ARL

US Army Research Laboratory

Setting Single Photon Detectors for Use with an Entangled Photon Distribution System

by Daniel E Jones, Drew Weninger, and Michael Brodsky

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

US Army Research Laboratory

Setting Single Photon Detectors for Use with an Entangled Photon Distribution System

by Daniel E Jones and Michael Brodsky
Computational and Information Sciences Directorate, ARL

Drew Weninger
Intern, US Naval Academy, Annapolis, MD

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
December 2017	Technical Report	6 June–21 July 2017

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Setting Single Photon Detectors for Use with an Entangled Photon Distribution System	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Daniel E Jones, Drew Weninger, and Michael Brodsky	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
US Army Research Laboratory Computational and Information Sciences Directorate (ATTN: RDRL-CIN-T) Aberdeen Proving Ground, MD 21005	ARL-TR-8229

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

It is often a difficult task to find the optimal operating conditions of a single photon detector (SPD). The proper use and measurement of the entangled photon pairs generated by an entangled photon pair source require at least 2 SPDs operating at their highest possible detection efficiency and lowest possible dark count rate and with the lowest amount of counts due to afterpulsing. However, tuning of the detector bias and threshold values results in a tradeoff in detector performance where increasing the detector efficiency also increases afterpulsing and the dark count rate. In this report we discuss the work of a student intern from the US Naval Academy and how he learned to optimize the detector settings to detect and evaluate the entangled photon pairs generated by an entangled photon pair source.

15. SUBJECT TERMS
single photon detectors, entangled photon pairs, quantum networks, quantum state tomography, detection efficiency, entanglement distribution

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Michael Brodsky
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	26	19b. TELEPHONE NUMBER (Include area code)
Unclassified	Unclassified	Unclassified			(301) 394-4664

Contents

List of Figures

Acknowledgments

INTENTIONALLY LEFT BLANK.

1.   Introduction

The development of quantum networks has recently become a significant goal in the scientific community due to the possibility of demonstrating network functionalities that cannot be performed using classical networks.[1,2] Quantum networks consist of many nodes connected to each other with quantum channels, which could be existing telecom fiber channels. The nodes generate, store, and manipulate quantum states such as entangled photon pairs, and the channels transport quantum states from node to node.[3,4] The primary equipment needed to construct the nodes of a quantum network include sources of entangled photon pairs and single photon detectors (SPDs). To begin building a quantum network, a fundamental knowledge of how to operate the entangled photon pair sources and SPDs is required. The proper use and measurement of the entangled photon pairs generated by an entangled photon pair source require SPDs operating with high detection efficiency, low dark count rate, and few counts due to afterpulsing. However, tuning the detector bias and threshold values results in a tradeoff in detector performance where increased detector efficiency is accompanied by increased dark counts and afterpulsing.

In this report we describe how to operate the NuCrypt entangled photon distribution system located in the US Army Research Laboratory (ARL) Quantum Network Testbed. First, we provide a brief introduction to the NuCrypt entangled photon distribution system, which consists of an Entangled Photon Source (EPS), Correlated Photon Detection System (CPDS), and 2 Polarization Analyzers (PAs). Next, we detail the process to physically set up the system and identify all equipment with the NuCrypt Entangled Photon Analyzer (EPA) software. We then explain the process required to set the bias and threshold settings of the SPDs to optimize the detection efficiency, dark count rate, and afterpulsing. Finally, we explain the process to operate the EPA software to perform quantum state tomography and two-photon interference (TPI) measurements of the entangled photon pairs generated by the EPS.

2.   Generation, Detection, and Measurement of Entangled Photon Pairs

The entangled photon distribution system utilized in the ARL Quantum Network Testbed consists of 4 primary pieces of equipment procured from NuCrypt, LLC[5] by the Quantum Network group at ARL's Computational and Information Sciences Directorate: an EPS, a CPDS, and 2 PAs. A basic diagram of the experimental setup is shown in Fig. 1.
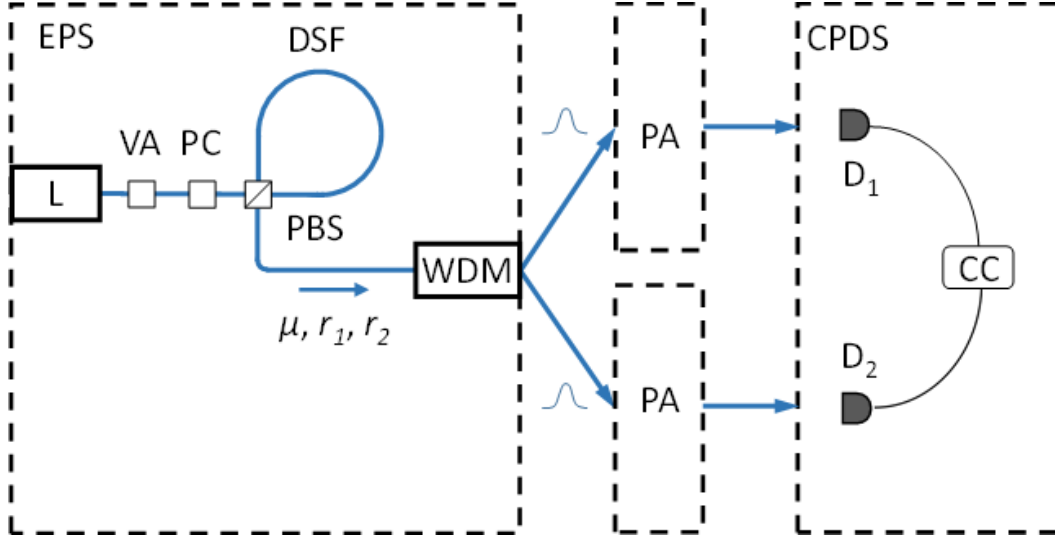
Fig. 1 **Diagram of experiment setup, which includes wavelength-division multiplexer (WDM) and coincidence counting (CC) electronics**

2.1 Generation of Entangled Photon Pairs

Various internal components of the equipment are shown in Fig. 1 to explain their basic operation; however, the majority of components are not depicted. The EPS generates photon pairs (the individual photons are denoted signal and idler) entangled in time-energy and polarization[6,7] using a 1552.52-nm pump laser pulsed at a 50-MHz rate. The laser power can be adjusted using a variable attenuator (VA) to adjust the entanglement properties of the photons generated by the EPS. After the VA, a polarization controller (PC) and polarizer are used to set the polarization of the pump laser to 45°. The 45° polarized pump is then incident on a polarization beam splitter (PBS), which transmits and reflects equal powers of horizontally (H) and vertically (V) polarized pulses in opposite directions around the loop of a dispersion-shifted fiber (DSF), which has a zero-dispersion wavelength centered near the pump wavelength.[7,8] This satisfies the necessary phase-matching conditions for 2 photons from the pump pulse to generate signal and idler pair photons with a low probability through the $\chi^{(3)}$ nonlinear process of four-wave mixing (FWM).[9]

Horizontally polarized signal and idler photons are created by the H-polarized pump pulse, and V-polarized photons are created by the V-polarized pulse traveling in the opposite direction around the loop. The PBS then sends the signal and idler photons traveling in opposite directions (H and V pairs) to the same output port. Polarization controllers are included within the DSF loop to adjust the birefringence of the fiber such that the H and V pairs arrive at the PBS at the exact same time. Since signal and idler photons are generated through FWM with a very low

probability, it is highly unlikely that a pair is created by both the horizontal and vertical pump pulses at the same time. Therefore, only one pair is output from the PBS at a given time, and the PBS eliminates all knowledge of which path was taken (i.e., the polarization is unknown), thus creating the following polarization-entangled Bell state at the output of the PBS[7]:

$$|\phi^+\rangle = \frac{1}{\sqrt{2}}(|H\rangle_s|H\rangle_i + |V\rangle_s|V\rangle_i). \tag{1}$$

The entangled photon pair is then directed to a WDM, which "chops" the broadband signal and idler spectra into 4 separate channels on the 100-MHz ITU (International Telecommunications Union) grid symmetric about the pump wavelength of 1552.52 nm (channel 31). The signal channels are channels 26–29, and the idler channels are channels 33–36. The channels are anticorrelated in frequency/wavelength due to energy conservation of the FWM process. All 8 of these signal and idler output channels are directly accessible with fiber connections on the front panel of the EPS.

2.2 Detection and Measurement of Entangled Photon Pairs

The EPS generates polarization-entangled photon pairs; however, the PAs and the CPDS are needed to detect the photons and measure their entangled properties. Upon exiting the EPS, the signal and idler photons are each sent to a PA before being detected by the gated SPDs within the CPDS. The PAs contain various waveplates and a polarizer to adjust the polarization of any incoming light signal. The CPDS contains all necessary electronics to record the amount of photons detected by each detector (known as single counts) and the amount of occurrences where photons were detected by both detectors at the exact same time (known as a coincidence count). This setup allows measurements to be taken in the specific polarization bases required to perform quantum state tomography and TPI measurements.

Quantum state tomography is the process by which a quantum system (i.e., entangled pairs generated by the EPS) is completely characterized by measuring many copies of the unknown quantum state.[10] For an entangled photon source such as ours, this requires measuring the amount of single and coincidence counts at 36 different polarization settings of the 2 PAs. After taking these 36 measurements, the singles and coincidence counts recorded by the CPDS are analyzed by the EPA software, and the quantum state of the generated entangled photon pairs is determined. Likewise, TPI measurements consist of adjusting the polarization of the signal to H using the PA and then measuring the coincidence counts when adjusting the polarization of the idler PA in 30° increments of the Poincare

sphere.[11,12] When measuring an entangled pair source such as ours, this results in a sinusoidal variation of the coincidence counts when plotted versus the polarization of the idler PA. After performing the measurements with an H-polarized signal, the signal polarization is adjusted to a right-circular polarization (R) using the PA, and the idler polarization is once again rotated in 30° increments while measuring the coincidence counts.

3.   Experiment Procedure

3.1 Physical Setup of Equipment and Identification with EPA Software

To set up the entangled photon distribution system, the EPS, CPDS, and PAs must first be connected to a laboratory computer installed with the NuCrypt EPA software via USB cables. Next, the EPS, CPDS, and PAs must be appropriately connected using optical fibers and SubMiniature version A (SMA) cables as shown in Fig. 2. To simplify the diagram, only ports that are actively used for the purpose of this report are shown. Before each fiber connection is made, the optical fiber patch cord that is used to connect the 2 ports must be properly cleaned using a fiber cleaning device such as the Optipop R optical connector cleaner.[13] The fiber tip also must be examined and determined to be defect-free using an optical fiber microscope so that a sufficient connection is made between the 2 optical fiber ports. To detect 2 photons of an entangled pair, specific output channels of the EPS are used. The correlated pairs to be used are the following: 28/34, 29/33, 27/35, and 26/36 (Fig. 2). If other combinations of 2 channels are used, the resulting measurements performed will show no evidence of entanglement.
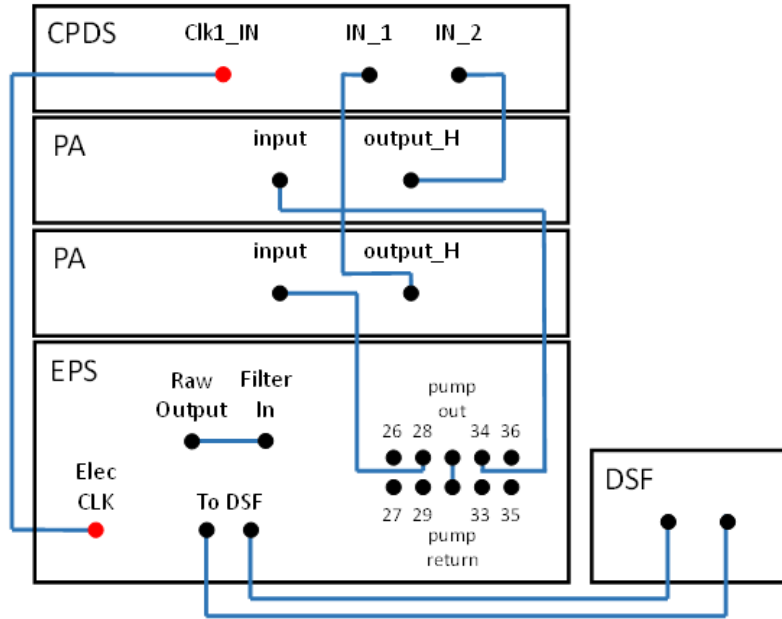
Fig. 2   Diagram of how the equipment is connected: red dots represent electrical ports to be connected by SMA cables, and black dots represent fiber ports to be connected by optical fibers

After physically connecting all of the ports, the EPA software must be opened on the laboratory computer. For the computer to recognize all of the equipment, the user must hit the "identify" button in the devices panel of the EPA user interface. Then, graphical depictions of the EPS, CPDS, and PA should be labeled with the serial numbers of the equipment that is connected to the computer via USB. Verify that all equipment was detected by the EPA software and that all serial numbers listed on the EPA interface match the serial numbers of the actual equipment. If any piece of equipment is not properly identified, verify that the equipment is indeed powered on and properly connected to the computer before re-identifying the equipment with the EPA software. If all equipment is properly identified by the EPA software, set the detector parameters.

3.2 Setting Detector Parameters for Optimal Performance

The NuCrypt CPDS in the Quantum Networks Testbed contains 2 single photon avalanche detectors (SPADs), a specific type of SPD. The basic operation principle of a SPAD is that the diode is kept at a user-specified bias voltage until a gate pulse (in our case, supplied by the electrical clock output of the EPS) is received, which raises the diode voltage by a set amount over the breakdown voltage. The breakdown voltage of a SPAD is the voltage at which increasing the diode voltage causes the diode to "break down", triggering the output of a large avalanche voltage pulse. By increasing the diode voltage above the breakdown voltage, any small

voltage change in the diode (as small as that provided by one photon incident on the detector) triggers an avalanche pulse. This output avalanche pulse is then compared with the user-determined threshold voltage, and if the output voltage exceeds the threshold value, the detector "clicks" (i.e., the detector registers that it received a photon). For more details, see Cova et al.[14] and the NuCrypt CPDS documentation.[15]

Therefore, to set the SPDs of the CPDS to their optimal operating conditions, the bias and threshold values must be adjusted by the user to maximize detection efficiency and minimize the dark count rate and afterpulsing (specifications provided by NuCrypt quote approximately 20% detection efficiency, dark count rates on the order of 10^{-5} per gate pulse, and afterpulsing <4%). As mentioned in Section 2, it can be tricky to find the optimal operating conditions because increasing the detection efficiency also increases the dark count rate and counts due to afterpulsing.

A new CPDS is initially set so that the detector bias is close to the breakdown voltage, meaning that many dark counts occur because they are due to spontaneous voltage variations that exceed the breakdown voltage. To properly adjust the detector bias and threshold values, the user must use the following procedure:

1) Make sure that no light is incident on the detector. Next, the user must open TeraTerm on the computer connected to the CPDS. TeraTerm is a program that directly controls the CPDS in a manner similar to the command prompt on a computer. From the main menu of the TeraTerm window, type "5" to start the detector in "continuous mode". In this mode TeraTerm constantly outputs the number of detections registered by the detector per the user-defined number of gate pulses.

2) Type "<" to lower the bias voltage so that the detector never breaks down (i.e., there are no counts [continuous mode constantly outputs zero]). Once you have reached this bias voltage, press the space bar to stop lowering the bias voltage.

3) Set the threshold so that the count rate is approximately 10^{-5} per gate (10 counts per million gates). The threshold value is adjusted by typing "+" (to increase) or "−" (to decrease). Similar to adjusting the bias voltage, pressing the space bar will also stop changing the threshold value. After reaching the desired threshold value, type "e" to exit continuous mode and return to the main menu.

4) Type "6" to scan the gate phase of the detector. This command scans the detector over a small amount of time and outputs the number of counts at

each "gate phase" (time value). Ideally, the number of counts for all phases would be the same value of approximately 10^{-5}; however, this is unlikely after the first attempt. There will likely be some phase values where there are very many counts and others where there are very few counts. Type "m" to set the detector to the gate phase at which the maximum counts were measured. Now repeat step 3 and rescan the gate phase until there are no longer any phases that result in a large number of counts. This step is crucial because the large counts would be mistaken for light pulses if the threshold is not adjusted properly to reduce them.

5) Return to the main menu by typing "e" and put the detector in continuous mode once again by typing "5". Now raise the bias by typing ">" until the count rate reaches the recommended dark count rate of approximately 10^{-4} per gate (100 counts per million gates). Type "e" to return to the main menu.

6) Type "6" to scan the gate phase again and confirm that there is very little variation in the count rate. There should not be any phase values with a large number of counts that could be mistaken as a light pulse.

7) Connect a pulsed photon source to the detector and scan the gate phase by pressing "6". When a light source is connected to the detector, a peak in the counts at a certain gate phase signifies that the pulse arrives at the detector at the same time as the time represented by that value of the gate phase. Obviously, we want to set the detector phase such that it "sees" the incoming pulse, so type "m" to select the gate phase that maximizes the count rate. The pulsed photon source that is used for the purposes of this report is one of the signal or idler channels of the EPS. See Section 3.3 to determine how to operate the EPS and generate the entangled photon pairs.

8) To verify that the detectors are indeed optimized, the user must directly measure the efficiency with a calibrated measurement device.

   a. To do this, assemble a system of fiber couplers and attenuators such that an incoming signal is almost entirely transmitted through one output but experiences >50 dB of attenuation through another output. This is done by cascading a 99:1 fiber coupler with >30 dB of additional attenuation at the 1% output of the fiber coupler. This is required so that the power of the high-transmission channel can be measured with a power meter without sending too strong of a signal to the SPD (which will be placed at the output of the attenuated channel).

b. Measure the relative transmission of the attenuated channel and the high-transmission channel using a high-power light source and a sensitive power meter (able to measure signal powers of approximately −80 dBm).

c. Connect the "residual pump" port of the EPS to a variable attenuator and connect the variable attenuator to the input of the attenuated fiber coupler system built in step 8a. Connect the high-transmission output to the same power meter used in step 8b and connect the attenuated output to the SPD being tested.

d. Adjust the variable attenuator so that the power measured by the power meter corresponds to an average of one photon incident on the SPD. The power value that corresponds to an average of one photon incident on the SPD can be easily calculated from the equation for the energy of one photon, the number of photons incident on the power meter, and the relative transmission of the high-transmission path and the attenuated path of the system built in step 8a (measured in step 8b). The energy of one photon is given by $E = \frac{hc}{\lambda n}$, where h is Planck's constant, c is the speed of light, λ is the wavelength, and n is the refractive index of silica fiber. The number of photons incident on the power meter is given by $N_{PM} = \frac{P}{f_{rep}\, E}$, where P is the reading on the power meter and f_{rep} is the frequency (repetition rate) of the residual pump of the EPS (50 MHz).

e. Measure the number of single counts detected by the SPD and divide this by the number of detection gates to determine the efficiency of the SPD. Also measure the dark count rate and the afterpulsing using the EPA software.

f. Verify that that the detector is operating with approximately 20% efficiency, $<10^{-4}$ dark counts/gate, and <4% afterpulsing. If the detector does not perform to these specifications, make slight changes to the detector bias and threshold values to improve the performance.

3.3 Operation of Entangled Photon Distribution System with EPA Software

Now that the detector bias and threshold values have been set, return to the EPA interface to operate all components of the entangled photon distribution system.

1) Properly adjust the pump polarization to 45° by clicking the "eps init" (short for initialize) button on the EPA user interface. When the EPS is first powered on, the laser polarization is set to some default value not equal to 45°. To properly generate the entangled state of Eq. 1, the pump must be 45°, as explained in Section 2.1. By clicking the "eps init" button, the EPS automatically adjusts the internal PC (Fig. 1) and monitors the power of the EPS after the PBS. The PC is adjusted until the power is maximized, signifying that the polarization has been properly adjusted. The message panel on the EPA interface will display a notification when the adjustments are complete. The power reading on the front panel of the EPS will also reach its maximum value after initializing, at which point the power of the EPS pump laser will be set to a value of 3600 in the EPA software. The practical range of powers that can be set using the EPA interface ranges from 3000 to 3600, corresponding to a peak power of approximately 5–150 µW (measured at the raw output port of the EPS).

2) Set the number of detection gates (measurement time) to 1 million gates using the "gates" text box on the EPA interface and click the "other CPDS ctl" button to open a new window of the EPA interface. From this window, the bias, threshold, gate phase, and delay of one detector relative to the other can all be adjusted. Click the "gate phase" button for channel 1 to scan the gate phase of detector 1. This ensures that the detector is measuring the incoming signal or idler photons at the same time that they are arriving. Repeat this step for channel 2 to set the gate phase of detector 2 as well.

3) Delay channel 1 so that the photons arrive at both detectors at the same time. For technical reasons, channel 2 of the CPDS is delayed relative to channel 1; therefore, channel 1 must be delayed with the EPA software for coincidences to be measured between photons incident on detectors 1 and 2. In the "synchronization" tab of the "Other CPDS Control" panel, check the boxes to maximize correlation c_{12} and to delay channel 1. Now set the number of gates to 10 million and click the "search" button. This adjusts the delay of channel 1 over 20 different values and measures the coincidences of detectors 1 and 2 for each delay in order to set the delay such that the maximum possible number of coincidences are measured between detectors 1 and 2.

4) Measure the dark count rate of detectors 1 and 2 by clicking the "measure" button in the "Dark Counts" panel of the primary EPA interface. The rates for both detectors should not exceed 10^{-4} counts per gate. If so, the detector bias and/or threshold settings must be readjusted as described in

Section 3.2. The number of gates should be ≥10 million to obtain an accurate measurement. The NuCrypt entangled photon distribution system is now fully ready to operate, and measurements of the single count rates, coincidence count rate, and afterpulsing of each detector can be performed by clicking the "measure" button on the EPA interface (the results are output on the message panel of the EPA software).

5) If a TPI measurement is to be performed, the polarization of the PAs must first be adjusted to account for the birefringence of the fibers connecting the EPS and PAs. This step is not needed to perform tomography. Connect an external polarized light source to the "External Alignment Source" port of the EPS and click the "align H & D singles" button in the "Alignment" panel of the EPA interface. By doing this the PAs are automatically adjusted to various polarization settings and the single count rates of both detectors are measured for each polarization setting. The EPA software then analyzes the data and calculates the polarization transformation applied by the fibers connecting the EPS and the PAs and adjusts both PAs to invert this transform (i.e., it cancels out the transformation applied by the fibers).

3.4 Measurement of Entangled Properties of Entangled Photon Pairs

After completing the steps explained in the previous section, TPI measurements and quantum state tomography can be performed to examine the entangled behavior of the photon pairs generated by the EPS. A TPI measurement can be performed by clicking the "start" button in the "Two-Photon Interference" panel of the EPA interface. The PAs and CPDS automatically perform all required polarization adjustments and measurements (as described in Section 2) to make a sinusoidal plot of the coincidence counts as a function of the signal and idler polarization. The EPA software also automatically calculates and outputs the visibility of the TPI. The visibility is given by the following equation:

$$V = \frac{C_{max} - C_{min}}{C_{max} + C_{min}},$$ (2)

where C_{max} denotes the maximum coincidence counts measured for any setting of the idler polarization (i.e., the peak of the sinusoidal TPI curve), and C_{min} denotes the minimum coincidence counts measured for any setting of the idler polarization (i.e., the minimum of the TPI curve).

To perform tomography, check the "stack" and "max likelihood" boxes in the "Tomography" panel of the EPA interface and click the "start" button. The PAs

will automatically adjust themselves to all of the 36 polarization settings required to perform tomography (as described in Section 2), and the CPDS will record the single and coincidence counts of both detectors. The software will also perform a maximum likelihood estimation to determine the density matrix of the quantum state generated by the EPS. The raw detector measurements are automatically saved to a text file named tomoXXX (XXX corresponds to a number assigned to that data set beginning at 000 and increasing by one for each subsequent data set), and the calculated density matrix and its corresponding entanglement measures are saved to a text file named tomoXXX_Analysis. A figure is also generated that includes a plot of the elements of the density matrix and a table of the fidelity, tangle, linear entropy, concurrence, and purity of the entangled state described by the calculated density matrix. Example results of TPI and tomography measurements are shown in Section 4.

4.   Data and Results

4.1 Two-Photon Interference

TPI measurements were performed to analyze the entangled nature of the photon pairs generated by the EPS. The power of the pump laser was adjusted over the entire accessible range of powers, and the optimum power (resulting in the greatest TPI visibility) was found to be an EPA interface value of 3100 (~10 µW measured at the raw output port of the EPS). With this pump power, a TPI visibility of >85% was measured, easily exceeding the 70.7% visibility required to violate a Bell inequality for proof of polarization entanglement as seen in Fig. 3.
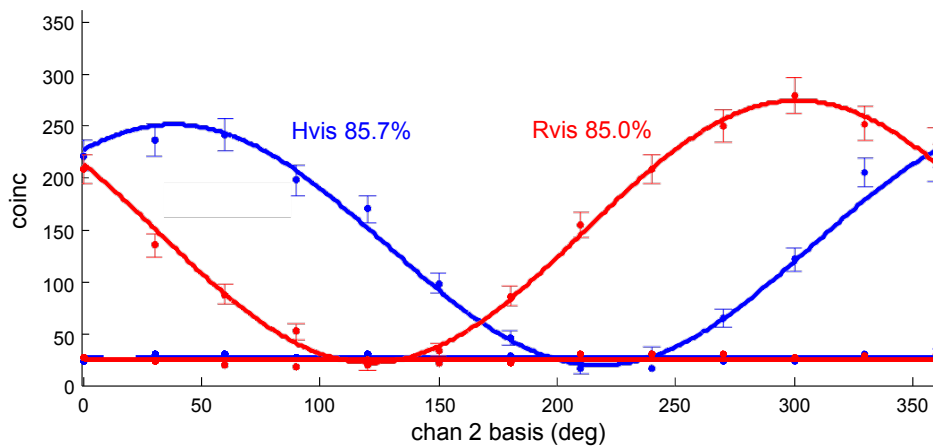
Fig. 3   Plot of coincidence counts as the polarization of the idler PA is rotated around the Poincare sphere. The TPI fringes show >70.7% visibility when the signal is horizontally (blue curve) and right circularly (red curve) polarized, violating a Bell inequality for proof of the polarization entanglement of the photon pairs generated by the EPS.

4.2 Quantum State Tomography

Quantum state tomography was also performed on the pairs generated by the EPS to determine the density matrix of the system. Once again, measurements were made over the entire accessible range of pump powers, and proof of polarization entanglement was clearly shown with raw concurrence and fidelity (compared with the Bell state given by Eq. 1) values of 0.871 and 0.934. Furthermore, the accidental-subtracted concurrence and fidelity values of 0.975 and 0.985 also show the strong polarization entanglement of the pairs generated by the EPS. The density matrix of the entangled photon pairs generated by the EPS and the relevant entanglement measures are shown in Fig. 4.


```
gates 50.000e6
coinc_max 70
epspump_pwr 3100

figures        accid     dark      raw
of merit       sub       sub       data
-----------------------------------------
fidelity:      0.985     0.951     0.934
tangle:        0.950     0.823     0.758
lin entropy:   0.032     0.115     0.158
concurrence:   0.975     0.907     0.871
purity:        0.976     0.914     0.882
```
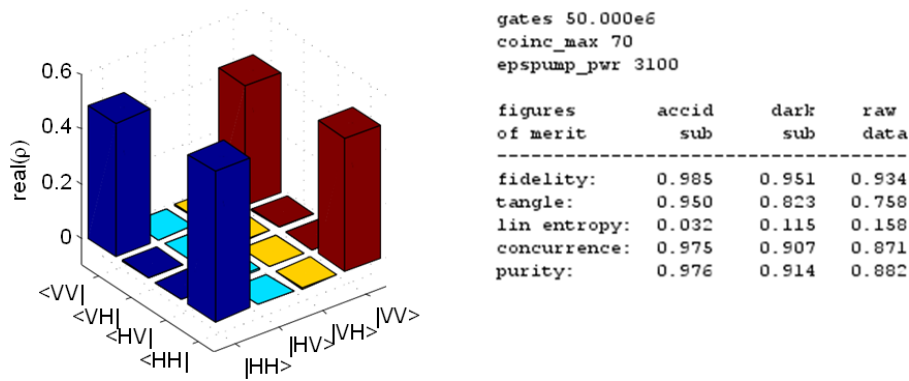
Fig. 4   Plot of the density matrix describing the quantum state of the photon pairs generated by the EPS. Various parameters are displayed in the table to show the entanglement of the photon pairs generated by the EPS.

5.   Conclusions

To efficiently operate an entangled photon distribution system, the user must optimize the performance of 2 SPDs by adjusting their bias and threshold values in order to reliably detect the photons generated by an entangled photon pair source. However, it can be difficult to optimize the 3 performance specifications of an SPD (high efficiency, low dark count rate, and low afterpulsing) because tuning the detector bias and threshold values results in a tradeoff in detector performance where increased detector efficiency also results in increased dark counts and afterpulsing. In this report we have detailed the process to optimize the SPDs used in the ARL Quantum Network Testbed in order to achieve 20% detection efficiency, $<10^{-4}$ dark counts per detection gate, and <4% afterpulsing. The steps required to generate, detect, and evaluate the entangled properties of the entangled photon pairs generated by the NuCrypt EPS were then explained, and the results of measurements performed by a student intern from the US Naval Academy (Fig. 5) were reported.

Fig. 5   Midshipman intern Drew Weninger operates the entangled photon distribution system in the ARL Quantum Network Testbed

6. References

1. Kimble H. The quantum internet. Nature. 2008;453:1023–1030.

2. Van Meter R. Quantum networking. Hoboken (NJ): John Wiley & Sons; 2014.

3. Duan LM, Lukin M, Cirac J, Zoller P. Long-distance quantum communication with atomic ensembles and linear optics. Nature. 2001;414:413–418.

4. Munro W, Harrison K, Stephens A, Devitt S, Nemoto K. From quantum multiplexing to high-performance quantum networking. Nat Photonics. 2010;4:792–796.

5. NuCrypt, LLC. Product overview: quantum optical instrumentation. Evanston (IL): NuCrypt, LLC [accessed 2017 July]. http://www.nucrypt .net/quantum -optical-instrumentation.html.

6. Kwiat PG, Mattle K, Weinfurter H, Zeilinger A, Sergienko AV, Shih Y. New high-intensity source of polarization-entangled photon pairs. Phys Rev Lett. 1995;75:4337–4341.

7. Fiorentino M, Voss PL, Sharping JE, Kumar P. All-fiber photon-pair source for quantum communications. IEEE Photon Technol Lett. 2002;14:983–985.

8. Wang SX, Kanter GS. Robust multiwavelength all-fiber source of polarization-entangled photons with built-in analyzer alignment signal. IEEE J Sel Top Quantum Electron. 2009;15:1733–1740.

9. Inoue K. Four-wave mixing in an optical fiber in the zero-dispersion wavelength region. J Lightwave Technol. 1992;10:1553–1561.

10. Altepeter JB, Jeffrey ER, Kwiat PG. Photonic state tomography. In: Berman PR, Lin CC, editors. Advances in atomic, molecular, and optical physics. Amsterdam (Netherlands): Elsevier; 2005. p. 105–159.

11. Pittman TB, Strekalov DV, Migdall A, Rubin MH, Sergienko AV, Shih YH. Can two-photon interference be considered the interference of two photons? Phys Rev Lett. 1996;77:1917–1920.

12. Collett E. The Poincare sphere: field guide to polarization. Bellingham (WA): The International Society for Optics and Photonics (SPIE); 2005. p. 10.

13. USConec Ltd. The OPTIPOP R refillable cassette cleaning tools. Hickory (SC): USConec Ltd.; 2015 [accessed 2017 July]. http://www.usconec.com/products/cleaning_tools/optipop_r_refillable _cassette_cleaning_tools.htm.

14. Cova S, Ghioni M, Lacaita A, Samori C, Zappa F. Avalanche photodiodes and quenching circuits for single-photon detection. Appl Opt. 1996;35:1956–1976.

15. NuCrypt, LLC. Correlated photon detection system. Evanston (IL): NuCrypt, LLC; 2017 [accessed 2017 July]. http://nucrypt.net/CPDS-1000.html.

List of Symbols, Abbreviations, and Acronyms

ARL	US Army Research Laboratory
CC	coincidence counting electronics
CPDS	Correlated Photon Detection System
DSF	dispersion-shifted fiber
EPS	Entangled Photon Source
EPA	Entangled Photon Analyzer
FWM	four-wave mixing
H	horizontally
ITU	International Telecommunications Union
PA	Polarization Analyzer
PBS	polarization beam splitter
PC	polarization controller
R	right-circular polarization
SMA	SubMiniature version A
SPAD	single photon avalanche detector
SPD	single photon detector
TPI	two-photon interference
USB	Universal Serial Bus
V	vertically
VA	variable attenuator
WDM	wavelength-division multiplexer

1	DEFENSE TECHNICAL
(PDF)	INFORMATION CTR
	DTIC OCA

2	DIR ARL
(PDF)	IMAL HRA
	RECORDS MGMT
	RDRL DCL
	TECH LIB

| 1 | GOVT PRINTG OFC |
| (PDF) | A MALHOTRA |

1	DIR ARL
(PDF)	RDRL CIN T
	M BRODSKY

INTENTIONALLY LEFT BLANK.