Entangled Photon Pair Source Demonstrator Using the Quantum Instrumentation Control Kit System

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***Abstract*— We report the first demonstration of using the Quantum Instrumentation and Control Kit (QICK) system on RFSoC-FPGA technology to drive the electro-optic intensity modulator that generate time-bin entangled photon pairs and to detect the photon signals. With the QICK system, we achieve high levels of performance metrics including coincidence-to-accidental ratio exceeding 150, and entanglement visibility exceeding 95%, consistent with performance metrics achieved using conventional waveform generators. We also demonstrate simultaneous detector readout using the digitization functional of QICK, achieving internal system synchronization time resolution of 3.2 ps. The work reported in this paper represents an explicit demonstration of the feasibility for replacing commercial waveform generators and time taggers with RFSoC-FPGA technology in the operation of a quantum network, representing a cost reduction of more than an order of magnitude.**

***Index Terms*— Quantum network, quantum communication, fiber optics, photon pair, C-band, FPGA, control electronics.**

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I. Introduction

QUANTUM networks hold great promise for revolutionizing the way we communicate and process information [1], [2]. They can offer unparalleled security; enable new fundamental scientific discoveries through networks of quantum sensors and quantum computers; serve critical practical solutions applications in industry such as in finance, supply chain management, or cybersecurity; and drive technological innovation and economic growth through the creation of new industries and markets.

Field Programmable Gate Arrays (FPGAs) are highly configurable hardware devices that can be programmed to perform specific tasks, making them well-suited for implementing quantum communication protocols. By using FPGAs, researchers and developers can easily reconfigure their systems to support different types of quantum operations, allowing them to rapidly iterate and improve upon their designs. FPGAs can also help improve the efficiency of quantum communication systems by offloading certain tasks from the main processor, reducing the overall cost and complexity of the system. In addition, FPGAs can support the scalability of quantum communication systems by allowing them to be easily deployed, reconfigured, and upgraded as needed.

System specific control and readout increase the functionality of quantum systems, integrate complex functions, and eliminate the bottlenecks and synchronization problems of using expensive off-the-shelf controls. In this paper we present results of a photon entanglement distribution experiment using accurate pulse generation and readout based on an FPGA with integrated analog-to-digital and digital-to-analog conversion. The control electronics is based on the open Quantum Instrumentation and Control Kit (QICK) system [3], developed at Fermilab and widely adopted for control of superconducting qubit experiments. The QICK was expanded to provide the functionality required for Quantum Networks. The board used in this experiment was the ZCU216, as it provides 10 Gsps digital-to-analog converters (DACs) and 2.5 Gsps analog-to-digital converters (ADCs).

Experimental demonstration are shown using this control system for a quantum network by producing entangled photon-pairs and measuring its entanglement quality. Through this demonstration, we show the feasibility in realizing quantum networks with nodes that are fully controllable with a single FPGA, allowing for an economical and easily deployable solution to scalable quantum networks.

II. Experimental Setup

Using a standard entangled photon-pair source, we constructed a simple demonstrator experiment illustrating the use of the RFSOC-FPGA in photonic time-bin encoded quantum networks. The same source has been used for past work ranging from demonstration of high fidelity quantum teleportation [4] to demonstration of picosecond precision time synchronization [5], [6]. The full experimental setup is shown schematically in Fig. 2. Light at 1536 nm wavelength produced by a continuous wave fiber-coupled laser is directed into a fiber-coupled Mach-Zehnder electro-optic intensity modulator (MZM) [7] to produce pulsed light.

We use time-bin quantum encoding where the two basis states are defined by the time of the detected photons as either "early" or "late". The early and late basis states are denoted as $|e\rangle$ and $|l\rangle$, respectively, and are conventionally referred to as the "z-basis". Pulses with width 100–200 ps in time are produced, with the "early" and "late" states separated by 1–2 ns. The repetition rate is set to be 100 MHz, so that each repetition is separated by 10 ns.

The MZM is driven by radio-frequency (RF) pulses generated either by a commercial arbitrary waveform generator (AWG) or by the DAC functionality of the RFSOC-FPGA, and subsequently amplified to achieve the maximum extinction ratio of the MZM. The MZM used is a lithium niobate electro-optical intensity modulator optimized for operation with 1550 nm light with 18 GHz electro-optical bandwidth and an RF V_π of about 5.5 V. The DAC sampling rate of our RFSOC-FPGA is 10 Gsps, resulting in the shortest possible pulses with a width of 100 ps. Because the bandwidth of our current setup is limited by the RF amplifier used, the shortest pulse that we can meaningfully test have width of 200 ps. Thus, we create pulses with a width of 200 ps on the RFSOC-FPGA, resulting in amplified RF pulses with a width of about 250 ps at half maximum, as shown in Figure 1. The pulsed light is directed into an erbium-doped fiber amplifier (EDFA) and then sent through a periodically poled lithium niobate (PPLN) waveguide, upconverting the 1536 nm light to 768 nm. A band-pass filter is used to remove residual 1536 nm light. Time-correlated photon pairs at the original wavelength of 1536 nm are produced through the Type-II spontaneous parametric down conversion process (SPDC) in a second PPLN waveguide receiving the 768 nm light as input.

A fiber-based polarizing beam splitter (PBS) separates the resulting pair of photons and both are directed into fiber Bragg grating (FBG) narrow-band spectral filters before they are directed into different superconducting nanowire single photon detectors (SNSPDs). These FBG spectral filters are primarily used for ensuring photon indistinguishability in Bell-state measurements when the same experimental setup is used for experiments involving quantum teleportation or entanglement swapping. For the current experiment, the FBG spectral filters restrict the bandwidth of each of the photons to about 6 GHz. The SNSPD signals are either time-tagged by a commercial time-to-digital (TDC) converter, or digitized by the ADC functionality of the RFSOC-FPGA. The SNSPDs along with the readout electronics used in this experiment have a time jitter of about 40 ps.

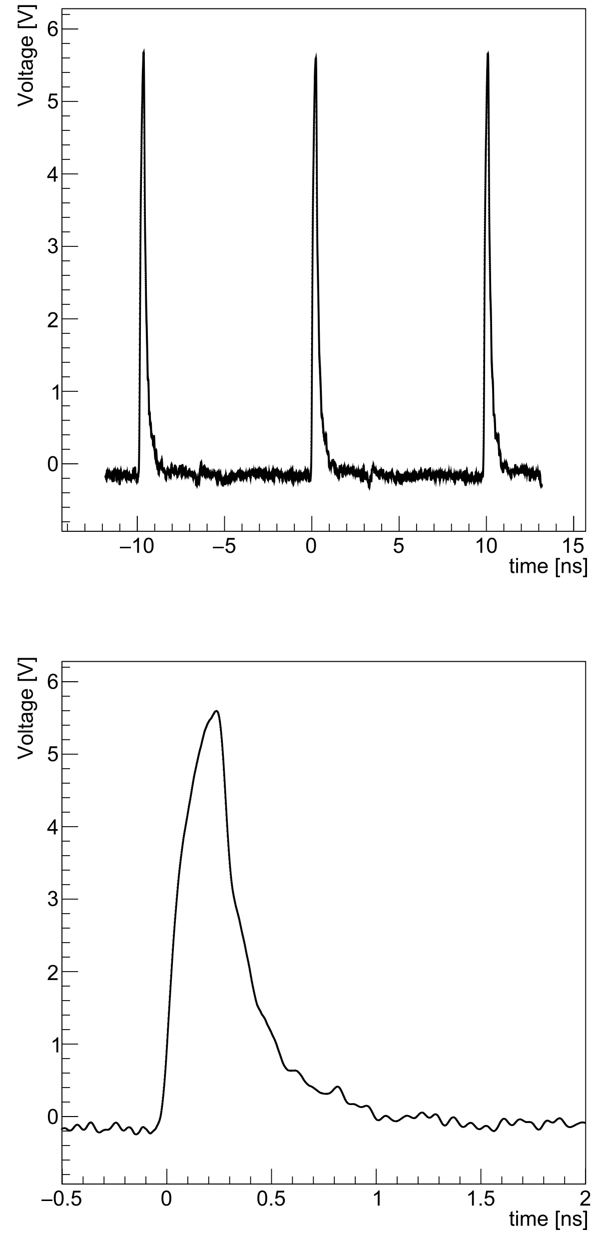

Fig. 1. Oscilloscope traces of the pulses generated by the RFSoC FPGA DAC after amplification. On the top, we show three repetitions of the same pulse structure with a rep rate of 100 MHz. On the bottom, we show a zoomed in version of a single repetition of the pulse.

We build coincidences in the detection of the photons from the two output fibers of the PBS and record the differences in their detection time. The coincidences will exhibit a main large peak representing the detection of the two photons from the same entangled pair (coincidence), and many smaller peaks separated by the repetition period, in this case 10 ns. These smaller peaks represent the detection of two photons not from the same entangled pair (accidental). The ratio between the number of coincidences to the number of accidentals is referred to as the coincidence-to-accidental (CAR) ratio, which is a measure of signal-to-noise quality of the entangled photon-pair source system. In this experiment, we use the CAR to compare the quality of the entangled photon-pair source driven by the more conventional AWG and by the RFSOC-FPGA.

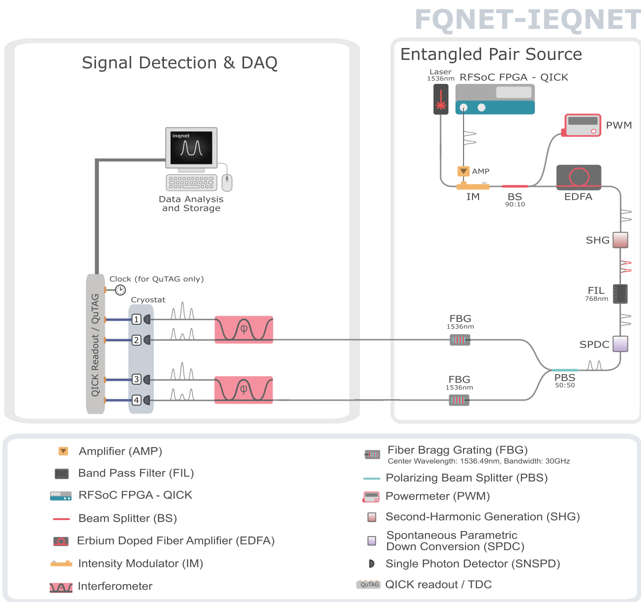

Fig. 2. Schematic diagram of the entangled photon-pair source setup used to characterize the RFSOC-FPGA QICK functionality.

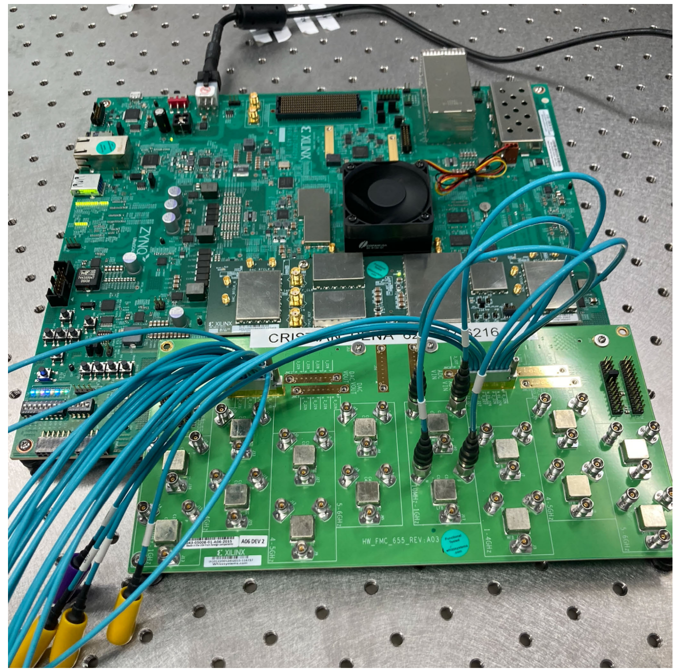

Fig. 3. A photograph of the QICK System based on Xilinx's ZCU216.

As mentioned above, in time-bin encoding we typically use the two z-basis states $|e\rangle$ and $|l\rangle$. It is also important to characterize the quality of the entangled photon-pair source in the x-basis, which refers to superposition of the two z-basis states as $(|e\rangle+|l\rangle)$ and $(|e\rangle-|l\rangle)$. Therefore, it is also important to characterize the quality of the entangled photon-pair source in the x-basis. To achieve that we use a Michelson interferometer to measure the entanglement visibility of the entangled photon-pair source in the x-basis driven by the RFSOC-FPGA. Finally, we demonstrate the use of the RFSOC-FPGA in the detection of the photon signals by comparing the CAR measured using the commercial TDC and the one measured using the custom digitizer firmware and pulse-shape reconstruction software.

III. QICK for Quantum Networks

QICK was originally developed for Superconducting Qubit experiments [3]. The first version was deployed over the Xilinx ZCU111 development board. Later it was extended to fully support ZCU216 and RFSoC 4 × 2 boards. The ZCU216 version of the QICK was selected for this experiment. This board features a Xilinx RFSoC generation 3 UltraScale+ device, and it can provide up to 16 output DACs at a speed of 10 Gsps, and up to 16 input ADCs at 2.5 Gsps, which makes this platform ideal for Quantum Networks applications. Figure 3 shows a photograph of the ZCU216 connected to the experiment.

The requirements for the control systems of quantum networks are different from those of superconducting qubit experiments. For quantum networks, very fast and short pulses need to be generated to drive the electro-optic intensity modulators used to create time-bin entangled photon pairs that are ideal for long distance fiber-based quantum networks. For this application, pulses that are 100–200 ps wide are produced, with the "early" and "late" states in the time-bin basis, separated by a time delay of about 1–2 ns. The repetition rate is set to be 100 MHz.

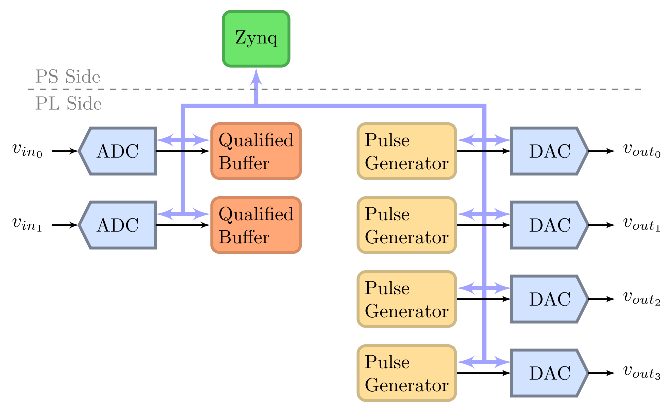

Fig. 4. Block diagram of the QICK firmware used for this entangled photon pair source demonstrator experiment. The shape of the output pulses are specified in the Pulse Generator block, which drives a DAC to produce the output pulses ($v_{out\ i}$). These output pulses are amplified and then sent to the MZM electo-optic intensity modulator to produce the desired pulsed light. The signal pulses ($v_{in\ i}$) from the SNSPDs are digitized by the ADCs and then sent to the Qualifier Buffer, which determines whether they should be saved to memory for further post-processing.

The block diagram of the FPGA firmware customized for this experiment can be seen on Fig. 4. Output pulses are specified as 32 arbitrary amplitude samples with a custom block called Pulse Generator. Samples are read circularly inside this block and sent out by driving a DAC channel, which creates the analog output signal. As seen in Fig. 4, four instances of the Pulse Generator Block were added, connecting to four independent DACs. The FPGA design was carefully done such that the four output analog signals are phase aligned. This feature allows to output multiple pulses with specific phase relationships between them.

The sampling frequency of the output DACs for this experiment was set to $f_s = 8.1$ Gsps, which gives about 123 ps per sample. This frequency was selected such that the time difference in the lengths of the two arms of the external interferometer used is an exact integer multiple of the sampling period. This is done to more accurately align the separation of the early and late pulses to the delay needed for the interferometer. The sampling frequency could otherwise be increased up to a maximum of 10 Gsps.

The repetition rate of the 32-samples pattern is programmable from 0 to 2^{32} clock ticks. This clock is related to the sampling frequency of the DAC on the RFSoC-FPGA and results in a clock tick of 1.97 ns. Thus, a maximum interval of 8.4 s can be set. A value of 0 means the pattern is repeated without any gaps. Additional wait times can be added to slow the repetition rate.

On the detection side, superconducting nanowire single photon detectors (SNSPDs) [8] produce signal pulses with amplitude between 500 and 900 mV, which are then sent to the ADC input channels of the QICK system. The sampling frequency of the ADC was set to its maximum of 2.5 Gsps. The digitized samples at the output of the ADC are sent to Qualifier Buffer blocks, as shown in Fig. 4. Although the RFSoC-FPGA allows a maximum of 16, we implemented only two such instances for this experiment. Each Qualifier Buffer block connects to independent ADC channels, to allow precision timing measurements of the incoming signals.

The Qualifier Buffer block was specifically designed to lower the FPGA memory requirements. The action of these special buffers is to compare the digitized samples with a configurable threshold. If the signal exceeds this value, pulses are captured and stored on FPGA memory. The block captures a window of samples that is configurable from the software interface and includes a portion of the pulse previous to the crossing. This information is required to perform the post-processing and compute the precise timing. The buffer block adds a time-tag to allow the measurement of signal pulses correlated across different channels. Once the signal pulses are captured, the user can retrieve the buffer information with all the pulses and time-tags for further offline processing. These offline processing routines can be easily implemented on the FPGA ARM processors to allow for continuous and real-time event count and tagging, an important next step towards operating scalable quantum networks that we leave for future work.

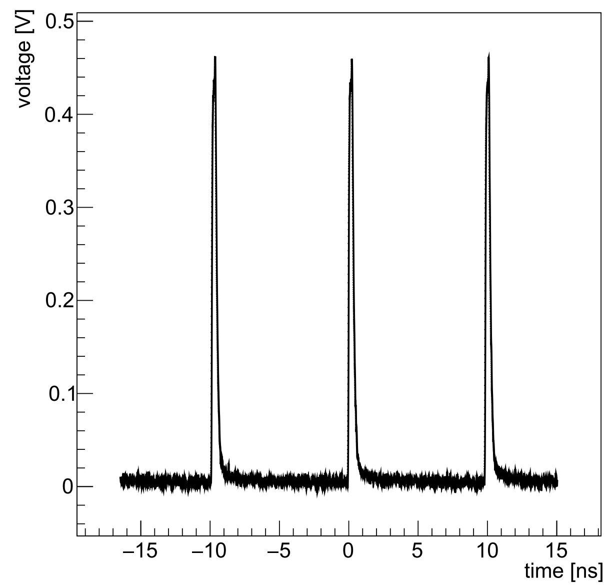

Fig. 5. Oscilloscope trace of the optical pulses at the output of the EDFA amplifier as measured by a 30 GHz InGaAs photodetector.

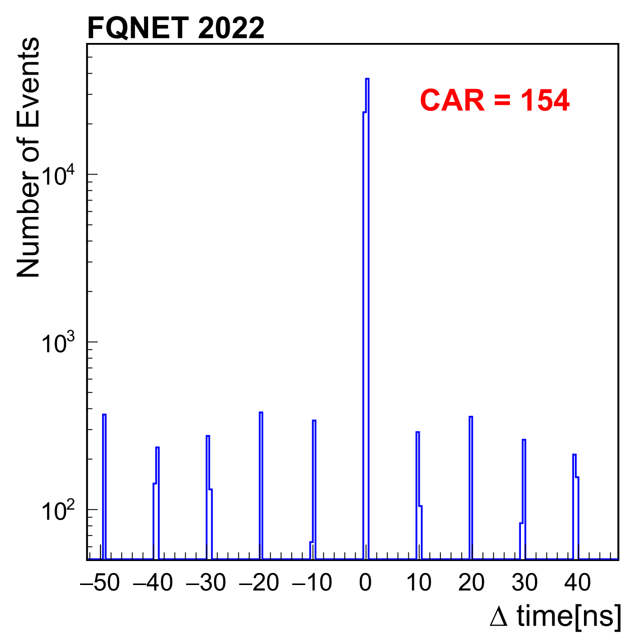

Fig. 6. Histogram of the time difference between the photon pairs detected by two SNSPD detectors. From the histogram we measure a CAR of 154.

IV. Results

We show two sets of results to characterize the performance of the pulse generation and signal readout functions of the RFSoC-FPGA, respectively.

A. Pulse Generation

For the pulse generation functionality, we use the RFSoC-FPGA to drive the MZM electro-optic intensity modulator to produce the time structure of the entangled photon pairs as shown in Fig. 2. As a first step, we evaluate the quality of the output of the MZM electro-optic intensity modulator as driven by the RFSoC-FPGA by measuring the time structure of the pulsed light at the output of the MZM after amplification by an EDFA. This time structure is measured by a 30 GHz InGaAs photodetector and shown in Fig. 5. By comparing the amplitude (0.46 V) with the average of the floor (0.005 V) we observe that it is exhibiting an extinction ratio of about 20 dB.

In the next step, we use the entangled photon pairs produced by the pulsed light from the MZM driven by the RFSoC-FPGA to measure the CAR and quantify the quality of the entangled photon-pair source. The time difference between the photons in the two detectors is shown in Figure 6 as measured using a commercial TDC time-tagger device. By integrating the counts in the main peak and comparing it with the average of the counts in the smaller side peaks we obtain a CAR of 154.

This CAR was achieved with an average photon number (μ) of 0.006. With a repetition rate of 10 MHz, the entangled photon pair source would produce an ideal entangled photon pair rate of 60 kHz. In this experiment, due to inefficient filters, coupling losses, and detector inefficiency resulting in an efficiency of about 6% per output, the actual measured entangled photon pair rate was about 200 Hz.

The key requirements for the pulse generation to achieve the necessary time structure and extinction ratio is to be able to generate RF pulses with sufficiently large amplitude to achieve the 5.5 V peak after amplification to match the V_π of the MZM, while maintaining pulse widths at or below 200 ps. Provided the pulse generation device is able to achieve these specifications without introducing extra noise, the entangled photon-pair source quality as measured by the CAR will be maintained. We see from Fig. 1 that the amplified RF pulse from the RFSoC-FPGA is able to reach 5.5 V at its peak, which suggests that it should be able to match the specifications of the MZM to give the expected best performance. Indeed, we observe that the same entangled photon-pair source with the same MZM driven instead by a commercial AWG with 25 Gsps sampling rate achieved the same extinction ratio and CAR. These comparative results indicate that the pulse generation from the QICK system yields the same quality of entangled photon-pair generation as state-of-the-art commercial pulse generators.

As mentioned previously in Section II, quantum network protocols based on time-bin encoding rely heavily on the use of the x-basis states and therefore it's important to validate the quality of the entangled photon pair source driven by the RFSoC-FPGA in that basis as well. To this end, we produce the x-basis time-bin entangled photon pair state by driving the MZM with a double pulse separated by 2 ns produced by the RFSoC-FPGA. Recall that we defined the early and late states with a 2 ns separation within the 10 ns repetition period. The resulting entangled photon pair exiting the SPDC is the superposition of the early and late pulses characterized by the state $|\Psi\rangle = (|ee\rangle + |ll\rangle)/\sqrt{2}$. We subsequently measure their entanglement visibility using two fiber-based Michelson interferometers. In Figure 7, we show the coincidence counts as a function of the relative phase difference between the interferometers. We perform a fit of the data to a sinusoidal function and measure the entanglement visibility to be 95 ± 5%, indicating high quality entanglement. The same measurement performed in the past [4] using the commercial AWG to drive the same MZM electro-optic intensity modulator, achieved a very similar entanglement visibility of 96%.

B. Signal Readout

To demonstrate the signal readout capability of the RFSoC-FGPA, we repeat the CAR measurement described above in Section IV-A using the ADC of the RFSoC-FPGA to digitize the signal pulses. An example of the SNSPD signal waveforms digitized by the RFSoC-FPGA ADCs are shown in Figure 8, where the signals from the two detectors have been intentionally separated by 2 ns. The shape of this signal waveform is determined by the SNSPD detection mechanism and the associated readout electronics, while the timestamp

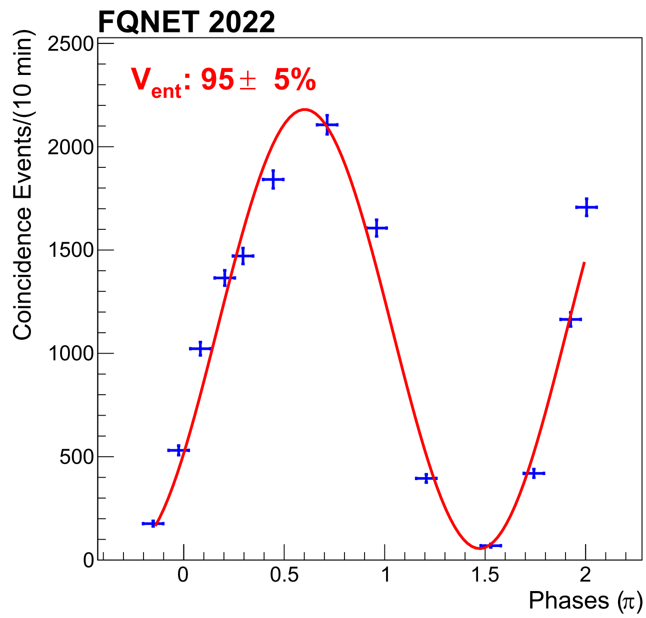

Fig. 7. Coincidence counts on the outputs of the Michelson interferometers for each of the photon pairs of the entangled photon pair source is shown as a function of the scanned phase of one of the interferometers. This measurement uses the x-basis time-bin state ($|e\rangle + |l\rangle$).

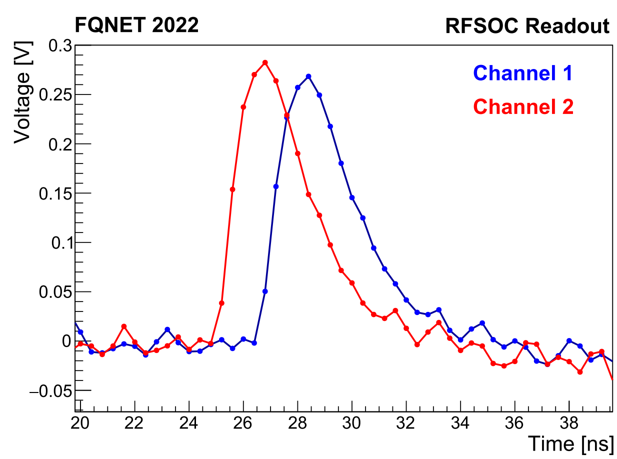

Fig. 8. SNSPD signal waveforms read out by the QICK system.

is typically obtained from a constant threshold or constant fraction discriminator algorithm.

We first measure the time resolution introduced by the RFSOC-FPGA. We split the electronic signal from a single SNSPD detector and connect them to two different input channels on the RFSOC-FPGA. We measure the time difference between the two channels over an ensemble of photon detection events and obtain the histogram shown in Figure 9. We fit the histogram to a Gaussian function and obtain a time resolution of 3.2 ps.

Finally, we use the waveform digitizer readout functionality of the RFSOC-FPGA to record pulses from two independent SNSPD detectors. We build coincidence events by searching for any pair of pulses detected within a window of 100 ns, and obtain the time difference histogram in Figure 10. From this histogram we measure the CAR to be 141, which compares well with a CAR of 154 measured using the commercial TDC readout system.

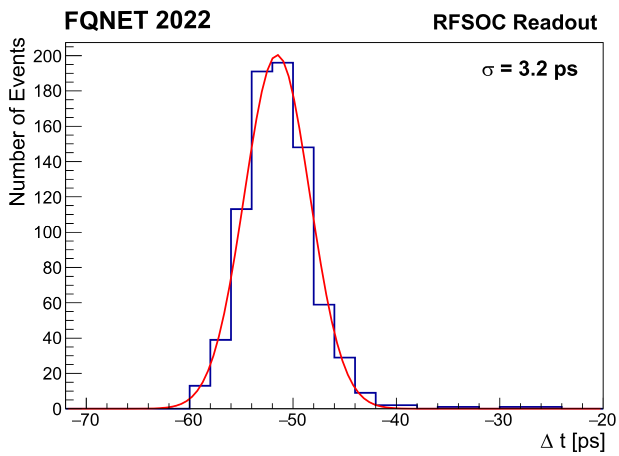

Fig. 9. A histogram of the time difference of an SNSPD signal detected on two different channels of the QICK system. The histogram is fitted to a gaussian function and the σ parameter of the gaussian represents the time resolution of the QICK system and is measured to be 3.2 ps.

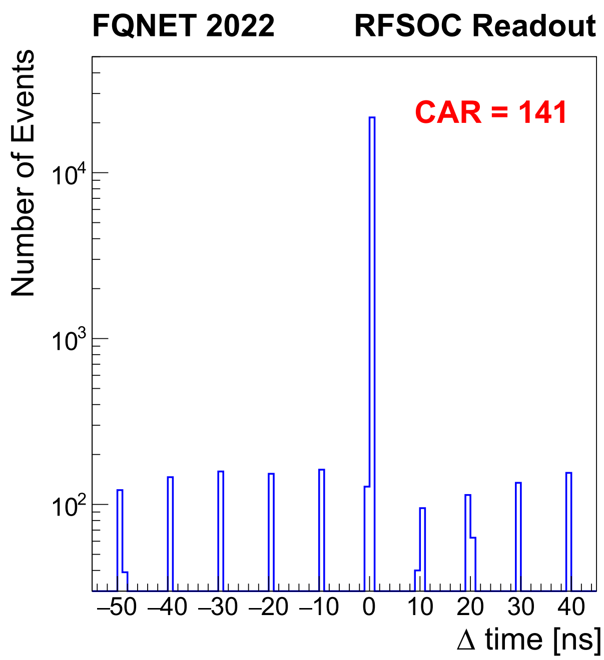

Fig. 10. Histogram of the time difference between the photon pairs detected by two SNSPD detectors and read out by the QICK system. Based on the histogram, we observe a CAR of 141.

V. Discussion and Outlook

The results reported in this paper represent the first feasibility demonstration for using the RFSoC-FPGA technology in key components of an operational quantum network. Using the RFSoC-FPGA equipped with our custom firmware in lieu of the more conventional commercial AWG and time taggers, we achieved the same levels of performance metrics including the coincidence-to-accidental (CAR) ratio, the entanglement visibility, and the cross-channel signal detection time resolution. This work represents a practical demonstration of the power and importance of the RFSoC-FPGA technology in future quantum network design and implementation. As of 2022, commercially available AWG's that can provide sampling rate necessary to produce 100–200 ps wide pulses cost on the order of 150K US dollars, while time taggers capable of achieving sub-10 ps time resolution cost on the order of 3K US dollars per channel. A system capable of generating the requisite pulses and detecting up to 16-channels of SNSPD detection signals would cost about 200K US dollars. As current state of the art RFSoC-FPGA's cost about 13K US dollars each and accounting for the additional cost of potentially necessary accessory boards, there is a potential for at least a 10 times reduction in the cost of the high speed electronics equipment necessary for operating quantum networks. Thus, the RFSoC-FPGA technology will no doubt play a key role in the deployment of scalable quantum networks.

The next steps for RFSOC-FPGA development includes developing and optimizing the online time-tagging functionality, customizing the noise filters on the signal input accessory boards to achieve optimal time resolution, and increasing the readout rate to the highest rate achievable by the RFSOC-FPGA. To further enhance our readiness for deployment and scability, we plan to work on the design of mechanical packaging that will physically integrate the RFSOC-FPGA with our entangled photon pair source into a rack-mountable form factor.

The successful implementation of these next steps will help to realize our vision for future rack-mounted quantum network nodes to be fully controllable through a single FPGA.

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