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RF-Pilot Based Frequency Offset Estimation and Phase Noise Compensation for CO-OFDM Systems

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ABSTRACT: One of the most severe impairments that affect coherent optical systems employing high-order modulation formats is phase noise due to transmit and receive lasers. The vulnerable sensitivity to laser linewidth induced inter-carrier interference (ICI) has long been recognized as a major problem to coherent optical orthogonal frequency-division multiplexing (CO-OFDM) systems. Among the existing phase noise compensation algorithms, the RF-pilot aided phase recovery (RAPR) method shows a better compensation capability to laser linewidth. However, RAPR may fail to extract the pre-inserted RF-pilot at the receiver due to the influence of carrier frequency offset (CFO). An effective frequency offset estimation (FOE) is thus required to implement before performing RAPR. In consideration of the fact that the conventional FOE algorithm not only has high computational complexity, but more importantly cannot work in coordination with RAPR, a new RF-pilot aided frequency offset estimation (RAFOE) algorithm is proposed, in which CFO can be easily estimated by searching the peak of spectral samples. Furthermore, in order to obtain the optimum compensation performance with lower computing cost at combining RAFOE and RAPR, a joint frequency offset and phase noise compensation scheme is also performed in this paper.

KEYWORDS: Frequency offset estimation, phase noise compensation, OFDM.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is a modulation technique which is now used in most new and emerging broadband wired and wireless communication systems, because it is an effective solution to intersymbol interference caused by a dispersive channel. OFDM is also a promising technology for optical communications. Due to the rapid growth of bandwidth demand on optical transport network, many efforts have been made on developing high-speed optical transmission systems. Among various emerging techniques and applications, coherent optical orthogonal frequency-division multiplexing (CO-OFDM) is one of the most promising candidates due to its excellent spectral efficiency, flexible constellation modulation, and low demand for oversampling rate. The CO-OFDM signal is extremely sensitive to phase noise, and system performance penalty induced by the line width in CO-OFDM is more obvious with respect to the single carrier systems.

CO-OFDM combines the advantages of coherent detection and OFDM modulation and posses any merits that are critical for future high-speed fiber transmission systems. First, the chromatic dispersion and polarization mode dispersion (PMD) of the transmission system can be effectively estimated and mitigated. Second, the spectra of OFDM subcarriers are

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partially overlapped, resulting in high optical spectral efficiency. Third, by using direct up/down conversion, the electrical bandwidth requirement can be greatly reduced for the CO-OFDM transceiver, which is extremely attractive for the high-speed circuit design, where electrical signal bandwidth dictates the cost. At last, the signal processing in the OFDM transceiver can take advantage of the efficient algorithm of Fast Fourier Transform (FFT)/Inverse Fast Fourier Transform (IFFT), which suggests that OFDM has superior scalability over the channel dispersion and data rate.

Multi-pilot subcarriers phase estimation algorithm (MSPE), which compensates for only the common phase impairments after OFDM demodulation was commonly used for carrier phase estimation. However, the laser linewidth must be small enough and the OFDM symbol should be short as well in order to mitigate the impact of the inter-carrier interference (ICI) and obtain a satisfying performance of phase noise compensation. These requirements will consequently increase the device cost and the overhead ratio of cyclic prefix (CP). Hence RF-pilot aided phase recovery algorithm (RAPR), compensates for the laser phase noise by extracting the phase of RF-pilot that is inserted beforehand at the transmitter in the center of OFDM spectra. The ICI-induced effects can thus be prevented effectively and spontaneously without such strict restrictions of MSPE, because the carrier phase compensation is performed prior to OFDM demodulation by using RAPR.

An important influencing factor is the change in frequency offset (FO). Due to the impact of uncertain Frequency Offset (FO), the RF-pilot cannot be filtered out directly, regardless of using whether a low pass filter (LPF) or a band pass filter (BPF) in coherent receivers. Therefore, frequency offset estimation (FOE) is necessarily required and implemented before RAPR. Also to obtain a good phase compensation performance, RF-pilot is required with large power in RAPR so as to suppress the interferences from OFDM signal and ASE noise.

The new technique involves the use of RF- pilot aided frequency offset estimation (RAFOE) algorithm, in which the high power characteristic of RF-pilot, regarded as a positive factor, is further exploited. FO can be easily estimated in RAFOE by searching the peak value of frequency domain samples without requiring any extra training overhead. Moreover, a large FOE range of fs/2 (fs is the sampling rate of analog to digital converter (ADC)) can be obtained, with the estimation accuracy that is definitely determined by the number of samples participated in the operation of RAFOE. A joint compensation scheme is also developed, in which only IFO needs to be estimated by RAFOE based on the aid of the pre-estimation of the fractional part of frequency offset (FFO). After that, RAPR utilizes a BPF to filter and compensate all the phase impairments simultaneously, depending on a known centre frequency provided by RAFOE.

II . THE RF-PILOT AIDED FREQUENCY OFFSET ESTIMATION (RAFOE)

In RF-pilot aided OFDM transmitter, a high power RF-pilot tone will be inserted in the middle of the OFDM band. However, the inserted RF-pilot may fail to be down-converted to zero frequency in the homodyne coherent receiver due to the frequency deviation between the transmitters and LO laser. Due to the change in FO, it is impossible to extract the RF-ilot tone by simply increasing LPF bandwidth. A Frequency Offset Estimation (FOE) algorithm is thus required and operated before RAPR. However, in the conventional FOE algorithms, the integral part of frequency offset (IFO) calculation cannot work correctly due to the high power effect induced by RF-pilot tone. In order to cope with the contradiction, a novel FOE algorithm (i.e., RAFOE) is proposed, in which the high power characteristic of RF-pilot, as a positive factor, is further exploited. Depending on the size of FO proportionally reflected in the deviation degree of RF-pilot, FO can be estimated in RAFOE by finding the spectral peak value, without requiring any extra training overhead. Moreover, a large FOE range can be obtained; with the estimation accuracy that is definitely determined by the number of samples participated in the operation of RAFOE. In order to obtain the optimum compensation performance with lower computing cost when combining RAFOE and RAPR, a joint compensation scheme is also developed, in which only IFO needs to be estimated by RAFOE based on the aid of the pre-estimation of the fractional part of frequency offset (FFO). After that, RAPR utilizes a BPF to filter and compensate all the phase impairments (including residual FFO, IFO and phase noise induced by line width) simultaneously, depending on a known centre frequency provided by RAFOE.

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III. PROPOSED APPROACH

The proposed method uses a combination of RAPR and RAFOE algorithms to generate a new joint frequency offset estimation and phase noise compensation scheme. In this scheme, RAFOE is implemented prior to RAPR.
The block diagram of the proposed approach is shown in Figure 1.

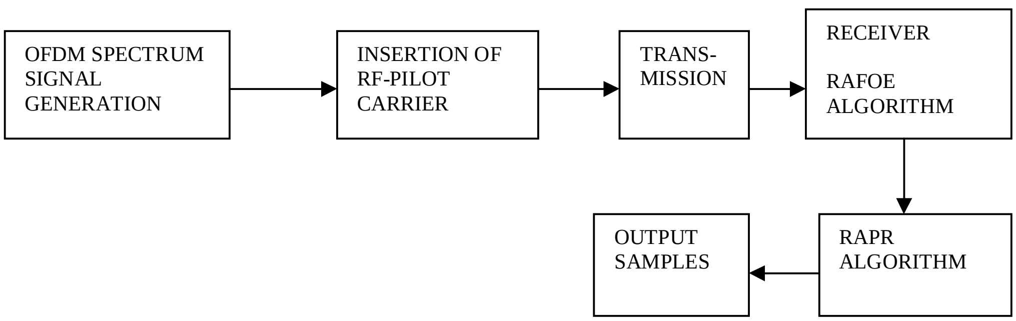

Figure 3.1: Block Diagram

First the OFDM spectrum signal is generated. A high power RF-pilot tone will be inserted in the middle of the OFDM band. Then the RF pilot inserted OFDM signal is transmitted. At the receiver the proposed RAFOE algorithm is performed to estimate the frequency offset. After estimating the frequency offset RAPR algorithm is performed by utilizing a band pass filter with the frequency offset as the centre frequency. Thus phase noise compensation can be performed with the help of frequency offset estimation by combining RAFOE and RAPR algorithms.

A. RAFOE ALGORITHM

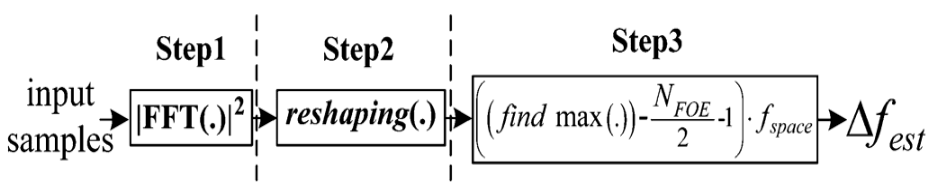

Figure 3.2: The block diagram of the RAFOE algorithm

Figure above shows the block diagram of the RAFOE algorithm, with three computational steps being taken into consideration. The steps are:

1. The signal discrete spectrum is obtained by performing FFT on N_{FOE} received samples. The intensity of signal discrete spectrum can thus be formulated as:

$$|R(k)|^2 = \left| \sum_{n=0}^{N_{FOE}-1} r(n) exp\left(\frac{-j.2\pi.kn}{N_{FOE}}\right) \right|^2$$

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where R and r represent the discrete spectrum samples and received digital samples, respectively. The FFT window bandwidth is determined by the ADC sampling rate, and the discrete spectral resolution f_{space} is related to N_{FOE} under a certain f_s as

$$f_{space} = \frac{f_s}{N_{FOE}}$$

2. In order to observe spectral shift and estimate FO conveniently, the discrete spectrum is reshaped based on the frequency distribution characteristic of FFT. After that, the out-of-order spectral samples are rearranged where the zero frequency component is returned to the middle of spectra (i.e., it is exactly located at the location of the N_{FOE} th sample).
3. The FO can therefore be estimated by finding an index of the sample that has the maximum intensity value, i.e.,

$$\Delta f_{est} = \left(find_{n=1,2,\dots,N_{FOE}} \, max\left(\left| R'^{(n)} \right|^2 \right) - \frac{N_{FOE}}{2} - 1 \right) . f_{space}$$

B. JOINT FREQUENCY OFFSET ESTIMATION AND PHASE NOISE COMPENSATION

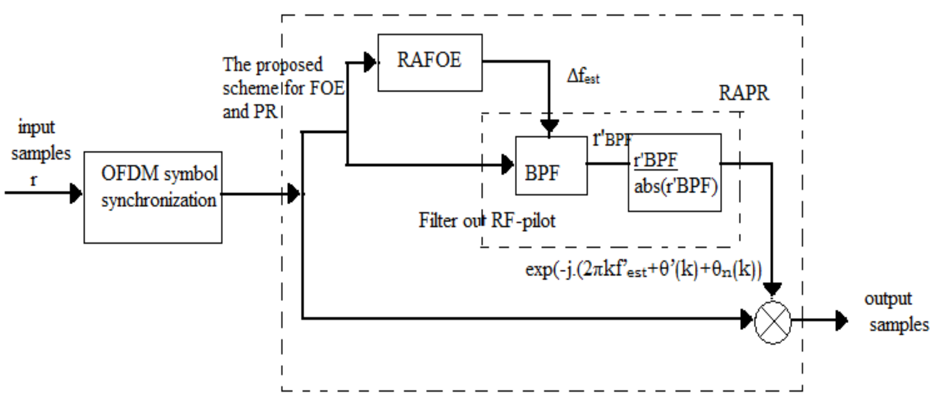

Figure 3.3: The block diagram of the proposed frequency offset and phase noise compensation

For obtaining the optimal compensation performance with less calculation cost, we design a joint FO and linewidth compensation scheme, as depicted in Fig. 3.3. In the proposed scheme, after OFDM symbol synchronization, the obtained correlation function is further utilized to estimate FFO so as to relax the fine granularity requirement on RAFOE. In RAFOE, the computational cost is independent of the estimation range, which is predominantly contributed by a FFT operation.

In order to avoid unnecessarily repeat operations for phase compensation, the estimated FO value is directly set as the central frequency for a BPF instead of employing a LPF to filter the RF-pilot after IFO correction. In this case, the extracted RF-pilot will include all the phase impairments, which are induced by not only the laser phase noise but the IFO as well as residual FFO (RFFO).

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IV SIMULATION RESULTS

The proposed system is simulated using MATLAB. First step involves the generation of OFDM spectrum signal. It is generated using a Pseudo Random sequence as input. 16 subcarriers Quadrature Amplitude Modulation (QAM) is used. Figure 4.1 shows the OFDM spectrum signal generated by performing FFT on the time domain signal.

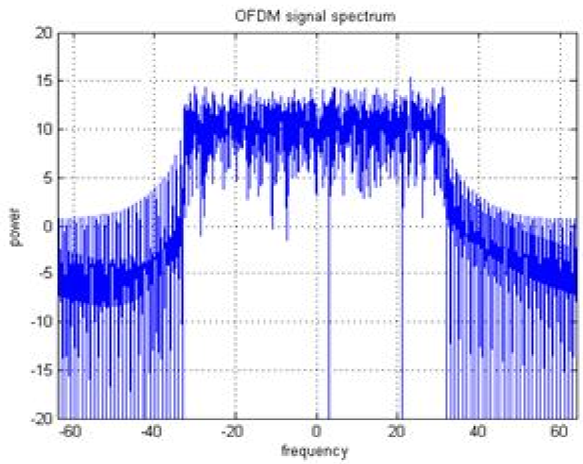

Figure 4.1: OFDM signal spectrum

After generating the OFDM signal, the RF- pilot carrier is inserted at the centre of OFDM signal. Figure 4.2 shows RF-pilot carrier inserted OFDM signal spectrum which is transmitted.

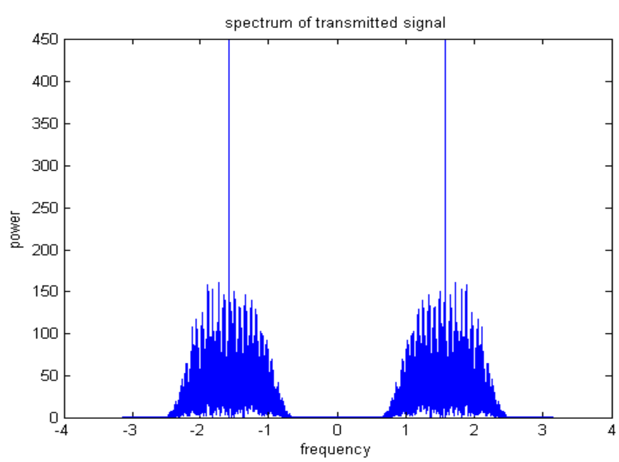

Figure 4.2 : RF-pilot carrier inserted OFDM signal spectrum

Figure 4.3 shows the transmitted and received signal spectrums with the generated frequency shift/offset. The green signal is the transmitted signal and the red signal is the received signal. It clearly shows the shift between the RF pilot carriers of transmitted and received signals.

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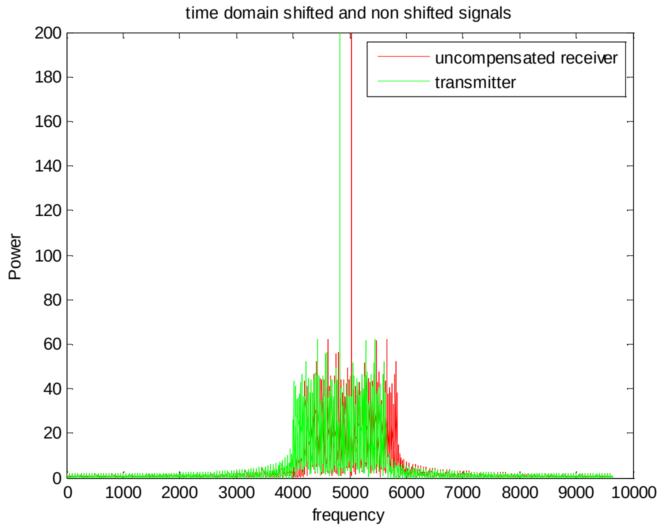

Figure 4.3 : Transmitted and received signal spectrums

Figure 4.4 shows the scatter plot of received signal which implies that the received signal is distorted. The signal points are highly scattered. Hence the frequency offset leads to improper and distorted received signal.

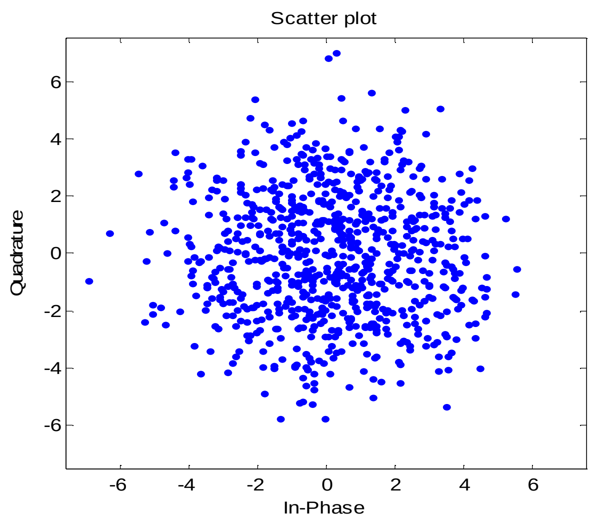

Figure 4.4: Scatter plot of received signal

Figure 4.5 is the compensated received signal spectrum which shows the overlapped blue spectrum signal over the transmitted green signal. Thus the frequency offset is compensated.

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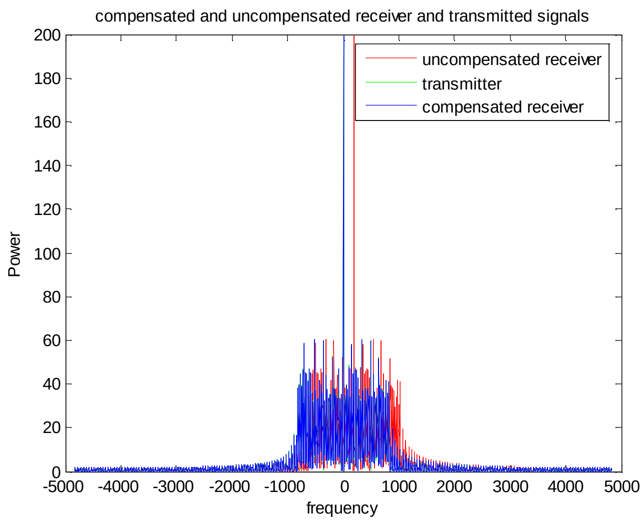

Figure 4.5 : Compensated receiver signal spectrum

Figure 4.6 shows the scatter plot of compensated received signal.

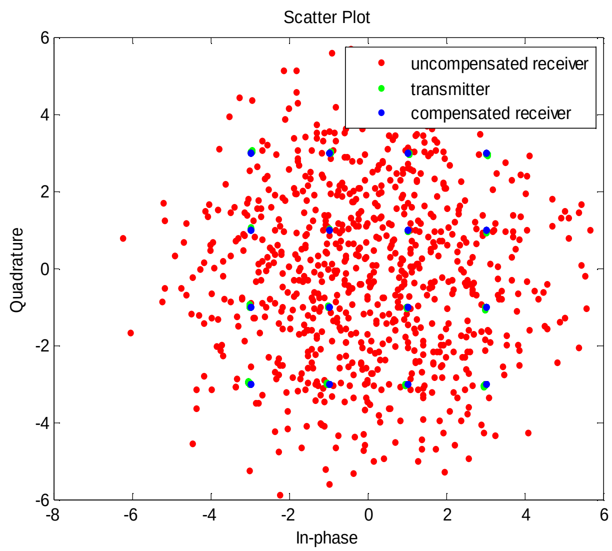

Figure 4.6 : Scatter plot of compensated received signal

The scatter plot shows the compensated received signals in blue overlapped over the transmitted green signal points. This depicts clearly distortion free received signal obtained after the joint frequency offset estimation and phase noise compensation scheme. Whereas the uncompensated received signal shown in red is completely distorted. Thus by combining RAPR and RAFOE algorithms an error free reception of OFDM signal is achieved.

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V. CONCLUSION

This paper deals with a joint frequency offset estimation and phase noise compensation scheme for OFDM systems. The use of RF pilot carrier insertion in the OFDM band for optical communication leads to error free reception of signal using the proposed scheme. Thus for obtaining the optimum compensation performance with lower computing cost when combining RAFOE and RAPR, a joint compensation scheme is designed, in which RAFOE based on the aid of FFO estimation only estimates IFO, and the estimated IFO is provided to RAPR as the BPF central frequency. After that, all the phase impairments, including residual FFO, IFO and linewidth induced phase noise, are filtered out simultaneously by using the BPF. The enhancement work involves a carrier recovery method applying a simple moving average filter (MAF) to extract the central RF-pilot for phase noise compensation.

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