

Digital Frequency Offset Compensation in High-speed Optical Intersatellite Data Transmission Systems

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Abstract We present an alternative approach for current homodyne detection systems in optical intersatellite links. Our approach is based on digital frequency offset compensation instead of optical phase-locked loop techniques, in order to achieve a more flexible coherent detection scheme.

Introduction

The increasing number of real-time earth observation applications, e.g. faster earthquake or Tsunami forecasts, requires high-speed communication links between satellites and between satellites and earth. Due to the lower power consumption and higher data rates, optical intersatellite links (OISL) offer an attractive alternative to conventional RF-communication. Furthermore, the narrow laser beam width and the lower weight ensure a better data security and reduced costs. The complex alignment of both satellites to achieve line-of-sight (LOS) connection is realised by the pointing, acquisition and tracking system (PAT) of the laser communication terminal (LCT).

The first European commercial system providing optical intersatellite communications is the upcoming European Data Relay System (EDRS). This network consists of several satellites in different orbits and allows laser links over distances of up to 45.000 km with data rates of up to 1.8 Gb/s¹. The core technology consists of the LCT which enables optical coherent BPSK transmission on satellites. To ensure homodyne detection, an optical phase-locked loop (OPLL) is used to adjust the frequency and phase of the local oscillator (LO) to the incoming data signal². However, in order to increase the data rate by applying higher modulation formats the OPLL complexity will significantly increase.

In this paper we propose for the first time, to the best of our knowledge, an alternative intradyne detection scheme for OISL transmission based on digital frequency offset (FO) compensation.

Optical Intersatellite Channel

Compared to fiber optics, the signal transmission through free-space will not be distorted by any nonlinearity or dispersion. Instead, the main impairments are free-space loss and Doppler-shift. The free-space

attenuation is very high (up to 300 dB) and has to be compensated for by high antenna gains as well as high receiver sensitivity. The Doppler-shift of the signal frequency due to the relative velocity between the satellites will cause an additional frequency offset of up to ± 7 GHz between LO and receive light. Since the altitude and velocity of the satellites are known, the frequency shift can be predetermined and the frequency of the lasers can be adjusted in real-time by using known trajectory data. Usually, a small frequency offset remains, which is conventionally compensated for by an OPLL. However, its structure is related to the modulation format, which increases in complexity when increasing the modulation order. Therefore, in order to achieve a flexible and transparent system, we propose a software-based intradyne detection scheme in OISL.

Digital Frequency Offset Compensation

The investigated compensation schemes are separated into a coarse and fine compensation stage. In the first step, coarse frequency offset compensation is applied, in our case by the phase differential algorithm (PDA)³. The PDA determines the phase difference between two consecutive symbols in order to estimate the FO. According to Fig.1 the output of the coherent receiver, separated into I - and Q -components, is sampled by an ADC with the symbol clock. The sampled input signal to the

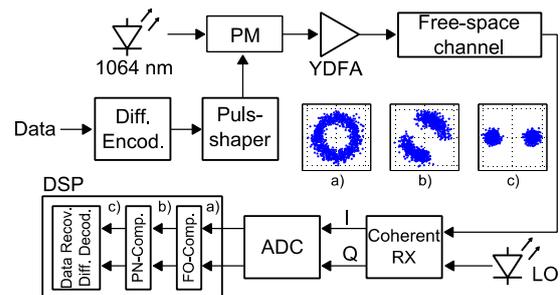


Fig. 1: OISL BPSK-transmission system based on DSP

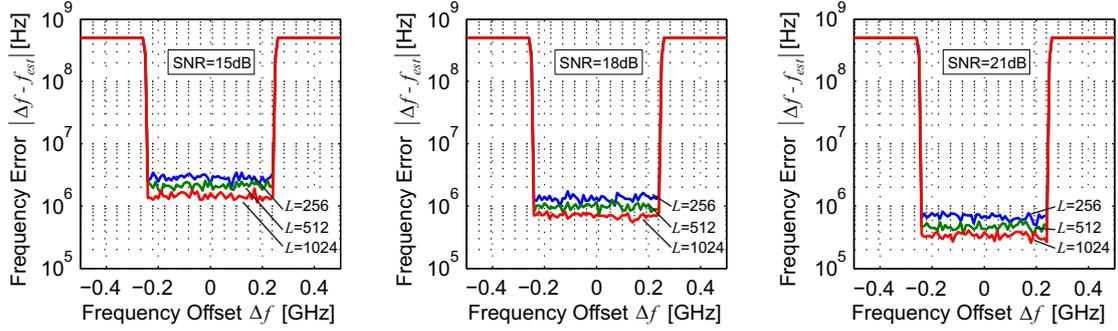


Fig. 2: Residual frequency error after coarse FO compensation for SNR=15,18 and 21dB and different averaging block length L

DSP is therefore

$$\begin{aligned} X[k] &= I[k] + jQ[k] \\ &= \hat{A} e^{j(\Delta\Phi[k] + \Phi_M[k] + \Phi_0 + \Phi_n[k])} + n[k], \end{aligned} \quad (1)$$

where \hat{A} denotes the intensity of the coherently detected signal, $\Delta\Phi$ the phase shift due to the frequency offset Δf , Φ_M the data modulation, Φ_0 a constant phase offset, Φ_n the phase noise and $n[k]$ the (complex) additive noise. By multiplying two consecutive samples we get the phase difference and applying the power of M will eliminate the modulation Φ_M ,

$$\Gamma[k] = (X[k] \cdot X^*[k-1])^M. \quad (2)$$

where M denotes the modulation order for M -PSK. If neglecting the noise terms eq. (2) results in

$$\Gamma[k] \sim e^{jM(\Delta\Phi[k] - \Delta\Phi[k-1])}. \quad (3)$$

The final estimated frequency offset is based on the mean value of L samples,

$$f_{est} = \frac{1}{2\pi T_s M} \cdot \arg \left\{ \sum_{k=1}^L \Gamma[k] \right\}, \quad (4)$$

where T_s denotes the symbol period. Due to the $\pm\pi$ restriction of the $\arg\{\}$ -operation the maximum frequency offset which can be compensated for is calculated by,

$$f_{est,max} = \frac{1}{2\pi T_s M} \cdot \pm\pi = \frac{\pm 1}{2MT_s}. \quad (5)$$

After applying the coarse compensation algorithm and in order to further compensate the residual frequency error as well as phase noise (PN), fine compensation based on the Viterbi & Viterbi algorithm⁴ is used. The method separates the incoming data into blocks of length N and calculates the mean phase shift of each block i ,

$$\tilde{\Phi}_i = \frac{1}{M} \arg \left\{ \sum_{n=1}^N (Y[n + (i-1)N])^M \right\}. \quad (6)$$

If $Y[k]$ is assumed to be the input to the fine

compensation, the resulting output is

$$\tilde{Y}[k] = Y[k] \cdot \exp(-j\tilde{\Phi}_i). \quad (7)$$

Obviously, the fine compensation accuracy is best for $N=1$. Each sampled constellation point would be re-rotated separately; however the computational effort and therefore the DSP speed requirements would be too high. The effort is minimal if compensating the whole data sequence once, but the accuracy would be worst. Hence, a trade-off between accuracy and computational effort is required, which depends on the available space-qualified DSP, SNR sensitivity and initial frequency offset.

OISL Simulation Setup

The presented compensation schemes are numerically investigated in a BPSK OISL transmission system based on Fig.1. Typical laser sources are pumped Nd:YAG Lasers at 1064 nm. The light is externally modulated by a Phase-Modulator (PM), driven by the data signal (here a De-Bruijn sequence of length 2^{23}), and amplified up to 2W by an Ytterbium-Doped Fiber Amplifier (YDFA). After transmission through the free-space channel the received optical signal is detected by the coherent receiver, containing a 90° optical hybrid, which superimposes the receive light with the LO light. The resulting I - and Q -signals are converted to the electrical domain by photodiodes and amplified by transimpedance amplifiers. After analog-to-digital conversion (ADC) the signal is forwarded into the DSP, thus to the digital frequency offset compensation schemes. The system parameters are given in Table 1. In order to change the SNR the link distance between the satellites, i.e. the Rx power, is varied.

Tab. 1: Simulation parameters

Tx power	P_{Tx}	32 dBm
Symbol rate	f_s	1 GS/s
Rx bandwidth	B_e	2 GHz
LO power	P_{LO}	12 dBm
Linewidth (Tx/Rx)	$\Delta\nu$	10 kHz

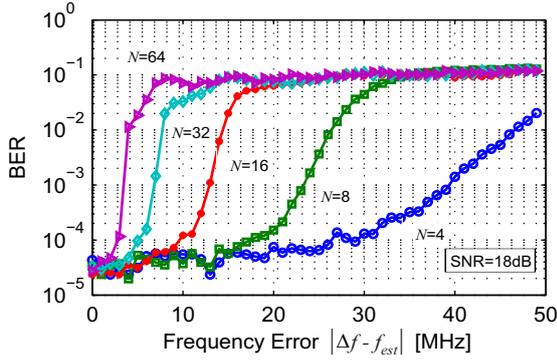


Fig. 3: Influence of fine compensation accuracy on BER

Results

In a first step, the performance of the coarse compensation stage is investigated. Fig. 2 shows the magnitude of the residual frequency error depending on the initial frequency offset Δf . It is obvious that the algorithm is only working in a specific range. In this case between approx. $\Delta f = \pm 250$ MHz, which can be verified by eq. (5). As expected, by increasing the averaging block length L the residual error decreases due to the fact that the mean phase difference in eq. (4) becomes more accurate. The same behaviour can be observed by increasing the SNR. Fig. 3 presents the simulation results after the fine compensation stage. Here, the BER is estimated for different frequency errors which are assumed to be the residual errors from the previously discussed coarse compensation. First, the block length N is varied. At a frequency error of 0 Hz only shot and phase noise affect the BER, which can be seen as reference level, here at approx. $3 \cdot 10^{-5}$. As discussed above, the compensation performance is better for lower N . This is confirmed by changing N from 4 to 64. Depending on N the algorithm can only properly compensate the error in a specific range, before the BER increases. However, the residual errors of the coarse FO compensation as depicted in Fig. 2 are within this range for every investigated N . The influence of the SNR is investigated in Fig. 4. With increasing SNR the shot noise will decrease and so does the reference BER level. The compensation range is the same. To achieve error free transmission we aim a BER of 10^{-3} , which allows modern forward error correction codes (FEC) to further decrease the BER. As shown in Fig. 5 this threshold is reached for $P_{Rx} \approx -46.3$ dBm. The low received input power results from the high free-space attenuation, which requires high receiver sensitivity. For comparison, in case of OPLL-BPSK a received input power of $P_{Rx} \approx -44$ dBm is needed. The OPLL is based on a Costas loop scheme with an electrically controlled fast tuneable laser and active loop filter. The loop

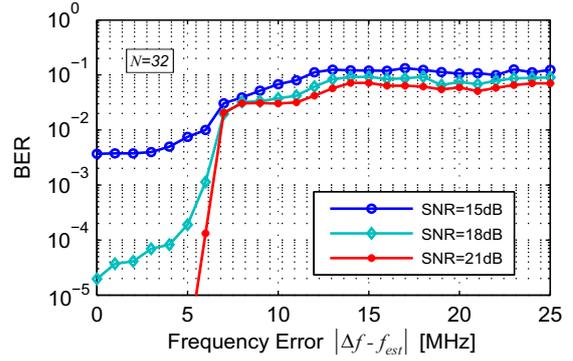


Fig. 4: Fine FO compensation vs. SNR influence

parameters are optimized in the sense that phase noise is compensated for such that no phase jumps, i.e. cycle slips, occur⁵.

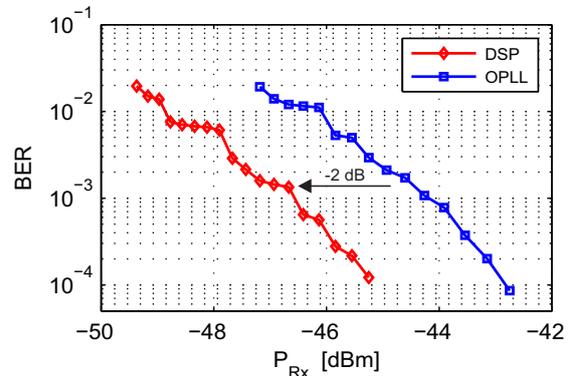


Fig. 5: BER performance for DSP compared to OPLL; DSP setup: $L=1024$, $N=32$, $\Delta f = 100$ MHz

Conclusions

We present an approach of digital frequency offset compensation for optical coherent satellite communication systems. BER simulations indicate that the combination of coarse and fine compensation can successfully reduce the FO and seems to be an attractive alternative to current OPLL techniques.

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