Coherent Receiver Design for Optical Inter-satellite Links

Semjon Schaefer

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Hamburg

Lehrstuhl für Nachrichten- und Übertragungstechnik
Technische Fakultät
Christian-Albrechts-Universität zu Kiel
Motivation

Advantages compared to RF:
- Data rates of several Gb/s
- Lower power consumption
- Lower weight → lower costs
- Data security

Main challenges:
- Pointing, Acquisition, Tracking system (PAT)
  → For line-of-sight connection (LOS)
- No transmission through atmosphere/clouds

→ Optical Inter-satellite Link
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1. Optical Inter-satellite Links

2. Homodyne Detection with Optical Phase-Locked Loop

3. Intradyne Detection with Digital Signal Processing

4. Conclusions
Optical Intersatellite Link (OISL)

Current RF Scenario:
- LEO: Low-Earth Orbit
- GEO: Geostationary Orbit

OISL Scenario:
- LEO: Low data rate
- Short time window

- GEO: High data rate (LEO → GEO)
- Long time window (GEO → GS)

LEO → GS:
- Low data rate
- Short time window

LEO → GEO → GS:
- High data rate (LEO → GEO)
- Long time window (GEO → GS)
Doppler Frequency Shift

- Caused by the relative velocity between the satellites
  - Maximum frequency offset of approx. ± 7 GHz
  - Coarse compensation by using satellite trajectory data (frequency sweeping)
  - Fine compensation by optical PLL (homodyne) or DSP (intradyne)
    - Residual Doppler shift, natural frequency drift and phase noise

\[
 f_{Rx} = f_{Tx} \frac{\sqrt{1 - \frac{v^2}{c^2}}}{1 - \frac{v}{c} \cos \alpha}
\]

- \( f_{Tx} \): Transmitted frequency
- \( f_{Rx} \): Received frequency
- \( c \): Speed of light in vacuum
- \( v \): Relative velocity

\( T_{\text{LEO}} = 100\text{min} \)
\( T_{\text{GEO}} = 24\text{h} \)
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OISL Transmission System with Homodyne Detection

Laser Communication Terminal (LCT) Setup:

Typical Setup:

- Solid-state laser at 1064 nm
- Tx-power of up to 5 W
- BPSK transmission of up to 1.8 Gb/s
- Coherent homodyne detection
  - Carrier recovery based on OPLL techniques

PM: Phase modulator
YDFA: Ytterbium-doped fiber amplifier
OPLL: Optical phase-locked loop
LO: Local oscillator
Optical phase-locked loop for BPSK transmission based on Costas loop

Demodulated data signal after coherent detection:

\[
U_I(t) \sim \cos(\phi_1(t) - \phi_2(t) + \phi_M(t)) \\
U_Q(t) \sim \sin(\phi_1(t) - \phi_2(t) + \phi_M(t))
\]

\[
\varepsilon(t) = U_I(t) \cdot U_Q(t) \\
\sim \sin(2[\phi_1(t) - \phi_2(t)])
\]

Phase error
**Frequency Acquisition**

**Example:** Residual frequency offset of 5 MHz (after coarse Doppler compensation)

![Error Signal $\varepsilon(t)$](chart1)

![Frequency Error](chart2)
QPSK Extension for Future Systems

- Higher data rate e.g. by higher order modulation formats
  - Modifications in transmitter structure (e.g. optical IQ-modulator)
  - Modifications in receiver/OPLL structure (e.g. phase discriminator)

- OPLL complexity increases with modulation order!
  \[
  \rightarrow \text{Intradyne detection with DSP as alternative}
  \]
BER Performance: BPSK vs. QPSK

Simulation Setup:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx Power $P_{Tx}$</td>
<td>32 dBm</td>
</tr>
<tr>
<td>Baud Rate $D_{bd}$</td>
<td>1 Gbaud</td>
</tr>
<tr>
<td>OPLL Bandwidth $B_L$</td>
<td>3.5 MHz</td>
</tr>
<tr>
<td>LO Power $P_{LO}$</td>
<td>11 dBm</td>
</tr>
<tr>
<td>PD Bandwidth $B_e$</td>
<td>4 GHz</td>
</tr>
<tr>
<td>Linewidth (Tx/LO) $\Delta\nu$</td>
<td>10 kHz</td>
</tr>
</tbody>
</table>

- Low receive power due to high free-space loss
- High receiver sensitivity required
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Intradyne Detection with DSP

- No changes at transmitter compared to OPLL setup
- Free-running LO for intradyne detection
- Combination of coarse and fine compensation

ADC: Analog-digital-converter
FO: Frequency offset
PN: Phase noise
LO: Local oscillator
Coarse Compensation: Phase Differential Algorithm

1) Complex signal at coherent receiver output

\[ X(t) = I(t) + jQ(t) \quad \Rightarrow \quad X[k] = \hat{A}_{Rx} e^{j(\Delta \Phi[k] + \Phi_M[k] + \Phi_0) + \Phi_n[k]} + n[k] \]

2) Estimate the phase difference

\[ X[k] \cdot X^*[k-1] = \hat{A} e^{j(\Delta \Phi[k] + \Phi_M[k] + \Phi_0)} \cdot e^{-j(\Delta \Phi[k-1] + \Phi_M[k-1] + \Phi_0)} \]

\[ = \hat{A} e^{j(\Delta \Phi[k] - \Delta \Phi[k-1] + \Phi_M[k] - \Phi_M[k-1])} \]

3) Data elimination and phase averaging (BPSK \( \rightarrow M=2 \))

\[ (X[k] \cdot X^*[k-1])^M = \hat{A} e^{jM(\Delta \Phi[k] - \Delta \Phi[k-1])} \quad \Rightarrow \quad \Delta \tilde{\Phi} = \frac{1}{M} \arg \left[ \sum_{k=1}^{L} (X[k] \cdot X^*[k-1])^M \right] \]

4) Final estimated frequency offset

\[ \Delta \tilde{f} = \frac{\Delta \tilde{\Phi}}{2\pi T_s} \quad \Rightarrow \quad \Delta \tilde{f}_{\text{max}} = \frac{1}{2\pi T_s} \cdot \frac{\pm \pi}{M} = \frac{\pm 1}{2MT_s} \]

Semjon Schaefer, Future Photonics 2015, 17.09.2015
Coarse Compensation: Phase Differential Algorithm

Setup:
- BPSK $\rightarrow M = 2$
- $f_s = \frac{1}{T_s} = 1\text{GHz} \rightarrow \Delta f_{\text{max}} = \frac{\pm 1}{2MT_s} = \pm 0.25\text{GHz}$

Results (with shot/phase noise):
- Limited working range as expected
- Frequency error influenced by SNR and $L$
- Remaining error in the lower MHz range
Fine Compensation: Phase noise compensation

Based on Viterbi & Viterbi-method

Length $N$ of averaging influences compensation accuracy
Fine Compensation: Phase noise compensation

- BER simulations depending on the frequency offset, $N$ and SNR

- Increasing $N$ → Working range decreases
- Increasing SNR → Shot noise influence decreases
- Compensation of a remaining frequency error of 1 MHz possible
  → Trade-off between DSP speed and compensation accuracy
Conclusions

- OISL as an attractive alternative to current RF communications
  - Higher data rates, lower power consumption
  - High free-space loss requires high receiver sensitivity

- OPLL based carrier recovery for homodyne BPSK detection

- OPLL-QPSK scheme for future OISL transmission systems

- Hardware complexity increases with modulation order

- Intradyne detection with digital frequency offset compensation as alternative
  - Shift complexity to the digital domain
Acknowledgment

For supporting part of this work!
Thank you!