Characterization of a photon counting test bed for space to ground optical pulse position modulation communications links

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Introduction

Motivation:

• Real time photon counting optical ground receivers are needed to enable space to ground communications for both public and private applications.

• Future NASA photon counting optical communications missions: LCRD, O2O, Psyche

Strategy:

1. Develop an optical communications photon counting test bed to enable development of a real time optical receiver which includes the following subsystems:
   • Aft optics (photonic lantern), single photon counting detectors, and real time FPGA-based receiver.

2. Model key optical communications system parameters to understand impact on system performance

Objective:

• Utilize system test bed and model to predict system performance
Optical Communications System Test Bed

**Optical Transmitter**
- 10 MHz
- CW
- 1550 nm laser
- PM SMF
- SDR: CCSDS Optical Communications Waveform
- Driver Amplifier
- EO Modulator

**Link Emulation**
- Variable Attenuator
- 50/50 splitter
- Optical power monitor

**Optical Receiver**
- Opus One™
- 50 Ω
- SNSPD 1
- SNSPD 2
- T = 2.5 K
- T = 300 K
- Cryogenic feed-thru
- Oscilloscope
- SNSPD 1
- SNSPD 2

**Bias/LNA**
- Output pulses

**Digitizer**
- 50/50 splitter
- Polarization controllers
- Fiber optic coupler
- PC
- Control & Software Receiver

**Polarization controllers**
- 10 MHz
Optical Transmitter – Software Defined Radio

- Based on Harris Corporation Reconfigurable Space processor development card
- A custom optical mezzanine card performs serialization of electrical signal generated on FPGA
- Xilinx Virtex 7 FPGA houses the optical transmit waveform
Optical Transmitter – Waveform

- Implements the full CCSDS Optical Communications Coding and Synchronization Red Book telemetry link
- Testing performed with the following waveform:
  - PPM-32
  - Code rate 1/3
  - Slot width 1 ns
  - Guard band: 8 slots (25%)
  - Data rate 40 Mbps
- Note: channel interleaver bypassed for testing purposes
Optical Transmitter – Electro-optic Modulator System

- Consists of two high extinction ratio electro-optic modulators cascaded in series
- Electrical signal driving modulators is offset in time to narrow the optical pulse position modulation signal, improving the extinction ratio

Link Emulation

- Free space loss is emulated with a variable attenuator
- No additional noise inserted
  - $K_b \approx 0.0001$ background photons/slot
- Power meter used to measure optical power into the receiver

![Link Emulation Diagram]

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- Power meter
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Optical Receiver – Single Photon Counting Detectors

Description:
- Contains two single mode fiber coupled detectors from the Quantum Opus, Opus One™ system

Characterization Results:
- Detector pulse rise time
  - 850 ps
- Detector reset time
  - 18-20 ps
- Maximum detection efficiency (polarization dependent)
  - 80% at maximum point
  - 50-60% at operating point due to detector blocking losses (1.5 dB blocking loss)
- Detector jitter full width half max:
  - Channel 1: 68 ps
  - Channel 2: 85 ps


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Optical Receiver – Waveform

- Detector pulses are sampled at 2 GHz with an oscilloscope and post-processed using a Matlab receiver model
- SCPPM decoder performs iterative decoding using the BCJR algorithm
- Sample jitter introduced by 2 GHz sampling of 850 ps detector pulse is ~45 ps RMS
- Calculated total receiver jitter:
  - Channel 1: 61 ps RMS
  - Channel 2: 68 ps RMS
System Simulations

Description:

- Matlab model of the CCSDS Optical Communications Coding and Synchronization telemetry link (downlink)
  - Transmit waveform
  - Floating point receive waveform has iterative decoding using the BCJR algorithm
- Simulations modeled key system parameters including:
  - Number of detectors
  - Detector blocking
  - Jitter
  - Background noise photons/slot (Kb)
  - Signal photons/signal slot (Ks)
- Performance metrics:
  - Bit error rate curves generated for fixed background noise
System Simulation Results – Capacity and Baseline

- PPM-32
- Code rate 1/3
- $K_b = 0.0001$ background photons/slot

![Capacity curve](capacity_curve.png)

Ideal number of detectors modeled as a Poisson process

Capacity curve generated through a Monte Carlo method
System Simulation Results – 1 Detector

- PPM-32
- Code rate 1/3
- $K_b = 0.0001$ background photons/slot

Due to very low background noise and use of a single detector, curve shifts to left.
System Simulation Results – 1 Detector + 20 ns Blocking

- PPM-32
- Code rate 1/3
- 1 ns slot width
- Guard band: 8 slots (25%)
- 40 Mbps data rate
- $K_b = 0.0001$ background photons/slot

No significant change in performance compared to no blocking due to pulse repetition rate of waveform selected
System Simulation Results – Detector Jitter

- PPM-32
- Code rate 1/3
- 1 ns slot width
- Guard band: 8 slots (25%)
- 40 Mbps data rate
- $K_b = 0.0001$ background photons/slot

60 ps RMS jitter: $\rightarrow 0.6$ dB loss
80 ps RMS jitter: $\rightarrow 0.8$ dB loss
Test bed System Testing Results – Channel 1

- PPM-32
- Code rate 1/3
- 1 ns slot width
- Guard band: 8 slots (25%)
- 40 Mbps data rate
- $K_b \approx 0.0001$ background photons/slot

Channel 1 (61 ps RMS jitter) matches simulation of 60 ps RMS jitter
Test bed System Testing Results – Channel 2

- PPM-32
- Code rate 1/3
- 1 ns slot width
- Guard band: 8 slots (25%)
- 40 Mbps data rate
- $K_b \approx 0.0001$ background photons/slot

Channel 2 (68 ps RMS jitter) matches simulation of 80 ps RMS jitter

System test from channel 2 (blue) matches simulation of 80 ps RMS jitter
Summary

• A photon counting optical communications system test bed was designed and characterized

• Key parameters of the system were modeled in simulation including:
  • Detector blocking
  • Detector jitter
  • Detector pulse rise time
  • Background noise

• BER curve results from the system test bed align with simulation results
  → Sources of loss in the system have been accurately characterized
  → Model can be used to predict performance of other waveforms
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Thank You!

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