Quantum Clock Synchronization: A Brief Overview

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A Classic Physics Problem!

Clocks are at a fixed distance and in the same inertial frame. Clocks are synchonized.

\[
f = f' \quad \text{[NIST]} \quad t = t' \quad \text{[Navy]}\]

Assumptions(*):
Clocks are at a fixed distance and in same inertial frame.
Clocks are synchonized.

(*) Not essential. Assumptions can be relaxed.
Which photons are members of a pair?
- Emitted \textit{simultaneously} (in the pair source’s reference frame)

Parametric down-conversion process:
Maximally entangled pairs emitted at fundamentally \textit{random times}.
Quantum correlations can be exploited to extract a \textit{secure key}.
Paired photons are a small fraction of detector events
Quantum Entanglement and Timing: Coincidence Detection

SPDC time-energy entanglement means pairs can be identified out of a strong background and used to define a **coincidence**

\[
a(t) = \sum_i \delta (t - t_i) \, dt
\]

\[
b(t') = \sum_j \delta (t - t'_j) \, dt
\]

\[
c_{AB}(\tau) = (a \ast b)(\tau) = \int a(t)b(t + \tau)dt
\]
Quantum Entanglement and Timing: What Can Be Extracted

Maximum of correlation at:

\[ \tau_{AB} = \Delta t_{AB} + \delta \]

\[ \tau_{BA} = \delta - \Delta t_{BA} \]

Channel controlled by Eve/Damon

\[ \Delta t_{AB}, \Delta t_{BA} \]

Propagation time and true offset are inextricably bundled together.

Correlation peak for Bob to Alice direction from an SPDC source at Bob's location.
Quantum Clock Synchronization (QCS): Core Protocol

Quantum Clock Synchronization (QCS): Syntonization + Time-Transfer

QCS

Unspoofable

Very accurate (~1 picosecond)

- Lab demo: ~7ps accuracy
- Monogamy of entanglement + no-cloning guarantees signal origin - authentication
- Robust against large noise background
Timestamping: Nominal 4 ps resolution
Detected Count Rate (R): 200 pairs/s
Source Brightness: 200k pairs/s
Sync Accuracy: ~7 ps (T_a = 20 sec)

Total: ~20000 pairs detected

Sync error: \[ \delta t = \frac{1}{\sqrt{2}} \frac{1}{2V(\tau = 0)} \frac{1}{\sqrt{RT_a}} \]

Our goal is to utilize QCS to distribute precision time globally (and lay a foundation for future long-distance Quantum Networks).

Therefore, we are exploring the design of Satellite-based QCS networks.

As a first step, we now look at using a single satellite to synchronize two distant clocks on the ground.

At a minimum the QCS protocol must be robust against:

• Realistic optical link losses
• The motion of the satellite
• Relativistic effects (GR & SR)
Over to Stav