Implementing free-space QKD systems between moving platforms: polarization vs. time-bin encoding

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Quantum Internet – the Long Term Vision

Qubit distribution with moving systems: satellites, aircraft, vehicles, ships, handheld
Polarisation vs. Time-bin Encoding for Free-Space QKD Links

Traditionally polarization encoding is preferred for free-space links implementations. Essentially implements the BB84 protocol.

Optical photons: Polarization is only affected by turbulence and atmospheric effects.

Confirmed by many QKD tests:
- Horizontal QKD links (144km): QBER ca. 5%
- Laser links with satellites: Pol. Error 3.2 deg, QBER ca. 3%

†Yoshima et al., Vol. 17, No. 25 / OPTICS EXPRESS 22333 (2009)

Polarization Reference Frames between Moving Platforms

- Can move in many degrees of freedom for Alice, and Bob

Active control of polarization, via measurement and correction

Reference Frame Independent Protocols, which essentially test the purity of received qubits

Use: L/R for Key, and P/M and H/V for link integrity test


Laing, Scarani, Rarity, O’Brien, PHYSICAL REVIEW A 82, 012304 (2010)
Canadian Quantum Satellite Studies

- **QYESSat**
  - Mission proposal for a micro-satellite quantum receiver
  - IROC scientific lead
  - Designed with Canadian Industry
  - LEO
  - Mass: 50 kg
  - Dimensions: 80×60×60 cm³
  - Status: Feasibility studies, mission and payload development (STDP), Form-fit-function prototype + robustness, outdoor trials

- **NanoQEY**
  - Concept for a Nano-Sat based Quantum Key Exchange satellite
  - Mass: 15 kg
  - Dimensions: 40×26×20 cm³

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Outdoor Trials with Moving Truck

- 1st generation system
- Quantum transmission range 650 m
- Quantum receiver truck driving 30 km/h
- Generated 160 bit secure key
- Realtime compensation of pointing, polarization and timing

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Experiments:

- Timing information retrieved from beacon
- GPS timing, frequency and location
- Quantum signals
- Classical Comms
- Tracking + Feedback switch
- Polarization
- Decoy state QBER
- Signal state QBER
- Raw key rate

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References:


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Image credits:

- Quantum truck
- Outdoor Trials with Moving Truck
- Canadian Quantum Satellite Studies

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Physical Parameters

<table>
<thead>
<tr>
<th></th>
<th>IOA</th>
<th>Detectors</th>
<th>CDPU</th>
<th>Overall</th>
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<tbody>
<tr>
<td><strong>Volume Budget</strong></td>
<td>150 × 150 × 200 mm</td>
<td>150 × 150 × 200 mm</td>
<td></td>
<td></td>
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<tr>
<td><strong>Measured</strong></td>
<td>48.2 × 56.8 × 120 mm</td>
<td>30 × 127 × 143 mm</td>
<td>25.4 × 106.6 × 118.4 mm</td>
<td></td>
</tr>
<tr>
<td><strong>Mass Budget</strong></td>
<td>(3 kg)</td>
<td>(5 kg)</td>
<td>(4 kg)</td>
<td>12 kg</td>
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<tr>
<td><strong>Measured</strong></td>
<td>0.32 kg</td>
<td>0.516 kg</td>
<td>0.129 kg</td>
<td>&lt; 2 kg</td>
</tr>
<tr>
<td><strong>Power Budget</strong></td>
<td>(2.5 W)</td>
<td>(2.5 W)*</td>
<td>6 W*</td>
<td></td>
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<tr>
<td><strong>Measured</strong></td>
<td>2.46 W</td>
<td>4 W*</td>
<td>6.46 W*</td>
<td></td>
</tr>
</tbody>
</table>

Optical Fine Pointing

- Intrinsic source QBER = 2%
- Near constant QBER over full FOV (0.7 deg)
- Count rate drops at the edges, reducing key length
APT system in ‘action’

Lab-demonstration of QKD with expected link losses

- Because of finite size effects, secure key extracted only after 575 ms
- 500 MHz QKD at 38.76 dB key vs. time
- Full BB-84 QKD protocol with decoy states (error correction, PA)
- The key length is predicted to reach 40 kbit after 162 s
- The key length is predicted to reach 75.8 kbit after 250 s

Airborne QKD with quantum receiver

2nd generation system: Satellite prototype on aircraft
Goal: demonstrate quantum link with up to 1 deg/s angular speed
Analysis of air-speed, altitude, distance (graph on right)
Tests conducted week of Sept. 19th/2016

Polarization Issues within Optical Systems

Polarization effect of mirrors due to Fresnel-coefficients

Silver Mirror:

Fig. 6.—Reflection maps for each mirror element (first three panels) and the cumulative reflectance for the entire telescope (last panel).

Fig. 4. Measurement error, induced by a Cassegrain telescope

The Quantum Transmitter setup
Integration & Test of Payload at aircraft
Quantum Receiver Payload
Alternative Encoding for Quantum Information on Free-Space Photons?

- In principle, degrees of freedom (DF) of photons can be utilized to encode photonic qubits
  - Spatial mode
    - paths
    - Orbital angular momentum, LG modes
  - Time bin
    - related: Differential Phase Shift, COW
  - Frequency bins, side bands
  - Quadrature of light
    (only continuous variables)

Are they suitable for a long distance free-space link?
Motion errors, atmospheric turbulence

Time bin encoding for free-space

- Requires, that the unbalanced interferometers for encoding / decoding the qubits can work with multimodal beams

Uncorrected Interferometer:

\[ V(\alpha) = V_0 \exp \left( -\left( \frac{\Delta l_0 \tan(\alpha)}{\sqrt{2} \sigma(1 + \tan(\alpha))} \right)^2 \right) \]
Multi-mode Michelson Interferometers

Used in applications for multi-mode images in Doppler-LIDAR Velocimetry with incoherent light sources, Astronomy, Narrowband Filters in LIDAR

Superimposing Interferometers


Field-Widened Michelson Interferometers


Unbalanced Interferometer Suitable for Quantum Communications

• Compatibility with Photonic Qubits:
  • Dispersion, Polarization effects, stability?

ZEMAX modelling of optical configuration

Demonstration using Entangled Photons

Type-I interferometer, relay lens
Time delay: 2 ns
Hybrid entangled State:

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|V\rangle_A|H\rangle_B + |H\rangle_A|V\rangle_B) \]

\[ |V\rangle \mapsto |E\rangle \text{ and } |H\rangle \mapsto |L\rangle \]

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|R\rangle_A|H\rangle_B + |L\rangle_A|V\rangle_B) \]


Experimental Test of Hybrid Entanglement

Highly multimodal beams, variation of angular input
Interferometer visibility > 90%, the system visibility reduced to ca.80% due to source, conversion, alignment

Quantum Tomography of Heralded Photon

Apply tomographic measurements on polarized photon: HV, RL and PM basis

Entanglement and QKD verification

Two-basis measured: Early/Late basis high contrast, Superposition basis using interference
Outdoors? Time bin QKD over telescope link

- Preliminary link demonstrated
- QBER: ca. 5%
- Uses 2nd generation interferometers: >95% intrinsic visibility

Time-bin interferometer using glass

- Tested a different approach: using refraction to compensate field
- Refractive index cancels walk-off

\[ \frac{d_1}{n_1} - \frac{d_2}{n_2} = 0. \]

Measured Interference Visibilities, 118 mm glass cube:
Time delay: 0.57 ns
Multimode Fiber input beam:
V= 0.95 (comp basis), V=0.90 (superposition basis)
Demonstration of Glass-based Interferometer

Type-II interferometer, refractive index

Hybrid entangled State:

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|V\rangle|H\rangle_n + |H\rangle|V\rangle_n) \]

\[ |V\rangle \rightarrow |H\rangle \text{ and } |H\rangle \rightarrow |V\rangle \]

\[ |\psi\rangle = \frac{1}{\sqrt{2}} (|E\rangle|H\rangle_n + |H\rangle|E\rangle_n) \]


Results for Type-II interferometer

- Test with MMF, with (green) and without (black) glass
- Alignment turned out to be “very easy”
- Challenge: dispersion of 5.48 waves/nm and 5.21 waves/°C

V= 0.95 (comp basis)
V=0.90 (superposition basis)
Quantum Interferometers for Multi-Mode beams Widely Studied


Conclusion

• Time bin encoding viable for multi-mode channels!
• Purely passive optical correction of beams
• 80% coupling throughput of input signal into detectors
• Stable and consistent interference visibilities of up to 97% achieved

• Challenges:
  • stabilizing transmitter and receiver interferometers
  • Designing thermally stable and compact interferometers
  • Dispersion effects need to be cancelled
Outlook

- **Time-bin over free space channels, opens up several new directions**
- Polarizing effects of telescopes and optical path can be overcome
  - Broad variety of fine-steering systems technology
  - Compact, short telescopes
  - Optical fiber interfaced of photons with source and detectors
- Interfacing of fiber optical and free-space links straightforward
- Direct compatibility between QKD and classical laser coms
- Implementation of differential-phase shift protocols over free-space DPS-QKD, COW-QKD
- Novel protocols for free-space
  - Reference-frame independence
  - Hyper-dimensional encoding
- Novel media QKD, such as over multi-mode fiber (plastic fiber), depolarizing channels
- QIP: capture of multi-modal photons also suitable for experiments

Thank You

- **Polarization systems well advanced**
- **Time-bin can be an important alternative**
- Could simplify optical systems design, pointing
- Enable novel protocols and schemes

Thank You