Performance and Complexity Comparison of Carrier Phase Estimation Algorithms for DP-64-QAM Optical Signals

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Abstract - A detailed simulative and experimental analysis of different CPE schemes for 64-QAM systems is presented. The best compromise between linewidth tolerance and complexity is achieved using a recently proposed multi-stage architecture, based on a modification of the standard V&V algorithm.

The performance of various CPE algorithms is compared:

- QPSK Partitioned V&V
- V&V+CT+MLE
- V&V+CT+2MLE
- Modified V&V (V&V*)
- V&V*+CT+MLE
- V&V*+CT+2MLE
- BPS
- BPS + MLE
- S-DD-PLL
- S-DD-PLL+ MLE
- DA–MLE

Simulation model

Received noisy samples:

\[ y_k = x_k e^{j\theta_k} + \eta_k \]

Phase noise:

\[ \theta_k = \sum_{i=-\infty}^{\infty} v_i \]

\[ \sigma^2_f = 2\pi\Delta v T_s \]

Simulation Results

Figure. 1: SNR vs. linewidth times symbol duration (\(\Delta v \cdot T_s\)) product at BER=10\(^{-2}\) for different CPE schemes. (a) Algorithms having worst performance (b) Algorithms having best performance

Table. 1: Laser phase noise tolerances and their equivalent linewidths at 20 Gbaud for various CPE algorithms

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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</thead>
<tbody>
<tr>
<td>CPE</td>
<td>V&amp;V</td>
<td>V&amp;V</td>
<td>V&amp;V+CT+MLE</td>
<td>V&amp;V+CT+2MLE</td>
<td>V&amp;V*+CT+MLE</td>
<td>V&amp;V*+CT+2MLE</td>
<td>BPS</td>
<td>BPS+MLE</td>
<td>S-DD-PLL</td>
<td>S-DD-PLL+MLE</td>
<td>DA–MLE</td>
</tr>
<tr>
<td>(\Delta v \cdot T_s) 1dB penalty</td>
<td>8.0\times 10^{-5}</td>
<td>10^{-5}</td>
<td>4.5\times 10^{-5}</td>
<td>5.6\times 10^{-5}</td>
<td>6.0\times 10^{-5}</td>
<td>7.1\times 10^{-5}</td>
<td>5.7\times 10^{-5}</td>
<td>5.4\times 10^{-5}</td>
<td>3.0\times 10^{-5}</td>
<td>3.0\times 10^{-5}</td>
<td>2.5\times 10^{-5}</td>
</tr>
</tbody>
</table>

\(|\eta|\) (PPM) (MHz):

0.16 MHz
0.20 MHz
0.90 MHz
1.12 MHz
1.20 MHz
1.42 MHz
1.14 MHz
1.08 MHz
0.60 MHz
0.60 MHz
0.50 MHz
An external cavity laser (ECL) with a linewidth of 100 kHz and wavelength 1553.32 nm is modulated by an integrated IQ modulator, whose I and Q branches are driven by two 20-Gbaud 8-level electrical signals in order to generate a 64-QAM signal QPSK Partitioned. The dual-polarization (DP) 64-QAM signal is generated by using a polarization multiplexing emulator. By loading different amounts of ASE noise, the optical-signal-to-noise-ratio (OSNR) values were varied between 25 and 37 dB. At the receiver side, an optical band pass filter (OBPF) with bandwidth 0.6nm is used for filtering the out-band noise. The received signal is coherently detected by an integrated coherent receiver with a local oscillator (ECL, with line-width 100 kHz). The detected signal is sampled by a 50GS/s real-time sampling scope. The captured data are processed offline.

### Complexity analysis

<table>
<thead>
<tr>
<th>CPE</th>
<th>Real Multipliers</th>
<th>Real Adders</th>
<th>Comparators</th>
<th>Look-Up Tables</th>
<th>Decisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>V&amp;V</td>
<td>8N</td>
<td>3N+2</td>
<td>4N+2</td>
<td>1</td>
<td>N1</td>
</tr>
<tr>
<td>V&amp;V+CT</td>
<td>8N1+6N2</td>
<td>3N1+3N2+30</td>
<td>4N1+7</td>
<td>2</td>
<td>N2</td>
</tr>
<tr>
<td>V&amp;V+CT+MLE</td>
<td>8N1+6N2+N3</td>
<td>3N1+3N2+N3+29</td>
<td>4N1+7</td>
<td>3</td>
<td>2N3</td>
</tr>
<tr>
<td>V&amp;V+CT+2MLE</td>
<td>8N1+6N2+N3+N4</td>
<td>3N1+3N2+N3+N4+28</td>
<td>4N1+7</td>
<td>4</td>
<td>N3+2N4</td>
</tr>
<tr>
<td>V&amp;V*</td>
<td>8N</td>
<td>3N+2</td>
<td>4N+2</td>
<td>1</td>
<td>N1</td>
</tr>
<tr>
<td>V&amp;V*+CT</td>
<td>8N1+6N2</td>
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<td>N2</td>
</tr>
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<td>3N1+3N2+N3+29</td>
<td>4N1+7</td>
<td>3</td>
<td>2N3</td>
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<tr>
<td>V&amp;V*+CT+2MLE</td>
<td>8N1+6N2+N3+N4</td>
<td>3N1+3N2+N3+N4+28</td>
<td>4N1+7</td>
<td>4</td>
<td>N3+2N4</td>
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<tr>
<td>BPS</td>
<td>NM+2NM</td>
<td>2NM+M+3</td>
<td>M+1</td>
<td>0</td>
<td>NM+N</td>
</tr>
<tr>
<td>BPS+MLE</td>
<td>NM+2NM+M+N2</td>
<td>2NM+M+M+N2+2</td>
<td>M+1</td>
<td>1</td>
<td>NM+M+N2</td>
</tr>
<tr>
<td>S-DD-PLL</td>
<td>2N</td>
<td>2N</td>
<td>0</td>
<td>0</td>
<td>2N</td>
</tr>
<tr>
<td>S-DD-PLL+MLE</td>
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<td>2N+N2-1</td>
<td>0</td>
<td>1</td>
<td>N1+N2</td>
</tr>
<tr>
<td>DA-MLE</td>
<td>3N+1</td>
<td>3N-2</td>
<td>0</td>
<td>0</td>
<td>N+1</td>
</tr>
</tbody>
</table>

**Table 2: Computational complexity for various CPE algorithms**

### Experimental Results

**Figure 2: BER vs OSNR performance (back to back) for different CPE algorithms.**

### Conclusions

A detailed simulative and experimental analysis of different CPE schemes for 64-QAM systems is presented. The recently proposed multi-stage algorithm achieves the best performance for 64-QAM systems with reduced complexity with respect to the BPS algorithm.