Frequency Offset Estimation in M-QAM Coherent Optical Systems Using Phase Entropy

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Abstract: A novel approach for Frequency Offset Estimation in coherent optical M-QAM systems using the received symbol phase entropy is investigated. It is accurate, non-data-aided, oblivious to modulation format and requires no gain control.

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1. Introduction

Research on Frequency Offset Estimation (FOE) for coherent optical systems has focused on schemes involving the measurement of phase increments between successive symbols, after modulation removal [1]. While straightforward to achieve with QPSK, it becomes significantly more difficult for higher modulation orders. QPSK-partitioning has been used for 16QAM [2], but this scheme requires gain-control and sacrifices accuracy, as it only uses successive Class I symbols for the estimation. An alternative that has not been investigated yet in an optical communications context is the phase entropy (PE) approach [3]. It is modulation format-independent and does not need modulation-stripping or gain-control. We present a first application of the concept for optical coherent systems up to 32QAM and show that it retains sufficiently high accuracy with the range of linewidth-symbol period ($\Delta\nu \cdot T_s$) products expected in real systems using available DFB or external cavity lasers. In addition, we propose a simple modification to the basic algorithm to yield a coarse-estimation version. Since it requires no a priori knowledge of the transmitted constellation size or shape, PE-FOE is especially attractive for blind estimation in flexible, multi-format QAM coherent receivers.

2. Principle of PE-FOE

Let p_{cw} be the instantaneous phase probability density function (PDF) of a continuous wave carrier. If M-QAM is applied, the PDF of the phase (ψ) of the modulated baseband signal is then given by $p_{mqam} = \sum_{k=0}^{M} p_{cw}(\psi + arg(d_k))$, where $d_k = a_k + jb_k$ ($a_k, b_k \in 2m-1 : m = 1,2,\ldots \log_2(M-2)$) are the M-QAM constellation points. The PE can then be calculated using the Shannon Entropy: $PE_{mqam} = -\int_{-\pi}^{+\pi} p_{mqam}(\psi)\ln(p_{mqam}(\psi))d\psi$.

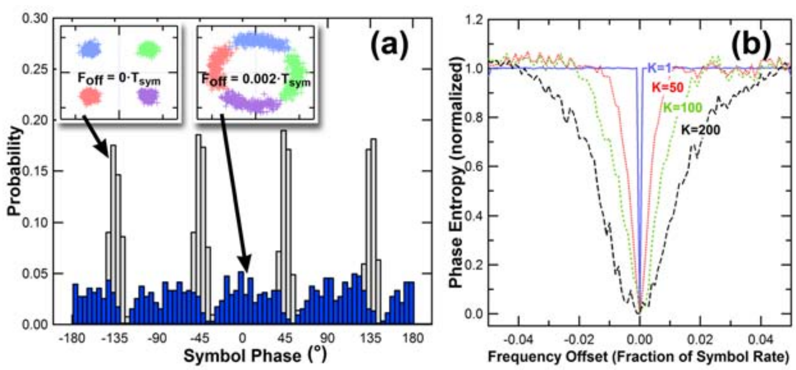

Fig. 1. (a) Phase histograms for frequency offsets $\Delta F \cdot T_s = 0$ (grey) and 0.002 (blue), in a simulated QPSK signal. (b) Phase entropy as a function of frequency offset, for various values of parameter K.

Fig.1(a) shows the simulated phase PDFs of 1000 symbols of a QPSK signal with and without an offset of $\Delta F \cdot T_s = 0.002$. Significant spreading of the phases is evident, leading to higher entropy for the signal with offset. Our algorithm operates on N symbols and exploits the sharp trough exhibited by the PE as a function of frequency offset, as illustrated in 1(b) (solid line, $K = 1$). As shown in Fig. 2, a range of test frequency offsets are applied in parallel and the PE calculated for each. Of the resulting signals, the one with the minimum PE has the lowest residual frequency offset.

Sufficient granularity is needed in the frequency search to successfully locate the sharp trough. To reduce the computational cost of a fine search over a large frequency range, a first, coarse-estimation stage can be employed. We describe a simple approach for achieving this with PE-FOE. The key is that the block of N received

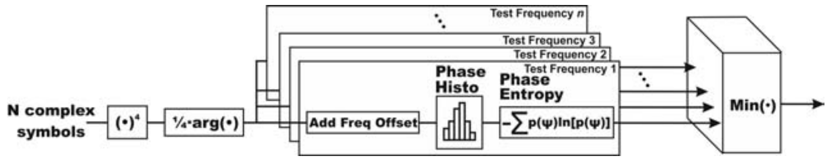

Fig. 2. DSP implementation of PE-FOE

symbols is further subdivided into K subgroups, each with L elements (L=N/K, K being an integer.). The PE is calculated for each one of the K subgroups, and the final estimate is obtained by averaging these together: $PE_{avg} = \sum_K [-\sum_L p_{mqam}(\psi)\ln(p_{mqam}(\psi))d\psi]$. Fig.1(b) shows that for larger values of K the trough is expanded, thus easing the requirement for fine granularity in the frequency search, and allowing a rough estimate to be made.

3. Simulated and Experimental Performance

A 10Gbaud intradyne QAM system was simulated in VPI TransmissionMaker. 100 runs were carried out for each OSNR value, each with a random frequency offset between ±0.8GHz. The laser linewidth was set at 1MHz for QPSK and 16QAM, and 100KHz for 32QAM. PE-FOE was performed over 1024 symbols, and compared to phase increment/QPSK-partition schemes (QPSK [1], 16QAM [2]). The QPSK-partition scheme was extended for operation with 32QAM. Fig.3(a) shows the resulting normalized frequency error variances (NFEV). PE-FOE is superior compared to phase-increment estimation for QPSK, with the two schemes converging for higher OSNR values. For 16 and 32QAM, PE-FOE requires a higher OSNR to achieve reliable results, but once this threshold is exceeded, its estimation accuracy is significantly better than that of the QPSK-partition algorithm. The results highlight the power of PE-FOE: The same implementation can be used regardless of modulation format.

A 22Gbaud QPSK intradyne experiment was also carried out to verify performance in a realistic setting, with standard unlocked DFB lasers (linewidth<5MHz). Frequency compensation and carrier phase recovery (CPR) were performed offline. The latter was used to compare PE-FOE to the phase-increment scheme. Any residual frequency offset not compensated by the FOE shows up as accumulated phase in the CPR algorithm, plotted in Fig.3(b). PE-FOE achieves near zero residual offset compared to ∼30MHz for the phase-increment FOE.

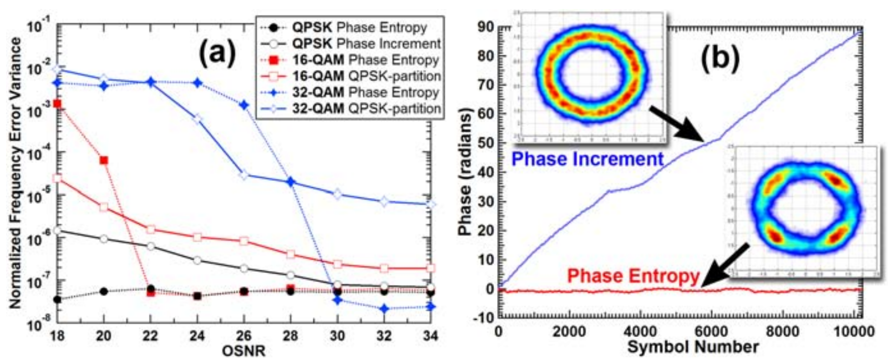

Fig. 3. (a) Simulated NFEV of FOE schemes. (b) Experimental data: Measured phase of 10240 symbols, after performing FOE (block size=1024). Insets show frequency-compensated constellations before phase recovery, with significantly less symbol rotation for the PE-FOE case.

4. Conclusion

We have presented the first simulated and experimental assessment of phase entropy-based FOE for coherent optical QPSK and 16QAM with $\Delta\nu \cdot T_s$=10^{-4}, and 32QAM with $\Delta\nu \cdot T_s$=10^{-5}. We have demonstrated that phase entropy-based FOE is a viable option for photonic communication systems employing multi-format coherent receivers.

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References

1. A. Leven *et. al.*, "Frequency Estimation in Intradyne Reception," IEEE PTL, 19, pp. 366-368 (2007).
2. I. Fatadin and S. Savory, "Compensation of Frequency Offset for 16-QAM Optical Coherent Systems Using QPSK Partitioning," IEEE PTL, 23, pp. 1246-1248 (2011).
3. M. Pedzisz and A. Coatanhay, "Minimum Entropy Approach for Carrier Frequency Recovery", IEEE Trans. Wireless Commun., 5, pp. 1-5 (2006).