Fast and Accurate Automatic Frequency Control for Coherent Receivers

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Abstract *We demonstrate an algorithm for non-data aided spectrum-based automatic frequency control in coherent receivers. The proposed algorithm is independent of modulation formats, robust against channel distortion and outperforms the well-known spectrum-based algorithms.*

Introduction

Spectrum based automatic frequency control such as balance quadricorrelator (BQ)[1,2] and double power measurement (DPM)[3] can be applied in coherent receivers prior to other digital signal processing (DSP) to estimate and compensate the coarse frequency offset of the free running local oscillator (LO) in the range of GHz. Moreover, BQ and DPM are robust against channel distortions and independent of the modulation format[4]. Hence, BQ and DPM are suitable algorithms for coherent receivers, where the frequency offset can be up to 5GHz[5]. However, estimation accuracy can only be achieved with the trade-off against tracking speed. Since the estimation error in tracking mode is proportional to the tracking speed, the addressed trade-off has a significant consequence in the case of a LO frequency leap. In this paper, we propose a novel algorithm for digital non-data aided spectrum based automatic frequency control. The algorithm is demonstrated for coherent receivers with a frequency domain equalizer[6,7] and can accurately estimate the LO frequency offset Δf w/o the trade-off against the tracking speed by using the proposed frequency leap detector. Polarization-multiplexed quadrature phase shift keying (PolMux-QPSK) and polarization-multiplexed 16 quadrature amplitude modulation (PolMux-16QAM) w/ and w/o channel distortions are investigated.

Algorithm Principle

The proposed algorithm estimates Δf based on the asymmetrical characteristic of the signal spectrum similar to BQ and DPM[4,8]. The main difference to BQ and DPM is that the signal spectrum is accessed directly in the frequency-domain dispersion equalizer. Hence, we call the algorithm frequency-domain automatic frequency control (FD-AFC). Moreover, with the leap detector and the novel method for the update of the frequency estimation, the speed of the estimation convergence and the estimation accuracy are significantly improved. Fig. 1 depicts the block diagram of the FD-AFC. An FFT with the block length of N transforms the digitized received signal vector $\vec{x}_i$ with $\frac{T}{2}$-spaced sampling to the signal spectrum $\vec{X}_i$. The power of $\vec{X}_i$ is calculated by squaring of the spectrum magnitude. Afterwards, a bandpass with the transfer function H_{BP} as shown in Fig. 2 is applied to the power of the spectrum. The error signal $e[i]$ is given by

$$e[i] = \sum_{\nu=1}^{N} \left|\vec{X}_i[\nu]\right|^2 \cdot H_{BP}[\nu] \quad (1)$$

The error signal $e[i]$ of the FD-AFC is equivalent to $e[i]$ of DPM with a significant implementation complexity reduction due to the FFT.

For the frequency leap detection we define the leap indicator $l[i]$ as

$$l[i] = w \cdot l[i-1] + |e[i]|^2 \quad (2)$$

whereas w is the forgetting factor with the value $0.9 \leq w < 1$. Since $l[i]$ is proportional to $|e[i]|^2$ as shown in Eq.(2), $l[i]$ is rapidly increased by the occurrence of the LO frequency leap.

The update of the estimated frequency offset $\Delta\tilde{f}[i]$ is the key procedure for the performance of FD-AFC. At the beginning of the estimation or during an LO frequency leap, high convergence speed is preferred. During the tracking of $\Delta\tilde{f}[i]$, the standard deviation σ of $\Delta\tilde{f}[i]$ should be minimized. For the purpose, the convergence factor $k[i]$ is defined as

$$k[i] = \begin{cases} 1 & \text{, if } (l[i] > \lambda \text{ and } k[i-1] > \kappa) \text{ or } i = 1 \\ k[i-1]+1 & \text{, if } k[i-1] < M \\ k[i-1] & \text{, otherwise} \end{cases} \quad (3)$$

with λ and κ being suitable design constants. $\Delta\tilde{f}[i]$ can

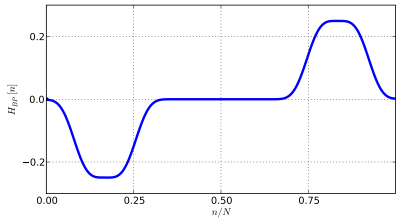

Fig. 2: Transfer function of the bandpass H_{BP}

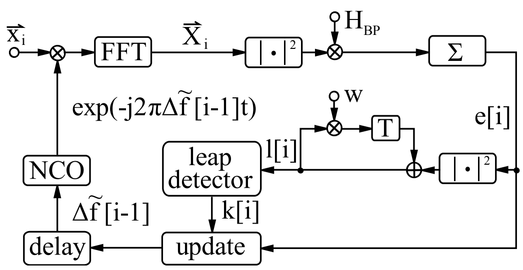

Fig. 1: Block diagram of FD-AFC

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be updated by

$$\Delta\tilde{f}[i] = \Delta\tilde{f}[i-1] + \mu \cdot \frac{e[i]}{k[i]} \quad (4)$$

where μ is the update factor. Eq. (4) shows that the update step-size is inversely proportional to $k[i]$. For $i = 1$ or a detected frequency leap with $l[i] > \lambda$ and $k[i-1] > \kappa$, $k[i]$ is minimal and the convergence speed is maximal. Otherwise, $k[i]$ is increased with the time and the update step-size is decreased. Since the estimation standard deviation σ is proportional to the update step-size, the estimation accuracy of FD-AFC is improved with an increasing $k[i]$. We initially optimized $w = 0.95$, $\lambda = 0.001$, $\kappa = 40$, $M = 5e4$ and $\mu = 16$. Afterwards, the numerically-controlled oscillator (NCO) is applied using $\Delta\tilde{f}$ to compensate for the frequency offset. Although the frequency estimation is biased, due to the frequency offset correction in the digital domain, the bias can be removed if the filter settings at the receiver are known[4].

Simulation Setup

For the analysis of the algorithm performance, 11 wavelength-division multiplexed (WDM) channels of 43Gb/s PolMux-QPSK with 50GHz channel spacing and 111Gb/s PolMux-16QAM with 25GHz channel spacing were simulated. The OSNR was set to 11dB for PolMux-QPSK and 18dB for PolMux-16QAM. The optical channel is characterized by 13 spans of 80km SSMF on a optimized dispersion managed link. At the receiver, Δf is estimated and compensated with the FD-AFC algorithm w/o the need for prior timing information and equalization.

Algorithm Performance

Fig. 3 shows the convergence of $\Delta\tilde{f}$ for the FD-AFC in the PolMux-QPSK simulation. The results show that with the FD-AFC $\Delta\tilde{f}$ can be speedily converged for all preset values of Δf. For a performance comparison, DPM algorithm with the optimized parameter as shown in[4] is also demonstrated. The performance of FD-AFC and DPM for a frequency leap of $\mp$ 5GHz for PolMux-QPSK and PolMux-16QAM is illustrated in Fig. 4. Although both algorithms can track the given frequency leap w/o the dependency of the modulation format, the convergence speed is clearly improved by using a leap detector. For the evaluation of the estimation accuracy, the standard deviation σ for FD-AFC and DPM is calculated over $2 \cdot 10^7$ symbols for back-to-

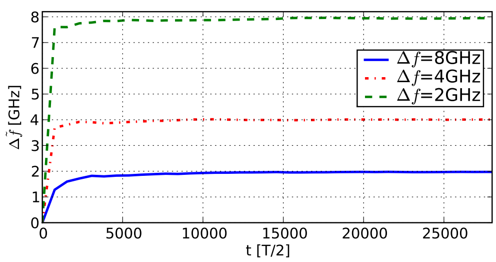

Fig. 3: FD-AFC estimation convergence vs. Δf for PolMux-QPSK with 11dB OSNR transmitted over 1040km of SSMF

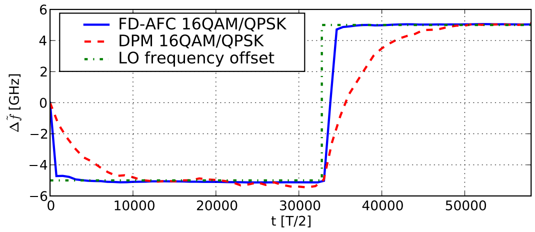

Fig. 4: FD-AFC vs. DPM by frequency leap of $\mp$ 5GHz

back (B2B) and transmission over 1040km SSMF simulations as shown in Fig. 5. With FD-AFC, the difference of σ between all simulations is marginal showing that FD-AFC is robust against the channel distortion like chromatic dispersion, polarization-mode dispersion, or cross-phase modulation. In comparison to DPM, a σ reduction of nearly two magnitudes can be achieved. It should be noted that the pre-decision based frequency offset estimation such as pre-decision-based angle differential estimator (PADE)[9] can also estimate a wide range of frequency offsets w/o the trade off of convergence speed. However, PADE can not operate without the prior DSP e.g. a timing recovery, an equalizer and the estimated frequency offset is limited to the half of the baud-rate.

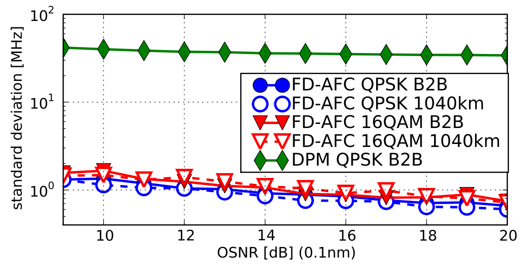

Fig. 5: σ of FD-AFC and DPM vs. OSNR for PolMux-QPSK and PolMux-16QAM with Δf=5GHz

Conclusion

We demonstrated the FD-AFC algorithm for non-data-aided digital automatic frequency control. The algorithm is independent of the modulation format and can therefore be used in various future receivers based on coherent detection. Since the algorithm is robust against channel distortion, prior timing recovery and equalization are not required. In comparison to well-known algorithms, FD-AFC provides a significant improvement of convergence speed and estimation accuracy with a reduction of the implementation complexity.

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