SeaQuaKE: Sea-optimized Quantum Key Exchange

Technical Progress Report No. 1

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14. ABSTRACT

This is the 1st quarterly Technical Progress Report summarizing progress on the Sea-optimized Quantum Key Exchange (SeaQuaKE) project, which is led by Applied Communications Sciences under the ONR Free Space Optical Quantum Key Distribution Special Notice (13-SN-0004 under ONRBAA13-001).

In this technical report, we describe our first steps towards developing the hyperentanglement source architecture and associated mathematical model. In addition, we discuss our initial progress towards the free-space quantum channel model and planning for the experimental validation effort.

15. SUBJECT TERMS

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1 Summary

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2 Introduction

The objective of the ONR SeaQuaKE project is to optimize the performance of free-space optical (FSO) quantum key distribution (QKD) operating under challenging maritime atmospheric conditions. In particular, a modeling framework will be developed to guide optimization of the *system operating wavelength* in order to maximize throughput and/or transmission distance over a wide range of atmospheric conditions. The framework will consider the major components of the quantum communication system including the transmitter, quantum channel, and receiver elements. Applied Communication Sciences (ACS) will focus its efforts on the transmitter and receiver elements, while Stevens Institute of Technology (SIT) will focus their effort on the free-space channel.

The focus areas at the start of the program include the hyperentanglement transmitter model and free-space channel loss model, which are being led by ACS and SIT respectively. Preliminary steps towards developing these models have been taken in this first quarter of the project, as described below.

3 Methods, Assumptions and Procedures

3.1 Source Architecture and Modeling

We are assuming the use of a hyperentanglement-based source to serve as the primary transmitter element of the quantum communications system. Such a source allows for entanglement in multiple degrees of freedom, resulting in potentially greater throughput per entangled photon pair compared to alternative sources that encode in only a single degree of freedom. In addition, the use of entanglement-based system versus a prepare-and-measure quantum communications approach can simplify the need for high-speed random number generation. The two degrees of freedom we will focus on in our study include polarization and time-bin, both of which can be carried, at least in principle, within a single spatial mode of an optical waveguide. Higher order spatial modes (e.g. orbital angular momentum), on the other hand, will not be considered, at least initially, due to the challenges that harsh atmospheric propagation environments present for such signals [1].

The focus of our source effort is to understand the critical components and key performance parameters that vary as a function of system operating wavelength. As shown below, the hyperentanglement source can be broken down further into three smaller subsystems, including the pump source, time-bin multiplexer, polarization entanglement & pair generation elements. Also shown are some of the relevant parameters in each of these subsystems.

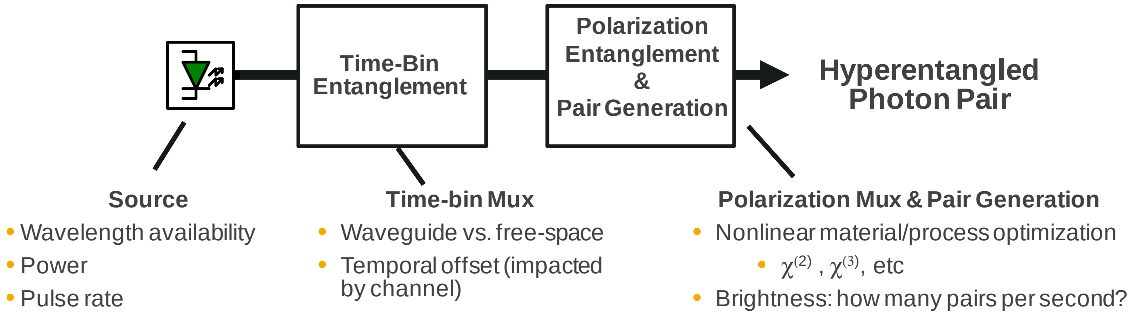

Figure 1: Block diagram of a hyperentanglement source with time-bin and polarization degrees of freedom

The approach we are taking in the development of a hyperentanglement source model is to survey the current body of literature on this topic to understand architectural options, state-of-the-art performance capabilities, trends towards improved performance, as well as fundamentals limits of specific enabling technologies. It will be critically important to understand how each of these factors varies as a function of source operating wavelength. Ultimately, these factors will translate to a range of higher-level source metrics to be considered in our model including the following:

- Entanglement quality
- Pair probability
- Pump repetition frequency
- Signal-to-noise
- Mode quality

3.2 Channel Model and Validation

The channel consists of the free-space link separating the transmitter and receiver elements of the quantum communications systems. We are assuming the quantum signal may propagate through a challenging maritime environment with widely variable atmospheric conditions including haze, fog, clouds, and rain, as well as scattering and turbulence effects. We will also be considering additional sources of noise that can corrupt the quantum signal recovered at the receiver, including noise introduced by sunlight as well as blackbody radiation.

Our approach will be to build a free-space channel model with wavelength-dependent performance, starting from the most well understood atmospheric propagation effects first (e.g. absorption) and continuing to add increasing complexity to account for realistic atmospheric effects (e.g. scattering and scintillation).

The modeling effort will be supplemented with experimental measurements to validate our theory at five separate wavelength regions including 0.8 µm, 1.3 µm, 1.55 µm, 3.5 µm, and 9 µm. In order to ensure reproducible channel characteristics, loss measurements will be performed under controlled conditions using a synthetic fog generator in combination with a free-space propagation tube. Scattering measurements will be performed by measured the light detect in different directions after passing through a localized “fog” center where the aerosol distribution and concentration can also be controlled.

The theory and validated measurements for the quantum channel will eventually be used in combination with the quantum transmitter and quantum receiver models to consider not only the loss introduced by the channel but also the degradations that result on the polarization and time-bin entangled quantum states (e.g. reduction in entanglement visibility).

4 Results and Discussion

4.1 Source Architecture and Modeling

Our literature survey of hyperentanglement source technology was initiated in this first quarter of the project, and a listing of key source performance metrics has been identified. We have also begun surveying pump source technologies, including conventional DFB and mode-locked laser technologies as well as longer wavelength sources, including quantum cascade lasers (QCLs). There are no additional results to report on the source model in this first quarter of the project.

4.2 Channel Model and Validation

We've started outlining the detailed steps required for developing our theoretical scattering model and have begun planning the reconstruction and modification of the equipment setup for the experimental validation effort. There are no additional results to report on the channel model in this first quarter of the project.

4.3 Deliverables/Milestones

Date	Deliverable/Milestone	Status
June 2014	Progress Report No. 1: Year 1, 1st Quarter	✓
August 2014	Progress Report No. 2: Year 1, 2nd Quarter	
November 2014	Progress Report No. 3: Year 1, 3rd Quarter	
February 2015	Progress Report No. 4: Year 1, 4th Quarter	
May 2015	Progress Report No. 5: Year 2, 1st Quarter	
August 2015	Progress Report No. 6: Year 2, 2nd Quarter	
November 2015	Progress Report No. 7: Year 2, 3rd Quarter	
February 2016	Progress Report No. 8: Year 2, 4th Quarter	
May 2016	Progress Report No. 9: Year 3, 1st Quarter	
August 2016	Progress Report No. 10: Year 3, 2nd Quarter	
November 2016	Progress Report No. 11: Year 3, 3rd Quarter	
February 2017	Final Report	

5 Conclusions

Our SeaQuaKE project was started in this quarter, and we had our kickoff meeting with the ONR Program Manager on June 6, 2014. The ACS team has initiated a literature survey that will be used in the development of a wavelength-dependent hyperentanglement transmitter model. We anticipate completion of the source architecture within the next quarter. A subcontract was set up with Stevens Institute of Technology, who has started on the detailed planning of free-space quantum channel model including wavelength dependencies as well as the planning of the associated experimental validation setup. No problems are currently anticipated.

6 References

[1] Malik *et al.*, “Influence of atmospheric turbulence on optical communications using orbital angular momentum for encoding,” *Optics Express*, 20 (12), pg. 13195 (2012).