Timing Advance Tracking for Coherent OFDMA-PON Upstream System

C. Ruprecht[1], K. Habel[2], J. von Hoyningen-Huene[1], Y. Chen[3], N. Hanik[3], W. Rosenkranz[1]
[1] *Chair for Communications, University of Kiel, Kaiserstrasse 2, 24143 Kiel, Germany*
[2] *Fraunhofer Institute for Telecommunications, Heinrich-Hertz Institut, Berlin, Germany*
[3] *Institute of Communication Engineering, Technische Universität München, Munich, Germany*
cr@tf.uni-kiel.de

Abstract: A synchronization algorithm for coherent OFDMA-PON upstream is proposed. The feasibility of the tracking functionality is experimentally investigated. A differential delay of up to 37.6 ns was tracked and could be compensated at the ONU.

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

1. Introduction

In an orthogonal frequency division multiple access (OFDMA) based passive optical network (PON) [1], the upstream (US) signals are transmitted simultaneously using the same wavelength. The OFDMA-PON upstream is a multipoint (multiple optical network units (ONUs)) to singlepoint (optical line termination (OLT)) type of system. Each ONU generates the upstream signal independently and the OLT receives the combination of all the ONU upstream signals. In order to demodulate the OFDM-signal at the OLT without the inter carrier interference between different ONUs, the groups of OFDM-subcarriers allocated for each ONU must be orthogonal at the OLT. However, the subcarrier orthogonality is defected by laser phase noise (PN), carrier frequency offset (CFO) and the timing delay between the ONUs. A common approach is to treat the digital signal processing (DSP) for each ONU individually and thus to implement multiple virtual receivers in the OLT [2], which leads to a high implementation complexity. In this contribution, the CFO of the lasers is minimized by using a common laser source for all ONUs (seeded remotely from the OLT [3]) and the estimation and control of the different timing delays between the ONUs using the proposed timing synchronization scheme is investigated to ensure a combined ONUs' upstream signal to be orthogonal. With this scheme, the demodulation of the signals at the OLT is realized by using one single FFT for each polarization, which significantly decreases the implementation complexity. The varying timing delays between the ONUs are introduced by using different lengths of distribution fibers and by heating a single distribution fiber.

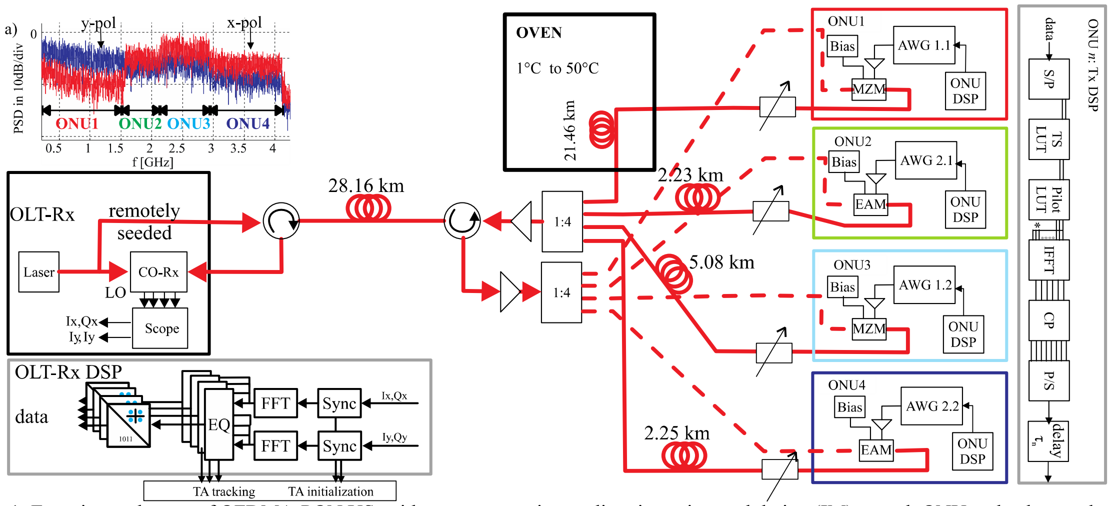

Figure 1: Experimental setup of OFDMA-PON US, with a remote carrier seeding, intensity modulation (IM) at each ONU and coherent detection of both polarizations (received signal PSD depicted in inset (a)) at the OLT.

The proposed scheme estimates the optimal differential timing delay named Timing Advance (TA) which will be fed back to the ONUs for timing adjustment so that the OFDM-symbols of all the ONUs are aligned within the same FFT-window at the OLT. The experiment has an accumulated net data rate of 6.67 Gbit/s (including 7% FEC).

2. Experimental System Setup

The experimental setup is illustrated in Fig. 1. Each ONU uses an FFT of size 512 with a cyclic prefix of 8 samples to generate its OFDM-symbols. The OFDM-frames are composed of 40 data carrying OFDM-symbols, a unique training symbol for synchronization (TS) and one TS for the 1-tap channel equalizer (EQ). The QPSK symbols are allocated only to the assigned subcarriers (ONU1: 1-69, ONU2: 70-98, ONU3: 99-137 und ONU4: 138-196), and a subcarrier pilot is included at each ONU for laser phase noise compensation. Two dual channel arbitrary waveform generators (AWG) operate at 10 GSamples/s, which then intensity modulate the signal onto the laser source with either a Mach-Zehnder modulator (MZM) (ONU1+3) or an electro-absorption modulator (EAM) (ONU2+4). In the proposed system all ONUs modulate the same optical carrier, seeded over the same fiber from the OLT, with a line width of 5 kHz. Due to the absence of CFO the subcarrier positions can be maintained and no guard carriers between the ONUs are needed. The OFDM-signals are transmitted through SSMFs of different length and combined using a 1:4 power combiner. After the feeder fiber of length 28.16 km, both polarizations of the combined signal are received using coherent detection and sampled using a 40 GSamples/s real-time scope. The EAM does not allow for carrier suppression and therefore the beating between the LO-Rx and the modulated carrier reduces the dynamic range of the receiver. To get rid of these lower frequency components, DC-block components were used at the OLT and subcarriers between DC-50 MHz were omitted. In the DSP, the frame synchronization for the signals from both polarizations is performed and the received signal is demodulated using a single FFT for each polarization. After equalization, the TA is calculated using the proposed synchronization algorithm and the laser phase noise is compensated using subcarrier pilots and data aided common phase noise estimation [4] separately for each ONU in the frequency domain. In reality, the TA is transmitted to the corresponding ONU via the downstream channel, but since we investigate an upstream system the feedback is emulated in the DSP.

3. Proposed Time Synchronization Scheme

The OFDM-symbol of each ONU must occur exactly within the FFT-window at the receiver. In [5], a delay in the DSP of each ONU is introduced so that the symbol transitions of all ONUs occur simultaneously at the OLT as shown in Fig. 2. The proposed algorithm is realized in two steps. First an initialization for TA is performed and then a consecutive tracking of the timing delay is conducted. For the initialization, each ONU allocates its own training symbols to the assigned subcarriers and the resulting waveform is known at the OLT. The orthogonality of these TSs enables the detection of frame start of each ONU. In addition, the combined training symbols of the synchronized ONUs form a common synchronization waveform, which is used to find the beginning of the superimposed signal. At the OLT, the time-domain received signal is cross-correlated with the stored synchronization waveform of each ONU (i.e. 4x cross-correlation). The differences between the correlation maxima (t_1...t_4) are calculated as shown in Fig. 3(a), and used as a first approximation for the optimal TA (τ_1...τ_4).

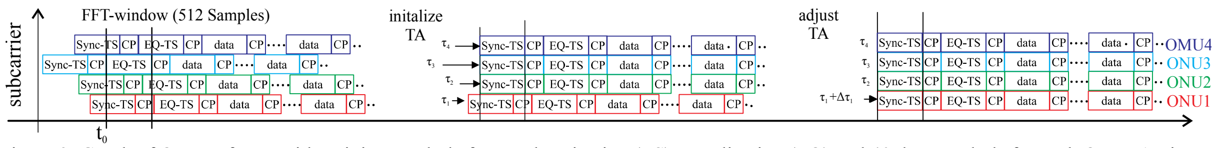

Figure 2: Graph of OFDM-frame with training symbols for synchronization (TS), equalization (EQ) and 40 data symbols for each ONU. At time t_0 the FFT-window is positioned correctly only wrt. ONU3. After initialization and tracking of the TA all ONUs can be received without crosstalk.

Without introducing additional overhead and disturbing the data transmission, the initial TA must be fine-tuned and the changes of the optimal delay must be tracked. In this contribution, a delay between the individual ONUs and the OLTs' FFT-window is tracked by investigating the channel transfer function. This is possible because an offset $\Delta\tau$ from the optimal timing position results in a linear phase change. The transfer function of the channel between OLT and ONUn for subcarrier f_k can be written as: $H_n(f) = H_{c,n}(f_k) \exp(j2\pi\Delta\tau_n f_k)$, with $H_{c,n}$ being the time invariant part of the channel transfer function. The information about the transfer function of the channel can be extracted from the coefficients of the 1-tap EQ. These coefficients are updated regularly by the EQ-TS (here: every OFDM-frame (2.184 µs). Fig 3(b) shows the result of the linear part of the estimated slope of the phase of the EQ coefficients. The slope is proportional to the offset $\Delta\tau$ between the receiver FFT-window and the start of the OFDM-frame of ONUn. The differential delay between the ONUs can be computed and a fine tuning in the TA can be realized. Since the alteration of the TA is done in DSP it can be adjusted with the resolution of the sample duration.

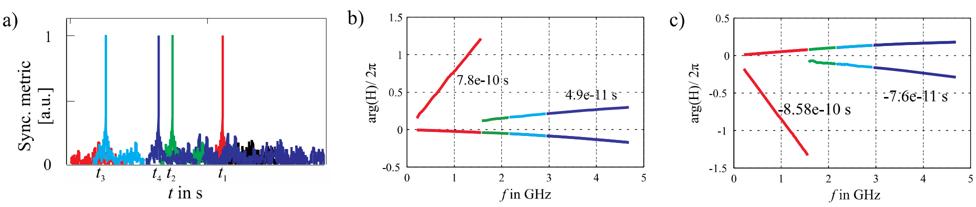

Figure 3: Results of the synchronization algorithm where a) shows the peaks of the cross correlations from which the timing advance is calculated. The phase of EQ coefficients with its slope depicted before and after adjustment with exemplary offset for ONU1 of +8 samples in b) and -8 samples in c).

4. Results

The OFDM-signals for the ONUs were generated by two dual-channel AWGs running at 10 GSamples/s with a fixed relative timing offset. This can also be realized by extracting the needed timing information out of the downstream [6]. The tracking algorithm of the TA was tested by changing the differential delay between the different ONUs. This was achieved by positioning the fiber of ONU1 inside an oven and changing the temperature between 1°C and 50°C. Every 30 s one OFDM-frame was transmitted and the TA was updated. The thermal expansion coefficient of the used SSMF fiber $\alpha \sim 6 \cdots 8x10^{-6}K^{-1}$ with a fiber length of 20 km and a temperature change of 49°C results in an expansion of 5.88···7.84 m. Therefore the expected differential delay between ONU1 and ONU2···4 should be between 29···39 ns (294···392 samples at 10 GSamples/s). This is clearly more than what can be compensated for by the CP (~8 samples = 0.8 ns) and the occurrence of intersymbol interference (ISI) and the multiple access interference (MAI) is to be expected.

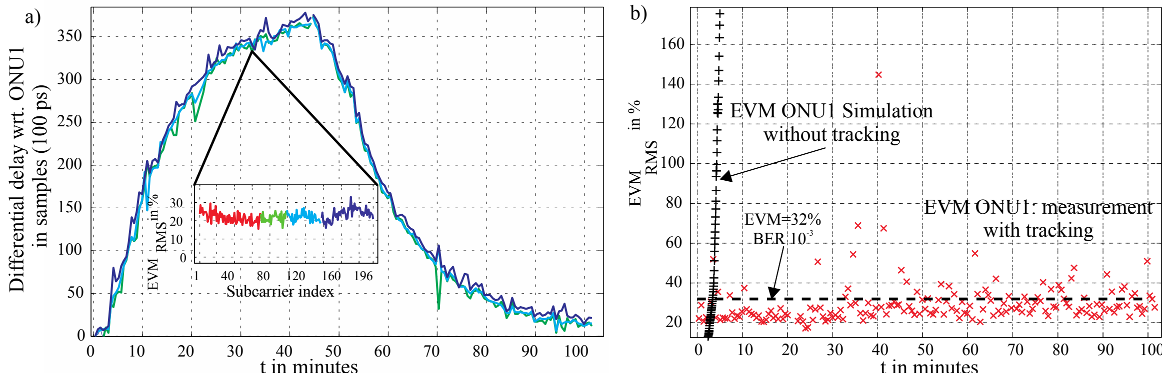

Figure 4: The oven heats the fiber from 1°C up to 50°C (t=0-45 min) back to 1°C. The resulting differential delay ($\tau_1 \cdots \tau_n$) measured between ONU1 and ONU2···4 (green, blue and purple) is depicted in a). In the inset, the EVM values are plotted over the subcarriers of the different ONUs at t=32 min. The EVM for ONU1 is shown in b) both for the measurement with tracking as well as for a simulation without tracking.

As shown in Fig. 4 (a), the differential delay between ONU1 and the remainder is plotted. It is shown that the tracking algorithm successfully tracks the change of the delay between the different ONUs. The temperature change of 49°C results in a differential delay of 376 samples, which is right between the predicted upper and lower bound. For the optimum TA, the EVM for all ONUs remains below the threshold of 32% allowing for a BER of 10^{-3}, as depicted in the inset of Fig 4 (a). During the change of temperature, the average EVM of the different ONUs is well below 32%, but occasionally as shown in Fig. 4 (b) the EVM rises above the threshold. A possible reason for this is that the temperature change between the transmitted frames was too large to compensate the differential delay and MAI and ISI occurred. Further crosstalk between the different ONUs is due to the non-linearities of the modulator, e.g. ONU2 also generates frequency components around twice the subcarrier frequencies (subcarrier range of ONU4). For comparison a simulation was done where ONU1 was delayed by the same numbers of samples, but the TA was not adjusted (indicated by the black cross in Fig. 4(b)).

5. Conclusions

In this contribution a tracking algorithm for the delay change between different ONUs in an OFDMA-PON was shown. A successful tracking using the phase of the 1-tap EQ could be realized. The algorithm was able to track a delay difference of 37.6 ns caused by a temperature change of 49°C. The TA could be accordingly adjusted and ISI and MAI because of timing mismatches were minimized.

This research was supported by BMBF Grant 01BP1031.

6. References

[1] D. Qian, et al. , “Optical OFDM transmission in metro/access networks,” . OFC 2009
[2] v. Hoyningen-Huene , J., “Experimental Demonstration of OFDMA-PON Uplink- Transmission with Four Individual ONUs,” OFC 2013
[3] N. Cvijetic et al. “Orthogonal frequency division multiple access PON (OFDMA-PON) for colorless upstream transmission beyond 10 Gb/s,” IEEE J. Sel. Areas Commun., vol. 28, no. 6, pp. 781–790, 2010.
[4] J. Tubbax, et al. “Joint compensation of IQ imbalance, frequency offset and phase noise in OFDM receivers,” Eur. Trans. Telecommun., vol. 15, no. 3, pp. 283–292, 2004.
[5] 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,” OFC 2013
[6] R. P. Giddings and J. M. Tang, “World-first experimental demonstration of synchronous clock recovery in an 11.25Gb/s real-time end-to-end optical OFDM system using directly modulated DFBs,” OFC 2011