Joint Symbol Synchronization and Dispersion Estimation in 16QAM Optical Fast OFDM

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Abstract

We show that joint symbol synchronization and channel estimation can be realized using single symbol with negligible penalty in 16QAM optical F-OFDM. This facilitates the application of F-OFDM for burst-mode transceivers in optical packet networks.

I. INTRODUCTION

Optical fast orthogonal frequency division multiplexing (F-OFDM) [1-2] is a promising multi-carrier scheme, where the subcarrier spacing is reduced to half of that in the conventional OFDM. This scheme exhibits greatly improved performance in frequency offset compensation [2] when compared to conventional OFDM, so is more suitable for wavelength-switching optical packet networks [3]. Similar to conventional OFDM [4], it also allows adaptive modulation of each subcarrier according to the traffic demands, which enables dynamic bandwidth allocation with low granularity and provides great system flexibility. One of major concerns in the implementation of F-OFDM based burst-mode transceivers in optical packet networks are fast symbol synchronization and rapid channel estimation that should operate on a packet-by-packet basis. Symbol synchronization specific to F-OFDM was proposed in [1], and was experimentally verified to be dispersion-transparent. In [5], least-square (LS) based channel estimation was shown to outperform the conventional time-domain averaging (TDA) and intra-symbol frequency-domain averaging (ISFA) [6]. In this paper, we apply LS channel estimation to the start-of-frame (SOF) symbol that is designed for symbol synchronization. A 37.5-Gb/s 16QAM optical F-OFDM experiment with 480-km transmission shows that single SOF symbol is sufficient for joint symbol synchronization and channel estimation with negligible performance penalty. The principle of the proposed method can also be applied to the conventional OFDM.

II. PRINCIPLE

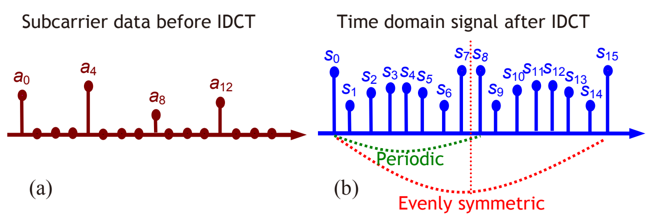

Fig. 1. (a) Subcarrier allocation and (b) the time-domain signal of the SOF symbol. The subcarrier number in the figure is assumed to be 16.

The principle of symbol synchronization is described in [1], where the values of the subcarriers in the SOF symbol are set to be non-zero and real only for a_i with $i = 4p$ (Fig. 1), where p is an integer. This method is dispersion-transparent, so can be applied to determine the DCT window before channel and phase estimation. On the other hand, the LS channel estimation method [5] builds up a channel model and estimates the unknown parameters that require rapid estimation for each packet by minimizing the sum of the squared errors:

$$S(A, D_a) = \sum_{i=1}^{N} \left| A \exp(j \cdot D_a \cdot \omega_i^2 / 2) - H_m(\omega_i) \right|^2 \quad (1)$$

where A and D_a are the channel gain/loss and the accumulated chromatic dispersion (CD), respectively. These parameters are unknown and vary packet by packet. $H_m(\omega)$ is the frequency response (normalized by the static channel response) obtained from the training symbols (TSs), with m being the number of TSs. N is the number of subcarriers in the TS(s) for parameter estimation. The minimization of Eq. (1) can be solved by a recursive algorithm in practical implementation [5], and it was shown that m = 1 could obtain optimal performance, in contrast to m of 10 and 5 for conventional TDA and ISFA, respectively.

The goal of this paper is to re-use the SOF symbol in Fig. 1 for Eq. (1). Two effects have to be considered: 1) Eq. (1) assumes that the phase noise is well mitigated. This is commonly achieved by inserting pilot tones in the near-zero-frequency region where the influence of dispersion is negligible. However, the design of the SOF symbol would result in reduced number of pilot tones, and consequently higher residual phase noise. 2) By using a conventional TS, N in Eq. (1) can be the total subcarrier number in the TS. However, N is reduced by a factor of four when employing the SOF symbol, which may reduce the precision of parameter estimation.

III. EXPERIMENTAL SETUP AND RESULTS

The experimental setup was similar to that in [5]. Two bi-polar Gray-coded 4-ASK data were generated in Matlab. The inverse-DCT (IDCT) and DCT used 128 points, of which 100 and 6 subcarriers were used for data transmission and phase estimation, respectively. Six samples were added to each symbol as a symmetrically-extended guard interval (GI). The generated F-OFDM signal was downloaded to a 12-GS/s arbitrary waveform generator. The signal rate including the GI and forward error correction overhead was 37.5 Gb/s. The laser linewidth was 100 kHz. The generated 16QAM optical signal was amplified by an EDFA, filtered by a 0.8-nm OBPF, and transmitted over a recirculating loop comprising 60-km SMF. The noise figure of the EDFA was 5 dB and another 0.8-nm OBPF was used in the loop to suppress the ASE noise. The launch power per span was around -5.5 dBm. At the receiver, the optical signal was detected with a pre-amplified coherent receiver and a variable optical attenuator (VOA) was used to vary the OSNR for BER measurements. The pre-amplifier was followed by an OBPF with a 3-dB bandwidth of 0.64 nm, a second EDFA, and another optical filter with a 3-dB bandwidth of 1 nm. A polarization controller (PC) was used to align the polarization of the filtered signal before entering the signal path of a 90^0 optical hybrid. The optical outputs of the hybrid were connected to two balanced photodiodes with 40-GHz 3-dB bandwidths, amplified by 40-GHz electrical amplifiers, and captured using a 50-GS/s real-time oscilloscope. The decoding algorithms included interpolation of the 50-GS/s data, down-sampling to 12 GS/s, symbol synchronization, DCT, phase estimation, and one-tap equalizers to compensate CD. 2400 F-OFDM symbols were measured, giving a total of 240,000 measured 16QAM symbols.

In order to investigate the two aforementioned effects, we firstly employed an SOF symbol followed by a TS for symbol synchronization and channel estimation, respectively. The number of pilot tones in the TS varied from six to one while that in the payload was fixed at six. N in Eq. (1) was the total subcarrier number. Figure 2(a) shows BER versus the number of pilot tones in the TS. It can be seen that the LS method is robust to the residual phase noise and the performance is insensitive to the number of pilot tones in the TS for phase estimation. We further investigated the influence of N in Eq. (1). We defined a parameter, q, and the subcarriers used for channel estimation had the index of $i = p \times q$, where p is an integer. For example, in Fig. 1(a), q is 4. Figure 2(b) depicts BER versus q with one pilot tone used in the TS for phase estimation. It is observed that the BER was stable as a function of q, and BER better than 2×10^{-3} was obtained for all q values up to 12. In fact, for q = 12, A and D_a can still be well estimated from an over-determined system, in which the number of used subcarriers is more than that of unknowns.

The SOF symbol was then used for joint symbol synchronization and channel estimation. Figure 3 shows BER versus the OSNR at 480 km by using the proposed method (triangles). For comparison, the curves for the conventional TDA with 20 (circles) and 1 (diamonds) TSs, and ISFA with 1 TS (squares), are also shown. For these conventional methods, the SOF symbol and the TSs for channel estimation are separated. It is shown that when the number of TSs was one, the channel response estimated from TDA was highly distorted by the noise, resulting in significantly degraded performance. ISFA improved the performance but still exhibited large penalty. On the other hand, the proposed method could achieve similar performance as TDA with m = 20.

IV. Conclusions

We have applied the LS dispersion estimation to the SOF symbol in coherent optical F-OFDM, and shown in a 37.5-Gb/s 16QAM coherent optical F-OFDM experiment over 480-km fiber transmission that the proposed method can achieve near-optimum performance for joint symbol synchronization and channel estimation by using single SOF symbol without prior transmission knowledge. This makes the optical F-OFDM scheme very promising for the future optical packet networks.

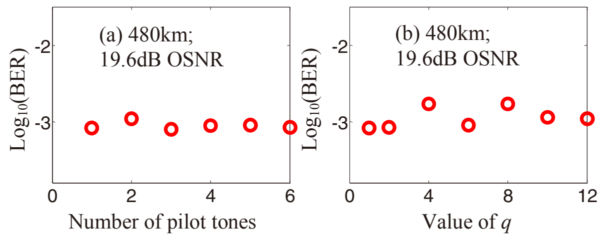

Fig. 2. BER versus (a) the number of pilot tones in the TS for phase estimation (b) the value of q when the subcarriers used in the TS for channel estimation have the index of $p \times q$, where p is an integer. In (a)-(b), LS method is used for channel estimation.

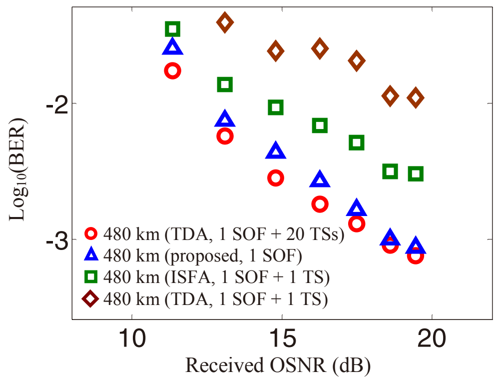

Fig. 3. BER versus the received OSNR. The subcarrier number for averaging in ISFA is 5. The amplitude of data subcarriers in the SOF is twice that of the payload to maintain the same average power.

Acknowledgment

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