Fraunhofer
HHI

APPLICATION NOTE

160 ps
QKD-Ready

Time Tagger

Sub-nanosecond Time-to-Digital Converter

APPLICATION NOTE

Time Tagger

Sub-nanosecond Time-to-Digital Converter

APPLICATION NOTE

Time Tagger

Sub-nanosecond Time-to-Digital Converter

1 Introduction

The Fraunhofer Heinrich Hertz Institute conducts research and development in secure key transmission using quantum key distribution (QKD). In these systems, the precise determination of individual photon arrival times is essential. To enable this measurement in a simple and cost-effective way, dedicated time-to-digital converters — so-called Time Taggers — have been developed in-house for the QKD systems.

This technology is now available for use in a variety of applications that require precise timing and detection of specific events. These include quantum communication, LiDAR, satellite laser ranging (SLR), time-correlated single-photon counting (TCSPC), and multi-channel scaling (MCS), where the accurate measurement of optical signal arrival times, down to single photons, plays a key role.

With the Time Tagger, the Fraunhofer Heinrich Hertz Institute offers a stand-alone, low-cost and and easy to setup device that ensures reliable determination of time events for a wide range of signals. By employing widely used technical standards, it allows for straightforward integration into existing systems. Thus, the Time Tagger enables reliable, sub-nanosecond time-to-digital conversion.

This application note describes how to set up the Time Tagger and configure the device for quick integration into various technical systems. Further information is available in the Time Tagger Data Sheet and the Programmer's Guide.

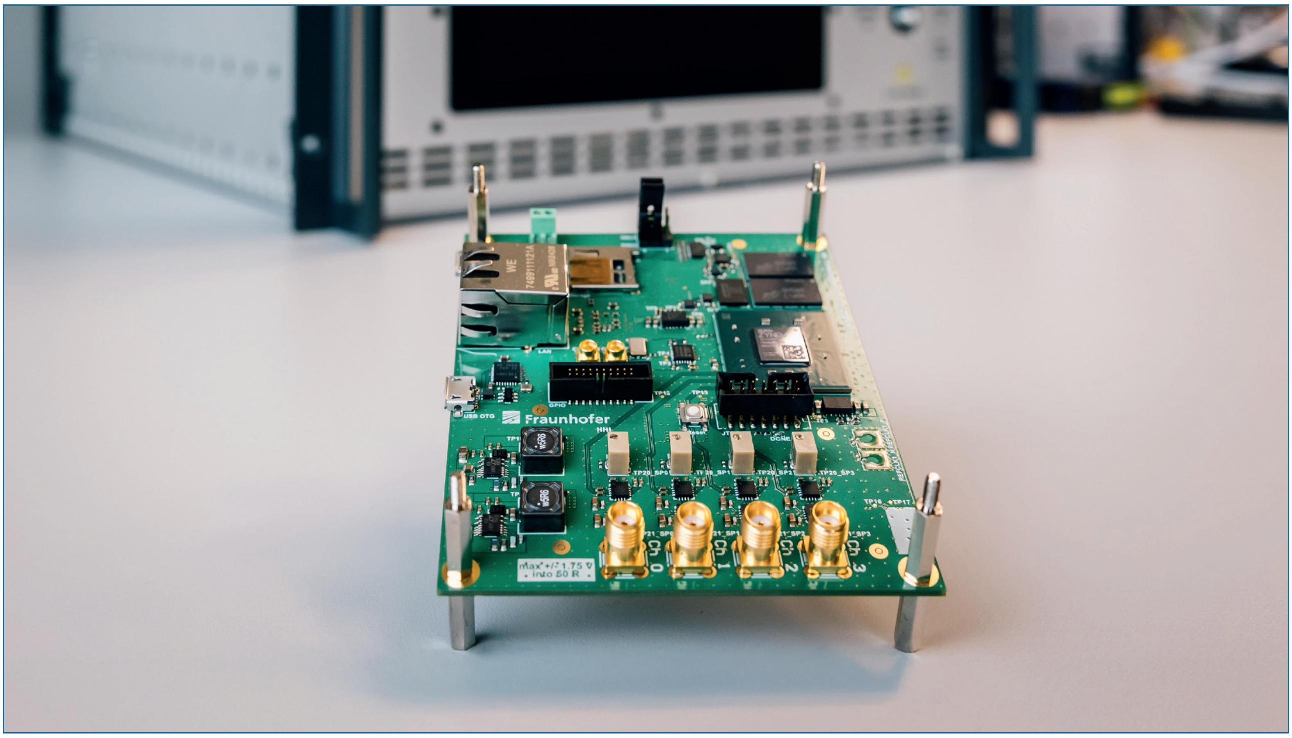

Figure 1: Time Tagger PCB – four-channel time-to-digital converter board

2 Overview of the Time Tagger

The Time Tagger is a versatile measurement device featuring four input channels for electrical signals. The signals are connected via standard SMA connectors, and each channel can be individually configured to accurately measure different signals simultaneously.

Time event digitization is performed with a resolution of 160 ps and a total throughput of up to 14 Mdec/s across all channels.

The device is operated entirely via one Ethernet interface, which allows both individual channel configuration and the readout of digitized time events through a single connection. Standardized software protocols are used for configuration and data access, eliminating the need for proprietary software.

For applications requiring synchronization with external systems, the Time Tagger provides a Clk In connector.
This input allows the device to be operated with an external reference clock, ensuring precise timing alignment between multiple Time Tagger units or with other time-critical instruments *(see Figure 2).* If no external clock is connected, the device operates using its internal timing reference.

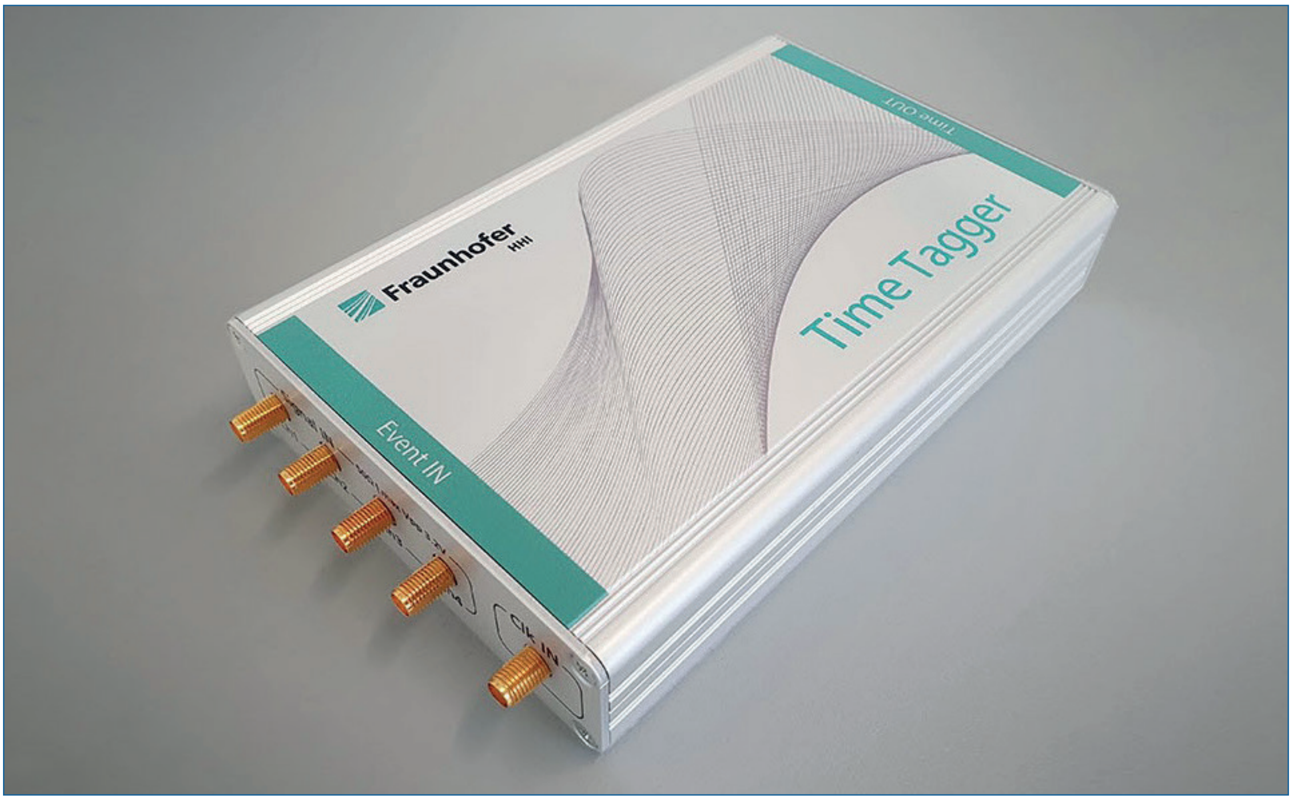

Figure 2: Time Tagger in enclosure – front view with SMA inputs and Clk In; Ethernet and power connector on the backside

3 Setting Up the Time Tagger

Setting up the Time Tagger requires only three steps:

- Connect the signal source to the SMA interfaces of the Time Tagger channels.
- Connect the Ethernet interface to the target system.
- Connect the power supply.

To ensure broad compatibility with various signal types, each input channel can be configured individually. Both the configuration and the readout of recorded event data are performed entirely via the Ethernet interface.

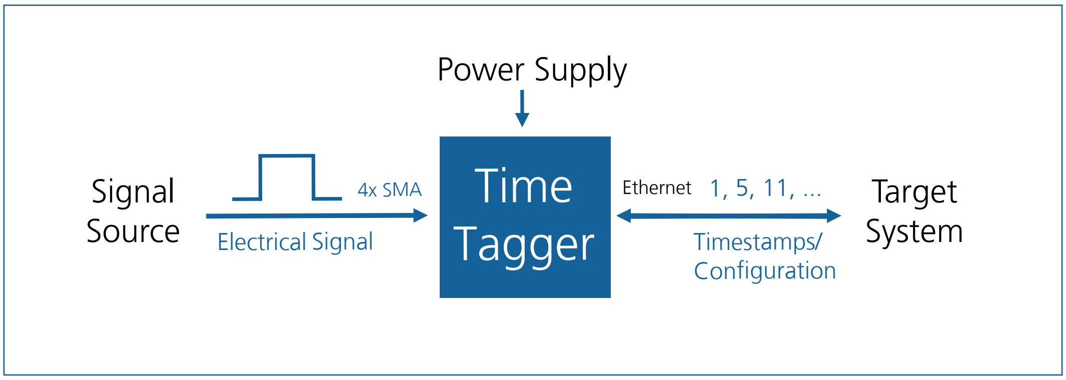

Figure 3: Typical setup for operating the Time-Tagger – signal sources, Ethernet link, and power supply

4 Read Out the Time Events

The time events determined by the Time Tagger are provided as differential timestamps, representing the time differences between consecutive events. These timestamps are transmitted as a continuous data stream of 32-bit data words to the target system via the Ethernet interface.

The connection between the Time Tagger and the target system is established through a standard TCP connection. The target system can process the received timestamps flexibly, according to the specific requirements of each use case. No additional drivers are required to access the timestamps from the Time Tagger.

5 Configuring the Time Tagger

To ensure reliable event detection across a wide variety of input signal types, the Time Tagger provides extensive configuration options. These parameters can be adjusted during operation via the Ethernet interface using SCPI (Standard Commands for Programmable Instruments).

5.1 Setting the Threshold

The **threshold** defines the voltage level of the input signal at which a timestamp is generated once the threshold is exceeded. Both positive and negative voltage values can be set to accommodate signals of different polarities.

5.2 Selecting the Signal Edge

The **edge configuration** determines whether the Time Tagger generates a timestamp on the rising or falling edge of the input signal. This allows precise detection and processing of both signal polarities and varying waveform shapes.

A complete list of supported commands can be found in the Time Tagger Programmer's Guide.

The following parameters can be configured individually for each of the four input channels:

5.3 Adjusting the Offset

The **offset** parameter allows the timestamps generated on a channel to be shifted by a defined amount to compensate for signal propagation times or other delays during timestamp generation. This eliminates the need for later software corrections.

5.4 Defining the Dead Time

After a timestamp is generated, a **dead time** can be defined during which no additional timestamps are recorded.
This feature suppresses unwanted signal components or effects such as afterpulsing, ensuring clean timestamp generation and removing the need for later software correction.

6 Application Examples

6.1 Quantum Key Distribution (QKD)

Quantum Key Distribution (QKD) is one practical field application of the HHI Time Tagger. In QKD systems based on the time-bin phase protocol, the qubits transmitted via the quantum channel are identified based on their arrival time at one of the three channels of the receiver. The figure below illustrates the use case of the Time Tagger within the receiver of a QKD system.

During a QKD key exchange, a single photon is sent from the transmitter (signal source) to the receiver (target system). The photon is randomly directed to one of the two outputs at the coupler and the Delay-Line Interferometer (DLI), which determines the single-photon detector (SPD) that will register it. When a photon is detected, the SPD generates an electrical pulse. For each pulse, a timestamp is created by the Time Tagger. Based on this timestamp and the specific SPD that detected the photon, the target system can identify the transmitted qubit.

As shown in the setup, there are three distinct signal paths with different path lengths between the signal source and the target system. Depending on the random transmission of the photon at the outputs of the coupler and the DLI, this results in varying photon arrival times at the SPDs. Since the arrival time is crucial for qubit detection, it must be identical regardless of the path taken by the photon.

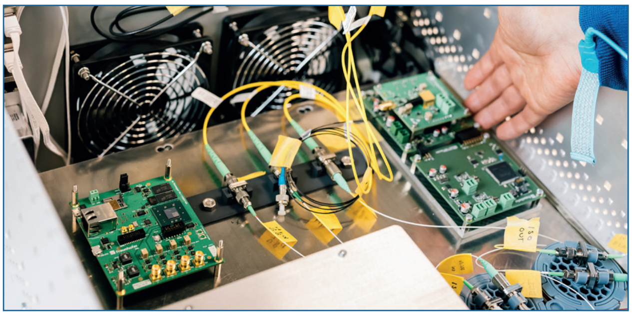

Figure 4: Laboratory setup of the QKD receiver – optical components and SPDs, connected to Time Tagger

These variations in arrival time can be compensated for using the offset configuration of the Time Tagger. The path lengths must be characterized in advance and configured in the Time Tagger, removing the need for additional software compensation.

The Time Tagger allows flexible configuration of thresholds, signal edges, and dead times even during live operation. This enables accurate processing of different SPD types. As a result, the Time Tagger is independent of predefined signal shapes and polarities. Afterpulses and false detections caused by signal shape can also be effectively suppressed using the configurable dead time.

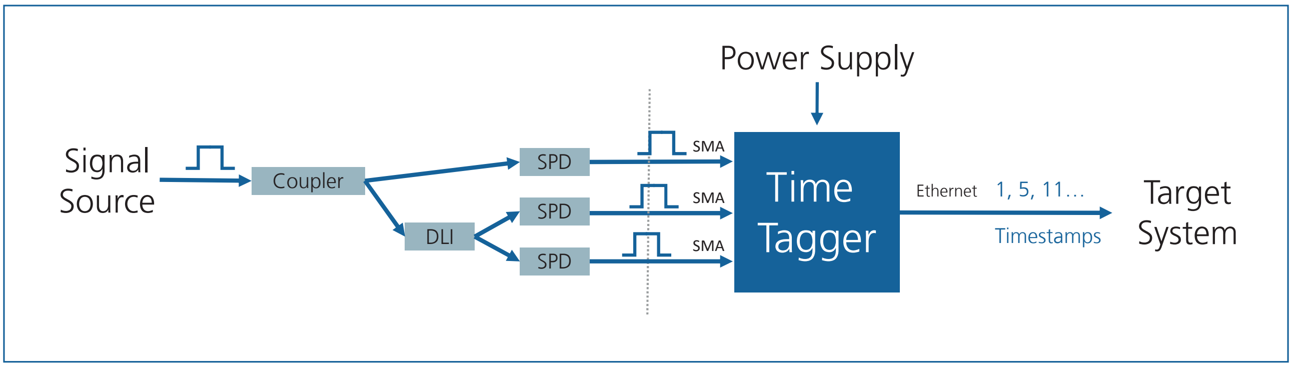

Figure 5: QKD receiver setup using the Time Tagger – photon detection and timestamp generation via SPDs

6.2 Satellite Laser Ranging (SLR) and Incoherent LiDAR

In this setup, a laser is used to generate short light pulses. These pulses are amplified and transmitted as free-space optical signals via a transmitter (Tx). The reflections of the transmitted pulses are received by an optical antenna (Rx) and converted into electrical signals using a photodiode (PD).

To determine the propagation time of the transmitted laser pulse in free space, the Time Tagger assigns a timestamp to both the transmission time of the laser pulse and the reception time of its reflection. For this purpose, the laser pulse driver is connected to one channel of the Time Tagger (transmission time), while the electrical signal from the photodiode is connected to another channel (reception time).

The timestamps from both channels are read and processed by the target system. The difference between these timestamps can then be used to calculate the distance to the reflecting object with an accuracy of approximately 24 mm.

The Time Tagger's configuration options ensure straightforward integration into existing systems. The offset configuration enables compensation for path length differences within the setup, while the adjustable signal levels and edge settings allow fine-tuning to match the electrical characteristics of the photodiode and laser pulse driver.

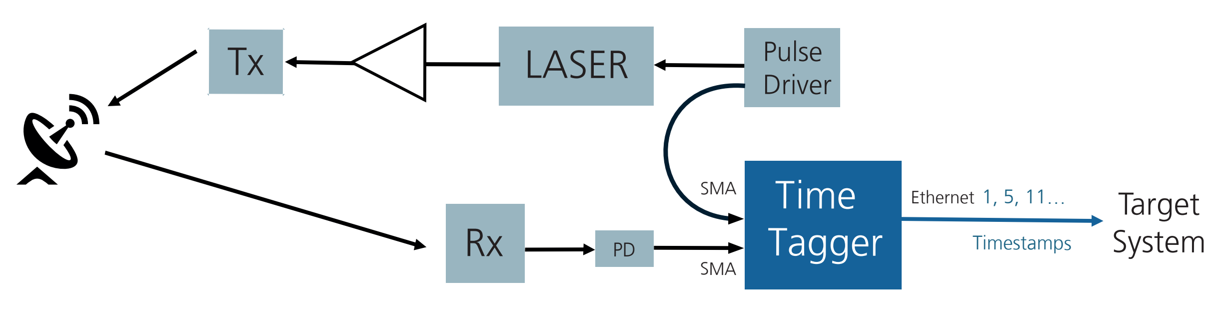

Figure 6: Satellite Laser Ranging (SLR) and LiDAR setup – laser pulse transmission and reflection timing with photodiode input

7 Further Information and Resources

https://www.hhi.fraunhofer.de/abteilungen/pn/hardware-loesungen/qkd.html

https://www.hhi.fraunhofer.de/en/time-tagger.html

https://www.ivifoundation.org/About-IVI/scpi.html