# Coherent Free-Space Optical Communications over an 800 m Urban Path

**Douglas McDonald**[1], **Raphael Bellossi**[1], **Szymon Gladysz**[1], **Andrew Lambert**[1,2]

[1] *Fraunhofer IOSB, Ettlingen, Fraunhofer Institute of Optronics, System Technologies, and Image Exploitation, Gutleuthausstr. 1, 76275 Ettlingen, Germany*

[2] *School of Engineering and IT, UNSW Canberra, Canberra ACT 2600, Austrailia*

**Abstract:** We have constructed a two-pass 800 m free-space optical link using a single telescope and retroreflector. At the start/end point of the monostatic link we have built an optical transceiver capable of coherent optical communications. Initial results demonstrate successful transmission of GBit/s quadrature phase shift keying (QPSK) signals. © 2021 The Author(s)

## 1. Introduction

We present here the design, implementation, and initial transmission results obtained from a two-pass 800 m free-space link capable of GBit/s coherent optical communications. The link consists of a single transmitter and receiver telescope which focuses a modulated 1550 nm laser beam onto a retroreflector located approximately 20 m above the ground 400 m away. The reflected light is collected by the same telescope and coupled to a single-mode optical fibre where the received signal is demodulated, and encoded data is extracted via offline digital signal processing (DSP). This work serves both to demonstrate data transmission using coherent optical modulation over a free-space channel, and as a platform to investigate the effect of atmospheric turbulence on the performance of free-space optical communications systems. Future goals of this work include: the implementation of alternative communications system architectures, further quantification of system performance in the presence of atmospheric turbulence, and the integration of adaptive optics systems for turbulence mitigation.

## 2. Transmitter and Receiver Optical Design

The optical design of the system used to aim and focus a modulated infrared beam on a retroreflector is detailed in Figure 1. The modulated infrared laser is first injected into the system via a single-mode fibre. The beam is then sent to an off-axis telescope (Wolterscope Multi-Schiefspiegler F11) with focal length 2200 mm and aperture diameter 200 mm. Each mirror in the telescope is coated in protective gold to maximize the power transmission coefficient at 1550 nm ($T = 88\%$). After being expanded by the telescope, a large flat mirror (Edmund Optics, diameter 300 mm, surface flatness = $\lambda/10$) installed on a motorized mount is used to aim the beam at a retroreflector (Edmund Optics hollow corner-cube, diameter = 63.5 mm) installed 400 meters away. The reflected beam then travels back to the telescope along the same optical axis.

To separate the transmitted and the received beams, a polarizing cube beam splitter is used in conjunction with a quarter-wave plate. After separation, the received beam is relayed to an optical table and split in two using a polarizing beam splitter. In one branch, the signal is coupled to a single-mode fibre and sent to the receiver of the communications system detailed in Section 3. In the other branch, the signal is filtered using 12 nm optical bandpass filter centred at 1550 nm, and the point-spread function (PSF) of the filtered signal is imaged using an infrared camera (Hamamatsu Photonics InGaAs C14041-10U, 14 bit resolution, 320×256 20-$\mu$m-pitch pixels).

## 3. Coherent Optical Communications System

The coherent optical communications system outlined in this work differs from intensity modulation systems typically used in free-space optical communications, as here data is encoded in both the amplitude and phase of the optical carrier. Coherent systems are advantageous as they provide access to spectrally efficient modulation formats which enable higher data rates. Additionally, since coherent systems preserve the phase of the received signal, powerful DSP algorithms can be used to mitigate a number of linear channel impairments [1].

Figure 2 depicts the hardware design and offline DSP blocks used to modulate, demodulate, and digitally process coherent optical communications signals in this work. In the transmitter, complex quadrature phase shift keying (QPSK) waveforms encoded with digital data are generated offline and stored in memory of a field programmable gate array (FPGA, Xilinx Ultrascale+). The real and imaginary parts of the signals are then generated by the FPGA, amplified, and used to drive an IQ-modulator (Covega LN86S-FC), which modulates the amplitude and phase of

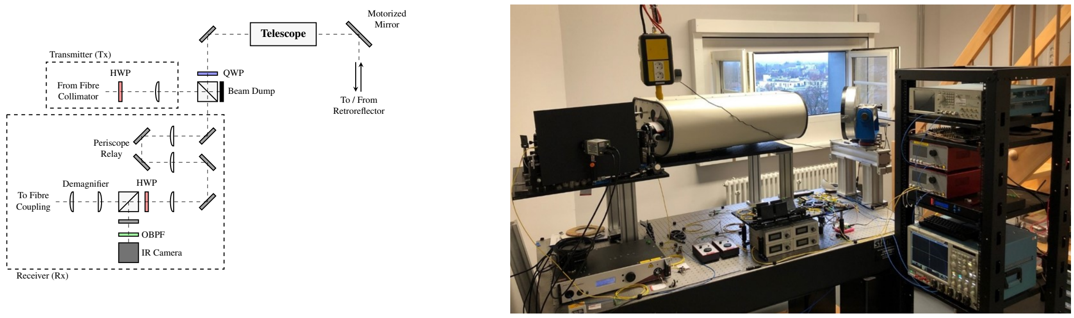


Fig. 1: Schematic and image of the optical hardware used in the transmitter and receiver. HWP = Half-Wave Plate, QWP = Quarter-Wave Plate, OBPF = Optical Bandpass Filter.

the fibre-coupled 1550 nm laser (NKT Photonics Koheras Adjustik, maximum power = 120 mW, wavelength = 1550 nm). The modulated signal is then amplified using an erbium doped fibre amplifier (EDFA), and attenuated using a constant-power-output, variable optical attenuator such that the power provided to the optical setup is kept constant. The attenuated signal is then launched into the transmitter detailed in Section 2 using a fibre collimator.

After passing through the free-space channel, the received signal is coupled back into the fibre, and mixed with a copy of the unmodulated carrier laser (local oscillator) using 90-degree optical hybrid (Kylia COH28X). To maximize mixing efficiency, the polarization of the received signal and local oscillator are mutually aligned using polarization controllers. The outputs of the 90-degree hybrid are then fed to two balanced photodetector circuits (Finisar BPDV2120R), which both demodulate and convert the optical signal to the analog electrical domain. The two signals produced by the photodetector circuits correspond to the received real (in-phase) and imaginary (quadrature) parts of the complex signal sent at the transmitter. The electrical waveforms are then sampled and stored using a digital storage oscilloscope (Tektronix DPO72304DX). The stored digital signals are then processed offline using MATLAB software.

In the digital domain, skew and imbalance between the in-phase and quadrature signals due to hardware imperfections is removed using a single coefficient feedforward equalizer [2]. Then, out-of-band noise is suppressed using a digital low-pass filter. Next, the correct sampling instants are determined using a spectral line clock synchronizer [3], and the signal is resampled using a Farrow structure polynomial interpolator [4]. The signal is then fed to an adaptive feed-forward equalizer based on the constant modulus algorithm (CMA) [5] to compensate for the frequency response of the channel. Remaining phase noise due to instability of the laser source is then estimated and compensated using a blind nonlinear estimator [6]. Lastly, the received bit values are estimated using a hard decision boundary, and signal metrics including the bit error ratio (BER) and error vector magnitude (EVM) are calculated. For further details on the DSP used in this work the reader is referred to our previous publication [7].

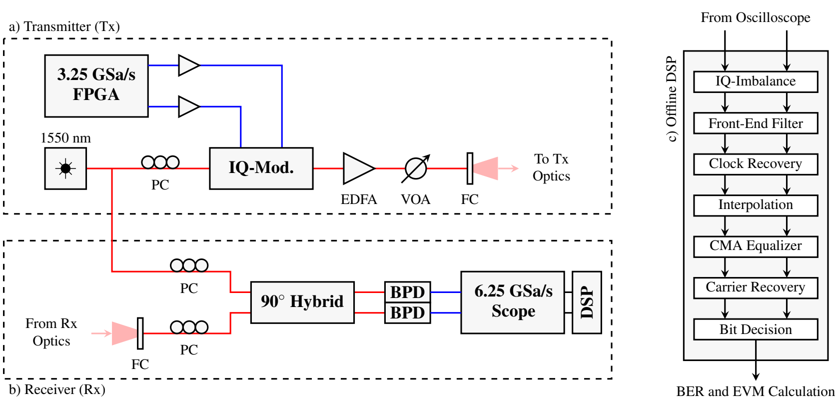


Fig. 2: a) and b) Schematic of coherent optical communications transmitter and receiver hardware. c) Offline digital signal processing (DSP) blocks applied to received signal to extract data bits and compute signal metrics. Analog electrical signals are represented by blue lines, single-mode fibre (SMF) coupled optical signals by red lines, and free-space optical signals by shaded red areas. PC = Polarization Controller, EDFA = Erbium Doped Fibre Amplifier, VOA = Variable Optical Attenuator, FC = Fibre Collimator, BPD = Balanced Photodetector.

## 4. Data Transmission Results

We present here the first coherent data transmission results which were achieved on the 20th of November 2020. A known pseudorandom bit sequence containing $2^{11} = 2048$ bits was generated and encoded in a complex QPSK waveform in software. The waveform was four-fold oversampled and spectrally shaped using a root-raised cosine filter with excess bandwidth factor $\beta = 0.5$. The signal was stored in FPGA memory and generated using the FPGA's digital-to-analog converter running at a sample rate of 3.25 GSa/s per channel, which corresponds to a symbol rate of 812.5 MHz. The electrical signal was then amplified and used to drive the electro-optical IQ modulator. When driving the modulator, the same 2048 bit sequence was continuously repeated such that a large number of bits could be recorded and analyzed. The power launched from the single-mode fibre to the transmitter optics was 100 mW. The received signal was then coupled back into a single-mode fibre and demodulated as described in Sections 2 and 3. The resulting electrical signals were digitized at a sample rate of 6.25 GSa/s per channel, which corresponds to an oversampling ratio greater than 7. Each recording contained $2^{17} = 1311072$ samples representative of over 30000 bits. The stored waveforms were then processed using the offline DSP described in Section 3. Figure 3 depicts a constellation plot of the received 1.625 GBit/s QPSK signal after offline DSP has been applied. The received signal verifies the first successful transmission of coherent data over the 800 m free-space optical link.

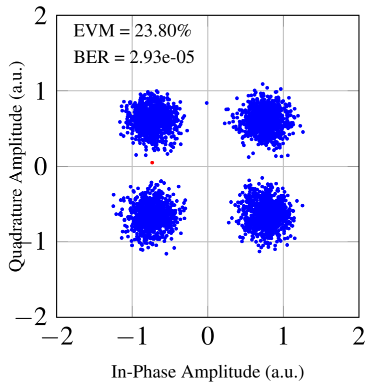


Fig. 3: Constellation plot of received 1.625 GBit/s QPSK signal transmitted over 800 m free-space link. A single bit error (red point) was measured in the transmission of over 34000 bits.

## 5. Conclusion

We have successfully demonstrated GBit/s data transmission using coherent optical modulation over an 800 m urban path. In the future we plan to carry out extensive studies on the effect of atmospheric turbulence on the performance of the communications system, and investigate strategies for turbulence mitigation.


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