

A Real-Time Feed-Forward System for Heralded Quantum Entanglement



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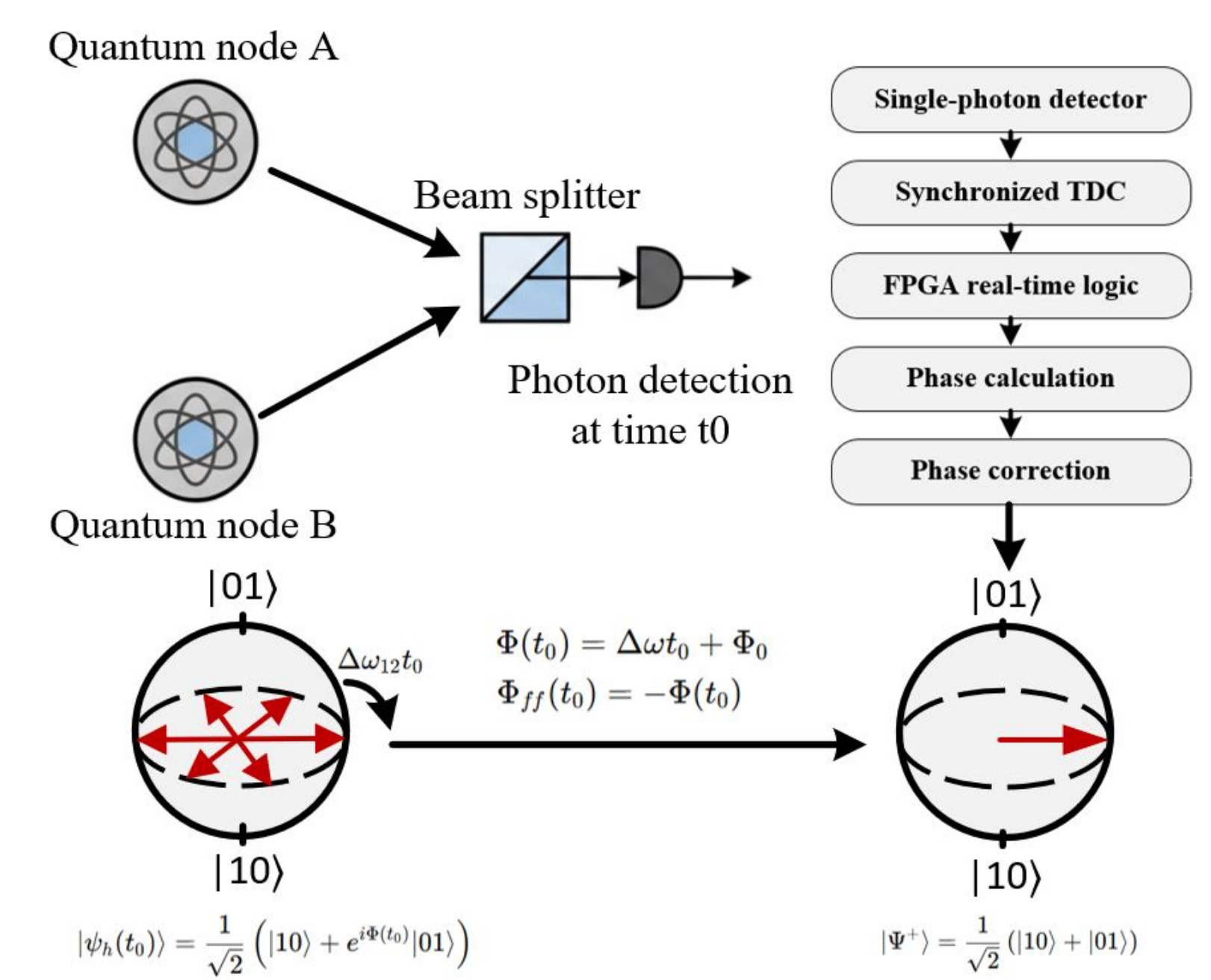
Introduction

- Remote entanglement generation is a fundamental primitive for quantum networks. In single-photon heralding protocols, the detection event indicates successful entanglement and provides timing information.
- For spectrally distinguishable emitters, the photon arrival time t_0 determines the relative phase of the heralded two-qubit state,

$$|\psi(t_0)\rangle = \frac{1}{\sqrt{2}} (|10\rangle + e^{-i\Delta\omega_{12}t_0}|01\rangle)$$

where $\Delta\omega_{12}$ is the optical frequency difference between the two emitters.

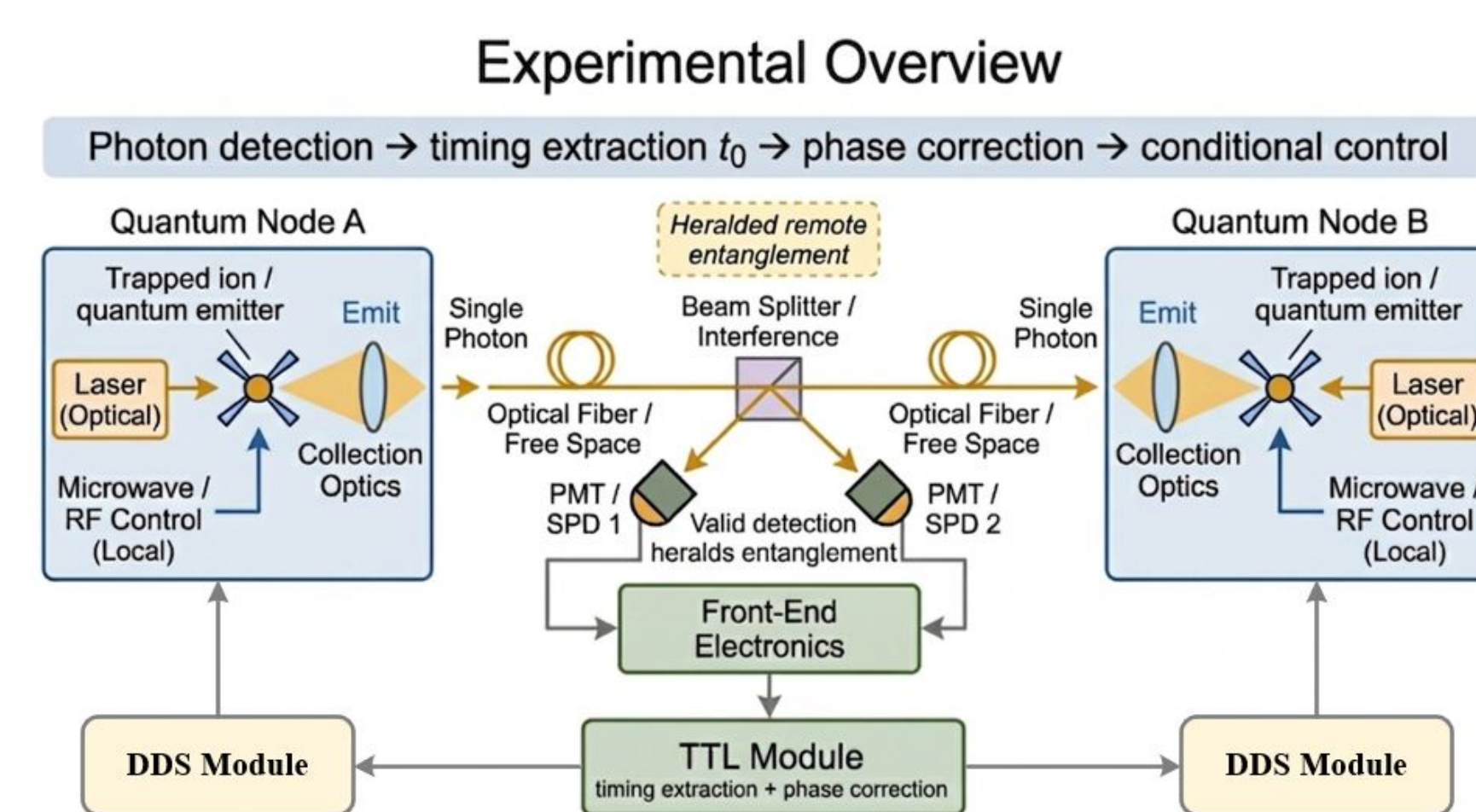
- The time-dependent phase $\phi(t_0) = \Delta\omega_{12}t_0$ causes phase spreading and reduces the fidelity of the generated entangled state.
- To recover a deterministic Bell state, measurement-conditioned real-time feedforward is applied through **dynamic rephasing and phase compensation**.
- This requires an FPGA-based controller capable of high-precision timing, real-time phase computation, and low-latency synchronized feedforward output.



Electronics Design

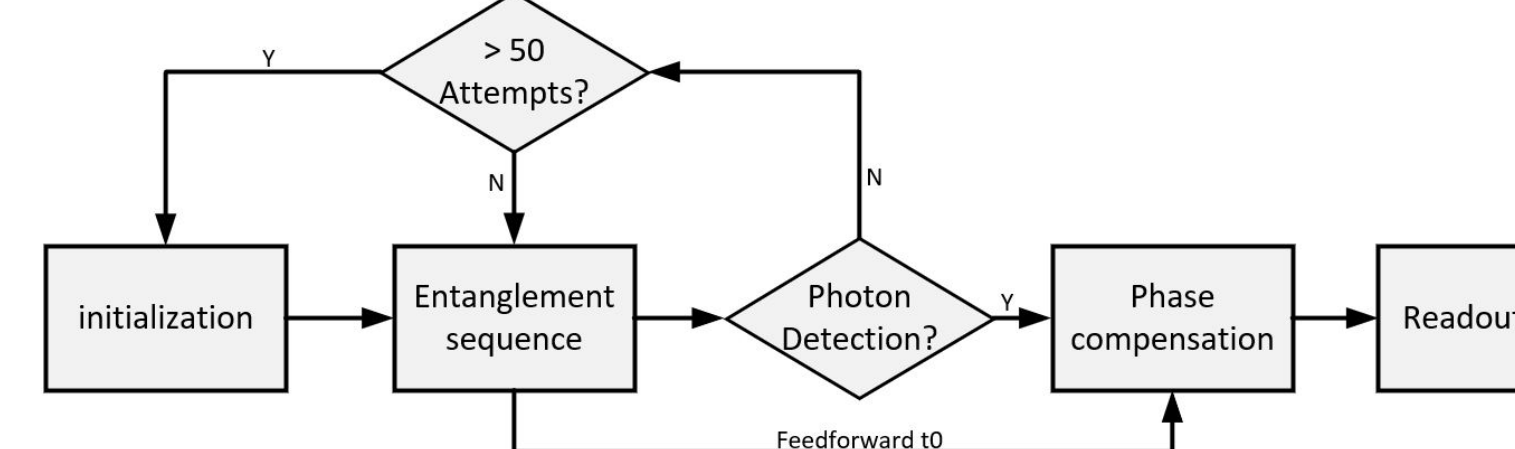
Overall Design

The electronic system links photon detection in the physical experiment with subsequent qubit control. Detection events are processed in real time, and the corresponding correction is applied to the following control sequence.



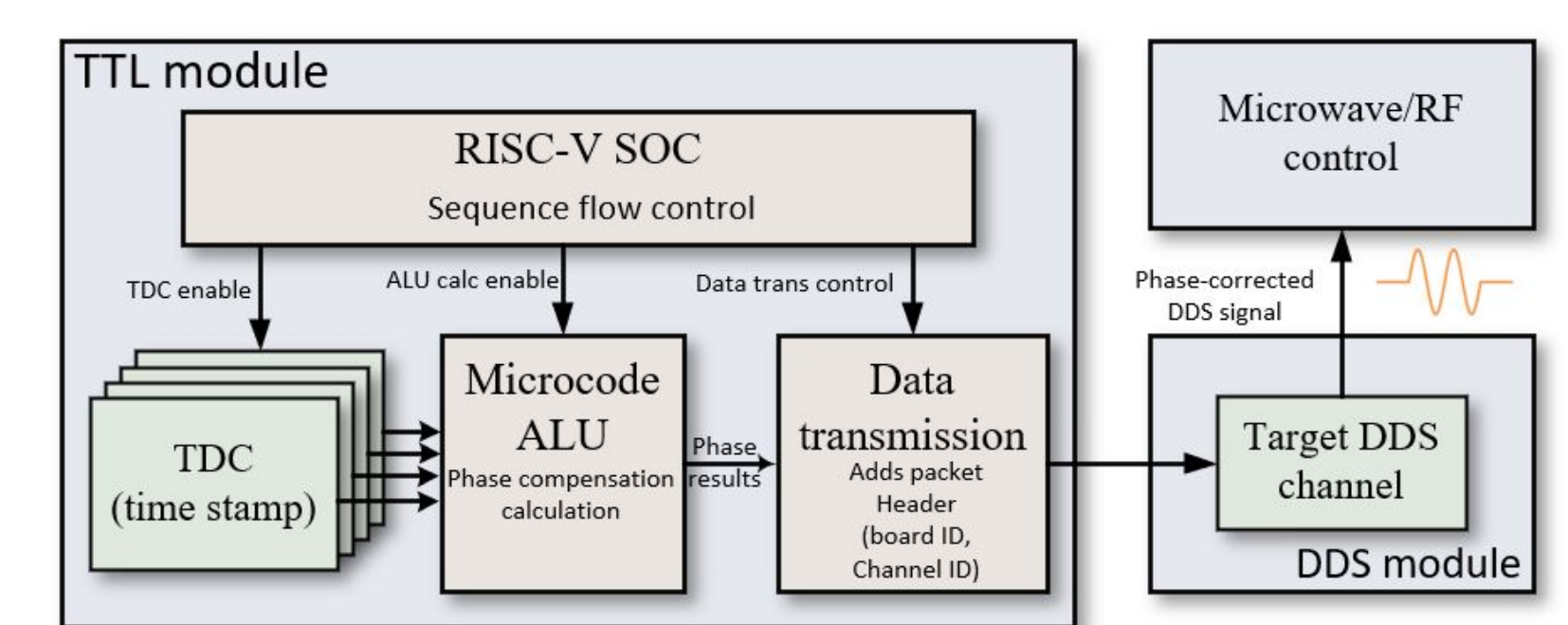
Experimental Workflow

The experiment proceeds in a deterministic sequence consisting of initialization, entanglement generation, photon detection, conditional phase correction, and final state readout. After initialization, the system enters the entanglement sequence and opens a photon-detection window. If a valid detection event is registered, the photon arrival time is used to calculate the required phase compensation before readout. Otherwise, the protocol returns to the entanglement sequence and repeats the attempt.



Internal Logic Module

The TTL module integrates a RISC-V control core, four TDCs, and a data transmission unit. The TDCs measure photon-arrival timestamps, which are processed by the microcode arithmetic unit for phase-compensation calculation. The computed result is then packetized with DDS board and channel information, routed through the TCM board, and delivered to the target DDS channel.



Performance Test

Experimental Setup

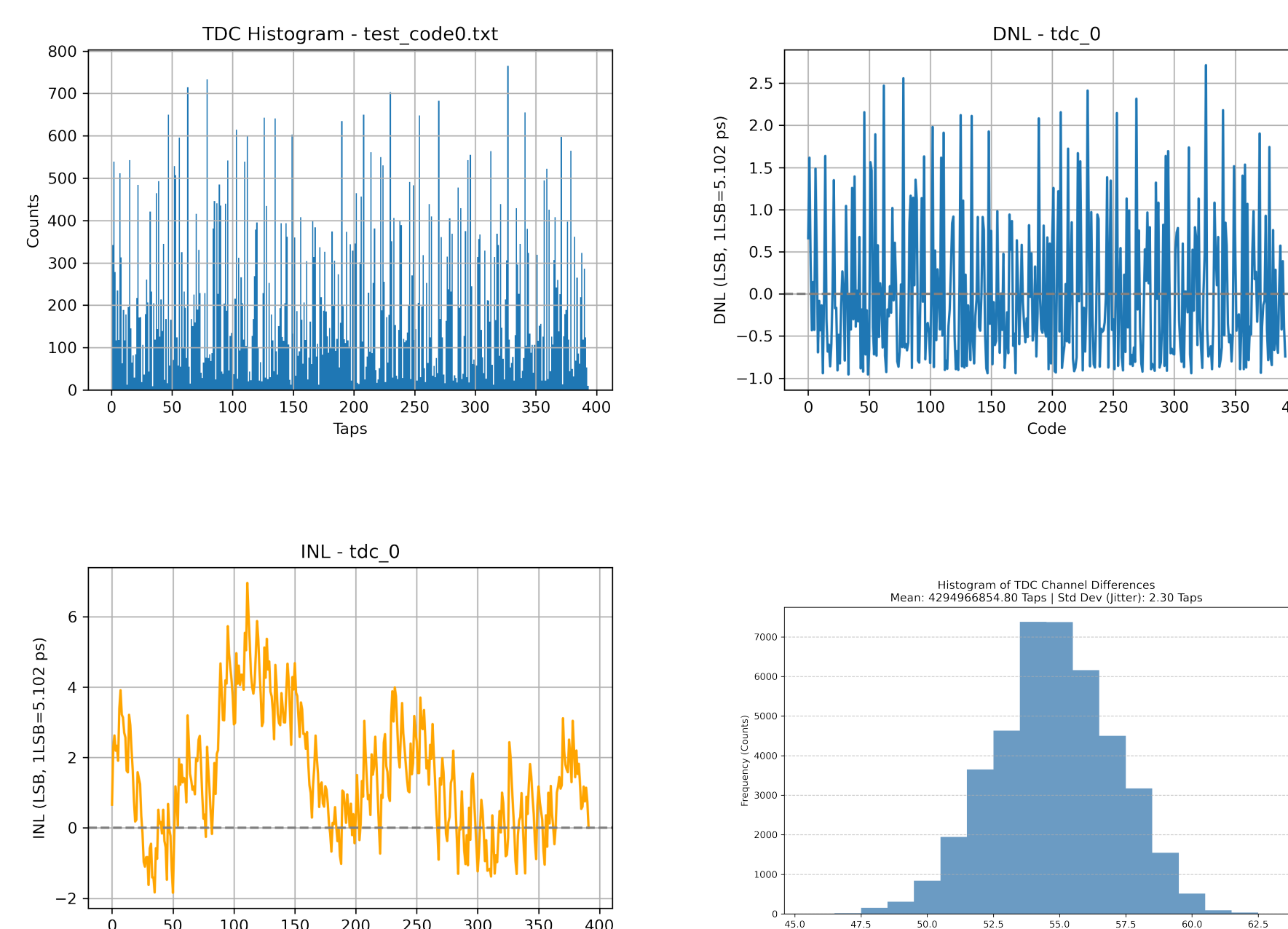
- Electronics implemented in a modular crate integrating TTL and DDS modules.
- TTL module serves as the central timing and control unit.
- Receives detector-like input signals and measures photon arrival times.
- Computes phase-compensation result for qubit control.



TTL module(TDC) DDS module(TDC)

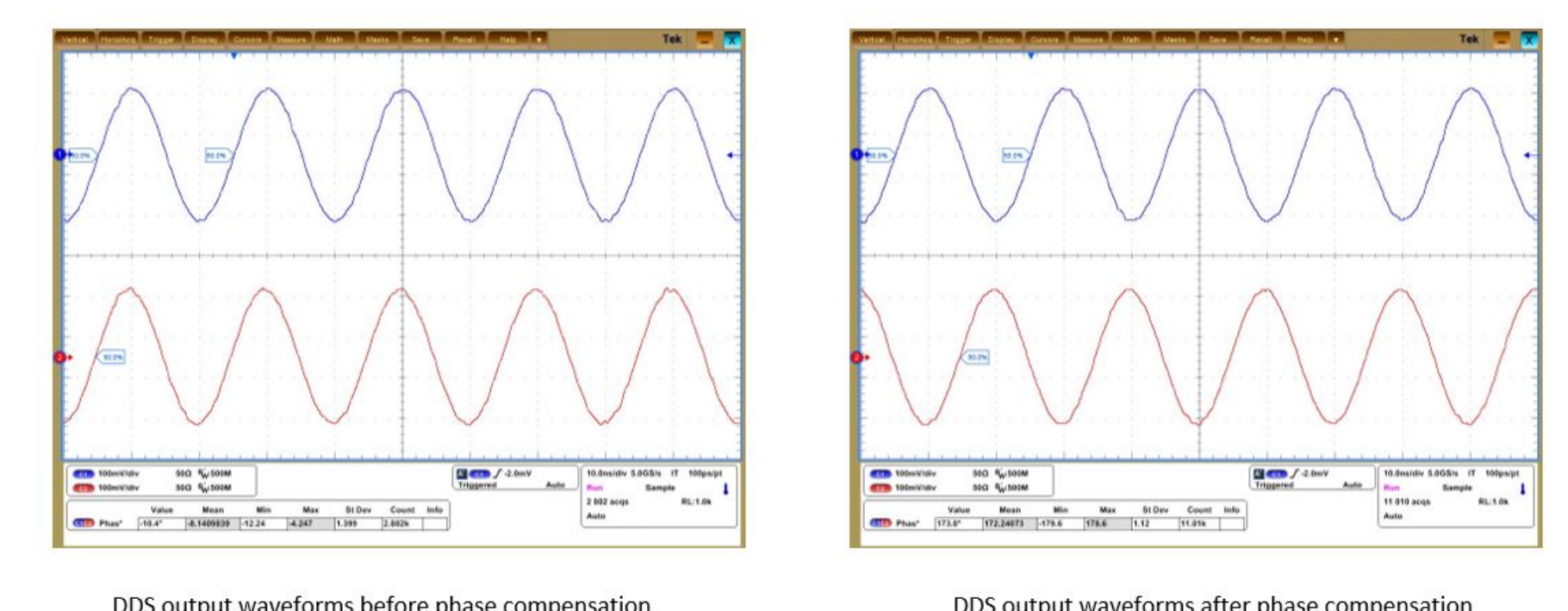
TDC performance test

- Characterized using controlled electronics test signals.
- Single-channel code-density measurement for bin-width distribution, DNL, INL.
- Two-channel time-difference test using different cable lengths for fixed delay.
- Evaluates timing resolution and system precision.



Simulated Feed-Forward Test

- Two DDS output channels used to verify timing-to-phase compensation.
- Both channels initially phase-aligned; one as reference, one as target.
- Simulated TDC input values emulate photon arrival timestamps.
- TTL module calculates required phase compensation in real time.
- Compensation applied to target DDS waveform; phase shift observed on oscilloscope.
- Confirms correctness and low-latency performance of the feed-forward control loop.



Conclusion

- A real-time FPGA-based feed-forward electronics system was developed to connect photon timing measurement with phase-corrected DDS control output.
- The TDC module achieves high timing precision, with a measured RMS timing resolution of 11.5 ps.
- The system supports low-latency feedback operation at the microsecond scale, enabling real-time conditional control in the experimental sequence.

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