Bell state optimizations for reliable quantum applications

Venkat R. Dasari[a], Ronald J. Sadlier[b], Billy E. Geerhart[a], Nikolai A. Snow[a], Brian P. Williams[b], and Travis S. Humble[b]

[a]U.S Army Research Laboratory, 320 Hopkins Road, Aberdeen Proving Ground, MD 21005
[b]Oak Ridge National Laboratory, One Bethel Valley Road, Oak Ridge, TN 37831

ABSTRACT

Well-defined and stable quantum networks are essential to realize functional quantum communication applications. In particular, the quantum states must be precisely controlled to produce meaningful results. To counteract the unstable phase shifts in photonic systems, we apply local Bell state measurements to calibrate a non-local quantum channel. The calibration procedure is tested by applying a time encoded quantum key distribution procedure using entangled photons.

Keywords: Quantum Networks, Programmable Networks, OpenFlow, Controller

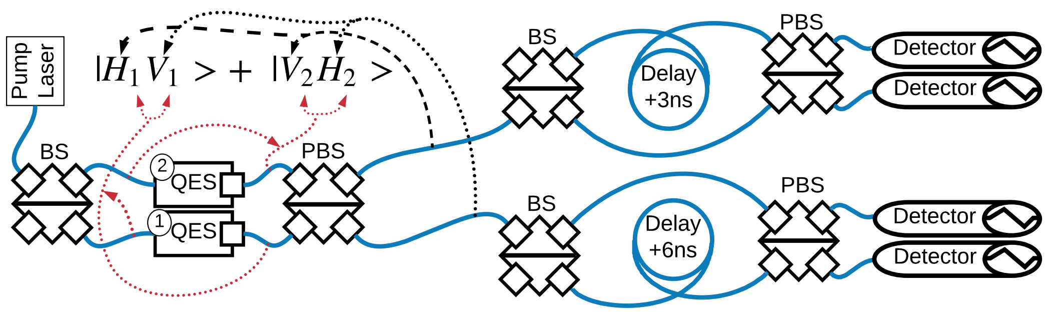

Figure 1: This schematic shows time encoded quantum key distribution in which the measurement basis is encoded into the relative time difference of the coincident photons. Note the critical points of phase control are indicated by the dotted lines.

1. INTRODUCTION

The current state of quantum applications is purpose built installations with custom protocols. Currently there is a push to make quantum applications such as quantum key distribution available to the public.[1,2] To become mainstream, many of these efforts focus on hardware implementations and software protocols to reduce the costs to the end user. Rather than focusing on optimization of hardware and software, our group has been looking at merging the quantum channel with the classical channel.[3–6] In particular, we want to leverage the research in programmable classical networks to control the quantum channel in a standardized way. The idea is that once the quantum channel topology can be controlled in a standardized way, then quantum information can be regarded as a resource that can be shared between multiple users. Further, the standardization should allow the end users hardware to be vendor agnositic which in turn should help drive down prices.

Our group has already reported on simulations of a quantum channel working in tandem with a classical channel, so our next overall goal is to demonstrate a real classical channel working in tandem with a real quantum channel. As such, the goal of this project is to create a well defined photonic quantum channel by performing calibrations that use local measurments as well as using active feedback to prevent the quantum phase from drifting. The motivation for these calibrations is to demonstrate a quantum key distribution method which uses entangled photons prepared in a Ψ Bell state. Certainly there are many QKD protocols that could be used,[7–10] but we would prefer to use a distribution method that is just a variation of the BB84 protocol in which one of the entangled photons is sent to Alice and the other is sent to Bob.

Further author information: (Send correspondence to Venkat R.Dasari)
Venkat R. Dasari.: E-mail: venkateswara.r.dasari.civ@mail.mil, Telephone: +01-410-278-2846
Travis S. Humble: E-mail: humblets@ornl.gov, Telephone: +01-865-466-3257

	Alice's Basis	*Bob's Basis*	Ψ_{final}	*measurement*
Ψ^+	0^o	0^o	$(\lvert HV\rangle + \lvert VH\rangle)/\sqrt{2}$	complementary
	45^o	45^o	$(\lvert HH\rangle - \lvert VV\rangle)/\sqrt{2}$	symmetric
	0^o	45^o	$(-\lvert HH\rangle + \lvert HV\rangle + \lvert VH\rangle + \lvert VV\rangle)/2$	random
Ψ^-	0^o	0^o	$(\lvert HV\rangle - \lvert VH\rangle)/\sqrt{2}$	complementary
	45^o	45^o	$(\lvert HV\rangle - \lvert VH\rangle)/\sqrt{2}$	complementary
	0^o	45^o	$(-\lvert HH\rangle + \lvert HV\rangle - \lvert VH\rangle - \lvert VV\rangle)/2$	random

Table 1: This table demonstrates how the measurement correlation depends on the sign of the Bell state created. Specifically the Ψ^+ and Ψ^- states produce different behavior when measured in the $45^o \otimes 45^o$ basis; this means care must be taken to maintain the sign of the Bell states.

Both Alice and Bob choose to randomly measure their photons in either the 0^o basis or the 45^o basis, and due to quantum correlations Alice and Bob will share a bit of information whenever they choose to measure in the same basis. To use only the four detectors available to us, the basis used by each user can be time encoded into the coincidence signal using a beam splitter combined with asymmetric time delays (see fig. 1). However; the quantum correlations used to assign bits to the secret key are highly dependent on the sign of the Bell state that was received by Alice and Bob (see table 1), which is unfortunate as the sign can be changed through thermal expansion of the optical fiber. The phase sensitivity can be seen by looking at the quantum state in fig. 1 where one photon is handed to Alice and one photon to Bob; i.e. $|HV\rangle$ represents a horizontally polarized (H) photon sent to Alice and a vertically polarized (V) photon sent to Bob. Meanwhile the source of the photons are indicated in the subscript; i.e. $|H_1 V_1\rangle$ represents the heralded photon source #1 distributing the photons to Alice and Bob. Given the quantum state outlined in fig. 1, the portion of fiber most sensitive to thermal expansion is just after the pump laser output is split using the first beam splitter. After this first beam splitter the thermal expansion will create an increasing path length difference on a single heralded photon source which in turn applies a phase to just one term in the quantum state in fig. 1; at this critical portion small temperature variations lead to large phase shifts between the two terms of the quantum state. The portion least sensitive to thermal expansion is after the photons are handed out using the first PBS. Once handed out, an increasing path length for one output arm will create a phase shift in both terms of the quantum state, but this doesn't affect the relative quantum phase between the two terms in the quantum state which in turn doesn't affect the physical observables. However; thermal expansion in the output fibers actually creates both an increasing path length due to the fiber being longer as well as a relative path length difference due to the birefringent fiber being longer; this increased relative path length difference due to the birefringent fiber changes the phase even after the photons are handed out albeit at a reduced rate in comparison to the critical portion. The thermal expansion before and after the photons are handed out causes a drifting phase shift which in turn changes the correlation results for the proposed QKD method. Given the sensitivity to phase, the goal of this project is to demonstrate a well defined quantum channel by calibrating and stabilizing the quantum correlations for 45^o measurements between two users.

2. QKD HARWARE CALIBRATION AND STABILIZATION

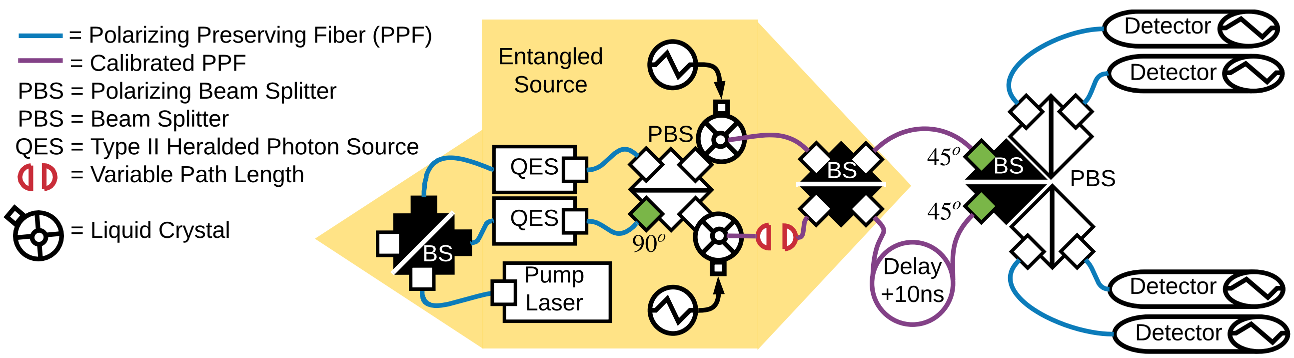

Figure 2: This shows the experimental setup used to verify the correlations in the 45^o basis.

The schematic shown in figure 2 is used to verify the 45^o correlations. Each QES produces an HV photon pair which is then entangled into a Ψ state using a PBS. The phase is controlled by two orthogonal liquid crystals on the output of the PBS. Each user has two PBS's to change the relative path length of the vertical polarization which is varied to erase measurments made by the birefringent fiber. As there was only one 45^o measuring device available, each user had to use the same 45^o measuring device, but this was only possible by adding a 10ns delay for one user to prevent photon interactions at the final beam splitter.

Once the schematic in figure 2 is set up, calibrations must be performed to ensure quantum correlations between the end users. The problem is the birefringent fiber seperates the horizontal and vertical polarized photons which in effect measures the polarization of the entangled photons in the 0^o basis. The purpose of calibration is to erase this measurement by erasing the timing information encoded in the relative spatial displacement of the photons. For the birefringent fiber on the QES, the timing information can be erased by pairing up the fast photon of one QES with the fast photon of the other QES; this is achieved by rotating one of the fiber inputs of the first PBS by 90^o so that the fast photon of one QES will go straight through the PBS while the fast photon of the other QES will be reflected to the same fast path. Once paired into fast and slow photons the system is coherent, but the remaining birefringent fiber also needs to be calibrated to prevent the quantum state from collapsing; this calibration can be done by splicing each fiber in the middle and mating them at 90^o to ensure symmetry between the horizontal and vertical photon paths.

Although calibration ensures a coherent quantum system, hardware stabilization must be performed to control the phase of the entangled photons. The test bed for this project was simple enough that two liquid crystals attached to the output of the first PBS could control the 45^o correlations (see fig. 2). Both liquid crystals are aligned in the 0^o basis, but one liquid crystal is orthogonal to the other. Given there are two degrees of freedom, one for each liquid crystal, there are two modes of operation: an anti-symmetric mode where one liquid crystal applies a phase shift in the opposite direction of the other liquid crystal, and a symmetric mode where both liquid crystals apply a phase shift in the same direction. Although there are two degrees of freedom, the anti-symmetric mode is not needed since the phase of one liquid crystal will cancel the phase of the other liquid crystal for this mode. Given one degree of freedom is wasted, the main benefit of two liquid crystals is a roll over event occurs after every two revolutions of phase change rather than every one revolution for a single liquid crystal.

3. RESULTS AND DISCUSSION

Originally the idea was to use the last beam splitter on the entangled source as a filter; by using a HOM inteferometer we could ensure only Ψ^- states were being sent to the detectors. However; early results showed the 45^o correlations were independent of the Ψ oscillation. Rather than give up, we decided to continue by adding two liquid crystals to control the input phase which we could detect by observing if two photons were sent to each user or if two photons were sent to one user. We built active feedback control software to force one photon to one user and the other photon to the other user (see figure 3). The A-B graphs of figure 3 show that we were successful in controlling the input Ψ phase, but figure 3-C shows that the early results still held: the 45^o correlations for each user were changing despite the input Ψ phase being controlled. Despite the negative results, this problem inspired a synchronization procedure wherein each user performs local synchronizations that lead to a global synchronization (see section 4).

The early control software was written in python while the data collection was done through a server written in C that collected data through an integrated FPGA on a Zedboard. The interface between the python code for control and the C code for data collection introduced latencies that were almost too high for the control code to work with. To reduce latencies, we incorporated the data collection and control software into a single C++ program. Even in the same program we had each module running in its own thread; e.g. the data collector was always connected to the Zedboard through ethernet and constantly collected data, the control software constantly made decisions on how to make changes to the phase based on the collected data, and a local server was always ready to divey out data to anyone that requested it as well as to perform data analysis every 0.1 seconds and write the results to a file. The early control software written in python worked, but the decisions being made to change the phase weren't as clear as the later control software written in C++; specifically the data collection being stored at a 10Hz sample rate allowed us to see what the trends in the output were despite decisions being made at only a 2Hz sample rate.

The control software itself made decisions for a biased walk based on proportionality rather than than the full proportionality-integral-derivative active feedback. The problem is we measure correlation counts while making phase changes; this means

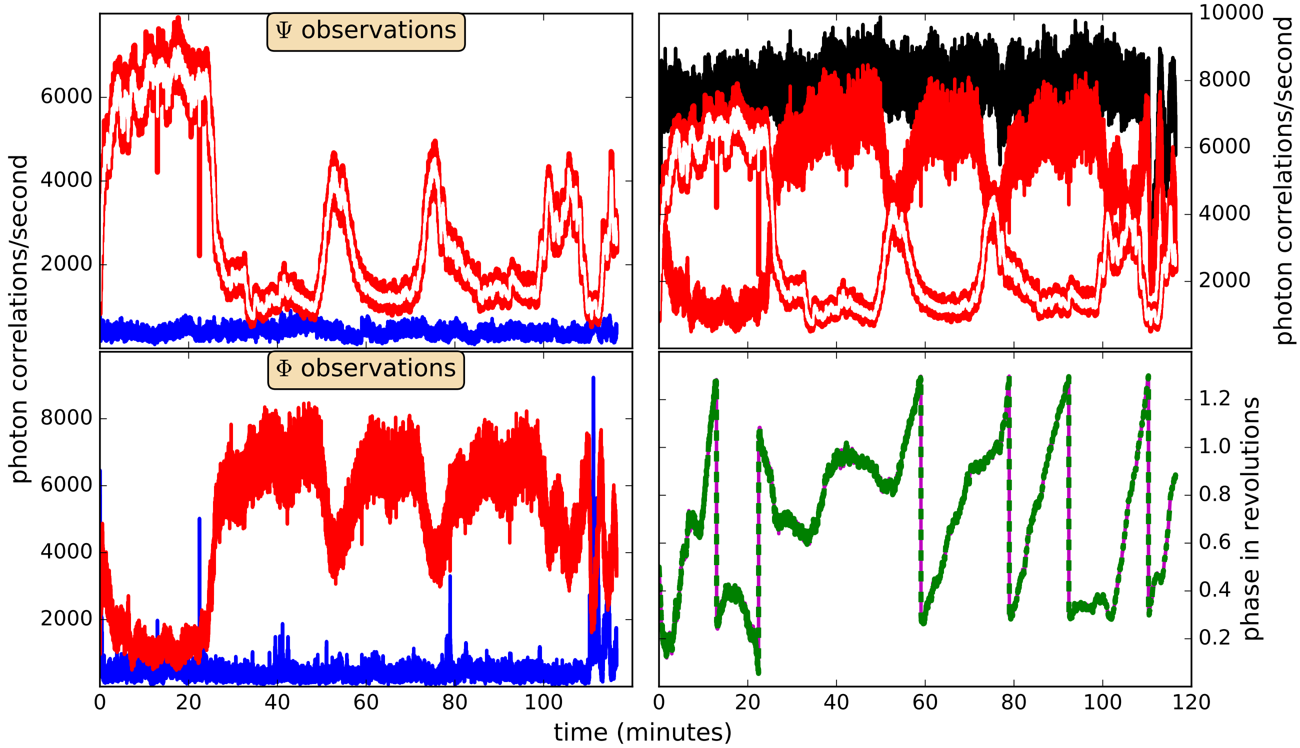

Figure 3: These graphs show phase control at last beam splitter on the entangled source, and an uncontrolled variation in the correlations at the end users. The left two graphs show the observed correlations in the 45^o basis for the case where a photon is handed out to each user (red lines), and for the case where both photons are handed to a single user (blue lines). The blue lines are low indicating control of the parity at the beam splitter. The right two plots compare variations in phase. The bottom-right plot is the applied phase which looks to have about a 10min period, while the top-right plot is the 45^o measurements which don't vary that much despite not being controlled.

the variable we are trying to control is indirectly related to the variable we are measuring. For instance, it is possible to observe a correlation count and still be uncertain about the actual phase; e.g. a maximum correlation count could correspond with a phase of $\pm 90^o$. This uncertainty in the actual phase meant we had to take a biased walk across the phase by always walking in one direction, except turning around only when the Ψ correlation counts dropped. Of course this meant the correlations counts had to drop before actually turning around. We attempted to find optimal parameters to minimize the dip in correlations. We found a very unstable phase required a high sample rate for decisions as well as requiring a relatively big dip before turning around due to the low accuracy of the correlation count. Once feedback to the applied drift phase velocity through the liquid crystals was normalized to the actual average drift velocity, the biased walk could be sampled at a lower sample rate which in turn allowed the decisions to be based on a smaller dip due to the increased accuracy of the correlation counts. Trying optimize for stability was a bit hard due to multiple sources of temperature variations in the lab. As such, the stability problem could be made much smaller by using more thermal insulation to keep temperature variations to a minimum.

4. CONCLUSION

Our goal was to create a well defined quantum channel to test protocols and network abstractions to merge a quantum channel with a programmable classical channel. We were only partially successful since we did control the phase of a psi state interacting at a beam splitter; from the photon pair we were able to send one photon to each user. However; the output correlations for the 45^o measurements from the users varied throughout time. This problem inspired a local calibration procedure. The entangled source should create a variable ratio of Ψ^- and Ψ^+ states, and the variable source should send those states into a beam splitter at 45^o. Under rotation the Ψ^- states are unchanged, while the Ψ^+ states are converted into Φ^- states. These Φ^- states will interact with the beam splitter creating two NOON states where a random user is sent two photons that are either both horizontal or both vertical. These two NOON states can be used by a single user to determine any phase changes via quantum sensing in a single fiber. Once the users can determine phase changes as the photons travel to their destination, they can apply a local phase change using a liquid controller to force the parity of their local two photon correlations. Before hand, both users can agree on what parity they want for their local observations, and this should in turn determine the parity of their non-local observations.

5. FUTURE WORK

Attempt three local synchronizations: at the entangled source and at each end user. Verify local parity control leads to global parity control. Once we have parity control on the 45^o correlations, we can integrate the quantum channel with a programmable classical channel to test the proposed protocols and network abstractions to merge the two channels into one programmable channel.

6. ACKNOWLEDGEMENTS

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