Space Quantum Communication

Report for the ammission to the final exam of the PhD course in "Scienze, tecnologie e misure spaziali" Curriculum STASA

Matteo Schiavon

C.I.S.A.S. - Center of Studies and Activities for Space
University of Padova
Via Venezia 1, 35131 Padova (Italy)
tel. +39 049 827 6837
http://cisas.unipd.it

24 October 2016

Quantum communication

Quantum communication

COMMUNICATION

Quantum communication

COMMUNICATION

- transfer of information

Quantum communication

COMMUNICATION

- transfer of information
- it requires a physical system (*carrier*)

Quantum communication

COMMUNICATION

- transfer of information
- it requires a physical system (*carrier*)

QUANTUM

Quantum communication

COMMUNICATION

- transfer of information
- it requires a physical system (*carrier*)

QUANTUM

- information carriers follow the rules of Quantum Mechanics

Quantum communication

COMMUNICATION

- transfer of information
- it requires a physical system (*carrier*)

QUANTUM

- information carriers follow the rules of Quantum Mechanics
- PROS:
  - a *measurement* is required to get information about a system
  - measurements *always disturb* the system

Quantum communication

COMMUNICATION

- transfer of information
- it requires a physical system (*carrier*)

QUANTUM

- information carriers follow the rules of Quantum Mechanics
- PROS:
  - a *measurement* is required to get information about a system
  - measurements *always disturb* the system

$$\Downarrow$$

Quantum Key Distribution

Quantum communication

COMMUNICATION

- transfer of information
- it requires a physical system (*carrier*)

QUANTUM

- information carriers follow the rules of Quantum Mechanics
- PROS:
  - a *measurement* is required to get information about a system
  - measurements *always disturb* the system

$$\Downarrow$$

Quantum Key Distribution

- CONS:
  - quantum states cannot be copied

Quantum communication

COMMUNICATION

- transfer of information
- it requires a physical system (*carrier*)

QUANTUM

- information carriers follow the rules of Quantum Mechanics
- PROS:
    - a *measurement* is required to get information about a system
    - measurements *always disturb* the system

$$\Downarrow$$

Quantum Key Distribution

- CONS:
    - quantum states cannot be copied $\Rightarrow$ *no amplification*

Quantum communication systems

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*
    - difficult to reach long distances because of losses

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*
    - difficult to reach long distances because of losses
    - distance record: 307 km - secure rate: 3 bps

    [B. Korzh, *et al.*, Nature Photonics **9**, 163168 (2015)]

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*
  - difficult to reach long distances because of losses
  - distance record: 307 km - secure rate: 3 bps

    [B. Korzh, *et al.*, Nature Photonics **9**, 163168 (2015)]
- *Free space*

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*
  - difficult to reach long distances because of losses
  - distance record: 307 km - secure rate: 3 bps

    [B. Korzh, *et al.*, Nature Photonics **9**, 163168 (2015)]
- *Free space*
  - Horizontal link

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*
  - difficult to reach long distances because of losses
  - distance record: 307 km - secure rate: 3 bps

    [B. Korzh, *et al.*, Nature Photonics **9**, 163168 (2015)]
- *Free space*
  - Horizontal link
    - requirement of line of sight between transmitter and receiver

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*
  - difficult to reach long distances because of losses
  - distance record: 307 km - secure rate: 3 bps

    [B. Korzh, *et al.*, Nature Photonics **9**, 163168 (2015)]
- *Free space*
  - Horizontal link
    - requirement of line of sight between transmitter and receiver
    - distance record: 144 km

      [T. Schmitt-Manderbach, *et al.*, PRL **98**, 010504 (2007)]

      [G. Vallone, *et. al*, PRA **91**, 042320 (2015)]

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*
  - difficult to reach long distances because of losses
  - distance record: 307 km - secure rate: 3 bps

    [B. Korzh, *et al.*, Nature Photonics **9**, 163168 (2015)]
- *Free space*
  - Horizontal link
    - requirement of line of sight between transmitter and receiver
    - distance record: 144 km

      [T. Schmitt-Manderbach, *et al.*, PRL **98**, 010504 (2007)]

      [G. Vallone, *et. al*, PRA **91**, 042320 (2015)]
  - Vertical link

Quantum communication systems

The quantum state must be preserved through all the transmission distance.

- *Optical fibers*
  - difficult to reach long distances because of losses
  - distance record: 307 km - secure rate: 3 bps

    [B. Korzh, *et al.*, Nature Photonics **9**, 163168 (2015)]
- *Free space*
  - Horizontal link
    - requirement of line of sight between transmitter and receiver
    - distance record: 144 km

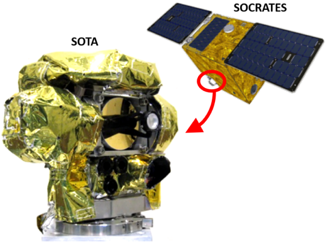
      [T. Schmitt-Manderbach, *et al.*, PRL **98**, 010504 (2007)]

      [G. Vallone, *et. al*, PRA **91**, 042320 (2015)]
  - Vertical link $\Rightarrow$ satellite quantum communication

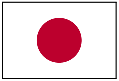
The race to space

The race to space

- Japan

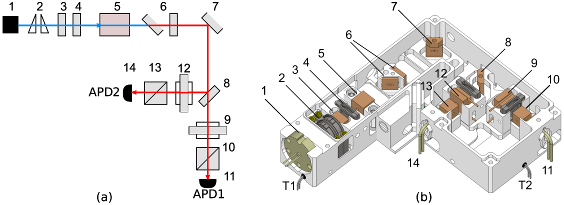


[A. Carrasco-Casado, *et al.*, Optics Express **24**, 12254 (2016)]



The race to space

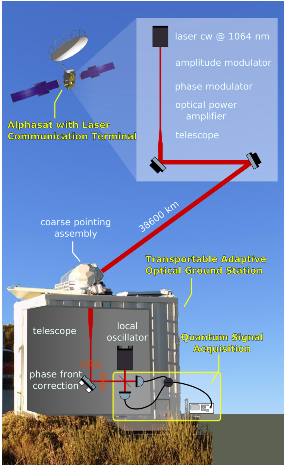
- Japan
- Singapore



[Z. Tang, *et al.*, Phys. Rev. Applied **5**, 1-5 (2016)]

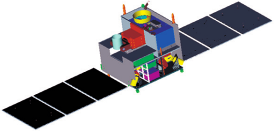
The race to space

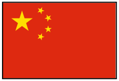
- Japan
- Singapore
- Germany



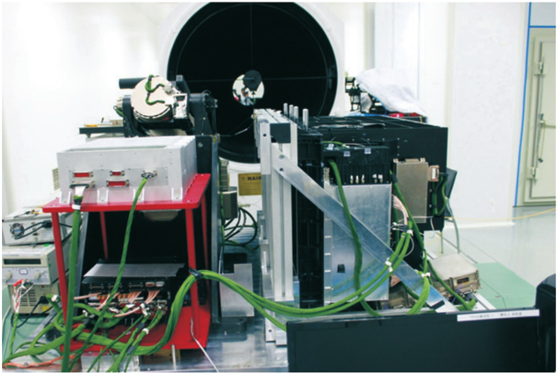
[K. Günthner, *et al.*, arXiv:1608.03511v1 (2016)]

The race to space





- Japan
- Singapore
- Germany
- China



[J. Pan, Chin. J. Space Sci. **34**, 547-549 (2014)]

The race to space

- Japan
- Singapore
- Germany
- China
- Italy?

The race to space

- *2003* - start of the SpaceQ project

- Japan
- Singapore
- Germany
- China
- Italy?

The race to space

- Japan
- Singapore
- Germany
- China
- Italy?

- *2003* - start of the SpaceQ project
- *2008* - first experimental demonstration of feasibility of single photon link

[P. Villoresi, *et al.*, New J. Phys. **10**, 033038 (2008)]

The race to space

- Japan
- Singapore
- Germany
- China
- Italy?

- *2003* - start of the SpaceQ project
- *2008* - first experimental demonstration of feasibility of single photon link

  [P. Villoresi, *et al.*, New J. Phys. **10**, 033038 (2008)]
- *2015* - first experimental demonstration of polarization encoding downlink

  [G. Vallone, *et al.*, Phys. Rev. Lett. **115**, 040502 (2015)]

The race to space

- Japan
- Singapore
- Germany
- China
- Italy?

- *2003* - start of the SpaceQ project
- *2008* - first experimental demonstration of feasibility of single photon link

  [P. Villoresi, *et al.*, New J. Phys. **10**, 033038 (2008)]
- *2015* - first experimental demonstration of polarization encoding downlink

  [G. Vallone, *et al.*, Phys. Rev. Lett. **115**, 040502 (2015)]
- *2016* - single-photon interference in the satellite-ground channel

  [G. Vallone, *et al.*, Phys. Rev. Lett **116**, 253601 (2016)]

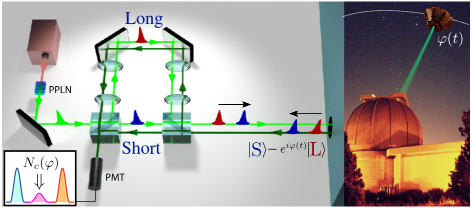
Single-photon interference in the satellite-ground channel

Single-photon interference in the satellite-ground channel

Time-bin encoded qubits

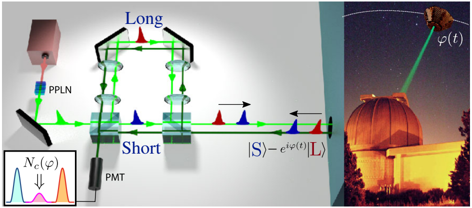
Single-photon interference in the satellite-ground channel

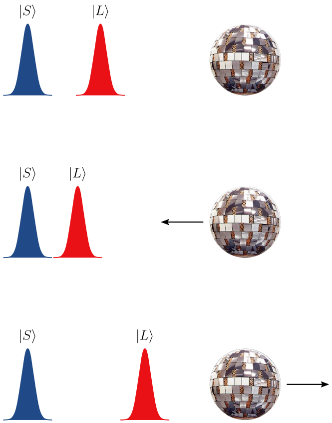
Time-bin encoded qubits



Single-photon interference in the satellite-ground channel

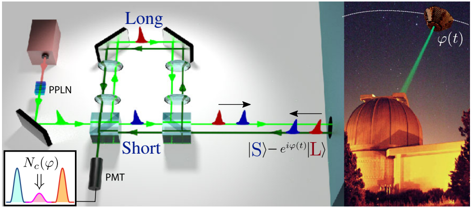
Time-bin encoded qubits

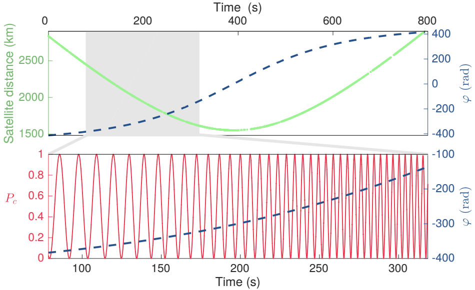


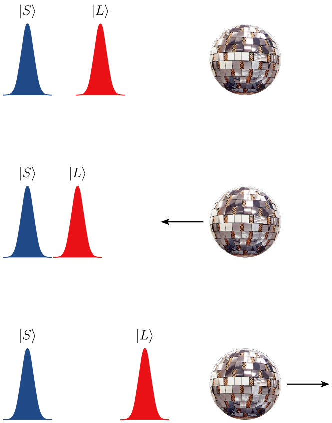


Single-photon interference in the satellite-ground channel

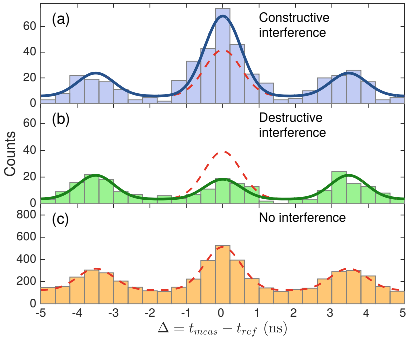
Time-bin encoded qubits



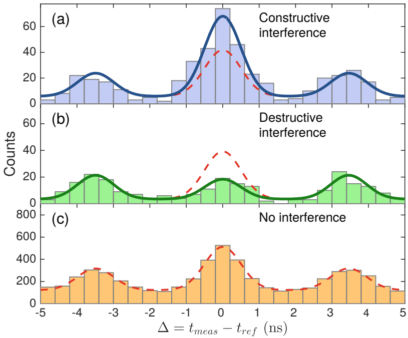


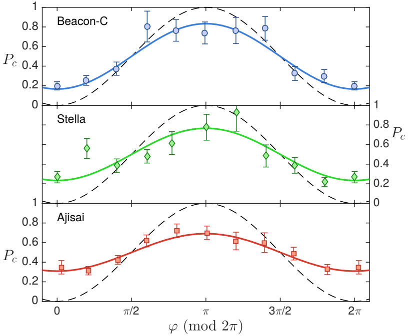


Single-photon interference in the satellite-ground channel



Single-photon interference in the satellite-ground channel





New experimental scheme for the ground station

Goals:

New experimental scheme for the ground station

Goals:

- extend quantum communication to MEO and GEO satellites

  [D. Dequal, *et al.*, PRA **93**, 010301(R) (2016)]

New experimental scheme for the ground station

Goals:

- extend quantum communication to MEO and GEO satellites

  [D. Dequal, *et al.*, PRA **93**, 010301(R) (2016)]

- proof of principle of new quantum communication protocols

New experimental scheme for the ground station

Goals:

- extend quantum communication to MEO and GEO satellites

  [D. Dequal, *et al.*, PRA **93**, 010301(R) (2016)]
- proof of principle of new quantum communication protocols

Characteristics of the new setup:

New experimental scheme for the ground station

Goals:

- extend quantum communication to MEO and GEO satellites
  [D. Dequal, *et al.*, PRA **93**, 010301(R) (2016)]
- proof of principle of new quantum communication protocols

Characteristics of the new setup:

- new detectors with improved time accuracy ($\sim 40\,\mathrm{ps}$ jitter)

New experimental scheme for the ground station

Goals:

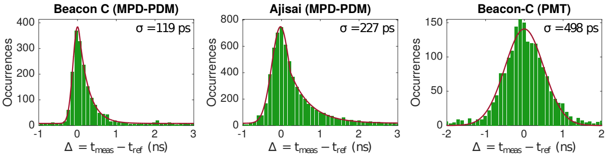
- extend quantum communication to MEO and GEO satellites

  [D. Dequal, *et al.*, PRA **93**, 010301(R) (2016)]

- proof of principle of new quantum communication protocols

Characteristics of the new setup:

- new detectors with improved time accuracy ($\sim 40\,\mathrm{ps}$ jitter)



[G. Vallone, *et al.*, Proc. SPIE 9900, Quantum Optics, 99000J (April 29, 2016)]

New experimental scheme for the ground station

Goals:

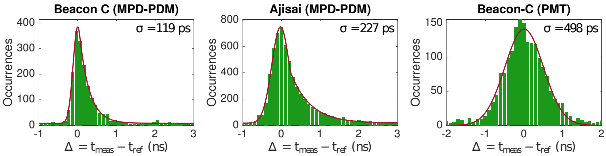
- extend quantum communication to MEO and GEO satellites

  [D. Dequal, *et al.*, PRA **93**, 010301(R) (2016)]

- proof of principle of new quantum communication protocols

Characteristics of the new setup:

- new detectors with improved time accuracy ($\sim 40\,\mathrm{ps}$ jitter)



[G. Vallone, *et al.*, Proc. SPIE 9900, Quantum Optics, 99000J (April 29, 2016)]

- new time-tagging unit ($1\,\mathrm{ps}$ resolution, $\sim 10\,\mathrm{ps}$ jitter)

New experimental scheme for the ground station

Goals:

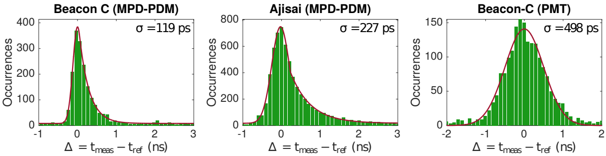
- extend quantum communication to MEO and GEO satellites

  [D. Dequal, *et al.*, PRA **93**, 010301(R) (2016)]

- proof of principle of new quantum communication protocols

Characteristics of the new setup:

- new detectors with improved time accuracy ($\sim 40\,\mathrm{ps}$ jitter)

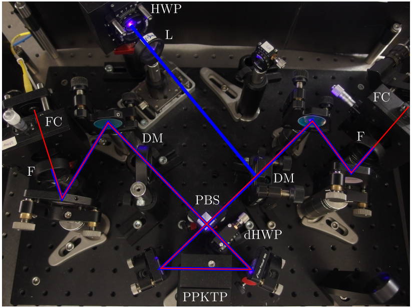


[G. Vallone, *et al.*, Proc. SPIE 9900, Quantum Optics, 99000J (April 29, 2016)]

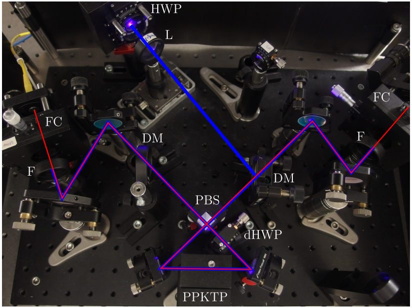
- new time-tagging unit ($1\,\mathrm{ps}$ resolution, $\sim 10\,\mathrm{ps}$ jitter)
- new data analysis software

Source of polarization-entangled photons

Source of polarization-entangled photons

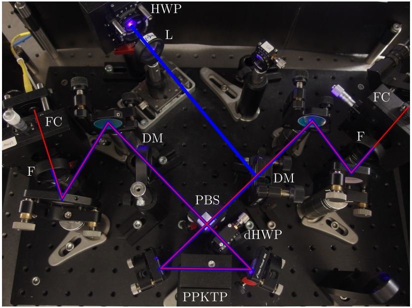


Source of polarization-entangled photons



Characteristics:

Source of polarization-entangled photons

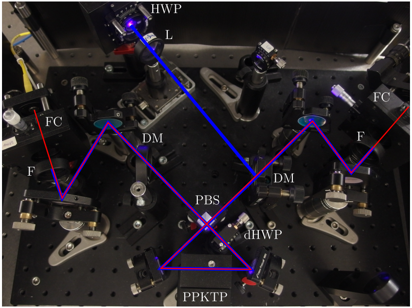


Characteristics:

- high brilliance

  ($\geq 100\,\mathrm{kHz}$ with few *mW* of pump power)

Source of polarization-entangled photons

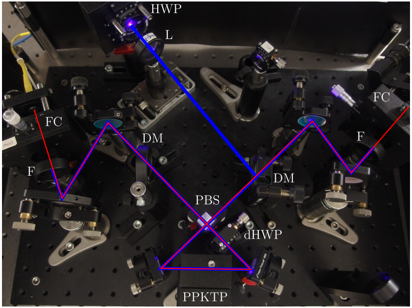


Characteristics:

- high brilliance

  ($\geq 100\,\mathrm{kHz}$ with few *mW* of pump power)
- narrow bandwidth ($< 0.2\,\mathrm{nm}$)

Source of polarization-entangled photons



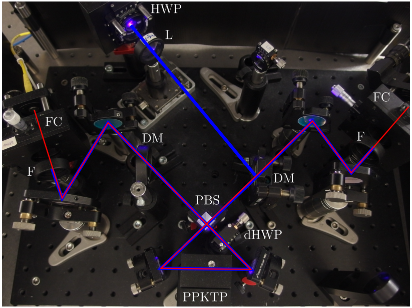
Characteristics:

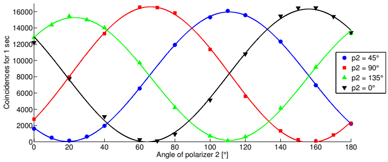
- high brilliance

  ($\geq 100\,\mathrm{kHz}$ with few *mW* of pump power)

- narrow bandwidth ($< 0.2\,\mathrm{nm}$)
- tunable wavelength

Source of polarization-entangled photons





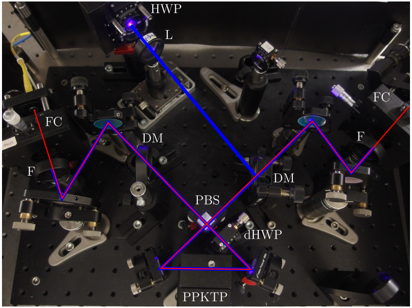
Characteristics:

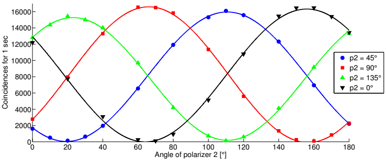
- high brilliance

  ($\geq$ 100 kHz with few *mW* of pump power)
- narrow bandwidth ($< 0.2\,\mathrm{nm}$)
- tunable wavelength
- high visibility

  ($>$ 98% in two mutually unbiased bases)

Source of polarization-entangled photons





Characteristics:

- high brilliance

  ($\geq 100\,\mathrm{kHz}$ with few mW of pump power)
- narrow bandwidth ($< 0.2\,\mathrm{nm}$)
- tunable wavelength
- high visibility

  ($>$ 98% in two mutually unbiased bases)
- adapt for integration into space missions

  [L. Xin, Physics World (August 16, 2016)]

Quantum Key Distribution

Quantum Key Distribution

Quantum Mechanics: *"measurements always disturb the system"*

Quantum Key Distribution

Quantum Mechanics: *"measurements always disturb the system"*

$$\Downarrow$$

any attempt to intercept the communication is detectable

Quantum Key Distribution

Quantum Mechanics: *“measurements always disturb the system”*

$\Downarrow$

any attempt to intercept the communication is detectable

$\Downarrow$

Quantum Key Distribution

Quantum Key Distribution

Quantum Mechanics: *"measurements always disturb the system"*

$\Downarrow$

any attempt to intercept the communication is detectable

$\Downarrow$

Quantum Key Distribution

Some protocols:

Quantum Key Distribution

Quantum Mechanics: *"measurements always disturb the system"*

$\Downarrow$

any attempt to intercept the communication is detectable

$\Downarrow$

Quantum Key Distribution

Some protocols:

- *BB84:* uses 4 states in 2 non-orthogonal basis
  PROS: loss tolerant (it works for QBER up to 11%)
  CONS: 4 detectors, or 2 detectors and active basis selection

Quantum Key Distribution

Quantum Mechanics: *“measurements always disturb the system”*

$\Downarrow$

any attempt to intercept the communication is detectable

$\Downarrow$

Quantum Key Distribution

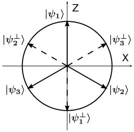
Some protocols:

- *BB84:* uses 4 states in 2 non-orthogonal basis
  PROS: loss tolerant (it works for QBER up to 11%)
  CONS: 4 detectors, or 2 detectors and active basis selection
- *B92:* uses 2 non-orthogonal states
  PROS: 2 detectors
  CONS: eavesdropper can hide behind channel losses

Equiangular three-state Quantum Key Distribution

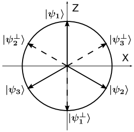
Equiangular three-state Quantum Key Distribution

- 3 symmetric states



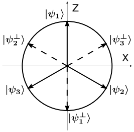
Equiangular three-state Quantum Key Distribution

- 3 symmetric states $\Rightarrow$ 3 detectors



Equiangular three-state Quantum Key Distribution

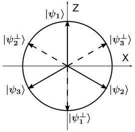
- 3 symmetric states $\Rightarrow$ 3 detectors



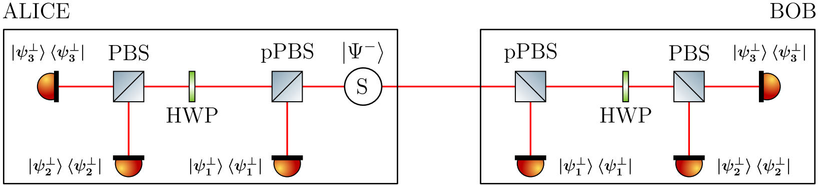
- loss tolerant (it works for QBER up to 9.81%)

Equiangular three-state Quantum Key Distribution

- 3 symmetric states $\Rightarrow$ 3 detectors

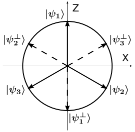


- loss tolerant (it works for QBER up to 9.81%)
- entanglement-based version with passive receivers

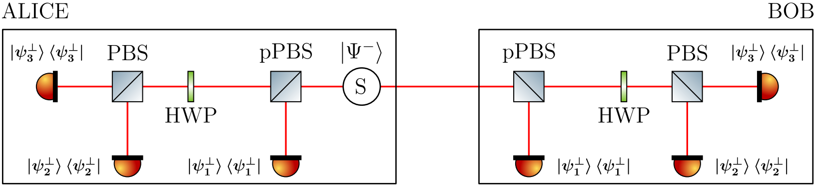


Equiangular three-state Quantum Key Distribution

- 3 symmetric states $\Rightarrow$ 3 detectors

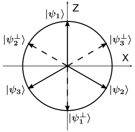


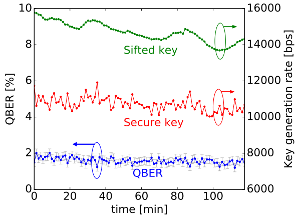
- loss tolerant (it works for QBER up to 9.81%)
- entanglement-based version with passive receivers $\Rightarrow$ high stability



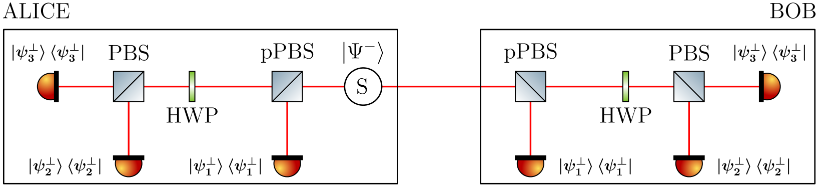
Equiangular three-state Quantum Key Distribution

- 3 symmetric states ⇒ 3 detectors





- loss tolerant (it works for QBER up to 9.81%)
- entanglement-based version with passive receivers ⇒ high stability



Bell's inequality

Bell's inequality

Einstein-Podolsky-Rosen (1935):

Bell's inequality

Einstein-Podolsky-Rosen (1935):

> *"[. . .] the quantum-mechanical description of physical reality given by wave functions is not complete."*

Bell's inequality

Einstein-Podolsky-Rosen (1935):

> *"[. . .] the quantum-mechanical description of physical reality given by wave functions is not complete."*

Bell (1964):

Bell's inequality

Einstein-Podolsky-Rosen (1935):

> *"[. . .] the quantum-mechanical description of physical reality given by wave functions is not complete."*

Bell (1964):

- all correlations explicable by a local model must satisfy the inequality

$$S_{CHSH} \leq 2$$

Bell's inequality

Einstein-Podolsky-Rosen (1935):

> *"[. . .] the quantum-mechanical description of physical reality given by wave functions is not complete."*

Bell (1964):

- all correlations explicable by a local model must satisfy the inequality

$$S_{CHSH} \leq 2$$

Quantum mechanics:

Bell's inequality

Einstein-Podolsky-Rosen (1935):

> *"[...] the quantum-mechanical description of physical reality given by wave functions is not complete."*

Bell (1964):

- all correlations explicable by a local model must satisfy the inequality

$$S_{CHSH} \leq 2$$

Quantum mechanics:

- there exist systems for which $S_{CHSH} = 2\sqrt{2} > 2$

Three-observer Bell inequality

Three-observer Bell inequality

Three *non-signaling* observers cannot share non-locality,

Three-observer Bell inequality

Three *non-signaling* observers cannot share non-locality,
BUT

Three-observer Bell inequality

Three *non-signaling* observers cannot share non-locality,

BUT

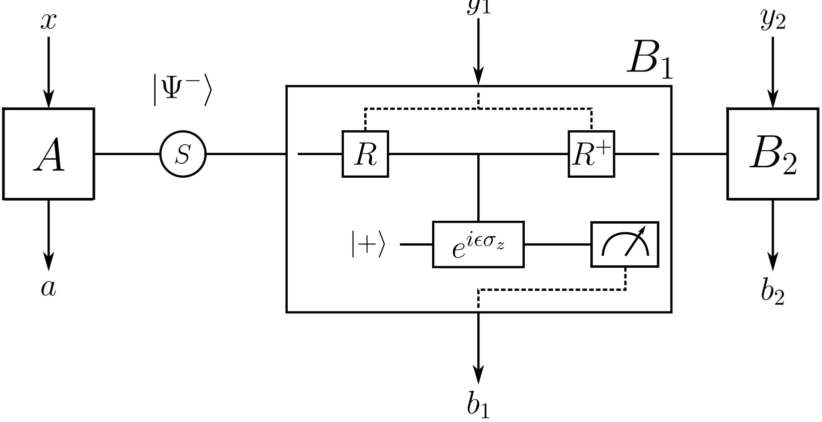
three *independent* observers can.

Three-observer Bell inequality

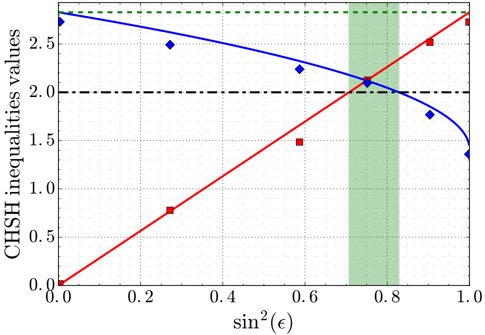
Three *non-signaling* observers cannot share non-locality,

BUT

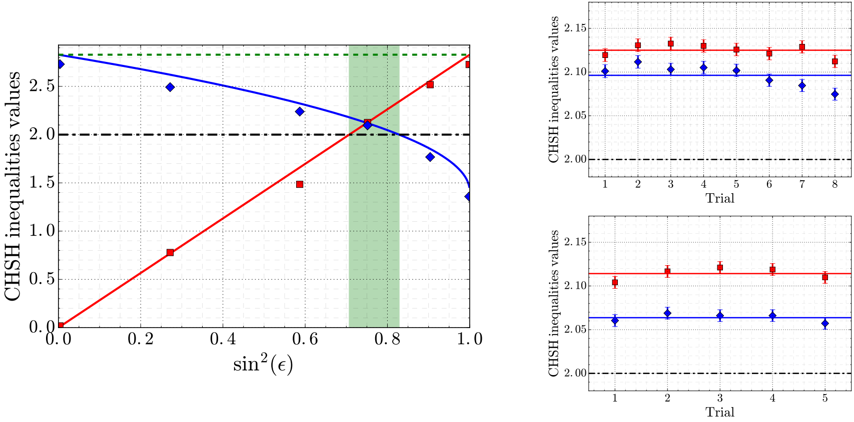
three *independent* observers can.



Three-observer Bell inequality



Three-observer Bell inequality



Conclusions

Main results of this thesis work:

Conclusions

Main results of this thesis work:

- setup of a source of polarization-entangled photons and its exploitation for quantum communication experiments,

Conclusions

Main results of this thesis work:

- setup of a source of polarization-entangled photons and its exploitation for quantum communication experiments,
- proof that time-bin encoding is exploitable for satellite quantum communication.

Conclusions

Main results of this thesis work:

- setup of a source of polarization-entangled photons and its exploitation for quantum communication experiments,
- proof that time-bin encoding is exploitable for satellite quantum communication.

Future perspectives:

Conclusions

Main results of this thesis work:

- setup of a source of polarization-entangled photons and its exploitation for quantum communication experiments,
- proof that time-bin encoding is exploitable for satellite quantum communication.

Future perspectives:

- further exploitation of the source for experiments in free-space,

Conclusions

Main results of this thesis work:

- setup of a source of polarization-entangled photons and its exploitation for quantum communication experiments,
- proof that time-bin encoding is exploitable for satellite quantum communication.

Future perspectives:

- further exploitation of the source for experiments in free-space,
- extend satellite quantum communication to MEO and GEO satellites, with the test of new protocols.

Conclusions

Main results of this thesis work:

- setup of a source of polarization-entangled photons and its exploitation for quantum communication experiments,
- proof that time-bin encoding is exploitable for satellite quantum communication.

Future perspectives:

- further exploitation of the source for experiments in free-space,
- extend satellite quantum communication to MEO and GEO satellites, with the test of new protocols.

Some publications related to this thesis work:

- [G. Vallone, *et al.*, Phys. Rev. Lett. **116**, 253601 (2016)]
- [M. Schiavon, *et al.*, Phys. Rev. A **93**, 012331 (2016)]
- [M. Schiavon, *et al.* Scientific Reports **6**, 30089 (2016)]
- [G. Vallone, *et al.*, *Proc SPIE 9900, Quantum Optics 99000J* (April 29, 2016)]