Efficient Free-Space Multi-Spatial-Mode Optical Communication

Edwin Ng
Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139
(Dated: October 15, 2012)

The following is a proposal for a senior thesis project submitted to the Department of Physics for approval. The proposed project will be in experimental optics, with the aim to demonstrate efficient free-space communication at the single-photon level using multiple spatial modes.

I. INTRODUCTION AND MOTIVATION

Information can be transmitted via photons by encoding it within the various physical properties of the photon, such as its frequency, polarization, spatial mode, etc. Practical communication using photons requires the development of an efficent, scalable protocol for encoding information in these physical resources and then transmitting this information efficiently across a physical channel. Two important measures for determining the efficiency of a given scheme are the (photon) *information efficiency*, which is the amount of information encoded in a photon (in bits/photon), and the *spectral efficiency*, which is the rate of information transfer over a given bandwidth (in bits/s/Hz).

These two measures of efficiency are often at odds, but one interesting way to increase the information efficiency without sacrificing spectral efficiency is to perform spatial pulse-position-modulation (spatial-PPM), in which the transmitter has the ability to send a photon in one of several spatial modes. This photon can then travel in this spatial mode through free space to be received by a detector, which then registers the spatial mode of the photon. The implementation and efficiency assessment of a spatial-PPM protocol for transmitting information using 1550 nm photons is the basis of this experimental project.

In addition to the intrinsic efficiency of a protocol, however, the physical channel also introduces errors and losses which must be circumvented using error-correcting codes. To implement these codes, it is necessary to determine the kind of physical errors—overlap of spatial modes, crosstalk at the transmitter and receiver ends, etc.—that are to be encountered. Precise characterization of these errors and the implementation of error-correcting codes will be central to the design and assessment of this protocol.

II. SCOPE AND IMPLEMENTATION

This project will be supervised by Dr. Franco N.C. Wong and Dr. Zheshen Zhang in the Optical and Quantum Communications Group at RLE. The work done in this thesis will also form part of the effort for the PIECOMM (Photon Information Efficient Communication) project, a collaboration between MIT and Raytheon BBN Technologies under the DARPA funded InPho (Information in a Photon) program.

The transmitter design consists of a 16-channel 4×4 fiber-coupled microlens array. Channels are selected using a series of high-speed optical switches driven by electronics that implement both the messages sent and the appropriate error-correcting codes. The channels determine the spatial modes of the photons that are sent through the array. Free-space optics then carries the photons through a scalable system towards the detector.

The detector design is under development by Prof. Karl Berggren's Quantum Nanostructures and Nanofabrication Group at RLE. The design consists of a free-space-coupled array of superconducting nanowire single-photon detectors (SNSPDs), with a readout registering the firing element and thus pinpointing its corresponding spatial mode.

III. PROGRESS AND GOALS

My involvement in this project began through a summer 2012 UROP and continues through a UROP this fall, to be followed by thesis credit units in the spring. Some of the achievements to date have been:

- Implementation of signal chain for two-pulse spatial-PPM scheme (8×8 symbols)
- Characterization of switch and transmitter crosstalk
- Determination of spatial-mode leakages for large and small beam separations
- Implementation of dynamic switch driving up to 10 kHz
- Demonstration of transmitter-receiver coupling through free-space optics using time-tagged photons

Some tentative, specific goals for this project will be:

- Increase the rate of dynamic switching control to the 10 MHz limit of the optical switches
- Explore alternative spatial-PPM techniques for better scalability (e.g., digital micromirror devices)
- Characterize crosstalk and leakages for entire transmitter-receiver coupled system
- Implement error-correcting codes and assess their effectiveness
- Determine the overall efficiency of system against theoretical predictions

Ideally, this thesis will follow the PIECOMM project through a self-contained proof-of-concept demonstration experiment which involves all aspects concerned—transmitter design, error-correction, free-space coupling, detector readout, and assessment of efficiency against theory—from which meaningful physical and information-theoretic conclusions can be drawn.