Power Budget Improvement for Coherent Optical – OFDM Access Upstream Transmission Using TCM with Constellation Shaping

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ABSTRACT
Power-budget improvement to support more Optical Network Units (ONU) is the most significant issue for passive optical access networks. Investigation on Trellis coded modulation for multi-user phase noise channel is conducted to improve the power budget for CO-OFDMA uplink transmission. The power budget is doubled enabling 37.4-km CO-OFDMA upstream transmission supporting 32 ONUs. To our best knowledge, this is the first field trial of optical access network using coherent optical - OFDM technique.

Keywords: power budget, trellis-coded modulation, CO-OFDMA, laser phase noise.

1. INTRODUCTION
For the future generation passive optical networks (PON), orthogonal frequency division multiplexing (OFDM) is a potential candidate. It offers the best granularity so that information can be allocated to the users by assigning jointly a set of subcarriers in frequency domain and in time domain with different time slots [1]. Besides, due to the flexibility in subcarrier-wise manipulation, it can also easily enable the convergence among heterogeneous technologies (e.g. WIMAX, LTE etc.) [2].

In the past few years, different kinds of realization of OFDM-PON upstream (US) transmission structures have been investigated. Since moderate complexity is feasible in the optical line terminal (OLT), coherent optical OFDM in the OLT is widely discussed. However, coherent detection OFDM is impaired by laser phase noise (PN) significantly. In previous experiments, each optical network unit (ONU) modulates a subset (continuous subcarrier indices) [3] of the overall subcarriers according to the chosen FFT size and a guard band is introduced to separate the different ONUs. Besides, the concept of reduced ONUs is applied so that each ONU is assigned a sub-band with continuous subcarrier indices out of the total available bandwidth and modulates the signal with a smaller FFT size [4]. For PN mitigation, a pilot tone is usually transmitted along with the ONU. In the receiver digital signal processing (DSP), this pilot tone is filtered and phase conjugation is performed to compensate the PN distortion. For both approaches, ONUs are transmitted in a sub-band manner. Therefore, the capability of dynamic bandwidth allocation (DBA) of OFDM is strongly compromised. Besides, it also decreases the spectral efficiency when the guard band is being introduced.

We investigated CO-OFDMA US transmission without guard-band and sub-band allocation with continuous subcarrier indices to enable DBA and increase the spectral efficiency. The US transmission can be modelled as a multi-user phase noise channel [5]. Besides the common phase error (CPE) PN compensation and data-aided PN compensation [6], we applied constellation shaping on common Trellis-coded modulation (TCM) to achieve higher PN tolerance and thus, the additional coding gain is utilized to increase the power budget. Finally, a 37.4 km experimental CO-OFDMA US transmission in a field fiber link deployed by Deutsche Telekom AG in Berlin, Germany is conducted. With the proposed scheme, a power budget supporting 32 ONUs is reported.

2. MULTI-USER PHASE NOISE CHANNEL
Figure 1 depicts the channel model for the CO-OFDMA US transmission. The received m-th OFDM symbol \( r_m(n) \) is described as (m indicates m-th OFDM symbol under observation, bold letter indicates vector):

\[
\begin{align*}
    r_m(n) &= e^{j\Delta\phi_m(n)} \left( h_m(n) \otimes \sum_{k=1}^{K_m} s_{m,k}^{(k)}(n) e^{j\Delta\phi_k(n)} \right) \text{Conv} h_k^{(k)}(n) + n_m(n) \\
    n_m(n) &= h_m(n) \otimes \sum_{k=1}^{K_m} s_{m,k}^{(k)}(n) e^{j\Delta\phi_k(n)} + h_m^{(k)}(n); \quad s_{m,k}^{(k)}(\mu) = \frac{1}{N} \sum_{p=1}^{N} X_{m,p} e^{j2\pi\mu/n}, \quad \mu = 0, \ldots, N-1
\end{align*}
\]

where \( s_{m,k}^{(k)}(n) = [s_m^{(k)}(0), \ldots, s_m^{(k)}(N-1)] \) with L samples cyclic prefix (CP), \( s_{m,k}^{(k)}(\mu) \) is the transmitted OFDM symbol of k-th ONU with data symbols \( X_{m,p} \) allocated on k-th subset of the available subcarrier indices set \( U_k \). \( \text{Conv} \) denotes circular convolution, \( \text{Conv} \) stands for discrete convolution, and \( h_k^{(k)}(n) \) is the channel impulse response (CIR) of k-th ONU. N is the chosen FFT size. \( e^{j\Delta\phi_m(n)} \) is the laser Wiener PN [7] at each ONU’s transmitter (TX) and is decomposed into \( e^{j\Delta\phi_m(n)} = e^{j\Delta\phi_m^{(L)}(n)} + e^{j\Delta\phi_m^{(L)}(n)} \) with \( e^{j\Delta\phi_m^{(L)}(n)} = [e^{j\Delta\phi_m^{(L)}(N-1)}, \ldots, e^{j\Delta\phi_m^{(L)}(N-1)}, e^{j\Delta\phi_m^{(L)}(0)}, \ldots, e^{j\Delta\phi_m^{(L)}(0)}] \) and \( e^{j\Delta\phi_m^{(L)}(n)} = [e^{j\Delta\phi_m^{(L)}(N-1)}, \ldots, e^{j\Delta\phi_m^{(L)}(N-1)}, 0, \ldots, 0] \) so that
\[ e^{j\phi_m(n)} \] has the cyclic structure. The non-cyclic term is considered as \( \xi_m \). \( h_i(n) \) is the CIR of the feeder fiber. \( e^{j\phi_m(n)} \) is the laser PN at the OLT receiver (RX). \( w_m(n) \) is the additive white Gaussian noise (AWGN). After removing the CP and performing FFT, the received signal in frequency domain is described as:

\[ R_{m}(p) = H_{c,p} H_{k,p} X_{m,p} + \sum_{i=0}^{N-1} e^{j\phi_i(n,p)} e^{-j2\pi \frac{p}{N}} \Phi_{m,n}^{(i)} e^{-j2\pi \frac{p}{N}} \]

\[ \Phi_{m,n}^{(i)} = \frac{1}{N} \sum_{\mu=0}^{N-1} e^{j\phi_i(n,p)} e^{-j2\pi \frac{p}{N}} \]

\[ \epsilon_p = \sum_{i=0}^{N-1} I_{m,i} + \sum_{i=0}^{N-1} e^{j\phi_i(n,p)} \Phi_{m,n}^{(i)} \]

\[ I_{m,j} = \sum_{k=0}^{N-1} e^{j\phi_i(n,p)} S_{k,m} H_{c,k}^{(k)} H_{k,p}^{(k)} \]

where \( \nu \) indicates that the TX PN is from \( \nu \)-th ONU in which \( p \)-th subcarrier located, \( H_{c,p} \) is the channel frequency response (CFR) of the feeder fiber on \( p \)-th subcarrier, \( H_{k,p}^{(k)} \) is the CFR of \( k \)-th ONU on \( p \)-th subcarrier. As shown in Eq. 3, 1st addend shows that the laser PN of \( \nu \)-th TX and RX causes a identical phase rotation jointly across all the subcarriers in \( U_{\nu} \) which is usually called common phase error (CPE). 2nd addend shows the inter-carrier interference (ICI) from the interaction between other data symbols with CPE introduced by TX laser PN and higher order RX laser PN. \( \epsilon_p \) is composed of the interaction between TX PN introduced ICI and higher order RX laser PN together with the Fourier transform \((F)\) of the multiplication of the RX PN and \( \Phi_{m,n}^{(i)} \). \( W_{m,p} \) is the AWGN in frequency domain.

3. CONSTELLATION SHAPING FOR TCM

For the conventional realization of TCM, the coding gain is achieved by doubling the constellation size of the modulation format with coded input bits using convolution encoder. For the original transmitted QPSK signal, one of the two incoming bits is encoded using the convolution encoder with code rate 1/2. Then the 3 bits are mapped onto 8-PSK for further transmission [8]. The most significant bit (MSB) is uncoded but the bit error ratio is decreased due to the maximization of the Euclidean distance in the constellation points using specific set-partitioning. The coding gain of the convolution codes is utilized for the decrease of the bit error rate (BER) of the least significant bit (LSB) [9]. However, the performance gain is evaluated under the prerequisite that the channel is an additive white Gaussian channel (AWGN).
3.1 Numerical simulation results

Numerical simulations based on Fig. 1 are carried out to illustrate the performance of the proposed scheme. 8 ONUs transmit their signals in US with a total bandwidth of 10 GHz with a FFT size of $N = 512$ assuming no carrier frequency offset and ideal time synchronization among the ONUs. The laser linewidth (LW) at TX and RX equals to 50 kHz. The OLT DSP performs frame synchronization, FFT and laser CPE compensation. Fig. 3 shows the total average BER of 8 ONUs over the signal to noise ratio (SNR). Fig. 3(a) depicts the difference when data is mapped onto either 8-PSK or 8-Circular QAM and it can be concluded that 8-PSK is more sensitive in a multi-user phase noise channel than using 8-Circular QAM. At a same BER of $10^{-3}$, 8-Circular QAM has 1.83 dB less required SNR than modulating using 8-PSK. Fig. 3(b) illustrates the difference among QPSK, TCM with bit-mapping onto 8-PSK and TCM using the proposed scheme. It shows that compared with TCM using 8-PSK, the proposed scheme achieves additional 1.05 dB gain in the required SNR for a BER of $10^{-3}$.

![Figure 3. Numerical simulation results. (a) Comparison of the BER performance between 8-PSK and 8-Circular QAM with LW@TX and LW@RX = 50kHz; (b) Comparison between the conventional TCM 8-PSK and the proposed scheme.](image)

4. EXPERIMENTAL SETUP

The experimental setup of the field trial is composed of both downlink and upstream transmission as depicted in Fig. 4 [10]. The carrier being modulated in each ONU is seeded in the OLT at 1549.3 nm whilst the co-transmitted downlink signal is modulated on an ECL laser operating at 1552.5 nm. They are separated using a band-splitter at the optical front-end of each ONU, thus the carrier frequency offset among the ONUs can be synchronized so that the orthogonality in the frequency domain is well preserved. Two incoming bits in each ONU’s transmitter are first coded using a rate 1/2 convolution encoder with 256 trellis states to generate 3 bits and mapped onto either 8-PSK or 8-circular QAM constellation. Due to the limitation of the available arbitrary waveform generator (AWG), each ONU generates a real signal using one channel of the AWG on the assigned subset of the available 512 FFT size.

![Figure 4. Field trial CO-OFDMA upstream transmission setup. (a) The received baseband upstream spectrum at the OLT Rx; (b) The spectrum at feeder fiber. λUS illustrates the seeded laser source.](image)

The details of the 4 ONUs signal using two 10G Samp/s AWGs are as follows: ONU₁: 1-60, 91-100 (2.29 Gbit/s), ONU₂: 61-90 (0.96 Gbit/s), ONU₃: 101-140 (1.29 Gbit/s) and ONU₄: 141-200 (1.96 Gbit/s) with the Hermitian data symbols on the negative frequencies. The DBA is demonstrated by ONU₁. In each ONU’s signal, one pilot subcarrier is inserted for later CPE PN compensation. The overall bandwidth of the US signal is 7.8 GHz. The signal is transmitted over the 37.4 km deployed feeder fiber which is a round trip between...
Winterfeldstrasse and Wannsee in Berlin, Germany. The supported ONU number is emulated using an attenuator (VOA) in the feeder fiber. For the emulation of 32 ONUs, the total power budget equals to 31.5 dB. The signal is detected in the OLT using coherent detection with an EDFA for pre-amplification. The offline DSP includes time-synchronization between ONUs [11], SIMO processing, CPE PN compensation. Afterwards, the detected symbols are sent into the TCM decoder to recover the binary data for BER calculation. Fig. 5 shows the measured BER performance compared with QPSK and TCM using 8-circular QAM. The average BER for transmitting QPSK on all ONUs equals to $8.05 \times 10^{-5}$ for 16-ONU scenario and $5.94 \times 10^{-3}$ for 32-ONU scenario, respectively. By applying proposed TCM with 8-circular QAM, the BER after decoding equals to $4.22 \times 10^{-5}$ for 16-ONU scenario and $1.52 \times 10^{-3}$ for 32-ONU scenario which are all below the targeting $3.8 \times 10^{-3}$ forward error correction limit.

5. CONCLUSIONS
Constellation shaping for TCM using 8-Circular QAM is introduced to achieve performance improvement in a multi-user phase noise scenario. In both numerical simulation and field trial experiment, TCM using 8-Circular QAM shows performance improvement compared with conventional TCM using 8-PSK. A power budget of 31.5 dB supporting 32 ONUs is realized based on this proposed scheme.

ACKNOWLEDGEMENTS
This research was supported by Federal Ministry of Education and Research (BMBF), Germany under Grant ATOB 01BP1031 and 16BP1037.

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