kHz. The carrier 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 uplink 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 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 the CP is cut off and 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

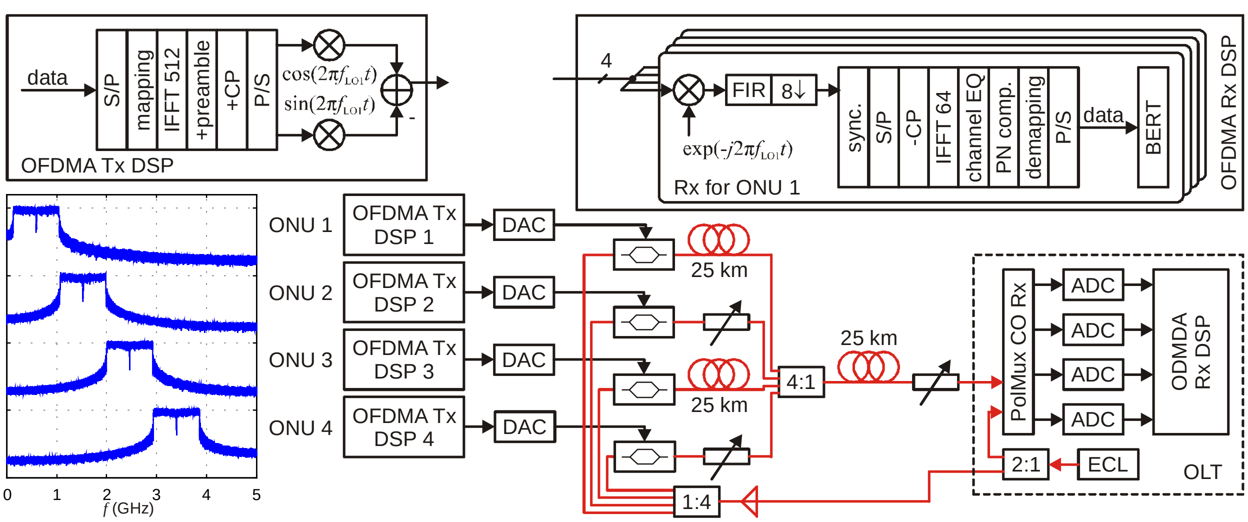


Fig. 2. Experimental setup with four transmitting ONUs and coherently receiving OLT.

handle the decorrelated laser phase noise. After demapping and serializing of the data symbols the BER is calculated for each uplink signal. Note, that no optical amplification is applied in the uplink part of the network. If a more powerful laser source could be applied for the distribution of the carrier, 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 uplink carrier. A single fiber could be used in a real system together with circulators as shown in Fig. 1.

## 4. Results

The measured optical spectra of the individual uplink signals 1...4 are shown in Fig. 3a with a resolution of 0.01 nm (the curves are shifted on y-axis for clarification). The carrier suppression and the different spectrally shifted OFDM spectra are visible. The thick line corresponds to the total optical spectrum after coupling. Note, that additional electrical low pass filter at the ONUs for out-of-band-power suppression could probably further improve the performance of ONU 3 and ONU 4. The electrical spectrum after coherent reception is shown Fig. 3b and Fig. 3c for both polarizations. The random polarization of the uplink signals require the detection of both polarizations since manual polarization control is typically not desired in the system. In our experiment the polarization was relative steady, but since the polarization sensitive equalizer is trained every OFDM-frame, slow variation of the polarization can be handled. For BER measurements OFDM frames are loaded into the four AWG channels. After transmission and signal detection the BER is evaluated. Since every data loading into both AWGs includes LAN communication and hard disk operations, which typically differ in execution time, we assume that the timing offset of both AWG is randomly distributed within the OFDM-frame duration of 3.7 µs. 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 corresponds to non-ideal case in terms of ICI. The mean BER of up to 80 measurement iterations vs. the received power into the OLT-Rx are shown in Fig. 3. With a received power of $P_{\mathrm{Rx}}$=-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 uplink system.

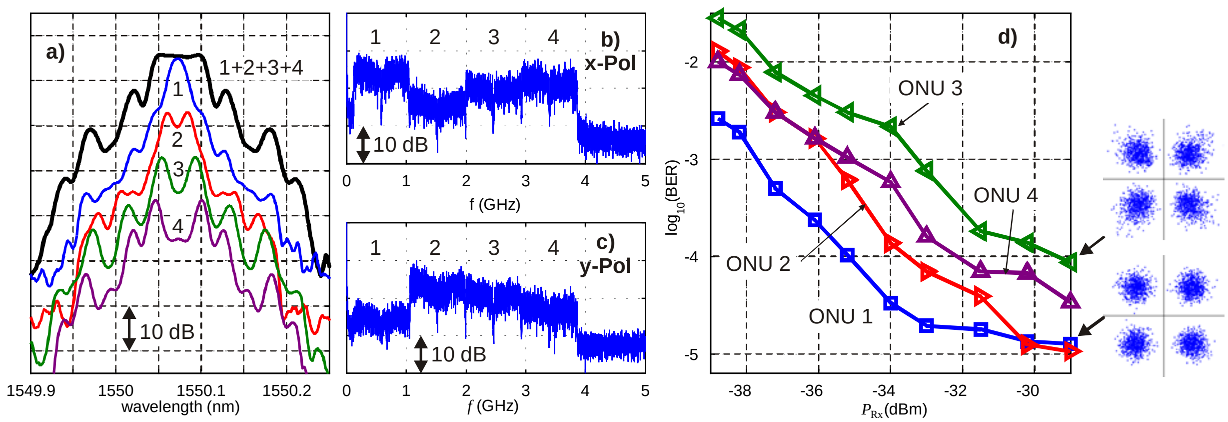


Fig. 3. Optical spectra of the uplink signals before and after coupling (a), electrical spectrum after coherent reception in x-polarization (b) and y-polarization (c), BER vs. received power of four ONUs (d) including constellation of ONU1 and ONU 3.

## 5. Conclusion

We demonstrated a realistic uplink scenario in an OFDMA-PON, including four ONUs which are connected via different fiber path lengths to a central office OLT. The achieved nominal bit rates were 1.79 Gb/s for each ONU, thus 7.16 Gb/s in total. OFDMA was used to combine signals from multiple ONUs operating on the same wavelength, which makes this technique scalable with WDM. This work is part of the project ADVAntage-PON and has been supported by the federal ministry of education and research of Germany under grant 13N10864.

## 6. References

[1] Dayou Qian, et al., IEEE JTL, vol.28, no.4, pp.484-493, Feb.15, 2010
[2] N. Cvijetic, et al., Proc. OFC 2012, paper OW4B.8, 2012
[3] J. von Hoyningen-Huene, et al., Proc. OFC 2012, paper OW4B.6, 2012
[4] N. Cvijetic, et al., Proc. OFC 2011, paper PDPD7, 2011.
[5] L. Anet Neto, et al., Proc. OFC 2011, paper OW4B1, 2012
[6] X. Q. Jin, et al., Proc. OFC 2012, paper OW4B5, 2012