

Initial ranging scheme based on interpolated Zadoff-Chu sequences for OFDMA-PON

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Abstract: Initial access to passive optical networks (PONs) requires upstream (US) synchronization of multiple optical network units (ONUs). We propose a low-complexity scheme for orthogonal frequency division multiple access (OFDMA) based PONs and demonstrate it experimentally. The scheme is based on interpolated Zadoff-Chu sequences, to synchronize the signal of each ONU arriving at the optical line terminal (OLT). Our experimental test bed consists of 4 colorless ONUs seeded by a single laser located at the OLT. Thermal expansion of a fiber is utilized to emulate a dynamic time drift in the demodulation-window positioning of OLT. The detected individual offsets at the OLT are fed back to the ONUs and are compensated at every data frame transmission. In this way, both inter carrier interference (ICI) and inter symbol interference (ISI) remain below acceptable levels.

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1. Introduction

Passive optical networks (PONs) in the various fiber-to-the-x architectures continue to emerge as a promising solution for next-generation broadband access networks due to their cost effectiveness and low energy consumption [1]. To accommodate multiple users, Time Division Multiple Access (TDMA), Wavelength Division Multiplexed (WDM) and orthogonal frequency division multiple access (OFDMA) PON systems capable of several Gb/s transmission rates have been proposed and demonstrated [2–4].

Recently, OFDMA-based PON has been highlighted as an attractive method to realize next generation converged optical and wireless access networks due to its desirable features such as resilience to linear dispersion, higher spectral efficiency, and better energy-efficiency compared to TDMA. OFDMA-PONs enable superior scalability and dynamic bandwidth allocation by their 2D resource sharing through subcarrier allocation and time division multiplexing. Due to the flexibility in forming multiple virtual transmission pipes at the physical layer OFDMA-PON is of particular interest for backhauling mobile networks (e.g. 4G and beyond) where e.g. the mobile traffic in multiple small cells, each serving a highly time-variant traffic, can be aggregated more efficiently [4,5].

An OFDMA communication system relies on the orthogonality of subcarriers to separate the users in the frequency domain. Ideally, US transmission of multiple users is orthogonal if their signals are perfectly time/frequency synchronized. However, any small synchronization inaccuracy causes ICI and ISI and can result in serious performance degradations.

While downstream (DS) synchronization in a PON can be achieved for each user individually with the same methods employed in point-to-point OFDM links, the situation is much more complicated in the US due to several inherent difficulties.

The US transmission in an OFDMA-PON with K ONUs suffers from the fact that the received signal is a superposition of K components, which pass through different optical channels and thus experience different path delays (reflecting different fiber lengths from each ONU to the OLT) and different frequency offsets (reflecting different local oscillators and optical wavelength drifts). As a result, the correction of timing and frequency offsets of each user in case of a common DFT cannot be accomplished at the OLT receiver, as the correction for one user would misalign all other users.

Therefore, synchronization parameters estimated at OLT should be fed back to the ONUs over a DS control channel. Based on this information, each ONU pre-compensates its relative time and radio frequency offset before the payload data are actually transmitted in the US so that they are received at the OLT nearly free of these impairments. This process of OLT-side parameter estimation and the relating compensation at individual ONUs, which must be accomplished prior to any payload data transmission, is known as initial ranging.

The initial ranging procedure in IEEE 802.16 family of standards for wireless metropolitan area network, adopting OFDMA in its uplink transmission, has been thoroughly studied by several research groups. Various ranging detection and estimation methods have been proposed [6–8], but the simplifying assumptions made in wireless environments, are not applicable in PON scenarios. For example, we cannot assume that users start to access the upstream channel at different times without collisions, because simultaneous access is considered rather likely for example in a long-reach PON with up to 1024 users. Moreover, high sample rates of several GS/s result in much shorter OFDM symbol durations, compared to mobile radio. Delay times due to signal propagation in long-reach PONs can be much larger than several OFDM symbol durations. Therefore, the assumption of a quasi-synchronous scheme, which could be handled using a cyclic prefix being longer than the largest round trip delay, is no longer applicable in PONs. Thus, the estimation procedure shall be designed so that delays of multiple OFDM symbol durations can be detected.

In this paper, we address the initial ranging procedure in OFDMA based PONs by proposing a novel design for the multiuser preamble and the corresponding multiuser ranging parameter estimation. The proposed approach employs the unique properties of Zadoff-Chu (ZC) sequences yielding a simple time-domain detection scheme eliminating the complexity of MC-CDMA based multi-user detection algorithms, typically used in wireless OFDMA networks [6–8].

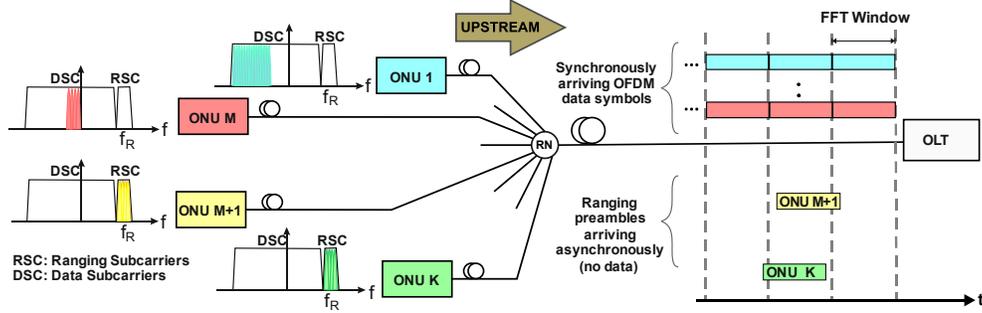


Fig. 1. Upstream transmission model in OFDMA-PON. Given example shows 2 synchronized ONUs carrying data and 2 ranging ONUs carrying no data.

2. Proposed ranging scheme

Figure 1 illustrates the upstream transmission model of an OFDMA-PON, consisting of K ONUs and an OLT. We assume ONU 1... M are already synchronized in the network and transmit payload data to the OLT. These ONUs map their data into the assigned data subcarriers (DSC). The number of allocated subcarriers is controlled by the OLT. Signals from each ONU combine into one upstream signal at the passive remote node (RN), then transmit to the OLT via the feeder fiber.

As shown, the received OFDM symbols of these M ONUs arrive synchronously to the FFT-window timing of the OLT, so they can be demodulated without ICI and ISI.

Furthermore we assume another set of ONUs ($M + 1$ - K), whose timing and frequency parameters are not yet aligned with the OLT's parameter. These asynchronous ONUs (ranging stations) transmit an initial ranging request with a known sequence. In order not to interfere with the data transmission of already synchronized ONUs, the ranging preambles occupy only the predefined ranging subcarriers (RSCs) and leave the rest of bandwidth (DSC) free (Fig. 1). These ranging requests require a high correlation to allow their differentiation from other OFDM symbols and noise at the OLT.

Constant amplitude zero autocorrelation (CAZAC) sequences are extensively employed in various OFDM synchronization schemes for timing and frequency estimation preambles because of their unique properties namely, zero peak to average power ratio (PAPR), perfect periodic autocorrelation and transparency to discrete Fourier transformation (DFT) [9,10]. Zadoff-Chu (ZC) sequences, a popular subset of CAZAC sequences, are widely used in various parts of the LTE cellular standard, particularly as random access channel preambles, as well as uplink sounding reference signals [11]. They were first analyzed by Frank and Zadoff in [12] and based on their work D. Chu proposed a sort of CAZAC sequence without restriction on its length in [13]. ZC sequences are defined as follows:

$$ZC_r(m) = \begin{cases} e^{-j\frac{2\pi r}{N}\left(\frac{m^2}{2}+m\right)} & N : \text{even} \\ e^{-j\frac{2\pi r}{N}\left(\frac{m(m+1)}{2}+m\right)} & N : \text{odd} \end{cases} \quad (1)$$

where N is the length of sequence, r is relatively prime to N and $m = 0 \dots N-1$. Wang proposed in [10] a preamble Eq. (2), which consists of a repeated ZC sequence of length N , where the first and third part is multiplied with a complex PN sequence also of length N .

$$T_U = [ZC \cdot PN_U \quad ZC \quad ZC \cdot PN_U \quad ZC] \quad (2)$$

In order to make the preambles user-specific and allow their overlap in time and frequency domain, we propose to use individual PN sequences for each ONU. This works like a signature at detection and helps to differentiate individual preambles in the superposed received signal. The resulting sequence of length $4 \cdot N$ is then interpolated with factor F , which is determined by the ratio $F = (DSC + RSC) / RSC$. The interpolation extends the sequence in the time domain thereby compresses it in the frequency domain, which afterwards can be shifted to the proper position in spectrum by a simple complex multiplication to occupy the predefined RSC:

$$Pre_u = e^{-j2\pi f_{gt} t} \cdot \text{interpolate}(T_u, F) \quad (3)$$

This idea utilizes another unique property of CAZAC sequences mentioned by Chu in [13]. He proved that certain linear phase shift when introduced into the sequence will not affect its correlation properties. The special structure of CAZAC sequences which produce sharp peaks at the correlation output are not damaged and at the same time a user specific preamble is achieved. Utilizing this architecture, each asynchronous ONU beginning the ranging procedure is assigned a PN code from the available predefined set and transmits the constructed preamble to the OLT as ranging request. It should be noted that the used ZC sequence is common between all ranging ONUs and after multiplication with a PN code through the proposed architecture an ONU specific preamble can be produced. At the OLT, a superposed signal consisting of OFDM data symbols and ranging request is received. The proposed ranging detection unit at the OLT receiver is based on a correlator bank consisting of several parallel or consecutive correlators. The whole set of used PN sequences, known as ranging codes is stored in the receiver's memory and used during the correlation operation to search for the potential preambles. The interpolated versions of all ranging codes are cross-correlated with the received signal in the detection unit as described in [10]. Consequently, a peak detection unit compares the correlation outputs with the appropriately selected threshold and determines the detected preambles. N should be determined by the SNR and the required crest factor ($|x|_{\max} / x_{rms}$) of the correlator output. Good results have been achieved with $N \geq F \cdot 64$. A doubling of N also doubles the crest factor of the correlator output. Once the relative location of peaks is calculated, the suitable positive or negative offsets i.e. delays or timing advances (modulo OFDM symbol length), are fed back to ONUs as ranging responses, to be pre-compensated at the data transmission phase. The ranging ONUs, which did not receive a positive ranging response, should repeat the ranging procedure with a higher transmit power and after waiting for specific back-off time.

3. Experimental setup

In order to experimentally investigate the feasibility of the proposed ranging algorithm, we have realized a simple optical OFDMA transmission system with 4 ONU, each connected to the remote node (RN) via individual fibers varying from 2.2...21.5 km. Bidirectional amplification is used at the RN to compensate for the loss of fibers, splitters and other optical components. The remote node is connected to the OLT using a 28.2 km fiber. In order to simplify the setup, we have used a circulator at the RN instead of individual circulators at the ONUs.

As illustrated in Fig. 2 the OFDM signals of the ONUs are generated in MATLAB and loaded to two synchronized dual-channel arbitrary waveform generators (AWG), which pro-

duce the required analog baseband signals with 10 GS/s per channel. The real-valued signals for each ONU have been generated using a DSP-based IQ-modulator and RF-LO at 2.5 GHz.

Deploying OFDMA over a common wavelength is possible by remotely seeding the common optical carrier to the ONUs and optical carrier suppression at individual ONUs to avoid inter-ONU optical carrier beating noise at the OLT. Optical carrier suppressed modulation can be achieved using a Mach-Zehnder modulator (MZM) biased at its minimum transmission point, as reported in [14]. We used two single input MZMs, biased at their minimum transmission point together with two electro-absorption modulators (EAM) to produce the optical OFDM signals at 4 ONUs. By carefully adjusting the optical power of 2 ONUs employing EAMs and inserting DC blocks at the OLT we could minimize the beating effect of optical carriers originating from these ONUs. The defined data frame consists of 170 OFDM data symbols and 10 training symbols at the beginning of each frame for channel estimation and single tap equalization. There are also some subcarriers defined as pilots multiplexed into data symbols to carry the predefined information for tracking the phase noise.

Because of the sensitivity of coherent reception to frequency offset and phase noise, we used a very narrow line-width laser (10 kHz) at the transmitter and receiver as LO. We also limited the number of subcarriers and the corresponding FFT-points to 256 and CP to 4, in order to avoid the need for sophisticated tracking and ICI cancellation algorithms, which are required to track laser frequency and phase behavior. The available bandwidth of 5 GHz is occupied by the 256 subcarriers. Each ONU is allocated 50 DSCs modulated with QPSK making it capable of transmitting a gross data rate of 1.953 Gb/s. The ranging preambles employ 32 RSCs and the remaining 24 subcarriers are unmodulated.

At the OLT receiver, the optical OFDMA signal is detected using an integrated coherent receiver module capable of detecting the I- and Q-components of both polarizations independently. The resulting electrical signals are captured by a 4-channel digital sampling oscilloscope (DSO) at 40 GS/s. The acquired traces are processed with a MATLAB program as OFDMA receiver, which performs all required tasks, namely synchronization, channel estimation, phase noise estimation and compensation and data extraction.

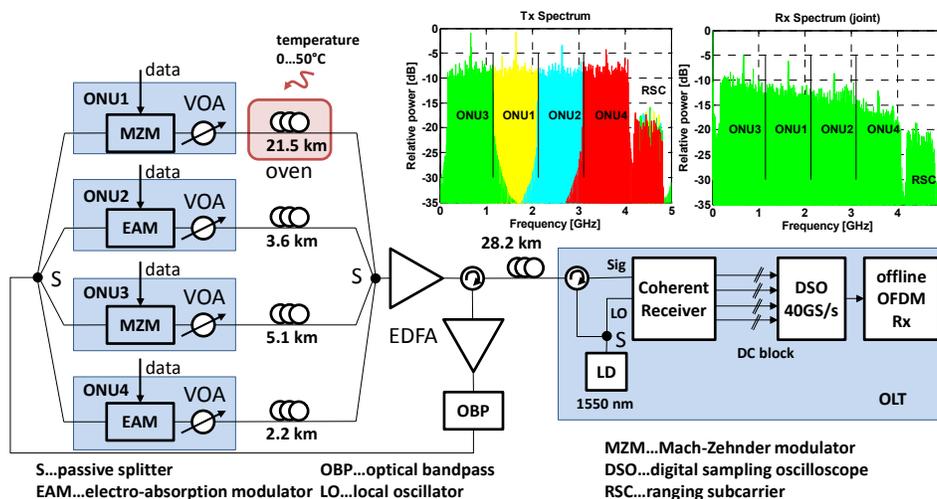


Fig. 2. Experimental setup of implemented upstream OFDMA-PON system.

4. Results and discussions

We placed the distribution (drop) fiber of ONU1 in a digitally controlled oven. By using the temperature dependency of the 21.5 km fiber, we can emulate a dynamic test environment. The OLT takes the ONU1 as reference and aligns its FFT-window timing with the OFDM

symbols originating from ONU1, any change in timing of ONU1, causes the variation in the FFT-window positioning of OLT. As a result, ONU2, ONU3 and ONU4 must dynamically update their timing offsets in order to remain synchronized with the OLT. The experiment starts with a nearly rapid decrease in temperature from the initial 50°C to 0°C and remains at 0°C for about 70 minutes and then goes back to 50°C.

Figure 3(a) shows the estimated timing advances of ONU2-4 in samples, which are calculated every 45 seconds at the beginning of data frame transmissions. It can be seen that the 50°C variation in temperature can cause a variation of approximately 400 samples with the sample duration of 0.1 ns, meaning a length difference of ~8 m. This is validated by the thermal expansion coefficient of optical fiber $6 \dots 8 \cdot 10^{-6}$ 1/K multiplied by fiber length $21.46 \cdot 10^3$ km and the temperature variation 50 K.

Figure 3(b) shows the measured Error Vector Magnitude (EVM) of the 4 ONUs over time. It can be seen that the EVM is nearly constant during the whole experiment, which proves the successful initial synchronization as well as the continuous tracking of ONU 2-4. However at particular moments in time, higher EVMs occur. This can be partly explained by the remaining beating noise originating from the carrier of EAM-based ONUs. Also the non-ideal compensation of phase noise can cause stronger ICI for some OFDM symbols.

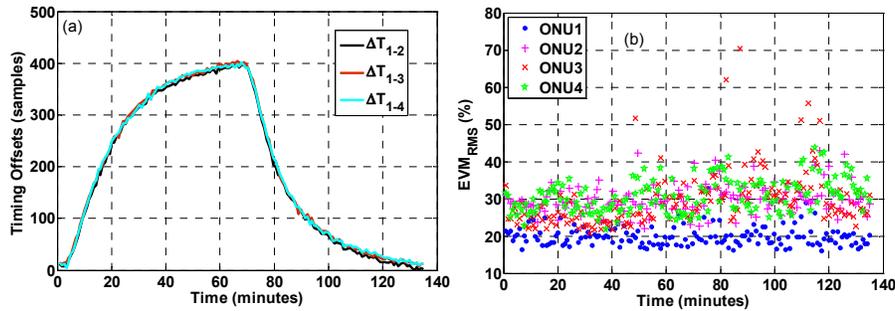


Fig. 3. Experimental results: Timing offsets (ΔT) for ONU#2-4 relative to #1 (a), EVMs of ONUs (b).

5. Conclusion

We have proposed and experimentally demonstrated a low complexity method for initial network entry synchronization in OFDMA-PONs. In comparison with ranging techniques typically used in the IEEE 802.16 standard, in our scheme no processing intensive MC-CDMA and the related ICI cancellations is needed, which simplifies the signal processing. Our experimental demonstration consisted of an upstream OFDMA-PON employing 4 ONUs each transmitting 1.95 Gb/s over distances of up to 50 km. We have verified the robustness of the proposed scheme in a dynamic test environment and examined its capability to keep the network elements synchronized by means of off-line processing over a test period of about 135 minutes.

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