# 37.5-km Urban Field Trial of OFDMA-PON using Colorless ONUs with Dynamic Bandwidth Allocation and TCM

**Christian Ruprecht(1), Yingkan Chen(2), Daniel Fritzsche(3), Johannes von Hoyningen-Huene(1), Norbert Hanik(2), Erik Weis(4), Dirk Breuer(4), Werner Rosenkranz(1)**

*1. Chair for Communications, University of Kiel, Kaiserstrasse 2 24143 Kiel, Germany, cr@tf.uni-kiel.de*
*2. Institute of Communications Engineering, Technische Universität München, Munich, Germany*
*3. EICT GmbH, EUREF Campus Haus 13, Torgauer Straße 12-15, 10829 Berlin, Germany*
*4. Deutsche Telekom AG;T-Labs, Berlin, Germany*

**Abstract:** An OFDMA-PON field trial using coherent detection in upstream and direct detection in downstream on 37.5 km feeder fiber is demonstrated. A power budget supporting 32 cost-effective colorless ONUs with dynamic bandwidth allocation is reported.
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## 1. Introduction

For the next generation optical access networks (NGOA), high data rates and flexible resource allocation in both up- and downstream for the optical network units (ONUs) are required. Possible solutions such as time division multiple access (TDMA) and wavelength division multiple access (WDMA) are being widely discussed for passive optical networks (PON). Likewise, orthogonal frequency-division multiple access (OFDMA) is also considered as a potential candidate for future PONs [1]. By assigning different subcarriers to different ONUs, OFDMA-PON has the inherent advantage of a flexible resource allocation, which meets the requirement of the future PON. Contrary to previous lab experiments where each ONU generates its own signal in a predefined subband with optional guard bands between adjacent ONUs [2] or with individual parallel receivers with a reduced FFT size [3], this field experiment uses a pure OFDMA approach in both up- and downstream (US and DS) transmission with highly flexible bandwidth allocation per ONU. With this scheme, the demodulation of the signals at the OLT is realized by using a single FFT for each polarization for all ONUs. This makes the guard bands unnecessary, and therefor increases the spectral efficiency and allows an arbitrary subcarrier allocation for the ONUs.

In this contribution, to the best of our knowledge for the first time a simultaneous upstream and downstream transmission in an OFDMA-PON over field installed fiber is shown. Dynamic bandwidth allocation is demonstrated over a 37.5 km long feeder fiber deployed by the Deutsche Telekom AG in Berlin, Germany. In the US, four colorless ONUs modulate a remotely seeded laser and the accumulated data rate of the ONUs results in 6.5 Gbit/s (QPSK). Dynamic bandwidth allocation and power loading are implemented. In the DS, a direct detection offset single-side band (SSB) approach is used to transmit 20 Gbit/s (8-QAM). In order to further increase the power budget, the trellis coded modulation (TCM) is applied to improve the BER performance without expanding signal bandwidth, so that a total of 32 ONUs are being supported in both up- and downstream transmission.

## 2. Realization of Proposed OFDMA-PON

In the field trial, the US and DS signals share the same field deployed feeder fiber using different wavelengths, as shown in Fig. 1 (a) and (b). In the DS, this concept uses intensity modulation and an optical filter to generate an offset SSB optical OFDM signal that can be directly detected by a photodiode so that a cost-effective ONU receiver can be achieved. At the OLT transmitter, two DACs within an arbitrary waveform generator (AWG) generate the baseband signal with 12 GS/s, which is then further up-converted to 12 GHz by an electrical IQ-modulator. In order to realize the colorless ONUs, the US carrier ($\lambda_{US}$=1552.5 nm, line width < 100 kHz) is added to the DS signal ($\lambda_{DS}$=1549.3 nm), then transmitted over the PON and extracted by each ONU for modulating its own data. The DS frame includes three training symbols for frame synchronization and channel equalization followed by 80 OFDM symbols carrying data (8-QAM) on 650 subcarriers (FFT size 1024 and a cyclic prefix (CP) of 2 samples). At the ONU, a band splitter (BS) separates the DS signal from the US carrier after the EDFA that is placed in front of the band splitter so that it can amplify both the US carrier and the DS signal. To achieve the best system performance, the launch power of the US carrier and the DS signal must be adjusted at the OLT so that the OSNR is optimized. Thereafter, the DS signal is detected using a photodiode, and after ADC (within a digital real time scope running at 50 GS/s) and digital IQ-demodulation, each ONU extracts its data from the allocated subcarriers.

In the US, each ONU generates its OFDM frames consisting of 80 OFDM data symbols and 5 unique training symbols for synchronization and equalization. The 4 DACs (within 2 AWGs) generate the data for the ONUs at 10 GS/s. Each ONU modulates its US data onto $\lambda_{US}$ using intensity modulation with the Mach-Zehnder modulator

(MZM) biased for carrier suppression. In the experiment the assignment of subcarrier indices and the resulting net data rates of each ONU are as follows: ONU 1: 1...60, 91…100 (2.29 Gbit/s), ONU 2: 61-90 (0.96 Gbit/s), ONU 3: 101-140 (1.29 Gbit/s) and ONU 4: 141-200 (1.96 Gbit/s). A pilot carrier for phase noise compensation was added at each ONU. An FFT size of 512 with a CP of 16 samples was used. In this field trial, the polarization was optimized in front of each MZM and it proved to be stable during the overall measurement. In a future realization, a polarization insensitive modulator [4] or an automatic polarization controller (PC) would have to be used. In the US, the signals of the ONUs are then multiplexed via a power combiner at the remote node (RN). After the transmission over the feeder fiber, a coherent receiver extracts the signal from both polarizations.

In order to preserve the orthogonality between the OFDM signals, the sampling clock, the correct timing alignment for the FFT and the same carrier frequency of all the upstream signals should be maintained. The clock can be readily extracted from the DS signal according to [5] and through the remotely seeded laser, the carrier frequency offset is under control so that the orthogonality in frequency domain is achieved. The timing alignment however must be exactly estimated (within the duration of the CP), which is realized by adding a timing advance (TA) in the DSP at each ONU. The TA for each ONU is initially calculated at the OLT by using the individual training symbols of each ONU and further adapted by analyzing the equalizer coefficients [6]. Thus, it compensates the different path delays and residual timing offsets can be tolerated within the duration of the CP [7].

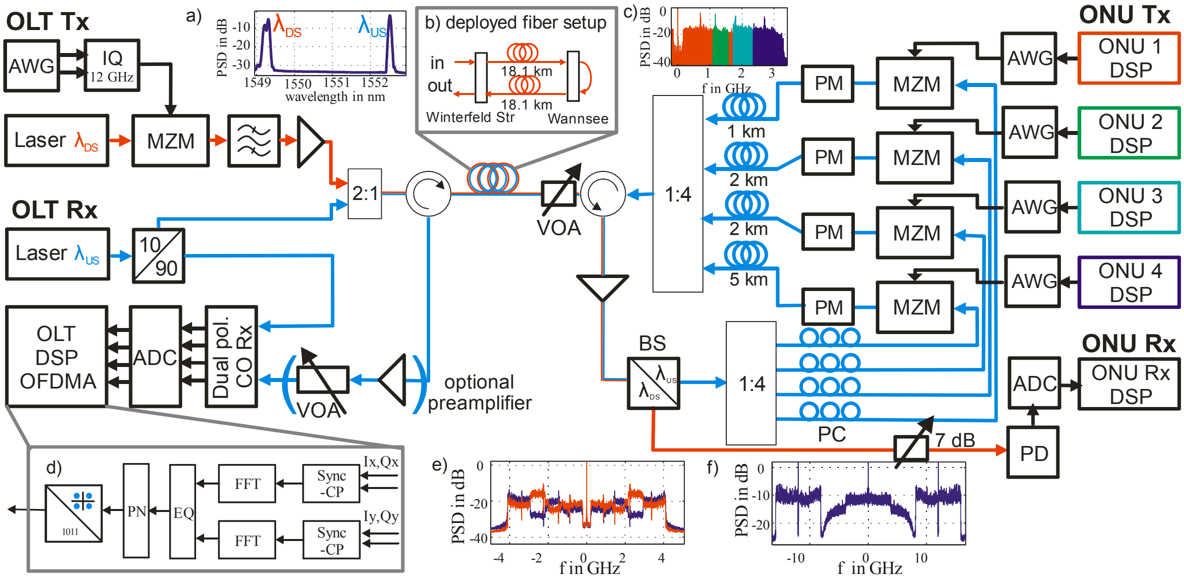


Figure 1: Experimental setup of the proposed OFDMA-PON (red: signal flow of DS, light blue: signal flow of US). (a) Spectrum of DS and US in the feeder fiber. (b) Field deployed bidirectional fiber. (c) Received spectrum in OLT Rx with all upstream signals. (d) DSP structure of the OLT Rx. (e) Spectrum of both polarizations (red, blue) after coherent detection at OLT Rx, (f) Received spectrum of the DS signal at ONU Rx.

After transmission over the drop fibers of different lengths, the US signal is transmitted over the two deployed fibers that are connected to realize a 37.5 km feeder fiber starting and ending at the lab located at the Winterfeld Str. in Berlin, Germany. Further in-house cabling (600 m included in the 37.5 km) and connectors result in a total attenuation of 14.7 dB for the deployed part of the PON. A variable optical attenuator (VOA) is used to emulate higher splitting ratios and thus user count of the system. At the OLT a dual polarization coherent receiver that uses the US laser as a local oscillator is used. After detection, the signal of the different ONUs may lie on different polarizations (Fig 1 (e)). A real time scope is used to record the signal and the digital signal processing (DSP) is done offline using Matlab. The DSP (Fig. 1 (d)) includes the synchronization, the calculation of the TA for each ONU, and a one tap equalizer combining both polarizations [3]. In the DSP, the laser PN is compensated in the frequency domain separately for each ONU. A pilot subcarrier added by each ONU is used for common phase error compensation and additional data aided PN compensation is applied for a fine-tuned phase correction [8].

In order to keep the spectral efficiency unchanged and improve the BER performance, TCM is implemented both in US and DS. In the US, one of the incoming 2 bits is coded using a 1/2-convolution encoder with 256 trellis states. Then 3 bits are mapped onto the 8-QAM symbols for further transmission. In the DS, a 2/3-convolution encoder with 8 trellis states is used. The 3 coded bits together with the uncoded bit are mapped onto 16-QAM symbols. The coding overhead is used for expanding the constellation size instead of expanding the signal bandwidth. Therefore, spectral efficiency is preserved, while coding gain is utilized to improve the power budget. The experiment targets BER=$3.8\cdot 10^{-3}$ after TCM decoder, assuming two interleaved extended BCH(1020,988) will be further concatenated.

## 3. Experimental Results and Discussion

After optimizing the launch power of the DS signal to 0.4 dBm and the US carrier to 3 dBm, a resulting launch power for ONU1…4 of -11.4 dBm, -16.8 dBm, -11.7 dBm and -11.8 dBm respectively was reached (measured using power meters (PM)). Different launch power of the ONUs may appear due to different drop fiber length, MZM and analogue bandwidth of the ADC. The received power at the ONUs optical front end was -5 dBm and the input signal for the coherent receiver was at -13.8 dBm. The total loss of the PON with the 1:4 power splitter amounts to 21 dB. In Fig. 2 (a) the average BER of all ONUs is plotted versus the received power at the coherent receiver without the optional amplifier at the OLT. When the feeder fiber is used in both directions, a penalty of 1.2 dB is observed compared to the back-to-back (B2B) case. However, no penalty for the bidirectional fiber was observed in the DS. For the investigation of the number of supported ONUs, the attenuation was raised each time by 3.5 dB per doubling of the number of supported ONUs. As plotted in Fig. 2 (b) the US can support 16 ONUs. When going to 32 users, the additional amplifier at the OLT alone is not able to bring the BER below the threshold of $3.8 \cdot 10^{-3}$.Thus in order to extend the splitting ratio to 32, the TCM is needed in combination with the additional EDFA, as depicted in Fig. 2 (b). In the DS, due to the EDFA at the ONU side, the received signal is not limited by the thermal noise of the optical front end but rather by the ASE noise of the EDFA. Therefore the DS transmission without additional coding is able to support 16 ONUs and TCM allows for a further doubling of the user count. As the signal is directly detected in the DS, it is thus robust against phase noise and a higher coding gain is observed. The constellations depicted in Fig. 2 (b) show the received signal for with and without coded modulation in DS and US.

Contrary to the shown measurement setup in a commercial system the drop fiber will be used in both directions, therefore the circulator must be placed at each ONU. In addition, if the amplifier can be provided in a cost efficient way, it could be placed at each ONU or, a single bidirectional amplifier would be placed at the remote node [5].

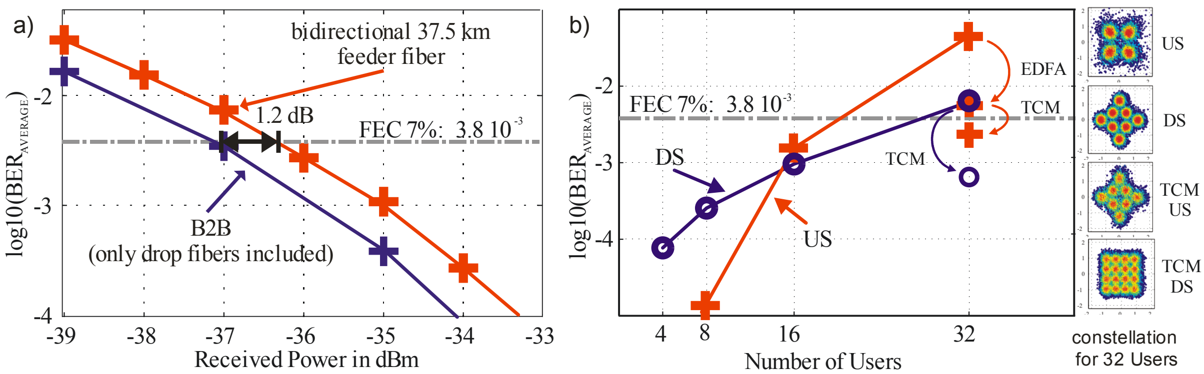


Figure 2: (a) A penalty of 1.2 dB can be noticed between the B2B transmission and the field trial. In b) a splitting ratio of 32 is reached when using the EDFA at the OLT Rx with a combination of TCM. In addition the constellation is depicted for the US (QPSK and the TCM 8-QAM) and the DS (8-QAM and the TCM 16-QAM).

## 4. Conclusion

In this contribution we demonstrated a realistic OFDMA-PON in upstream and downstream direction over a field deployed feeder fiber of 37.5 km. This is considered as the first field trial of an OFDMA-PON with a possible dynamic allocation of the subcarriers without frequency gap. A power budget supporting 32 ONUs was achieved by using the TCM. This research was supported by BMBF Grant ATOB 01BP1031 and 16BP1037. Special thanks are also due to the Fraunhofer Heinrich Hertz Institute for providing two additional AWGs for this experiment.

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