An Ultralow Complexity Algorithm for Frame Synchronization and IQ Alignment in CO-OFDM Systems

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Abstract: We present a simple and efficient method for CO-OFDM frame synchronization and IQ component aligning. A training sequence is used. Simulations and experimental results confirm that our proposed method outperforms the widely-used method of Schmidl&Cox.

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1. Introduction

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) is highly tolerant against channel impairments such as chromatic dispersion (CD) and polarization-mode dispersion (PMD), due to the added cyclic prefix (CP) [1,3]. However, one of the disadvantages of OFDM is the need to align the starting point of the OFDM symbols and the FFT window. In case of mismatches intersymbol interference (ISI) and intercarrier interference (ICI) would occur, because the received data fed into the fast Fourier transform (FFT) unit contains faulty data from the following OFDM symbol. Therefore it is essential to align the incoming symbol to the FFT window before any further signal processing.

The conventional widely-used technique for OFDM frame synchronization of Schmidl&Cox [2] has been applied to CO-OFDM communication by many researchers, such as in [3,4]. This approach uses one whole OFDM symbol which is split into two parts, both of which are identical in the time domain. At the receiver the starting point of the OFDM frame is obtained by detecting the correlation peak between these two parts. If the correlation result reaches a defined threshold, then the starting point is detected. However, this method results in a low OFDM frame efficiency due to the necessary size of the training sequence (TS). One complete OFDM symbol is needed for synchronization and the correlation peaks become plateaus because of Amplified Spontaneous Emission (ASE) noise and channel effects [2-4]. Additionally, this method cannot detect I and Q component swapping and inversion due to the random phase rotation which occurs in a real-time system environment.

Therefore we propose a very simple and powerful method to detect the starting point of an OFDM frame exactly, as well as to compensate for IQ swapping and inversion. To the best of our knowledge, this is the first method for a simultaneous IQ component alignment and OFDM frame synchronization in CO-OFDM.

2. Proposed OFDM frame synchronization and IQ aligning method

To overcome the problems described above we propose a simple and powerful synchronization scheme based on TS in both IQ components. Two different Gold codes [5] are, used for I and Q, inserted at the beginning of each OFDM frame. One frame contains many OFDM symbols, as shown in Fig. 1.

At the receiver, the sampled IQ data are correlated with the known TS pattern. The correlation is given by

\[ P_{IQ}(d) = \sum_{k=d}^{d+L} C_{IQ,k} r_{IQ}(d + k), \]

where \( P_{IQ}(d) \) is the correlation result, \( C_{IQ,k} \) denotes the known TS, \( r_{IQ}(d + k) \) is the I and Q component of received data sample, and \( L \) the length of the TS. The proposed algorithm searches for the maximum or minimum peak of the correlation for I and Q to detect phase-noise-based distortions, given by

\[ \hat{M}_{\text{max}}_{IQ} = \text{max}(P_{IQ}(d)) > \text{th}_{\text{max}} \quad \text{or} \quad \hat{M}_{\text{min}}_{IQ} = \text{min}(P_{IQ}(d)) < \text{th}_{\text{min}}. \]

Here \( \text{th}_{\text{max}} \) is the maximum threshold and \( \text{th}_{\text{min}} \) is the minimum threshold. To detect the starting point as well as to correct for swapped I and Q data channels both input frames have to be correlated with TS₁ and TS₀. Due to noise distortions the correlation peak can become positive or negative, so the algorithm has to search for the minimum as well as for the maximum. Hence, the swapped IQ components can be defined from the swapping between I and Q.
correlation peaks, as shown in Fig. 2A. Obviously, the proposed method can detect all the situations: 0°, 90°, 180°, 270° phase rotation. In terms of hardware efficiency this method is very simple compared with the conventional approach. The Gold code based TS constitute only +1 and -1, so only XOR-Gates and adders will be needed for correlation. Additionally, this concept can be applied to PolMux-Optical OFDM as well [6].

3. Simulation Results

The performance of the proposed algorithm for OFDM frame synchronization and IQ alignment was confirmed by simulations using the setup described in [6]. In this simulation one OFDM symbol was defined as 288 samples (=FFT size of 256 + 32 of CP length). Each subcarrier was modulated by 4-QAM. 128 subcarriers around the centre of the spectrum were modulated with zeros for oversampling. A pilot for one-tap channel equalization and carrier recovery was inserted at every 8th subcarrier location, by Comb-type [7]. The sampling rate was set to 28 Gs/s. A fiber length of 1,000 km of standard single mode (SSM) fiber with chromatic dispersion (CD) of 17 ps/ns/km was assumed.

![Fig. 2. Proposed algorithm(left) and proposed result(right) for CO-OFDM frame synchronization and IQ components aligning.]

Fig. 2B shows the result of the conventional scheme [2-4] compared to the results of the proposed scheme, Fig. 2C. The new method shows clear correlation peaks even for a low OSNR of 14 dB, for both I and Q components. Moreover, the proposed method also detects inverted IQ components.

4. Experimental Results

Fig. 3 shows the experimental setup. At the transmitter, the OFDM data are preprocessed in two synchronized Virtex-4 FPGAs for I and Q. The OFDM frame is generated as described in section 2. Then the digital samples are converted to the analog domain by two Micram digital-to-analog converters at 5 Gs/s with a resolution of 6 bits. For O/E conversion a Dual-Parallel Mach-Zehnder Modulator (DPMZM) is used to modulate the 1550 nm light of an external cavity laser (ECL) with a specified linewidth of 150 kHz and -3 dBm launch power. After transmission over 100 km of standard single mode fiber (SSMF) the signal is fed to a variable optical attenuator (VOA) followed by an EDFA. Polarization is controlled manually. At the receiver the signal is demodulated by a polarization-diverse 90° optical hybrid. Then, two differential photodiode pairs convert the optical signals to electrical ones (O/E). After photodetection and linear amplification, I and Q signals are sampled and stored in an oscilloscope (TDS6804B) for offline processing.

This work focuses on the synchronization units depicted as red blocks in Fig. 3. After that OFDM is processed for carrier recovery and channel compensation, by the following steps: removal of CP and TS, then an FFT to
transform the received data to frequency domain, cancelation of the channel effects by one-tap equalization and, as the final step, 4-QAM de-mapping and bit error ratio (BER) calculation. There are two transmitter operation modes. The first is the training sequence mode in which the TS of 32 samples is transmitted. The second mode is transmission of a sequence of 149 OFDM symbols. Therefore, the OFDM frame efficiency is 0.9993 (=288*149/(288*149+32)). Fig. 4A and 4B show the correlation peaks for the IQ components of one OFDM frame at received powers of -14dBm and -29 dBm.

![Correlation peak](image)

A: Correlation peak of IQ components at OSNR of -14 dB
B: Correlation peak of IQ components at OSNR of -29 dB

Fig. 4. The correlation peak of IQ component for one OFDM frame at the received power of -14dB(left) and -29 dB(right).

As is seen from Figs. 4A and 4B, the proposed method performs well under practical conditions even at the low received input power of -29 dBm. The calculated peak is sharp and clear. After frame synchronization BER performance was measured for different pilot durations, which means a pilot symbol is inserted in every 4th, 8th and 10th subcarrier, respectively. Fig. 5 shows an optimal performance for a pilot duration of 8 for this experimental setup. A BER of 9.6-10^-5 at a received power level of -14 dB and 3.2-10^-4 at a received power level of -29 dB was achieved. For pilot durations of 4 and 10 the BER performance was worse due to the slope of the phase fluctuation on each pilot duration can not be tracked. In this experiment the linewidth times sample duration product was 6 10^-7.

5. Conclusion

We have been proposed a simple and efficient algorithm for CO-OFDM frame synchronization and simultaneous IQ component alignment swapping and inversion. The TS is used for both purposes. The method has been evaluated by simulation and experiment. It shows that the correlation peak is clear and sharp; the base of the peak is narrow. This confirms that our proposed method outperforms the conventional technique in terms of accuracy and hardware efficiency.

6. References