FrFT Based Joint Time/Frequency Synchronization for Digital Subcarrier Multiplexing System

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Abstract: We propose an in-advance time/frequency synchronization method for SCM using fractional Fourier transform pilot. With low complexity and fast speed, the proposed method is validated to be robust against strong filtering and fiber nonlinearity. © 2022 The Author(s)

1. Introduction

Coherent detection along with digital signal processing (DSP) has established vital roles in high-speed optical transmission systems. With the explosive growth of communication capacity, the digital subcarrier multiplexing (SCM) system has been widely studied and applied, due to its ability to mitigate fiber nonlinearity, especially for long-haul coherent transmission [1].

The frequency offset (FO) between the transmitter laser and local oscillator leads to a time-variable phase fluctuation in the conventional intradyne system. In digital SCM systems, the FO estimation (FOE) and compensation (FOC) must be conducted in advance before subcarriers de-multiplexing and chromatic dispersion compensation (CDC) [2, 3]. But traditional FOE algorithms, based on Fast Fourier transform (FFT) or Viterbi-Viterbi (V-V) algorithm, must be implemented after CDC [3]. To solve the problem, several FOE algorithms have been proposed for digital SCM system [2, 3], utilizing the shape of frequency spectrum. However, they intended to be sensitive or time-consuming, even invalid with frequency spectrum changes on the conditions of poor optical signal-to-noise ratio (OSNR) or strong optical filtering.

Motivated by the remarkable properties of fractional Fourier transform (FrFT) training symbols, for instance, insensitive to modulation format, optical signal-to-noise ratio (OSNR) and nonlinear interference [4-6], we propose a pilot employing FrFT to achieve the time and frequency synchronization simultaneously with a fast processing ability and a further decrease of computation complexity compared with [6][7] for digital SCM system. Moreover, our designed narrow-bandwidth pilot tone located in the center part of subcarriers, hence is also insensitive to strong optical filtering.

2. Operation Principles

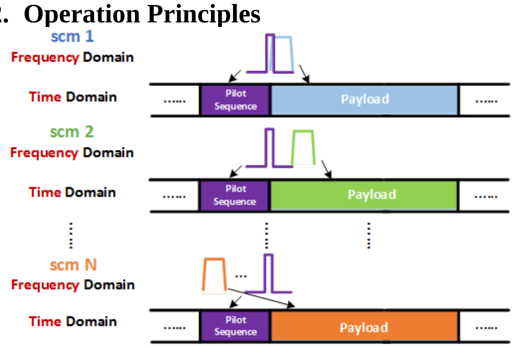

Fig. 1: Structure of FrFT-DC Pilot of Digital SCM

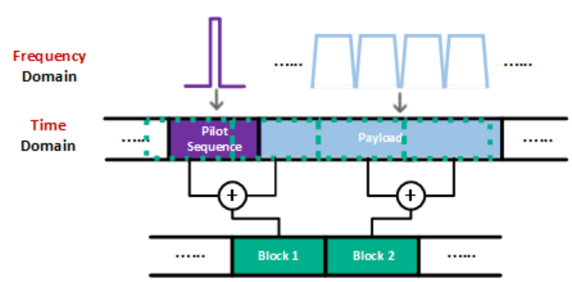

Fig.2 New optimized method of finding the rough place of FrFT

The FrFT-DC signals was proposed in [7], which can estimate FO and TO from the peak shift by geometrical analysis. The FrFT pilot affected by TO and FO consists of two FrFT-DC signals, with opposite orders P and -P. At the receiver, TO and FO can be estimated by operating 1-P and -1+P order FrFT separately. According to [4], the largest FO ($\Delta F_{\max}$) of digital SCM is

$$\Delta F_{\max} = \frac{1-\sin(p\cdot\pi/2)}{2\cos(p\cdot\pi/2)}\cdot\frac{Baud}{N} \tag{1}$$

The minimum estimated FO ($\Delta F_{\min}$) is

$$\Delta F_{\min} = \frac{1}{2\cos(p\cdot\pi/2)}\cdot\frac{Baud}{M\cdot N} \tag{2}$$

where Baud denotes the baud rate in the digital SCM system, N denotes the number of subcarriers and M denotes the length of FrFT pilot. It's obvious that the accuracy of FOE will increase with the decrease of the baud rate of subcarriers. The accuracy of TO can be illustrated similarly. To avoid the influence of CD, we choose P = 0.1 [6].

Based on the principles above, we design a novel pilot to estimate TO and FO before subcarriers de-multiplexing and CDC. As shown in Fig. 1, the FrFT pilot, located in the center of the frequency spectrum, is completely not overlapped in the time domain and hardly overlapped in the conventional frequency domain with the payload. Thus, we can protect the FrFT pilot from strong optical filtering to ensure the fast and stable ability to estimate TO and FO.

For estimating TO, the FrFT pilot with a length of N symbols in front of the payload can be found the rough place by scanning block by block [7]. Furthermore, to obtain a sharper peak at the receiver to cut further computation complexity, we can utilize the unitarity property of continuous FrFT [8]. Some kinds of discrete FrFT algorithm couldn't completely satisfy the unitarity property [8], but when we approximately express the discrete pilot at the transmitter as

$$PS[n] = FrFT(S[n],\ p) + FrFT(S[n], -p) \approx FrFT(S[n],\ p) + FrFT^{*}(S[n],\ p) \quad (4)$$

where $S[n]$ is a DC signal, $FrFT$ denotes the operation of $FrFT$, p and –p are two opposite orders, the estimation accuracy of FrFT-DC signals at the receiver will not be decreased even by the fast approximate FrFT discrete algorithm developed by Ozaktas [8]. Furthermore, for coherent transmission systems, we can multiplex the optimal real FrFT-DC signals $PS[n]$ in both in-phase (I) and quadrature-phase (Q) signals, which contributes to increasing the amplitude of the peak at the receiver without influence on the peak to average power ratio (PAPR). So, the optimal pilot of any single polarization can be expressed as

$$PS_{ONEPOL}[n] = PS[n] + j \cdot PS[n] \quad (5)$$

Thanks to the increased peak amplitude of the optimal FrFT pilot at the receiver, we can add up the two adjacent blocks to search the rough place of pilot, and thus cut the computation complexity by half compared with [6][7]. The optimized process of searching rough place is shown in Fig. 2 and the method of finding precise place is utilizing geometrical analysis and cross-correlation. Hence, we can estimate the TO and FO based on only one block of single FrFT pilot rapidly, without averaging or smoothing filter like averaging [2][3]. When affected by large polarization mode desperation (PMD), we can change the pilot to a superimposed pilot on the synchronization sequence located in its own spectrum of different subcarriers to ensure the precise synchronization after subcarrier de-multiplexing.

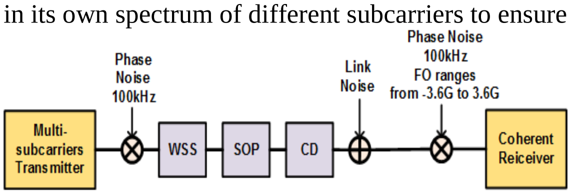

Fig.4 Simulation setup

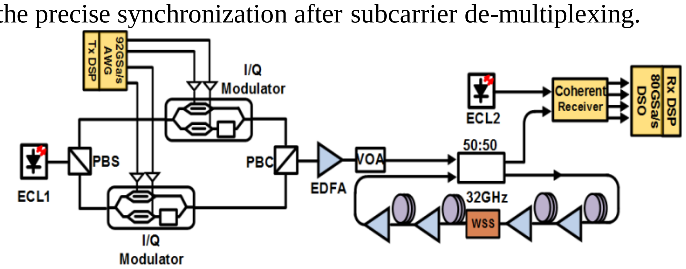

Fig.5 Experiment setup

3. Simulations and Experimental Results

As shown in Fig.4, we built a simulation system for 32Gbaud, 64Gbaud, 96Gbaud DP-16QAM and DP-64QAM Digital SCM systems with N = 2, 4, 8 subcarriers to investigate the performance of our proposed FrFT pilot. The roll-off factor of Nyquist shaping is 0.1 and there isn't guard band between subcarriers. The impairments including phase noise, frequency offset, CD and the ASE noise from EDFA are taken into account. The length of pilot is 128 for 16QAM and 256 for 64QAM, which is decided by the required range and the accuracy of FOE. And the order of FrFT-DC signals is 0.1 and -0.1. Implementation Agreement 400ZR suggests that frequency offset ranges from -3.6G to 3.6G. The linewidth of the transmitter laser and local oscillator is 100 kHz. The accumulated CD of single span of standard single mode fiber (SSFM) is 1200 ps/nm and there are 8 spans. The ROADM model, with 6-dB bandwidth of the wavelength selective switch (WSS) set to 32GHz, is built according to [9]. Firstly, we investigate the FOE performance of proposed FrFT pilot with respect to different number of subcarriers, baud rate and OSNR, as shown in Fig.6-7. Figure 10 shows that even for the case of 2 subcarriers with total 96Gbaud, due to the narrow-bandwidth characteristic of FrFT pilot, it suffers from minor filtering effect after passing through the WSS hence works well under strong filtering. Actually, as the baud rate of subcarriers decreases, the accuracy of FOE will increase. The conclusion agrees with (2). Next, we investigate the performance without WSS with the max value of FO error to compensate before subcarriers de-multiplexing with 16QAM and 64QAM modulation formats. The reference represents the case without FO. The result is shown in Fig. 8-9. There is almost no performance penalty on the digital SCM signals compared with the reference. Furthermore, if we design a two-stage FOE scheme with our

FrFT pilot before subcarriers de-multiplexing and traditional FFT after equalization, the length of pilot for 64QAM can be also reduced to 128.

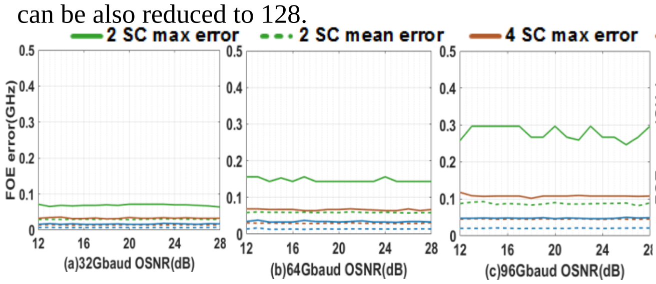

Fig6. FO error of the proposed FrFT pilot of 128 length on different numbers of subcarriers and OSNR conditions

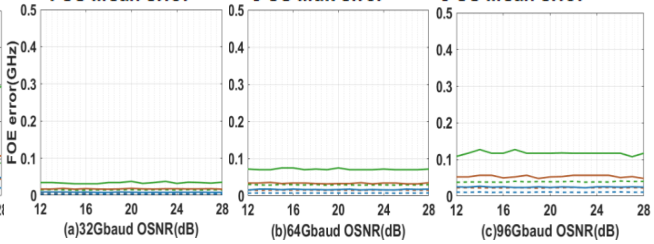

Fig7. FO error of the proposed FrFT pilot of 256 length on different numbers of subcarriers and OSNR conditions

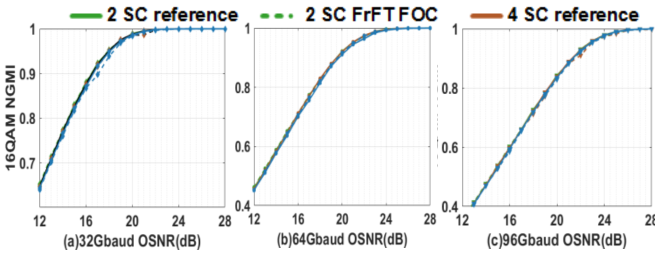

Fig8. Performance with the max FO error for 16QAM on different numbers of subcarriers and OSNR conditions

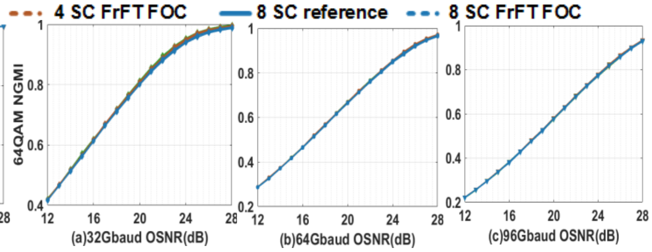

Fig9. Performance with the max FO error for 64QAM on different numbers of subcarriers and OSNR conditions

The setup of the practical PDM digital SCM transmission experiment is illustrated in Fig. 5. The baud rate of DP-16QAM signal with 4 digital subcarriers is 32Gbaud. There are 4 sections of 75 km SSMF and EDFAs in the fiber loop. The transmission distance is 600km with 2 loops. The performance of FOE on poor OSNR has been showed in [4].To evaluate the transmission performance against strong optical filtering, a wave-shaper (WS) with 3-dB bandwidth set to 32GHz is inserted after the second EDFA. Fig.11 shows the frequency spectrum of the received pilot and signals. The process of DSP at the receiver is similar with [6]. We design a two-stage FOC scheme with our FrFT pilot before subcarriers de-multiplexing and traditional FFT after equalization to fully compensate for the FO. Then, we make a one-stage scheme with our FrFT pilot for FOC before subcarriers de-multiplexing. By comparing the performance of the two-stage and one-stage scheme showed in Fig. 12, we can conclude that our proposed FrFT pilot secures high estimation accuracy without the performance penalty even with strong optical filtering and remarkable nonlinear interference. Moreover, it can be utilized as a startup sequence on the conditions of poor OSNR, strong optical filtering and nonlinear interference for ensuring the synchronization of TO and FO.

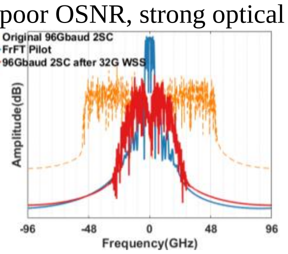

Fig 10. 96Gbaud 2SC frequency spectrum of simulations

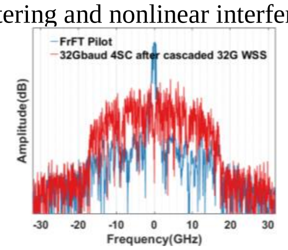

Fig 11. The 32Gbaud 4SC frequency spectrum at the receiver of experiments

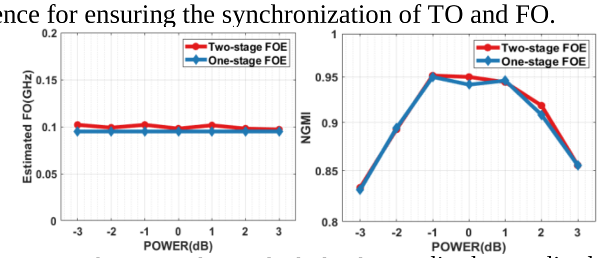

Fig 12.The estimated FO and calculated normalized generalized mutual information(NGMI) with different launch power

4. Conclusions

Both simulations and experiments demonstrate that our proposed FrFT pilot enables in-advance time/frequency synchronization, with computation complexity reduced to half of [5][6]. The modulation-format-transparent method is validated to be fast and effective before subcarrier de-multiplexing and chromatic dispersion compensation, as well as robust against poor OSNR, strong optical filtering and fiber nonlinearity.

Acknowledgment

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