Quantum Teleportation with Photons

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The distribution of single qubits over large distance via quantum teleportation is a key ingredient for realization of a quantum network.
Motivation

- The distribution of single qubits over large distance via quantum teleportation is a key ingredient for realization of a quantum network.
- Quantum teleportation is a secure way to send information.
Overview

1. The quantum teleportation protocol

2. Experimental realization
   - Setup
   - Results
   - Summary

3. Long Distance Teleportation
   - Setup
     - Feed-Forward
     - Noise Reduction
   - Results

4. Summary

5. References
**The quantum teleportation protocol**

1. Alice prepares or receives a quantum bit

\[ \Rightarrow |\psi\rangle_1 = \alpha |0\rangle_1 + \beta |1\rangle_1, \quad \text{where:} \quad |\alpha|^2 + |\beta|^2 = 1 \]
The quantum teleportation protocol

2. A pair of entangled qubits is created and sent to Alice and Bob

\[ |\psi^-\rangle_{23} = \frac{1}{\sqrt{2}} (|01\rangle_{23} - |10\rangle_{23}) \]
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\[ \Psi^{-}_{23} = \frac{1}{\sqrt{2}} (|01\rangle_{23} - |10\rangle_{23}) \]

3. Rewrite the state of the three qubits:

\[ |\psi\rangle_{123} = (\alpha |0\rangle_1 + \beta |1\rangle_1) \otimes \frac{1}{\sqrt{2}} (|01\rangle_{23} - |10\rangle_{23}) \]

\[ = \frac{1}{4} \sum_k (|\psi_k\rangle_{12} \otimes U_k |\psi\rangle_3), \]

where \( |\psi\rangle_3 = \alpha |0\rangle_3 + \beta |1\rangle_3 \), \( U_k \) is a unitary Matrix, and the \( |\Psi_k\rangle_{12} \) are Bell states
4. Alice performs a Bell state measurement on qubit 1 and 2:
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   \( \Rightarrow \) Bob’s state is projected onto \( U_k |\psi\rangle_3 \)
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5. Alice sends the outcome of her measurement to Bob via classical communication channel
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   \[ \Rightarrow \text{Bob’s state is projected onto } U_k |\psi\rangle_3 \]

5. Alice sends the outcome of her measurement to Bob via classical communication channel

6. Four possible outcomes:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Resulting state</th>
<th>Bob’s Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\psi^-\rangle_{12}$</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>\Phi^-\rangle_{12}$</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>\Phi^+\rangle_{12}$</td>
<td>$</td>
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<tr>
<td>$</td>
<td>\psi^+\rangle_{12}$</td>
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</tbody>
</table>
7. Bob performs the appropriate unitary operation on his qubit
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8. Bob is now in possession of the qubit Alice wanted to send!!

**Note:** Alice’s qubit is destroyed in the measuring process!
Experiment

Setup

Crucial steps:

1. Creation of entanglement
2. Realization of Bell-Measurement
3. Analysis of teleported state
1. Creation of entanglement

- Entangled photon pair $|\Psi^-\rangle_{23}$ created via type II-Parametric Down Conversion
- Laser pulse is reflected at mirror and creates $|\Psi^-\rangle_{14}$
2. Realization of Bell-Measurement
   - Photon 1 and 2 superimposed at BS with detectors f1 and f2
   - Coincidence click projects photons 1 and 2 into $|\psi^-\rangle_{12}$
   - Difference in arrival time $\leq 520$ fs $\equiv$ arrive „simultaneously“
3. Analysis of teleported state
   - Bob knows via CCC if photon 3 is in desired state
   - Polarization is analysed with PBS with detectors d1 and d2
**Experiment**

Theoretical prediction

Preparation in $+45^\circ$-polarization

<table>
<thead>
<tr>
<th>TP-region</th>
<th>Coincidence</th>
<th>d1</th>
<th>d2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Inside</td>
<td>25%</td>
<td>0%</td>
<td>100%</td>
</tr>
</tbody>
</table>

- Successful teleportation:
  3-fold coincidence d2-f1-f2 with absence of 3-fold coincidence d1-f1-f2
Results

Measured three-fold coincidences

<table>
<thead>
<tr>
<th>Polarization</th>
<th>Visibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>+45°</td>
<td>0.63 ± 0.02</td>
</tr>
<tr>
<td>−45°</td>
<td>0.64 ± 0.02</td>
</tr>
<tr>
<td>0°</td>
<td>0.66 ± 0.02</td>
</tr>
<tr>
<td>90°</td>
<td>0.61 ± 0.02</td>
</tr>
<tr>
<td>Circular</td>
<td>0.57 ± 0.02</td>
</tr>
</tbody>
</table>
Results
Measured four-fold coincidences

- Visibilities of the dip in the orthogonal polarization are $(70 \pm 3)$%
Summary

- Teleportation of a single photon achieved at fidelity of 70%.
- Next steps:
  - Show teleportation in other systems.
  - Conduct experiments on the fundamental nature of quantum mechanics.
  - Provide links between quantum computers.
  - Increase teleportation distance.
Physical setup on La Palma (Alice) and Tenerife (Bob)
Setup

- Creation of photons.
- Photon 1 heralded by click at (t)
Alice’s Bell state measurement.

\( |\Psi^-angle_{12} \rightarrow \) clicks at \( t-a-d \) or \( t-b-c \), \( |\Psi^+\rangle_{12} \rightarrow \) clicks at \( t-a-b \) or \( t-c-d \)
Bob’s measurement setup

Classical and quantum channels are separated via dichoric mirror
Alice’s BSM distinguishes 2 Bell states ($|\psi^+\rangle$ and $|\psi^-\rangle$)
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1. $|\psi^-\rangle \rightarrow$ Bob does nothing (no feed-forward)
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1. $|\Psi^-\rangle \rightarrow$ Bob does nothing (no feed-forward)
2. $|\Psi^+\rangle \rightarrow$ Bob applies a $\pi$ pulse (feed-forward)
Feed-Forward

Alice’s BSM distinguishes 2 Bell states ($|\Psi^+\rangle$ and $|\Psi^-\rangle$)

1. $|\Psi^-\rangle \rightarrow$ Bob does nothing (no feed-forward)
2. $|\Psi^+\rangle \rightarrow$ Bob applies a $\pi$ pulse (feed-forward)
**Problem:** Fluctuations in atmosphere (rain, snow, temperature, etc.) ⇒ very low signal-to-noise ratio
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Solutions:
- High creation rates of entangled photon pairs
Noise Reduction

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**Solutions:**
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- Ultra-low dark count detectors with large active area
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- Ultra-low dark count detectors with large active area
- Small coincidence windows
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**Solutions:**

- High creation rates of entangled photon pairs
- Ultra-low dark count detectors with large active area
- Small coincidence windows
- Closed-loop tracking system
Results

Density Matrix Representation

- To test the teleportation, a known state is polarization is created (photon 1) and measured by Bob.
- Results shown using density matrix representations.
Results
Density Matrix Representation

Input state: $|\psi\rangle = |H\rangle$
Results

Density Matrix Representation

Input state: $|\psi\rangle = |V\rangle$
Results

Density Matrix Representation

Input state: $|\psi\rangle = |P\rangle = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$
Input state: $|\psi\rangle = |L\rangle = \frac{|H\rangle - i|V\rangle}{\sqrt{2}}$
Fidelities ($\langle \psi_{\text{ideal}} | \rho_{\text{meas}} | \psi_{\text{ideal}} \rangle$) are always above classical limit [3]! (feed-forward results shown in red)
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Note: results for \(|H\rangle\) and \(|V\rangle\) with or without feed-forward differ only by global phase
Summary

- We have discussed the teleportation protocol and its original implementation.
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We have seen how it can be used to teleport information over 143 km.
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First steps to world wide quantum key distribution → quantum network.
