

Low-Latency Feed-Forward with Time Tagger X

Characterization of triggered coincidence feed-forward module

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Photonic quantum experiments often require an electrical control action conditioned on single-photon detection events. In applications such as heralded state preparation and active feed-forward, identifying the relevant detection pattern is only part of the task. The result must also reach the control electronics with low and predictable latency.

The *Time Tagger X* (TTX) addresses this requirement by evaluating user-configurable coincidence patterns directly on its internal field-programmable gate array (FPGA). A matching pattern produces a pulse on one of the two auxiliary outputs. Here, we describe the triggered-coincidence logic and characterize two electrical signal paths: the TTX trigger-to-output response and a combined configuration in which the TTX triggers a pulse sequence on a *Pulse Streamer 8/2*.

ON-DEVICE FEED-FORWARD LOGIC

The feed-forward module operates alongside the standard time-tag acquisition path (Fig. 1a). Time tags from the input stage pass through the delay stage before being copied and made available to the on-device logic, as well as to the filtering and buffering for transfer to the PC.

The triggered-coincidence module evaluates events across all 20 input channels of the TTX. One channel can be designated as an external trigger. Alternatively, an auto-trigger mode can be used, which generates an internal trigger at 750 MHz. The trigger marks the end of the user-configured coincidence window. The module checks the events within that preceding window against up to two user-configured coincidence patterns. Each pattern is linked to one of the two auxiliary outputs, and both patterns share the same trigger source.

Both inclusive and exclusive coincidence conditions are supported. Figure 1b illustrates an exclusive condition with channel 1 as the trigger, channels 2, 3, and 4 as active channels, and channels 3 and 4 as the required coincidence pattern. The coincidence window can be configured from 1 ps to 715 μ s, and both rising and falling input edges are supported. The relative timing of the input events and the trigger can be adjusted using the input-delay settings (*setHardwareDelay*) with picosecond resolution, allowing detection events to be aligned within the coincidence window.

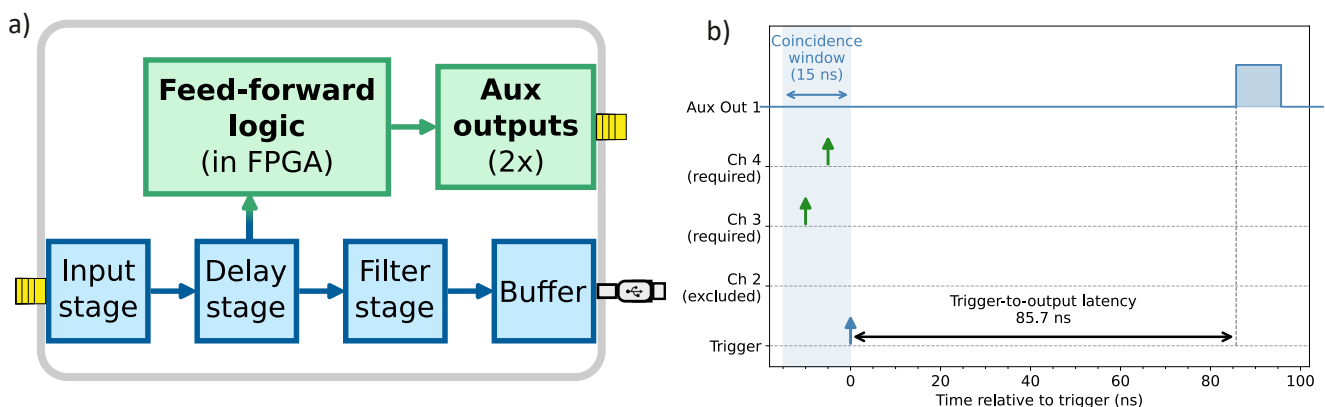


Fig. 1: On-device feed-forward with Time Tagger X. (a) The FPGA logic evaluates time tags alongside the standard acquisition path (in blue) and drives two auxiliary outputs. (b) Exclusive-coincidence example: events on channels 3 and 4, with no event on channel 2, satisfy the selected pattern within the 15 ns window preceding the trigger on channel 1.

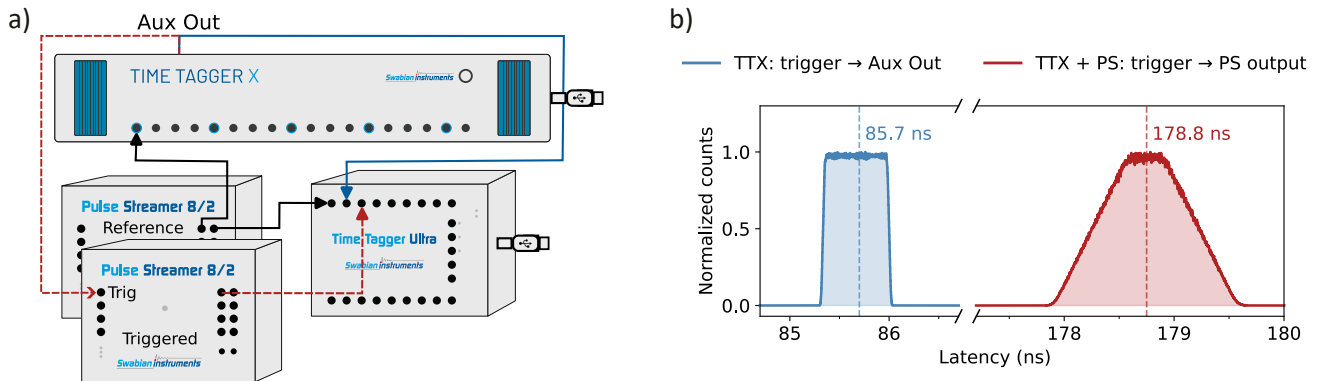


Fig. 2. Electrical latency characterization. (a) Two independent Pulse Streamer 8/2 units are used. The first generates the reference signal for the TTX coincidence trigger and the TTU histogram start. The TTX auxiliary output provides either the histogram stop directly (blue) or the trigger for the second Pulse Streamer, whose first output pulse provides the histogram stop (dashed red). (b) Cable-delay-corrected latency distributions for the direct TTX path (blue) and the combined TTX–Pulse Streamer path (red), with mean latencies of 85.7 ns and 178.8 ns, respectively.

EXPERIMENTAL SETUP

The latency measurements use two Pulse Streamer 8/2 units (PS 8/2) and a Time Tagger Ultra (TTU) (Fig. 2a). The first PS 8/2 generates a reference signal, split between TTX channel 1 (coincidence trigger) and TTU channel 1 (histogram start). For the direct TTX input-to-output measurement, the reference frequency is 10 MHz. For the TTX-PS 8/2 loop measurement, the frequency is reduced to 3.3 MHz (about 300 ns period) to avoid a subsequent trigger occurring within the closed-loop latency. Internal test signals at approximately 890 kHz on channels 2–20 of TTX provide the signal events. For both measurements, the TTX is operated with inclusive coincidence logic, channels 2–20 active, and a 10 ns coincidence window.

For the TTX input-to-output measurement, Aux Out 1 supplies the histogram stop on TTU channel 2. For the TTX-PS 8/2 measurement, Aux Out 1 triggers the second PS 8/2, whose first output edge supplies the histogram stop on TTU channel 3. Both measurements use the reference signal from the first PS 8/2 as their start, although at different repetition rates. Cable propagation delays are measured and subtracted.

MEASUREMENTS AND RESULTS

The direct TTX path has a measured mean latency of 85.7 ns, with 193 ps RMS jitter (670 ps FWHM). Triggering the PS 8/2 sequence increases the mean latency to 178.8 ns, with 349 ps RMS jitter (1.09 ns FWHM). The feed-forward latency is independent of the number of monitored input channels, the coincidence order, and the selected coincidence pattern.

The periodic output timing of the TTX (1.5 Gbit/s) and the PS 8/2 (1.0 Gbit/s) results in approximately uniform timing variations spanning 0.667 ns and 1 ns, respectively. The combination of these uncorrelated timing contributions produces the approximately trapezoidal distribution observed in Fig. 2b.

CONCLUSION AND OUTLOOK

The triggered-coincidence module extends the *Time Tagger X* from time-resolved acquisition to on-device feed-forward using existing TTX hardware. It combines configurable detection-pattern evaluation with two auxiliary outputs and a measured 85.7 ns trigger-to-output latency. The *Pulse Streamer 8/2* demonstration shows how a recognized coincidence pattern can initiate a subsequent pulse sequence, with a measured latency of 178.8 ns from the TTX trigger input to the first Pulse Streamer output edge.

The FPGA architecture also provides a path toward additional feed-forward logic. Functionality under consideration includes start-stop-based logic, count-rate-based logic, and coincidence-based logic without a dedicated trigger input.