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Blind Maximum-likelihood Frequency Offset Estimation for Coherent Fast OFDM Receivers

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Abstract

We propose blind maximum-likelihood carrier frequency offset (CFO) estimation for coherent fast OFDM receivers. Simulation results show that the estimation algorithm can greatly enhance the CFO tolerance, and is insensitive to chromatic dispersion.

I. INTRODUCTION

Characterized by high bandwidth efficiency, simple channel equalization, and versatility such as supporting adaptive loading, orthogonal frequency division multiplexing (OFDM) is a promising modulation technique which is widely used not only in wireless and cable transmission systems, but also in optical transmission systems [1]. Recently fast OFDM (F-OFDM) utilizing cosine carriers with subcarrier spacing reduced to the half of that in the conventional OFDM was proposed [2]. F-OFDM has greatly improved performance in residual carrier frequency offset (CFO) compensation when compared with conventional OFDM [3]. However, this work is based on that the CFO values are within 1~2f_s, where f_s is the subcarrier spacing, which is valid for either that the CFO has been coarsely estimated and compensated at the initial system setup stage or that the laser wavelengths drift over time. Since in a coherent F-OFDM receiver the local oscillator (LO) usually runs independently from the transmitter laser, the detuning between the LO and the transmitter laser could be as large as several GHz. In this paper, we propose a time-domain blind maximum-likelihood (ML) method to estimate the CFO. We show that the proposed method can exhibit a CFO estimation range of several GHz and is robust to chromatic dispersion (CD).

II. THE CFO ESTIMATION ALGORITHM

The proposed ML CFO estimation algorithm is based on the fact that the transmitted samples are real. Neglecting additive amplified spontaneous emission (ASE) noise for simple mathematical representation, after coherent detection the k^{th} received sample r_k can be expressed as

$$r_k = x_k e^{j(2k\pi f_c T_s + \varphi_c)}, \tag{1}$$

in which x_k is the k^{th} transmitted sample, f_c is the CFO, and T_s is the sampling time interval. φ_c is the carrier phase including the phase noises from the transmitter laser and the LO. By using narrow-linewidth lasers, this term is constant for each F-OFDM symbol, i.e. only the common phase error is considered.

We consider a metric which is the weighted summation of the squared received samples in the time domain:

$$\sum_{k=0}^{N-1} r_k^2 e^{-j4k\pi f T_s} = e^{j2\varphi_c} \sum_{k=0}^{N-1} x_k^2 e^{j4k\pi(f_c - f)T_s}, \tag{2}$$

where f is the trial CFO and N is the number of samples used for CFO estimation. Since x_k^2 is non-negative, the terms in the summation add constructively only when $(f_c-f)T_s$ is an integer multiple of 1/2. Therefore, the CFO can be estimated as

$$\widehat{f_c} = \underset{-1/(4T_s) \le f < 1/(4T_s)}{\arg\max} \left\{ \left| \sum_{k=0}^{N-1} r_k^2 e^{-j4k\pi f T_s} \right| \right\}. \tag{3}$$

The estimation range is [-1/(4T_s) 1/(4T_s)). In practice, the number of samples for CFO estimation N should be sufficient to mitigate the noise effect. As the sampling rate is commonly greater than 10 GSa/s, the estimation range could be several GHz.

III. SIMULATION SETUP

We investigated the performance of the ML CFO estimator by numerical simulation using MATLAB. For F-OFDM modulation, carriers #1 to #214 were utilized for data modulation, while carrier #0 and carriers #215 to #255 were left un-modulated. At the transmitter, two 2^{16} pseudorandom bit sequences were firstly combined and Gray-mapped to 4-ASK constellation. Then the symbols were serial-to-parallel converted into frames, which were padded with zeros and transformed by inverse discrete cosine transform (IDCT) for F-OFDM modulation. After F-OFDM modulation, symmetric 8-point prefix and 8-point suffix were appended to the F-OFDM symbols [4] and the samples were digital-to-analog converted to analog signal with a sample rate of 12 GSa/s. The analog signal was then used to drive a single-stage MZM biased at null point. The linewidth of the transmitter laser was assumed to be 100 kHz. In the transmission link the fiber Kerr effect was neglected for simplicity. After transmission the F-OFDM optical signal passed through a 50-GHz optical bandpass filter to remove the out-of-band ASE noise and was coherently detected with a 100-kHz LO. It was assumed that the optical-to-electrical converter and the following circuits had a 3-dB bandwidth of 5 GHz. After analog-to-digital conversion with a 12-GSa/s sampling rate, the received signal passed through CFO estimation and compensation with the proposed algorithm, followed by symmetric prefix/suffix removal, and discrete cosine transform (DCT) for F-OFDM demodulation. Then the signal was equalized by one-tap equalizers for CD compensation. Finally the signal was decided to obtain the transmitted data. The simulation was iterated for 100 rounds with different random number seeds to give a total simulated symbol number of 6.55 million.

IV. RESULTS AND DISCUSSIONS

We evaluate the performance of the systems by using the required optical signal-to-noise ratio (OSNR) at a bit error rate (BER) of 10^{-3}. Fig. 1 shows the required OSNR as a function of N, the number of samples for CFO estimation as used in (2) and (3), when the CFO is 1.5 GHz and the accumulate CD is 5,000 ps/nm. The required OSNR decreases from 12.6 dB to 10.6 dB when N increases from 2^7 to 2^9. When N increases further, the required OSNR remains to be around 10.6 dB. With some margin 2^{10} samples which correspond to only ~100 ns at 12 GSa/s are sufficient for the CFO estimation. This number is utilized for CFO estimation in the following simulations. In practice, this CFO estimation might be combined with symbol synchronization to further reduce the required training symbols.

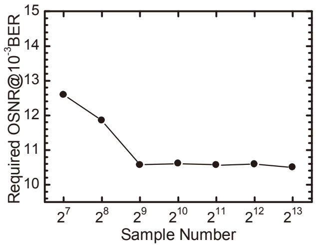

Fig. 1. Req. OSNR as a function of sample number for CFO estimation

Then we simulate the required OSNR as a function of CFO. In the simulation the accumulated CD is assumed to be zero. The inset of Fig. 2 shows that without CFO compensation, the required OSNR increases rapidly with the CFO, and when the CFO increases beyond ±10 MHz the OSNR penalty would surpass 3 dB. In comparison, when the CFO is estimated with the proposed algorithm and compensated, the CFO tolerance is greatly improved. When the CFO increases to nearly ±3 GHz, only 1.3-dB OSNR penalty is observed. Note that not all the penalty comes from the error of CFO estimation, because when the CFO is large, the received signal can also be distorted by the anti-aliasing filter.

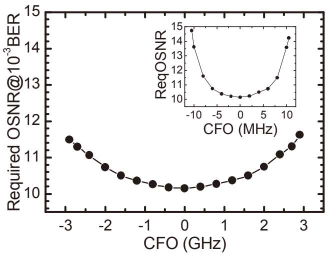

Fig. 2. Req. OSNR as a function of CFO with CFO compensation. (Inset: that without CFO compensation)

In deriving the CFO estimation algorithm, the property that the F-OFDM signal with zero CFO is real is utilized. However, when there is accumulated CD, this property is no longer held. Therefore, we also investigate the CD tolerance of the proposed algorithm. Fig. 3 shows the required OSNR as functions of accumulated CD with CFO being 0 GHz, 1 GHz, 2 GHz, and 2.5 GHz, respectively. When the CFO is zero, the required OSNR only increases by 0.16 dB as the accumulated CD increases from 0 ps/nm to 18,000 ps/nm. When the CFO increases to 1 GHz, the required OSNR does not degrade significantly. When the CFO increases to 2 GHz, there is a 0.6-dB OSNR penalty at zero CD, and an additional 0.6-dB OSNR penalty when the CD increases to 18,000 ps/nm. The required OSNR continues to increase when the CFO increases further. However, even when the CFO is 2.5 GHz, the required OSNR at 18,000 ps/nm is only 12.0 dB, which corresponds to less than 2-dB OSNR penalty compared with the case when CFO and CD are both zero. This proves that the proposed method has low sensitivity to the accumulated CD.

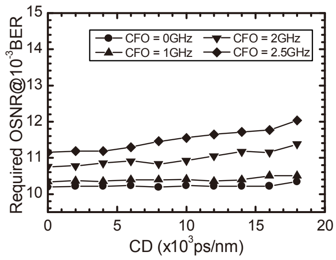

Fig. 3. Req. OSNR as functions of CD with different CFOs.

V. CONCLUSIONS

We have proposed a blind ML CFO estimation algorithm to enhance the CFO tolerance for coherent F-OFDM receivers, and investigated its effectiveness in a 12-GSa/s 4-ASK F-OFDM system. Simulation results show that the algorithm can accurately estimate a CFO as large as ±3 GHz at 12 GSa/s, which leads to 300-times tolerance enhancement over a system without CFO compensation. The proposed method has low sensitivity to CD and less than 2-dB OSNR penalty can be achieved in the presence of 18,000-ps/nm CD and 2.5-GHz CFO. This CFO estimation algorithm can greatly alleviate the requirement of the center frequency alignment between the transmitter laser and the LO in practical implementations, and consequently reduce the overall system cost.

ACKNOWLEDGMENT

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