37.5 km Urban Field Trial of OFDMA-PON Using Colorless ONUs With Dynamic Bandwidth Allocation and TCM [Invited]

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***Abstract*—The orthogonal frequency division multiple access (OFDMA)-based passive optical network (PON) is a potential candidate to meet the flexibility requirements for next-generation optical access networks. We propose an OFDMA-based PON with a transmission employing intensity modulation/direct detection in the downstream and a remodulation of a remotely seeded carrier provided by the optical line terminal with coherent detection in the upstream, which enables cost-effective colorless optical network units (ONUs). Furthermore, an OFDMA-PON field trial using the proposed scheme over 37.5 km feeder fiber is demonstrated. A power budget supporting 32 ONUs with dynamic bandwidth allocation and trellis coded modulation (TCM) is reported.**

***Index Terms*—Access; Field trial; OFDM; PON.**

I. Introduction

To meet the ever-increasing demand of high data rates and elasticity in the access network, future generation passive optical networks (PONs) have attracted significant interest. Among them, the realization based on the orthogonal frequency division multiplexing (OFDM) technique is regarded as one of the potential candidates [1]. With the rapid improvement of integrated circuits and analog–digital converters/digital–analog converters (ADCs/DACs), the cost for adopting OFDM as a modulation scheme keeps decreasing, enabling the feasibility of different OFDM-based techniques in PONs. Among them are different flavors, for example, hybrid OFDM time division multiple access (OFDM-TDMA) [2], hybrid wavelength division multiplexing orthogonal frequency division multiple access (WDM-OFDMA) [3], as well as exclusively OFDMA-based PON (OFDMA-PON) [4].

In this contribution simultaneous upstream (US) and downstream (DS) transmission in an OFDMA-PON over field installed fiber is realized and evaluated. An OFDMA-PON featuring both high data rate transmission and dynamic bandwidth allocation is demonstrated over a 37.5 km feeder fiber deployed by the Deutsche Telekom AG in Berlin, Germany.

In the DS, a direct detection (DD) offset single-sideband (SSB) approach is used to transmit an aggregated data rate of 20 Gbit/s [using the 8-quadrature amplitude modulation (8-QAM) format on all subcarriers] [5]. In the US, four colorless optical network units (ONUs) modulate a remotely seeded laser. The total accumulated data rate of the ONUs results in 6.5 Gbit/s [using the quadrature phase-shift keying (QPSK) modulation format on all subcarriers]. Dynamic bandwidth allocation and power loading are implemented to illustrate the full flexibility of the OFDMA-PON [5].

To further increase the power budget without additional expansion in the signal bandwidth, trellis coded modulation (TCM) is applied to improve the bit error rate (BER) performance, which leads to a total power budget supporting 32 ONUs in both DS and US transmission.

II. Concept of the Proposed OFDMA-PON

The concept of the OFDMA-PON is depicted in Fig. 1. In the DS, a broadcast signal together with an unmodulated laser are coupled into the PON at the optical line termination (OLT) and transmitted to the ONUs. To keep the ONU cost effective, DD using a single positive intrinsic negative (PIN) photodetector is the selected solution in the DS.

Therefore, the OLT generates an offset SSB-OFDM signal using two DACs and an additional electrical inphase–quadrature (IQ) modulator to generate the real-valued OFDM signal with a reserved guard band, which is needed for intensity modulation/direct detection (IM/DD) [6]. After the electro/optical conversion using a single Mach–Zehnder

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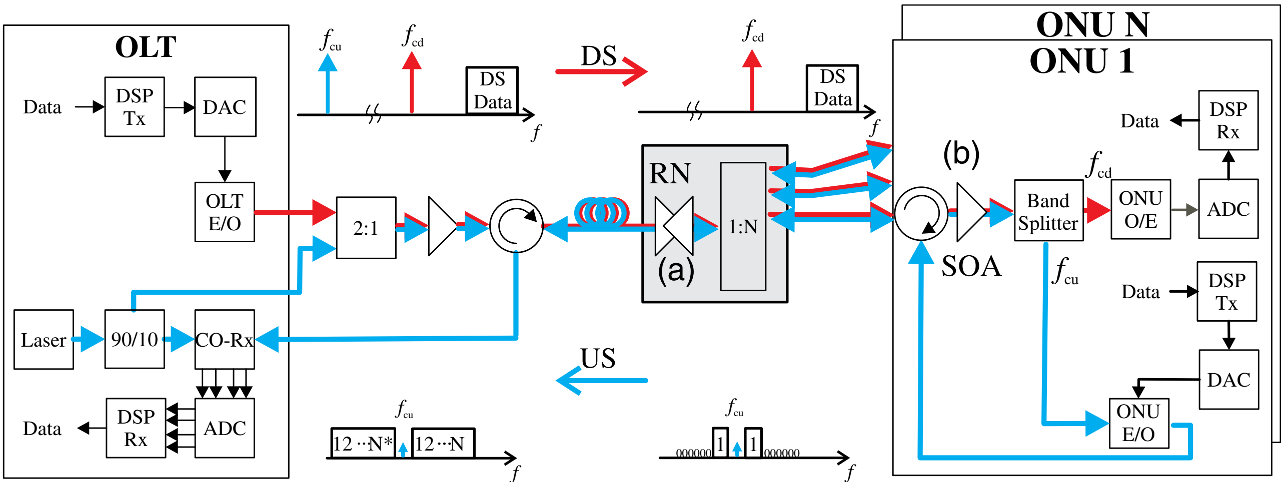

Fig. 1. Proposed OFDMA-based passive optical network. The DS transmission (red) is based on a broadcast with IM/DD. In the US (blue) a remotely seeded carrier is extracted at each ONU and modulated with an external modulator. Due to the high attenuation an optional amplifier placement (a) in the remote node (RN) or (b) in each ONU may be needed.

modulator (MZM) and SSB filtering, the DS signal is further combined with an unmodulated laser source (served as a remotely seeded laser for the ONU) via a 3 dB coupler, and the resulting signal is transmitted over the feeder fiber, the remote node (RN), and the distribution fiber. Subsequently the DS OFDM signal is extracted using a band splitter (BS). After DD, frame synchronization and fast Fourier transformation (FFT) demodulation in each ONU are conducted to extract the data from the preassigned subcarriers.

In the US, each ONU modulates its data onto the assigned subcarriers and upconverts them into the optical domain, thereby modulating the extracted remotely seeded carrier transmitted from the OLT to each ONU (zeroes are assigned to the remaining subcarriers). An example US frame is depicted in Fig. 2 with the frame starting with a synchronization symbol, followed by a symbol for equalizer training and data carrying symbols. The individual subcarrier pilot for phase noise compensation is depicted as well.

The US signal of each ONU is transmitted over the bidirectional distribution fiber. At the RN all US signals are multiplexed using a 1:N optical coupler. After the feeder fiber a circulator extracts the modulated US signal, which is then coherently detected. Due to the mode coupling, it is necessary to exploit the polarization diversity of the

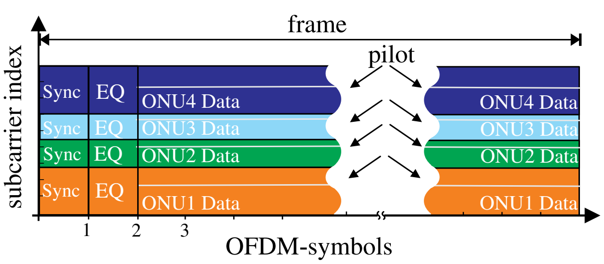

Fig. 2. US frames of four ONUs including TSs for synchronization and equalizer training and a subcarrier pilot for PN compensation.

received signal. Therefore a coherent polarization diversity receiver is used and a corresponding single input multiple output (SIMO) processing is developed in the digital signal processing (DSP) unit. Instead of assigning consecutive subcarriers to each ONU and using a virtually separate receiver structure for each ONU at the OLT [7,8], in this proposal an OFDM receiver with a single-stage FFT will be used at the OLT so that a dynamic bandwidth allocation can be realized. However, for a successful demodulation of the US signal, time domain and frequency domain alignment among different ONUs must be achieved so that multiple access interference (MAI) is minimized. In the following, the details of the DSP algorithms, as applied in the field trial, are discussed.

A. *Orthogonality at the OLT*

The orthogonality of the US signals at the OLT depends on the correct alignment in both the **time** and **frequency** domains. First of all to investigate the effects of an incorrect **frequency** alignment, numerical simulations were conducted, where four ONUs (setup no. 1 used as listed in Table I) are transmitting their data to the OLT (US transmission) using an individual US laser at each ONU. For this simulation all ONUs were correctly aligned with respect to the OLT FFT window. To simulate the effect of the laser drifting in frequency over time an additional carrier frequency offset (CFO) is added to ONU2 and increased incrementally during the simulation. Figure 3

TABLE I
Allocation, Fiber Length, and Data Rate

	ONU 1	ONU 2	ONU 3	ONU 4
Fiber	1 km	2 km	2 km	5 km
No. 1	1…60, 91…100	61…90	101…140	141…200
No. 2	1…70	71…100	101…40	141…200
Data rate	2.29 Gbit/s	0.96 Gbit/s	1.29 Gbit/s	1.96 Gbit/s

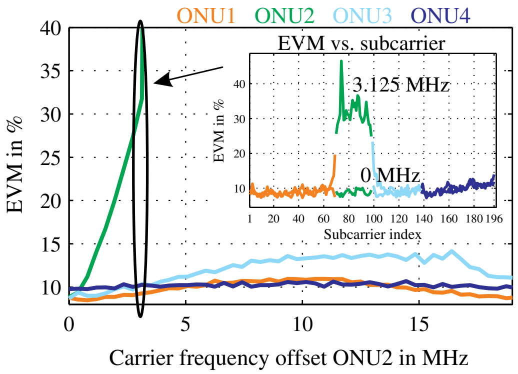

Fig. 3. Carrier frequency offset of ONU2 with respect to the LO and optical carrier at the OLT receiver. The inset depicts the EVM versus the subcarrier index for zero offset and 3.125 MHz.

indicates that a small CFO of 3.125 MHz (CFO of 16% with respect to subcarrier spacing of approximately 20 MHz) leads to an average error vector magnitude (EVM) higher than 32% (approximately a BER of 10^{-3} [9]) and results in a failing transmission link of ONU2. However, the empirical results show that the crosstalk decreases quickly with the subcarrier spacing. Therefore it is essential that the CFO among the ONUs is under control, implying that all subcarriers must fit onto the same subcarrier grid. Fine control of the carrier frequency among all the ONU Txs and the coherent OLT Rx is required for such a system.

In the **time** domain the individual signals of the ONUs must be aligned within the FFT window of the receiver. Numerical simulation illustrates the influence of ONU2, whose frame start is delayed from the optimal position with respect to the FFT window of the OLT. Meanwhile, the remaining ONUs are still optimally aligned, and there is no CFO. The average EVM for ONU2 at a timing offset of 2 ns is already above 32%, and the crosstalk on the neighboring subcarriers of the adjacent ONUs is considerably large, as shown in Fig. 4.

Both alignment requirements must be fulfilled to demodulate the US signals without MAI at the OLT. In the proposed setup, as described in detail below, the

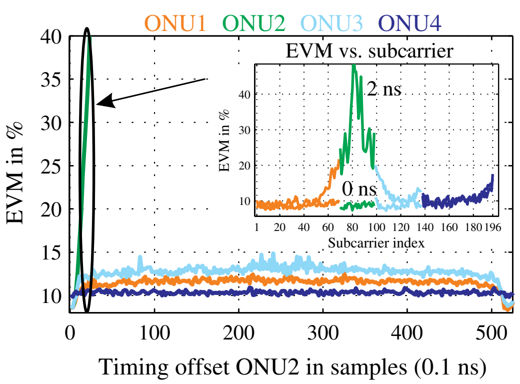

Fig. 4. Timing offset of ONU2 with respect to the optimal value. The inset depicts the EVM versus the subcarrier index for the ideal position and an offset of 2 ns.

frequency orthogonality is preserved by using a remotely seeded carrier and an estimation of the differential delay in each ONU. This is called timing advance, estimated through training symbol (TS)-based coarse estimation and equalizer coefficient based fine estimation and adjusted digitally at each ONU.

1) Remotely Seeded Carrier: The OLT adds an unmodulated carrier to the DS signal. This carrier should have a narrow laser linewidth to alleviate the perturbation due to laser phase noise in the uplink transmission and a high launch power to achieve a higher OSNR.

In the realized field trial, a linewidth of <100 kHz at a launch power of 3 dBm was applied. One BS in combination with a single circulator was used to separate US from DS for all the ONUs. Therefore the distribution fibers are only used for the US and are not bidirectional. An additional 7 dB attenuation is introduced to emulate the splitting in the DS.

2) Timing Advance: All ONUs must have the same clock frequency as well as the correct frame alignment. In the proposed setup each ONU will first extract its clock from the DS signal as, for example, demonstrated in a real-time realization by [10]. Consequently all ONUs will run at the same clock frequency and in addition will be aligned with respect to the OLT's FFT window. This is done by introducing a time delay, called timing advance (TA), at each ONU, realized in the digital domain. The required information of the delay between ONUs is extracted at the OLT and transmitted back to each ONU using the DS signal.

In the field trial, as offline processing instead of real-time computation was used, an alternative approach was chosen. First, to simulate an extracted DS clock an external 10 MHz clock was used to synchronize the clock of the two arbitrary waveform generators (AWGs). Second, to adapt the TA a manual feedback using Matlab was used. Furthermore the AWGs were triggered to guarantee a fixed delay between the US signals. Based on this approach the TA for each ONU is initially calculated offline at the OLT by using the individual TSs of each ONU with a correlation technique and peak detection and further adapted by analyzing the equalizer coefficients [11]. Thus, the differential delay among all the ONUs can be calculated and transmitted back to the ONUs to compensate the different path delays. The residual uncompensated timing offsets can be tolerated as long as the offset is within the duration of the cyclic prefix (CP) [12].

B. Digital Signal Processing

For the DS, an offset optical SSB-OFDM signal was generated, TSs were added for frame synchronization, and time domain cross correlation was used. Additional TSs were added for the channel equalization. Based on the measured EVM values for each subcarrier the signal-to-noise ratio (SNR) was calculated under the assumption that the noise source present in the system is additive white Gaussian noise [9]. According to the measured SNR

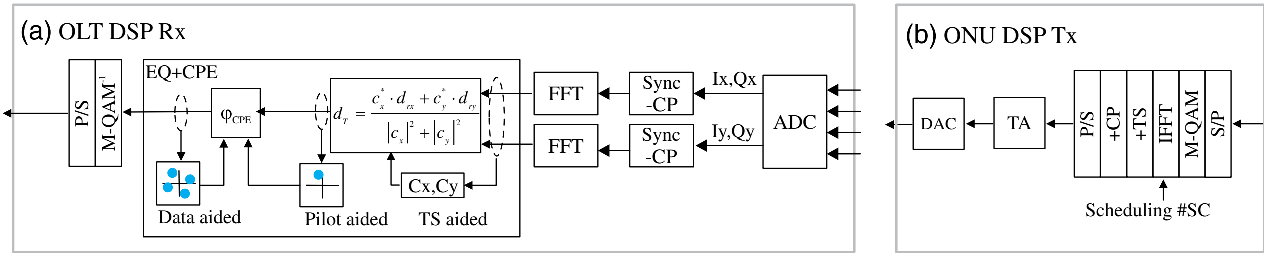

Fig. 5. DSP for US transmission at the OLT (a) including the adapted EQ with the common phase estimation (CPE) and the DSP at the ONU (b) including the variable TA.

an adequate power loading was derived to realize an equal BER for all subcarriers [13].

In the US, the signal from both polarizations must be detected to extract the signals from all ONUs. Thus after the frame synchronization with TSs of all ONUs superimposed, an FFT is done for each polarization; see Fig. 5 for the US-DSP. The equalizer is adapted to combine the signals from both polarizations, and the received signal d_{Total} can be extracted using

$$d_{\mathrm{Total}} = \frac{c_x^* \cdot d_{\mathrm{Rxpol}} + c_y^* \cdot d_{\mathrm{Rypol}}}{|c_x|^2 + |c_y|^2},$$

where d_{Rxpol} and d_{Rypol} are the received signals on each polarization and c_x and c_y are the equalizer coefficient vectors extracted using the equalizer TSs [5,7,11]. Due to the coherent detection phase noise compensation is necessary. Furthermore due to the different distances a random walk-off between the different ONUs of the common phase error (CPE), depicted in Fig. 6, is observed [5,8,14]. Hence an individual phase estimation is necessary for each ONU, which can only be done after the ONUs are separated using FFT. As a consequence the compensation must be performed in the frequency domain.

For the field trial, a pilot-based phase noise estimation was applied, followed by an additional data-aided feedback structure to improve the estimation [15]. For each ONU, one of the assigned subcarriers is reserved as a pilot subcarrier. The pilot subcarrier, continuously transmitting the

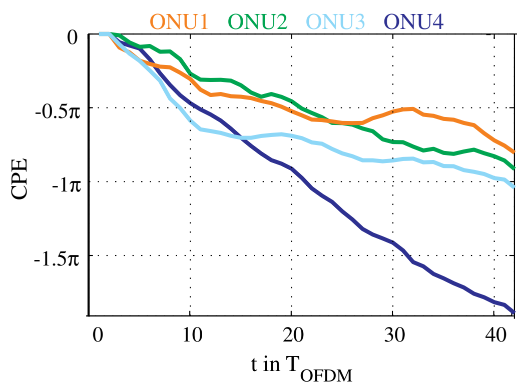

Fig. 6. Resulting common phase error (CPE) estimation plotted for 40 consecutive OFDM symbols for the four ONUs in the field trial.

symbol ‘1’, was assigned to each ONU as depicted in Fig. 2. At the receiver, after channel equalization, the CPE introduced by laser phase noise is obtained using a comparison between received and transmitted pilot symbols. Subsequently the data symbols are multiplied with the complex conjugation of the CPE estimates to compensate for the phase noise. Due to the additive noise and intercarrier interference (ICI) caused by laser phase noise, CPE estimates based on a single pilot subcarrier may not be accurate enough.

Therefore an additional data-aided phase noise compensation is implemented. After the first stage CPE compensation, a decision is made on the recovered and corrected data symbol. The updated CPE estimates are calculated using a comparison between the decided data symbol and the previously corrected symbols. Iterative decision feedback can be conducted to further optimize the CPE laser phase noise estimation.

III. Coding for Additional Reach and User Count

To improve the power budget, thereby realizing higher user count and/or longer transmission distance, TCM was introduced [16]. The required redundancy is realized through the expansion of the constellation size instead of additional bandwidth. Therefore, the spectral efficiency compared with the noncoded system remains unchanged, but an additional gain of the power budget can be achieved. The implemented TCM for the DS and US transmission must be treated in a different manner. In the DS, the dominant noise sources originate from the thermal noise of the photodiode (PD) and the amplified spontaneous emission of the optical amplifier. The launch power into the feeder fiber is optimized so that the system is not operating in the nonlinear regime. Thus, the conventional TCM optimized for the AWGN channel is implemented. The original modulation format for the noncoded system was 8-QAM. Therefore, using TCM, the two least significant bits (LSBs) out of every three incoming bits are coded using a convolutional encoder with a rate of 2/3 with 256 trellis states. In this case the most significant bit is left uncoded and the BER is minimized by performing set partitioning upon the rectangular 16-QAM constellation, to achieve the coding gain.

Due to the coherent detection in the US, the transmitted signal is impaired by laser phase noise from both the transmitter and the receiver. This scenario can be modeled as a

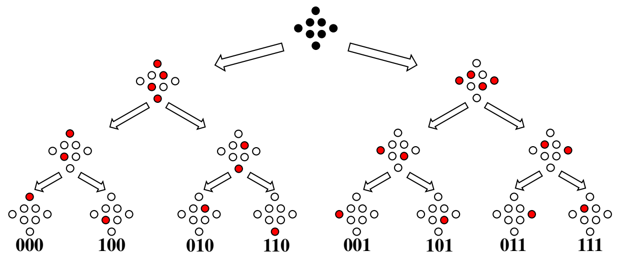

Fig. 7. Set partitioning of the US signal, adding an additonional symbol for coding, thereby transmitting 8-QAM instead of QPSK.

multiuser phase noise channel. As illustrated in [14], the impairments upon the received symbol of each subcarrier are composed of the multiplication of the CPE caused by Tx and Rx laser phase noise and a strong ICI term. Therefore, the conventional TCM (optimized for the AWGN channel) shows inferior performance in the US transmission. Investigation was conducted to enhance the transmitted symbol in the case of laser phase noise introduced impairments. The original modulation format designed for US transmission is QPSK; therefore the conventional TCM maps QPSK onto an 8-PSK constellation for the transmission. In the case of phase noise, instead of using 8-PSK, the coded three bits are mapped onto circular 8-QAM to enhance the tolerance against laser phase noise. The corresponding set partitioning, used for the US transmission, is shown in Fig. 7.

IV. Field Trial

The setup of the field trial is depicted in Fig. 8. At the OLT-Tx two DACs within an AWG generate the baseband signal with 12 GS/s, which is then further upconverted to 12 GHz by an electrical IQ modulator. To realize the offset SSB-OFDM signal the upper sideband is suppressed using a tunable optical filter. The DS frame includes three TSs for frame synchronization and channel equalization followed by 80 OFDM symbols carrying data (8-QAM) on 650 subcarriers (FFT size 1024 and a CP of two samples resulting in 16.7 ns CP duration).

In order to realize colorless ONUs, the US carrier ($\lambda_{\mathrm{US}} = 1552.5$ nm, linewidth <100 kHz) is added to the DS signal ($\lambda_{\mathrm{DS}} = 1549.3$ nm), and then transmitted over the PON and extracted by each ONU for remodulation. The corresponding spectrum is depicted in Fig. 8(b).

At the ONU, a BS separates the DS signal from the US carrier. An erbium-doped fiber amplifier (EDFA) is placed in front of the BS to amplify both the US carrier and the DS signal. Contrary to the field trial 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 RN [17].

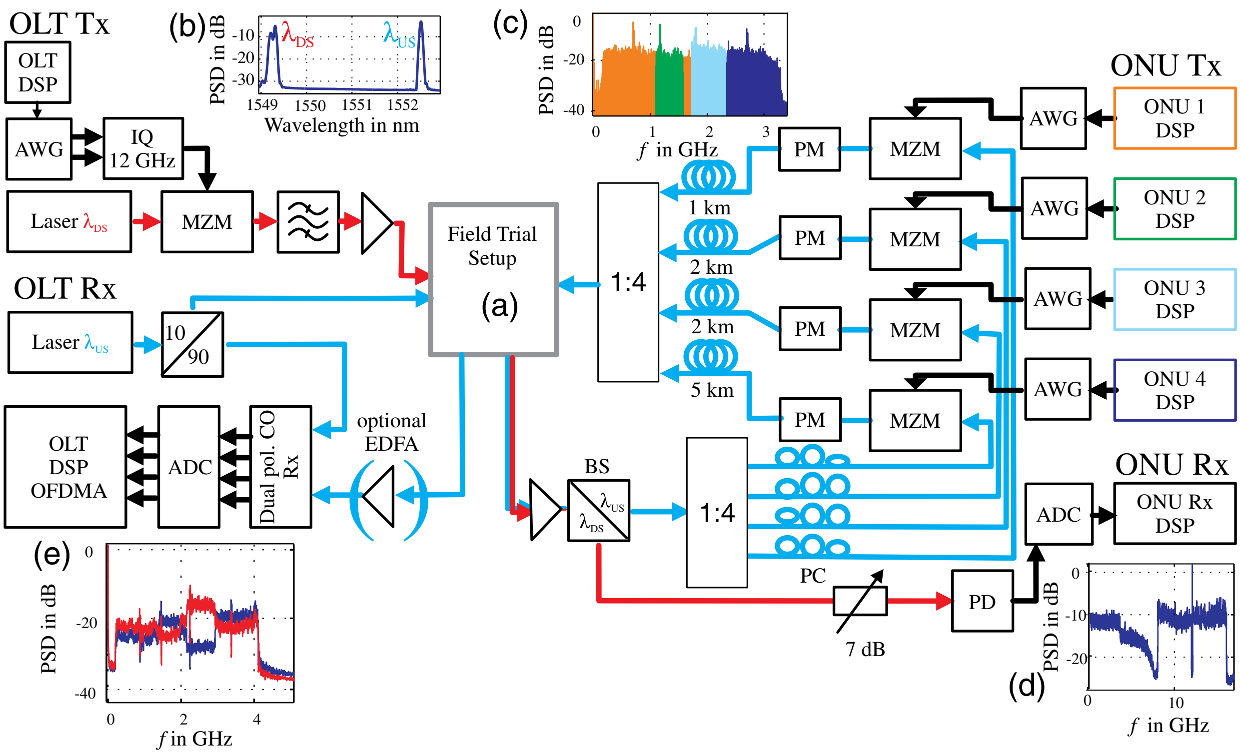

Fig. 8. Field trial realization of the OFDMA-PON, with field trial setup (a) further defined in Fig. 11. The combined DS signal and US carrier at the OLT are shown in (b), the combined electrical signal of all ONUs in (c), the received DS signal before IQ demodulation including intermodulation distortion in (d), and the coherently received US signal in X/Y polarization blue/red in (e). (PM, power meter; BS, band splitter; PC, polarization controller.)

To achieve optimal system performance, the launch power of the US carrier and the DS signal must be adjusted at the OLT to optimize the OSNR. Thereafter, the DS signal is detected using a PD followed by a transimpedance amplifier with a 20 GHz bandwidth. After ADC (within a digital real-time oscilloscope running at 50 GS/s), downsampling, and digital IQ demodulation, each ONU extracts its data from the allocated subcarriers. In the field trial, due to component constraints only a single ONU receiver was used.

In the US, each ONU generates its OFDM frames consisting of 80 OFDM data symbols and five unique TSs for synchronization and equalization. The four DACs (within two AWGs) generate the data for the ONUs at 10 GS/s. Each ONU modulates its US data onto λ_{US} using intensity modulation with a MZM biased for carrier suppression. The assignment of subcarrier indices used in the field trial and the resulting net data rates of each ONU are given in Table I, and in addition the subcarrier assignments are clarified in Fig. 9. A pilot subcarrier for phase noise estimation was added at each ONU, depicted in Fig. 2.

In the US, an FFT size of 512 with a CP of 16 samples was used. The 16 samples ensure robustness against chromatic dispersion, polarization mode dispersion, and the residual (uncompensated) timing offset among ONUs. In this field trial, the polarization had to be optimized in front of each MZM, and it proved to be stable during the overall measurement. In a future realization, a polarization insensitive modulator setup [17] or an automatic polarization controller (PC) would have to be used. In the US the signals of the ONUs are multiplexed via a power combiner at the RN. After the transmission over the feeder fiber, a coherent receiver extracts the signal from both polarizations.

As described in detail above, in order to preserve the orthogonality between the OFDM signals, the sampling clock, the correct timing alignment of the FFT frame, and the same carrier frequency of all the US signals must be maintained. In the field trial, all AWGs were supplied by a 10 MHz external clock to extrapolate their 10 GS/s sampling frequency. In addition one AWG served as a master that triggered the other AWG to emit the US signals. Consequently the signals of all four DACs (ONUs) emit their data at a fixed timing offset (with respect to the other ONUs). The timing alignment, however, must be exactly estimated (within the duration of the CP) and adjusted, which is realized by adding the TA in the DSP at each ONU before uploading the signal into the AWG.

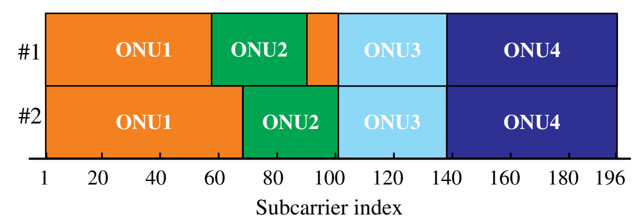

Fig. 9. Subcarrier allocation for the ONUs.

After transmission over the drop fibers of different lengths, the US signals from different ONUs are coupled and transmitted over the field trial setup, located at Winterfeldstrasse in Berlin, Germany, depicted in Fig. 10. Three different setups are evaluated in the field trial. A simple optical B2B transmission [Fig. 11(a)], a setup with the DS signal and US carrier on one fiber and the modulated US signal on the second fiber [Fig. 11(b)], and the bidirectional feeder fiber setup [Fig. 11(c)]. In the final scenario, Fig. 11(c), two deployed fibers realize a 37.5 km feeder fiber starting and ending at the lab, at Winterfeldstrasse in Berlin. Further in-house cabling (600 m included in 37.5 km) and connectors result in a total attenuation of 14.7 dB for the deployed part of the PON.

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 have different states of polarization [Fig. 8(e)]. A real-time oscilloscope is used to record the signal, and the DSP is done offline

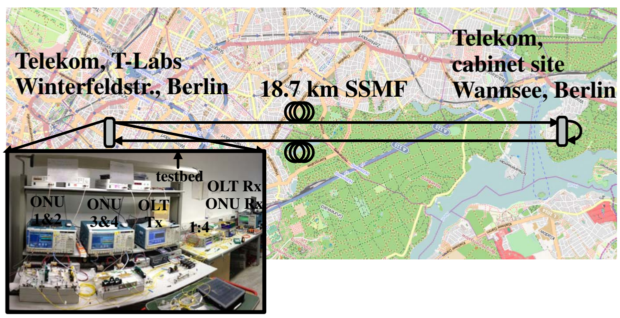

Fig. 10. Field trial location in Berlin, Germany.

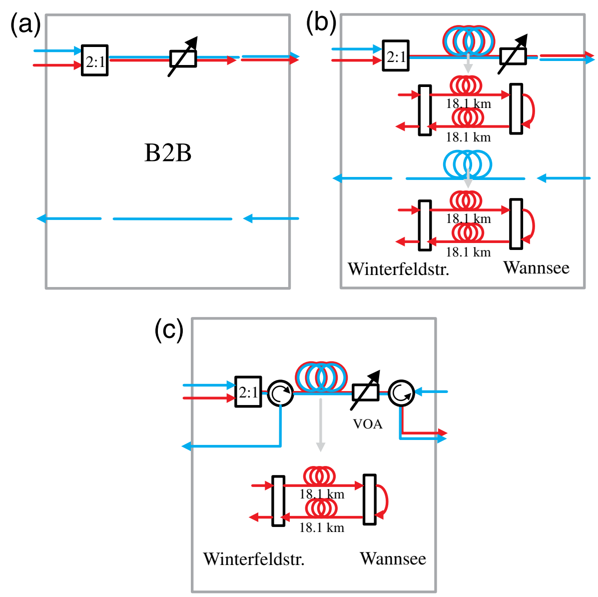

Fig. 11. Field trial fiber setup between Winterfeldstrasse and Wannsee in Berlin, Germany, (a) in the B2B case, (b) for different fibers used in the US and DS, and (c) for a bidirectional fiber.

using Matlab. The DSP [Fig. 5(a)] includes the synchronization, the calculation of the TA for each ONU, and a one-tap equalizer combining both polarizations [5,8]. In the DSP, the laser PN is compensated in the frequency domain separately for each ONU using the introduced pilot subcarrier. The resulting CPE estimate for 40 consecutive OFDM symbols transmitted in the field trial is depicted in Fig. 6.

After optimizing the launch power of the DS signal power is set to 0.4 dBm and the US carrier to 3 dBm, resulting in a launch power for ONUs 1–4 of −11.4, −16.8, −11.7, and −11.8 dBm, respectively [measured using in-line power meters (PMs)]. The different launch powers of the ONUs result from different drop fiber lengths, MZM insertion losses, and biasing, as well as the bandwidths of the DACs and of the amplifiers. The received power at the ONU's optical receiver front end (DS) was −5 dBm, and the received power of the US signal at the coherent receiver was at −13.8 dBm. The total loss of the PON including the 1:4 power splitting amounts to 21 dB.

V. Results of the Field Trial

During the field trial different setups were tested and compared. For the DS the receiver sensitivity was measured, by changing the optical input power to the photoreceiver and measuring the EVM. In the DS no penalty between the different field trial fiber setups was observed. The sensitivity for the DS transmission, depicted in Fig. 12, supports 3 bits/symbol at an input power of −14 dBm. Due to the high power loss, an amplifier located at the RN or at each ONU is needed to achieve this optical received power.

In Fig. 13, the results for the US sensitivity for the three different setups (pictured in Fig. 11) are shown. The average EVM 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 for US and DS, a penalty of 1.2 dB in terms of needed received power to achieve an EVM of 32% (equivalent to a BER of 10^{-3}) is observed with respect to the B2B transmission. However, if a second fiber is used for the US signal no such penalty can be observed.

For the investigation of the number of supported ONUs, the attenuation was raised by 3.5 dB per doubling the number of supported ONUs. As plotted in Fig. 14 the US can support 16 ONUs. When ramping up to 32 users, the additional amplifier at the OLT alone does not result in a BER below the threshold of 3.8×10^{-3} [two interleaved extended BCH (1020,988)]. Thus in order to extend the splitting ratio to 32, the TCM is needed in combination with an additional EDFA.

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 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. 14 show the received signal with and without coded modulation in the DS and US.

In addition to the user count, different subcarrier allocations were compared in the field trial. Two different scenarios are depicted in Fig. 15, where ONU1 is interleaved with ONU2 to generate additional transition between the different ONUs as a first step toward interleaved subcarrier allocation, which would allow for dynamic bandwidth

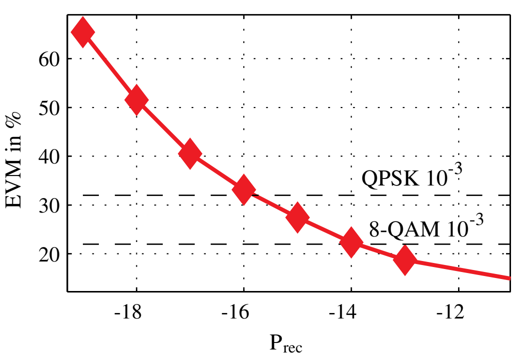

Fig. 12. Receiver sensitivity of the ONU with the EVM plotted over the received power.

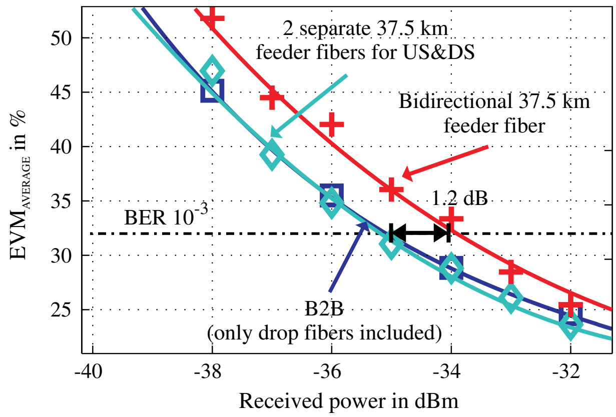

Fig. 13. Receiver sensitivity of the OLT using different field fiber setups explained in Fig. 11.

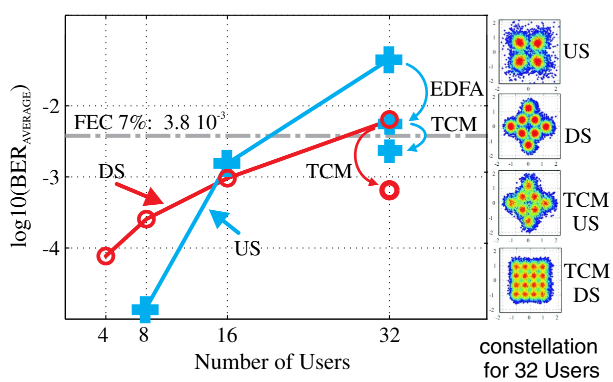

Fig. 14. Splitting ratio of 32 is reached when using the EDFA at the OLT-Rx with a combination of TCM. In addition the constellation is depicted for the US (QPSK and TCM 8-QAM) and the DS (8-QAM and TCM 16-QAM).

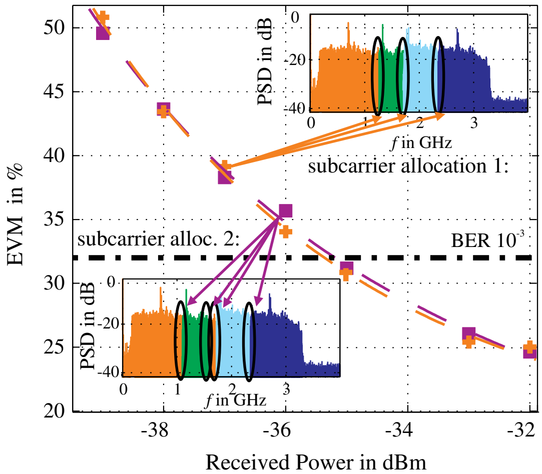

Fig. 15. US receiver sensitivity for different subcarrier allocations.

allocation. Due to the orthogonality of the US signals at the OLT-Rx no additional penalty can be observed for subcarrier allocation scenario no. 2 even though further transitions between the ONUs are apparent.

VI. Conclusion

In this paper, we proposed an OFDMA-PON and demonstrated transmission in both the US and DS directions over a field deployed feeder fiber of 37.5 km length. This was considered the first field trial of an OFDMA-PON with a possible dynamic allocation of the subcarriers without introducing a frequency gap among the ONUs. Furthermore, in the uplink, a solution for realizing the time synchronization of all ONUs was demonstrated so that at the OLT RX all signals are aligned as evaluated in a field trial.

In order to keep the ONU cost-effective and to keep the frequency offset under control, a remotely seeded laser from the OLT was used for the US and IM/DD was applied in the DS. This scheme ensures a laser source free ONU. Experimental results show that the orthogonality among the ONUs can be well preserved. Furthermore, adapted coded modulation based on TCM is applied for the US transmission to achieve a higher power budget. The final field experimental results show that a power budget supporting 32 ONUs can be achieved for both DS and US targeting a FEC limit of 3.8×10^{-3}.

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