Title: Long distance quantum communications: Quantum Experiments using Satellite Technologies (QUEST)

Speakers: Urbasi Sinha

Collection: QPV 2023: Advances in quantum position verification

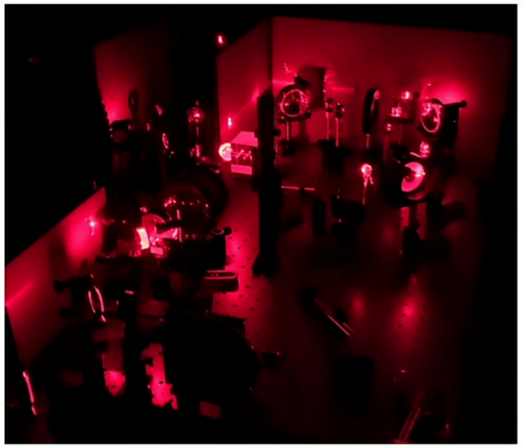
Date: September 20, 2023 - 1:00 PM

URL: https://pirsa.org/23090019

Quantum Experiments using Satellite Technology

QuEST

ISRO



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Prof. Urbasi Sinha

π: Quantum Information & Computing (QuIC) Lab

Raman Research Institute (RRI), Bengaluru, India.

Affiliate Faculty at IQC, Waterloo, Canada & CQIQC, Toronto, Canada

Simon's Emmy Noether fellow at Perimeter Institute, Canada.

QPV 2023

A string theorist caught in a loop quantum gravity conference…

The Star wars analogy…

QPV/ QG Theorist

The QPV experimentalist

Other quantum comm experimentalist?

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Long distance quantum communications

Why Satellites for QKD?

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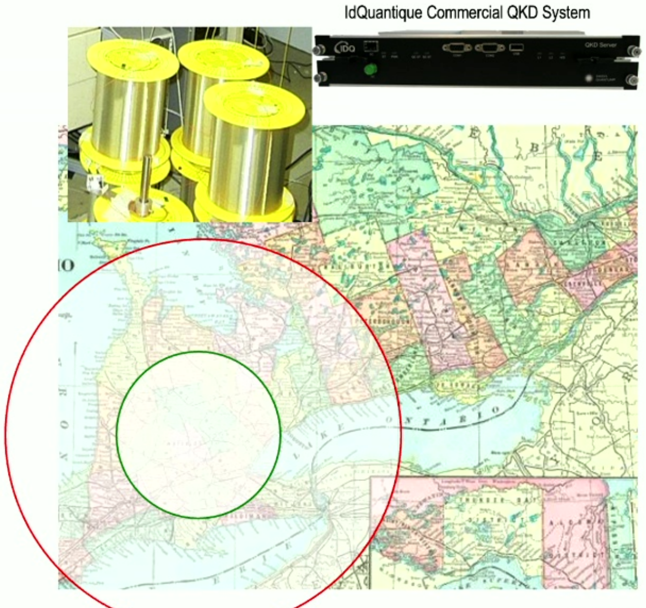
Distance Limits for Quantum Channels

- Ground-based
  - typically 100 km
  - Demonstrations to max. 300 km
  - Optic fibre loss 0.15 dB/km at best
  - Free-space limited due to line-of-sight
  - Commercial Devices available:
  - **Note: Optical amplifiers not possible!**

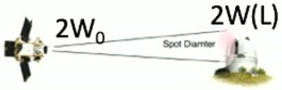
- Longer distances:
  - Trusted Repeaters (> 1000km networks under way)
  - Long lived Quantum Memories
  - Quantum Repeaters
  - **Satellites**



Takesue et al, Nature Photonics 1, 343 - 348 (2007)

Ma, Fung, Lo, Phys. Rev. A 76, 012307 (2007)

$$T_{geo} \approx \frac{D_R^2 D_T^2}{\lambda^2 L^2}$$



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- Satellite bridges the large gap between ground based quantum networks
  - short range connection via city-wide optical fibres (such as SECOQC or Tokyo QKD networks)

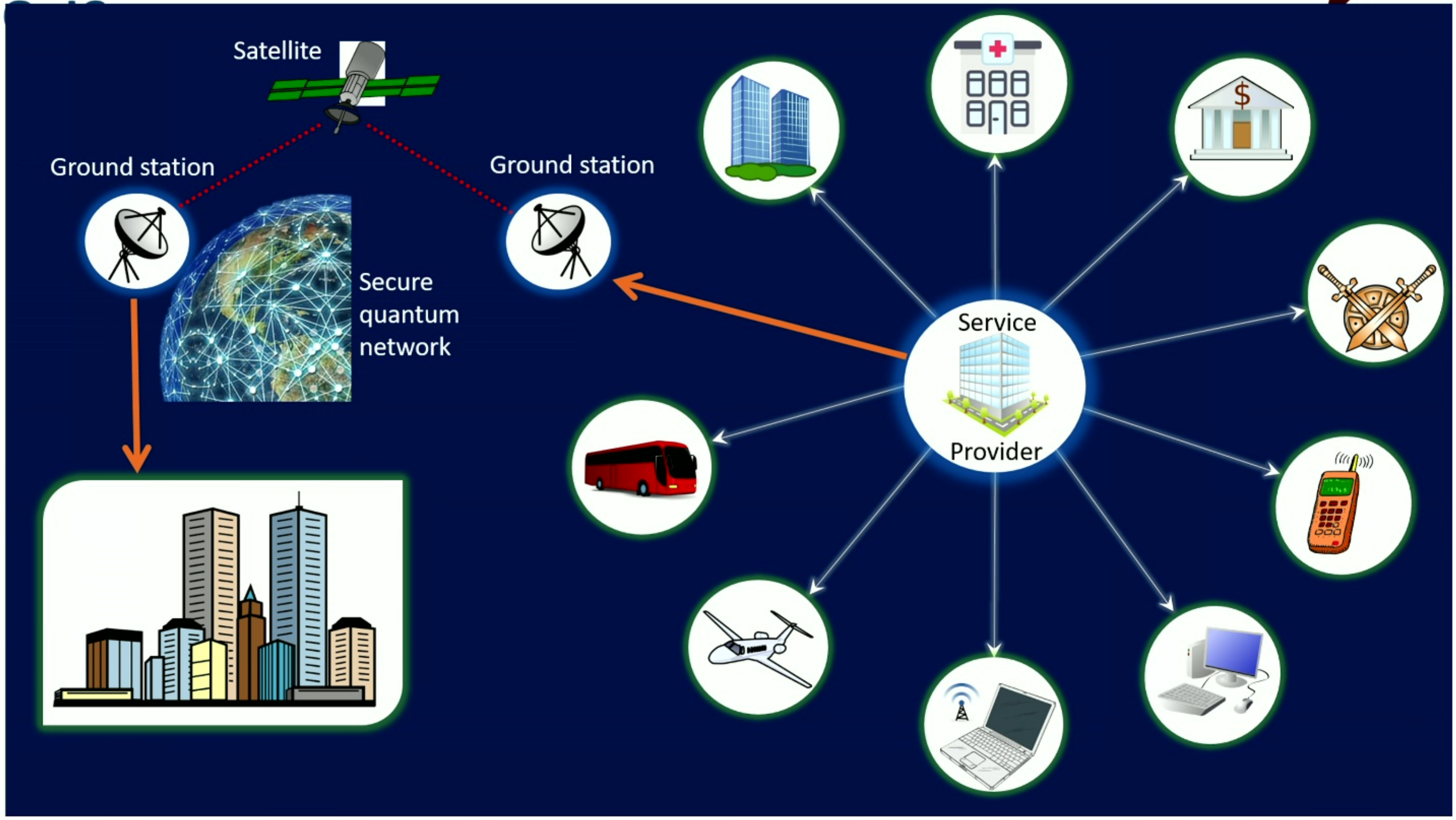

Photo courtesy: Quantum Information and Computing lab

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Fibre-based QKD record:

Previous distance record was 404 km (Measurement-device-independent quantum key distribution over a 404 km optical fiber) [H.-L. Yin et al., Phys. Rev. Lett. 117(19), 190501 (2016)]

Secure Twin-Field Quantum Key Distribution over 509 km [Jiu-Peng Chen et al., Phys. Rev. Lett. **124**, 070501 (2020). https://doi.org/10.1103/PhysRevLett.124.070501]

Recently, China successfully completed the 2000-km-long fiber-optic backbone link between Beijing and Shanghai (Y.-A. Chen et al., 2020 **YET TO BE PUBLISHED**). [Source: F. Xu et al., Secure quantum key distribution with realistic devices, Rev. Mod. Phys. 92, 025002 (2020). https://doi.org/10.1103/RevModPhys.92.025002]

Free-space QKD record:

Experimental implementation of a Bennett-Brassard 1984 (BB84) protocol type quantum key distribution over a 144 km free-space link using weak coherent laser pulses [Tobias Schmitt-Manderbach et al., Phys. Rev. Lett. 98, 010504 (2007). https://doi.org/10.1103/PhysRevLett.98.010504]

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And so our journey began....

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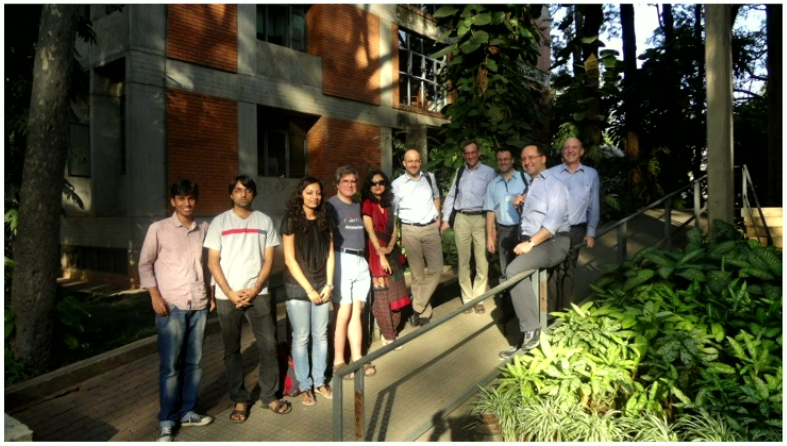

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With Photons....

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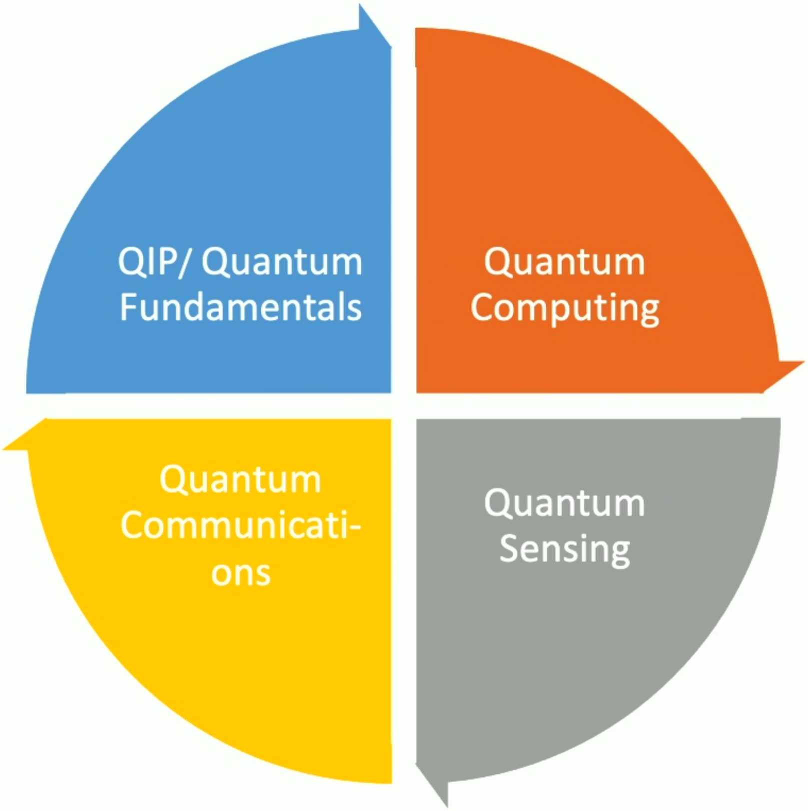
QIP/ Quantum Fundamentals

Quantum Computing

Quantum Communicati-ons

Quantum Sensing

QuIC

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1. **Quantum Communications**
   a) Quantum Key Distribution
   b) Quantum Teleportation, Quantum Relays and Repeater technologies
   c) Device independent Random Number Generation
   d) Integrated photonics based quantum communications

2. **Quantum Computing**
   a. Indigenous spatial photonic platform
   b. Cloud based quantum computing (member of Geneva Science and Diplomacy Anticipator (GESDA) Open Quantum Institute incubation advisory board as well as spearheading partner for the incubation from India, collaboration with CERN)

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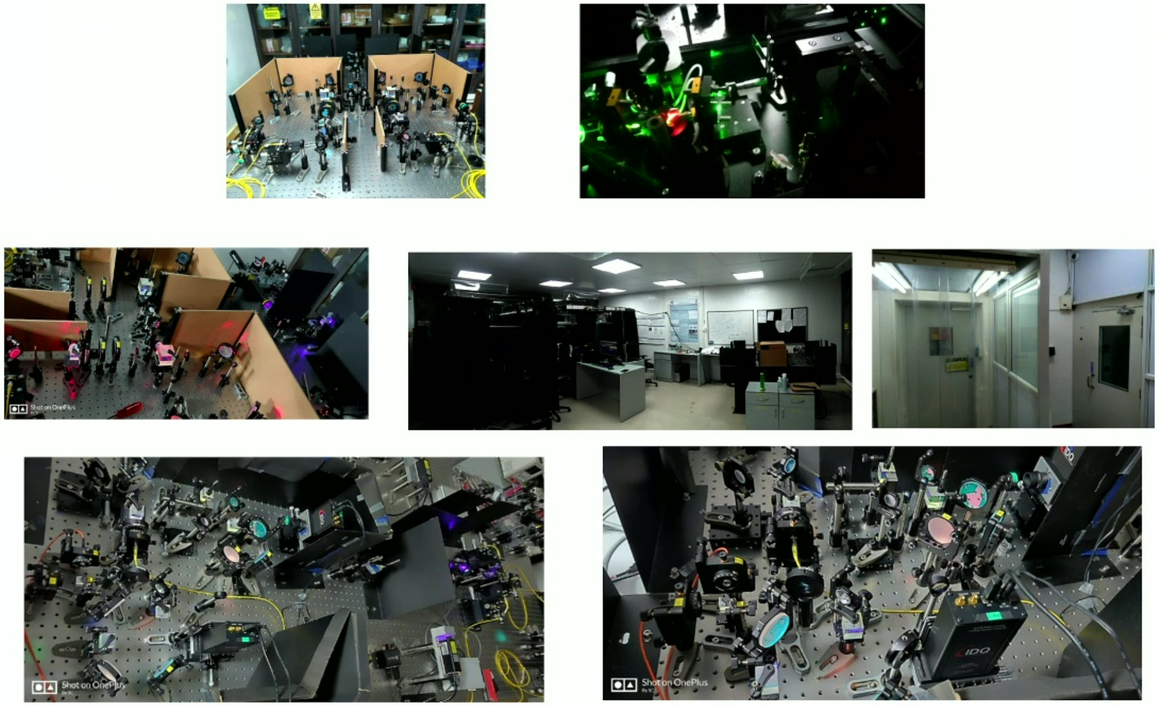
3. **Quantum Sensing**
   a. Quantum Imaging using entangled photons
   b. Quantum sensing using generalized measurements

4. **Precision tests of principles of foundations of quantum mechanics and quantum gravity**



https://wwws.rri.res.in/quic

Current members:

1. Dr. Satyaranjan Behera (Research Scientist C)
2. Dr. Animesh S Roy (Post Doc)
3. Dr. Kallol Sen (Consultant)
4. S Chakraborti (PhD)
5. Saumya Ranjan Behera (PhD)
6. Mehak Layal (PhD)
7. Pingal Pratyush Nath (co-supervised)
8. Srinivas Pattnaik (JRF)
9. Anwesha Hoodati (JRF)
10. Prabhakaran S (Project engineer)
11. Melvee George (research assistant)
12. Sujatha S (Consulting engineer)
13. Arnav (Masters student)

Former members:

1. Dr. Simanraj Sadana (post doc, Pavia/Fermilab)
2. Dr. Ashutosh Singh (post doc, Calgary, Canada)
3. Dr. Kausik Joarder (NCU, Poland)
4. Sourav Chatterjee (TCS)
5. Debadrita Ghosh (Gottingen, Germany)
6. A.Rengaraj (LMU)
7. U.Prathwiraj (QuTech, NL)
8. Eneet Kaur (LSU)
9. G Saha (Georgia Tech)
10. Sai Dheeraj Nadela (IIIT)
11. Siva P(INRM, Italy)
12. Karthik Joshi
13. Animesh Aaryan (TaqBit)
14. Pradeep N
15. Anjali P.S. (IIT M)
16. Shreya Ray (U Texas)
17. Aravind H.V. (TIFR)
18. Sunny Saurabh (Japan)
19. Sudhi Oberoi (IISc)
20. Reena Sayani (IPR)
21. A.Nagalakshmi (Research Scientist B)
22. Rakshita RM
23. A. Anuradha (NCU, Poland)
24. Nandini SG
25. Neha K Nasar (CUSAT)
26. Dr. Kaumudibikash Goswami (post doc, HK)
27. Arghyajoy Mondal (TCS Innovations labs)

To name a few...

(Most) Current members of QuIC lab

+ Madhumati

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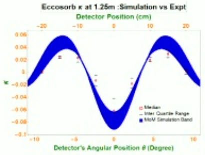
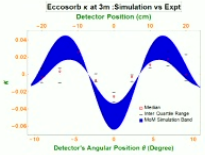
Fundamental tests of quantum mechanics.





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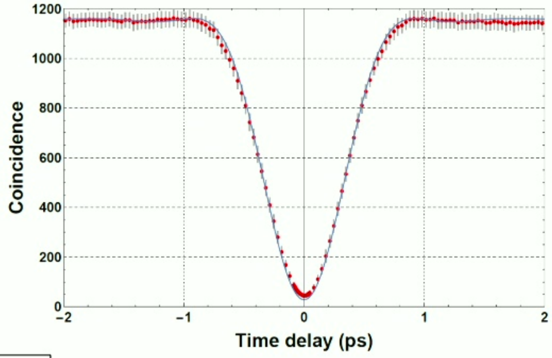
- *New Journal of Physics* **20** 063049, 2018.
- *International Journal of Quantum Information* **14** 1650024, 2016.
- *Scientific Reports*, **5** 10304, 2015.
- *Physical Review Letters*, **113** 120406, 2014 .
- *Science, **329** 5990 418 – 421, 2010.*

Fundamental Quantum Optics.



- *Physical Review A **100** 013839, 2019.*
- *Physical Review Letters **125** 123601, 2020*
- *Physical Review X Quantum* **3**, 010307, 2022.

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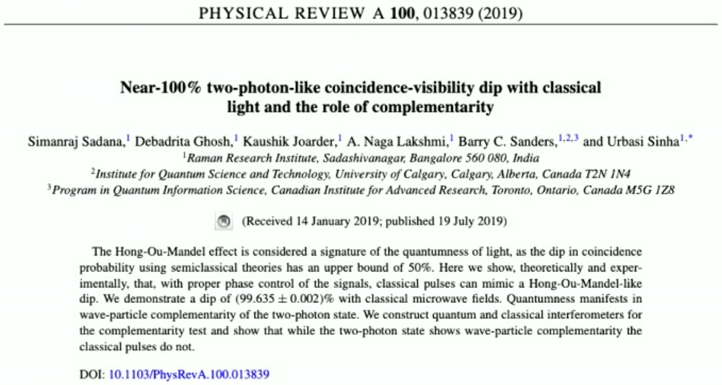
Fundamental Quantum Optics.

Simanraj Sadana, now@ University of Pavia Italy & Fermilab, USA.

Kaushik Joarder now@ NCU, Poland

Debadrita Ghosh, now@ University of Gottingen, Germany.



PHYSICAL REVIEW A **100**, 013839 (2019)

Near-100% two-photon-like coincidence-visibility dip with classical light and the role of complementarity

Simanraj Sadana,[1] Debadrita Ghosh,[1] Kaushik Joarder,[1] A. Naga Lakshmi,[1] Barry C. Sanders,[1,2,3] and Urbasi Sinha[1,*]
[1] *Raman Research Institute, Sadashivanagar, Bangalore 560 080, India*
[2] *Institute for Quantum Science and Technology, University of Calgary, Calgary, Alberta, Canada T2N 1N4*
[3] *Program in Quantum Information Science, Canadian Institute for Advanced Research, Toronto, Ontario, Canada M5G 1Z8*

(Received 14 January 2019; published 19 July 2019)

The Hong-Ou-Mandel effect is considered a signature of the quantumness of light, as the dip in coincidence probability using semiclassical theories has an upper bound of 50%. Here we show, theoretically and experimentally, that, with proper phase control of the signals, classical pulses can mimic a Hong-Ou-Mandel-like dip. We demonstrate a dip of $(99.635 \pm 0.002)\%$ with classical microwave fields. Quantumness manifests in wave-particle complementarity of the two-photon state. We construct quantum and classical interferometers for the complementarity test and show that while the two-photon state shows wave-particle complementarity the classical pulses do not.

DOI: 10.1103/PhysRevA.100.013839

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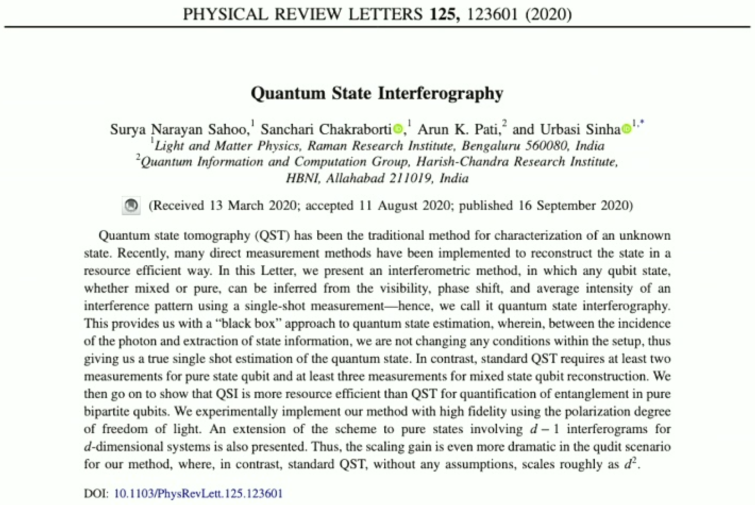
Fundamental Quantum Optics/ Quantum Information



PHYSICAL REVIEW LETTERS **125,** 123601 (2020)

Quantum State Interferography

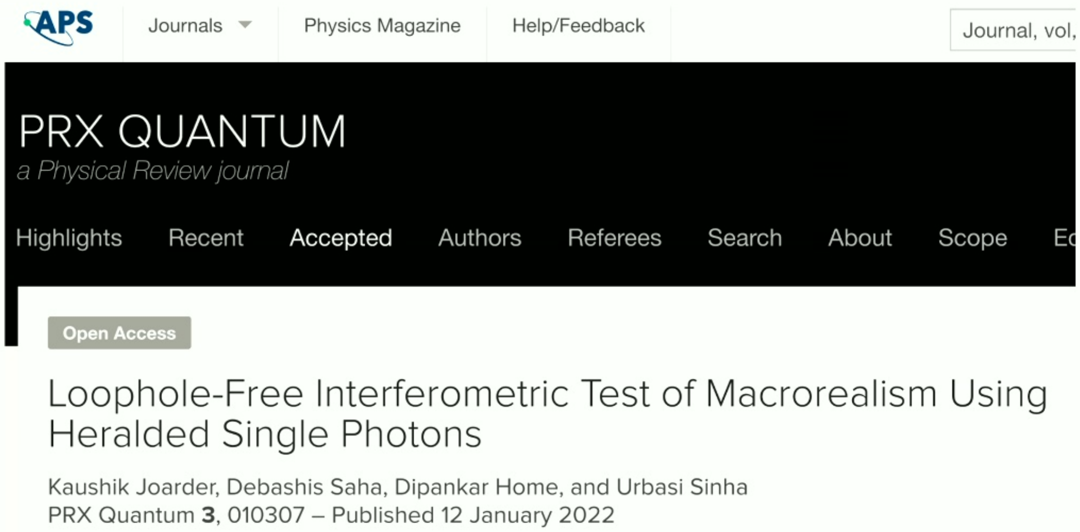
Surya Narayan Sahoo,[1] Sanchari Chakraborti,[1] Arun K. Pati,[2] and Urbasi Sinha[1,*]
[1] *Light and Matter Physics, Raman Research Institute, Bengaluru 560080, India*
[2] *Quantum Information and Computation Group, Harish-Chandra Research Institute,*
HBNI, Allahabad 211019, India

(Received 13 March 2020; accepted 11 August 2020; published 16 September 2020)

Quantum state tomography (QST) has been the traditional method for characterization of an unknown state. Recently, many direct measurement methods have been implemented to reconstruct the state in a resource efficient way. In this Letter, we present an interferometric method, in which any qubit state, whether mixed or pure, can be inferred from the visibility, phase shift, and average intensity of an interference pattern using a single-shot measurement—hence, we call it quantum state interferography. This provides us with a "black box" approach to quantum state estimation, wherein, between the incidence of the photon and extraction of state information, we are not changing any conditions within the setup, thus giving us a true single shot estimation of the quantum state. In contrast, standard QST requires at least two measurements for pure state qubit and at least three measurements for mixed state qubit reconstruction. We then go on to show that QSI is more resource efficient than QST for quantification of entanglement in pure bipartite qubits. We experimentally implement our method with high fidelity using the polarization degree of freedom of light. An extension of the scheme to pure states involving $d-1$ interferograms for d-dimensional systems is also presented. Thus, the scaling gain is even more dramatic in the qudit scenario for our method, where, in contrast, standard QST, without any assumptions, scales roughly as d^2.

DOI: 10.1103/PhysRevLett.125.123601

Fundamental Quantum Optics/ Quantum Information



PRX QUANTUM

a Physical Review journal

Loophole-Free Interferometric Test of Macrorealism Using Heralded Single Photons

Kaushik Joarder, Debashis Saha, Dipankar Home, and Urbasi Sinha

PRX Quantum **3**, 010307 – Published 12 January 2022

First ever loophole free violation of the Leggett Garg inequalities achieved by our lab in early 2022, a proud moment indeed for QuIC lab!

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Fundamental Quantum Optics/ Quantum Information

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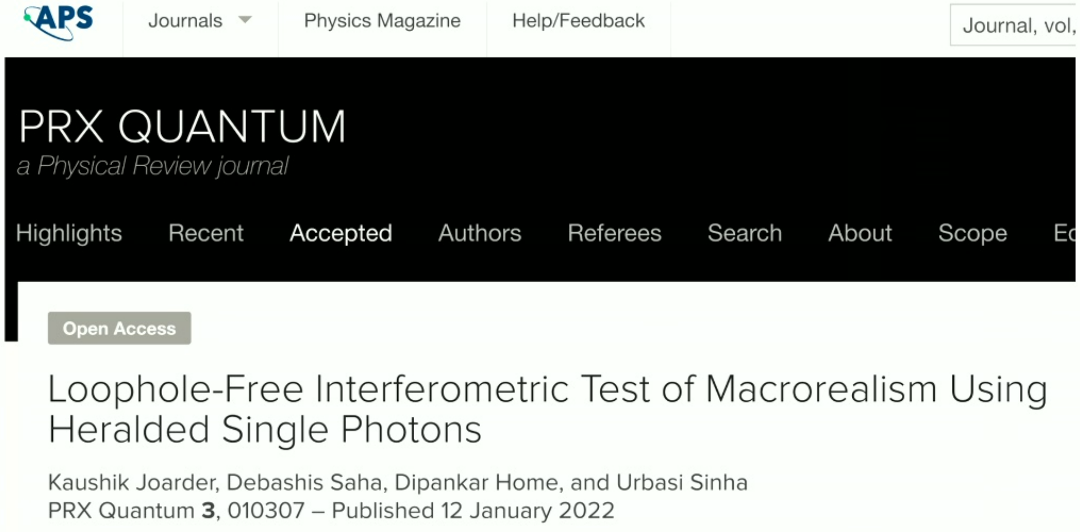
Sir Anthony Leggett, Nobel laureate 2003

Prof. Anupam Garg



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Now being used for secure quantum communications, like the Bell inequalities…

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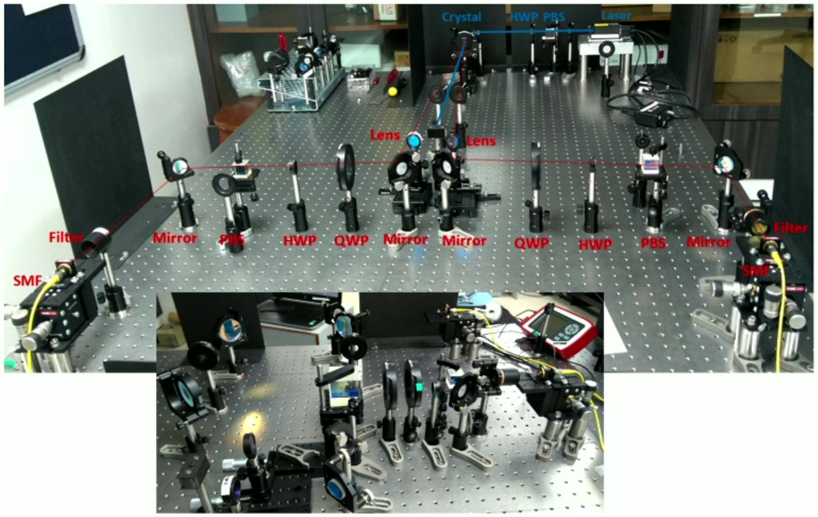
Entanglement measures and studies of entanglement dynamics

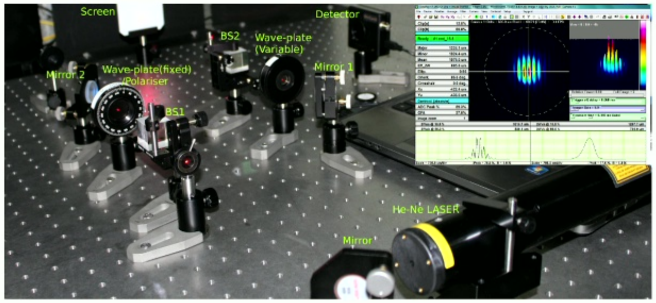


Ashutosh Singh
Now @University of Calgary,
Canada

- *Phys. Scr.* **97** 085104, 2022
- *Journal of Optical Society of America B, **37** (1), 157 – 166, 2020*
- *Journal of Optical Society of America B, **34**, 681, 2017*
- *Physical Review A* **91**, 012120, 2015

First Entangled Photon source in our lab & India

Generalized measurements or weak measurements as a tool



- *Communications Physics* **6**, no. 203, 2023
- *Physical Review A* **99** 022111, 2019.
- *Annals of Physics*, **391** 1-15, 2018.
- *Physical Review A* **92** 052120, 2015.

Photonic Quantum Computing
@ RRI, Bangalore

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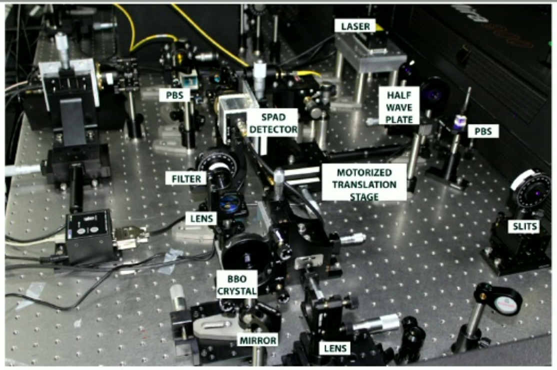
Completely indigenous development of novel photonic quantum computing architecture
Spatial-bin qudits

Correlated photonic qutrit pairs for quantum information and communication, D.Ghosh, T.Jennewein, P.Kolenderski and U.Sinha, *OSA Continuum* **1** (3), 2018.

- *Quantum Science and Technology*, **7** 045037, *2022.*
- arXiv: 2201.06188 (2022)
- *Physical Review A* ***101*** *022112, 2020*
- *New Journal of Physics* ***21*** *113022, 2019.*
- *OSA Continuum* **1** (3), 2018.
- *Physical Review A* **86** 012321, 2012.



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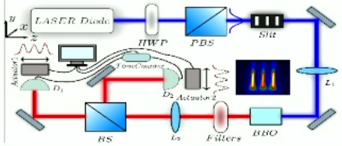

Quantum Information and Quantum Gravity

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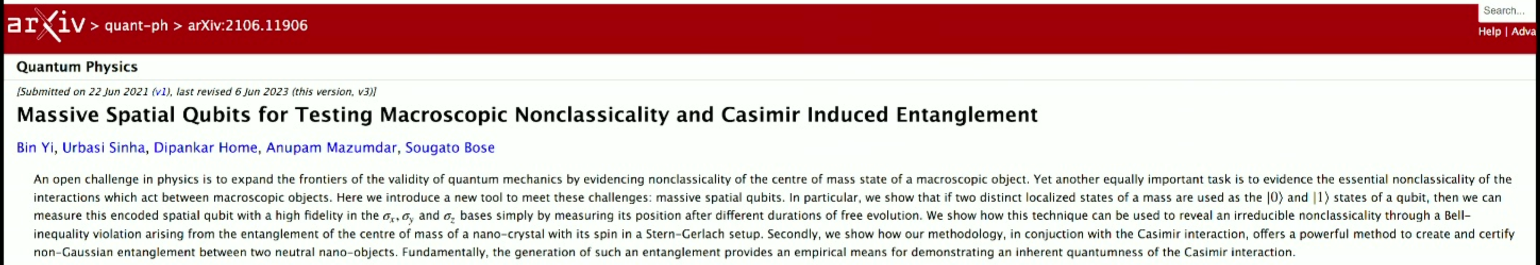
Accepted in *Physical Review Research*


arXiv > quant-ph > arXiv:2106.11906

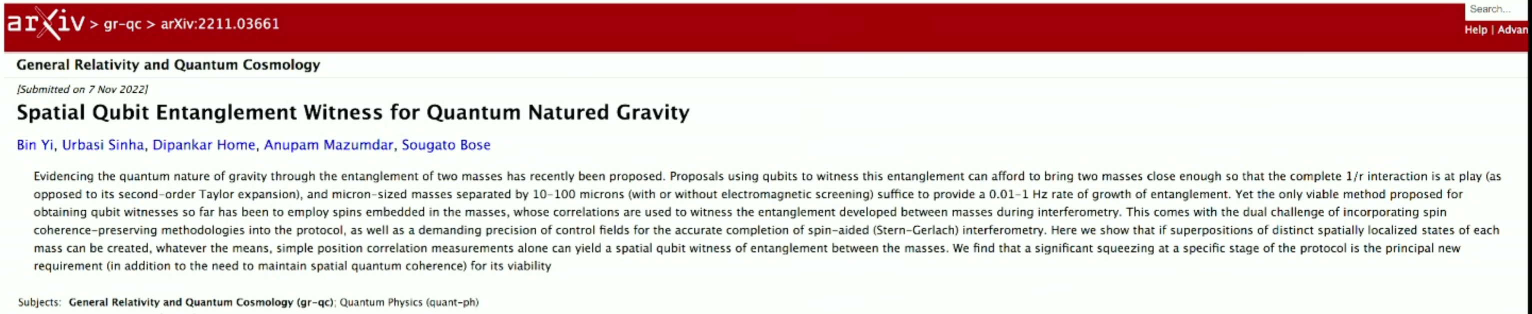
Quantum Physics

[Submitted on 22 Jun 2021 (v1), last revised 6 Jun 2023 (this version, v3)]

Massive Spatial Qubits for Testing Macroscopic Nonclassicality and Casimir Induced Entanglement

Bin Yi, Urbasi Sinha, Dipankar Home, Anupam Mazumdar, Sougato Bose

An open challenge in physics is to expand the frontiers of the validity of quantum mechanics by evidencing nonclassicality of the centre of mass state of a macroscopic object. Yet another equally important task is to evidence the essential nonclassicality of the interactions which act between macroscopic objects. Here we introduce a new tool to meet these challenges: massive spatial qubits. In particular, we show that if two distinct localized states of a mass are used as the $|0\rangle$ and $|1\rangle$ states of a qubit, then we can measure this encoded spatial qubit with a high fidelity in the σ_x, σ_y and σ_z bases simply by measuring its position after different durations of free evolution. We show how this technique can be used to reveal an irreducible nonclassicality through a Bell-inequality violation arising from the entanglement of the centre of mass of a nano-crystal with its spin in a Stern-Gerlach setup. Secondly, we show how our methodology, in conjuction with the Casimir interaction, offers a powerful method to create and certify non-Gaussian entanglement between two neutral nano-objects. Fundamentally, the generation of such an entanglement provides an empirical means for demonstrating an inherent quantumness of the Casimir interaction.


arXiv > gr-qc > arXiv:2211.03661

General Relativity and Quantum Cosmology

[Submitted on 7 Nov 2022]

Spatial Qubit Entanglement Witness for Quantum Natured Gravity

Bin Yi, Urbasi Sinha, Dipankar Home, Anupam Mazumdar, Sougato Bose

Evidencing the quantum nature of gravity through the entanglement of two masses has recently been proposed. Proposals using qubits to witness this entanglement can afford to bring two masses close enough so that the complete $1/r$ interaction is at play (as opposed to its second-order Taylor expansion), and micron-sized masses separated by 10-100 microns (with or without electromagnetic screening) suffice to provide a 0.01-1 Hz rate of growth of entanglement. Yet the only viable method proposed for obtaining qubit witnesses so far has been to employ spins embedded in the masses, whose correlations are used to witness the entanglement developed between masses during interferometry. This comes with the dual challenge of incorporating spin coherence-preserving methodologies into the protocol, as well as a demanding precision of control fields for the accurate completion of spin-aided (Stern-Gerlach) interferometry. Here we show that if superpositions of distinct spatially localized states of each mass can be created, whatever the means, simple position correlation measurements alone can yield a spatial qubit witness of entanglement between the masses. We find that a significant squeezing at a specific stage of the protocol is the principal new requirement (in addition to the need to maintain spatial quantum coherence) for its viability

Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; Quantum Physics (quant-ph)

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Quantum Communications overview

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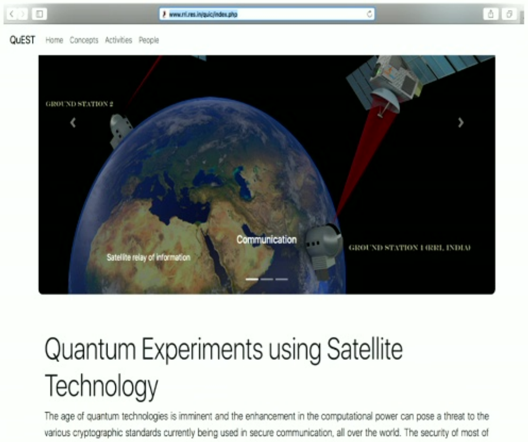
India's first project on satellite based QKD

http://www.rri.res.in/quic/



Quantum Experiments using Satellite Technology

The age of quantum technologies is imminent and the enhancement in the computational power can pose a threat to the various cryptographic standards currently being used in secure communication, all over the world. The security of most of

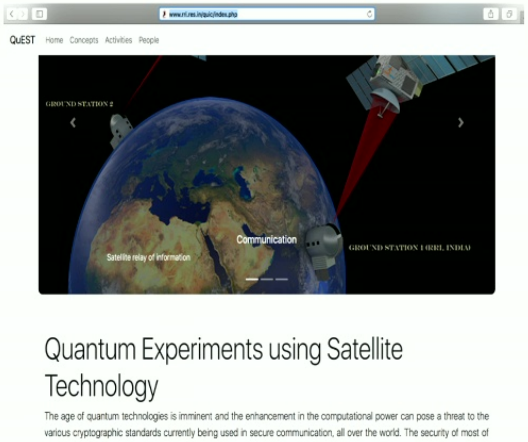
Experimental quantum communications using **integrated photonics**: Project under the India Trento Programme on Advanced Research (ITPAR): Indo-Italian bilateral programme.

Project under Quantum Enabled Science and Technology programme of the Department of Science and Technology on experimental **Quantum Teleportation**.

Quantum Communications overview

India's first project on satellite based QKD

http://www.rri.res.in/quic/



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Project under Quantum Enabled Science and Technology programme of the Department of Science and Technology on experimental **Quantum Teleportation**.

Project under Centre for Excellence in Quantum Technologies of the Ministry of Electronics and Information Technology on **Device Independent Random Number Generation.**

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Quantum Experiments with Satellite Technology
QuEST

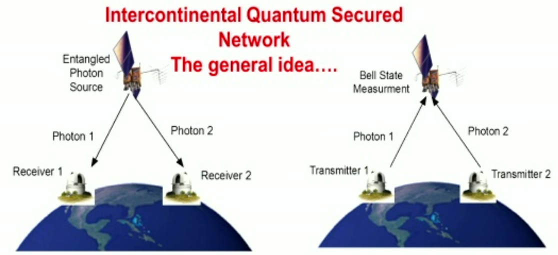
RRI-ISRO collaboration
2017 -

Why is this experiment exceptional?

- Security in communications is a top priority for various strategic applications including military, banking and many more.
- Current means of securing communications using public key cryptography stand to be compromised with the advent of algorithmic breakthroughs including quantum computing.
- Secure quantum communications thus becomes the need of the hour.
- The security should be operational across long distances, between countries and beyond.
- Using a satellite as a trusted node is a novel means towards long distance secure quantum communications.

QuEST is India's first project on satellite based quantum communications (Sep 2017 -). Started at a time when the field was not that popular, its achievements have played a major role towards putting India on the global map for quantum communications research.

The Chinese satellite demonstrated down link based QKD[1,2,3]. →



From GEO, almost half the Earth is visible.

- Quantum Repeater: N. Sangouard, C. Simon, et al, Rev. Mod.Phys, 2011
- Detector independent QKD: H.K. Lo, PRL, 2012

QuEST aims at demonstrating uplink based QKD – never been shown before globally.

1. Liao, S.K., et al.: Satellite-to-ground quantum key distribution. Nature. 549(7670), 43–47 (2017)
2. Chen, Y.A., et al.: An integrated space-to-ground quantum communication network over 4,600 kilometres. Nature. 589(7841), 214–219 (2021)
3. Yin, J., et al.: Entanglement-based secure quantum cryptography over 1,120 kilometres. Nature. 582(7813), 501–505 (2020)

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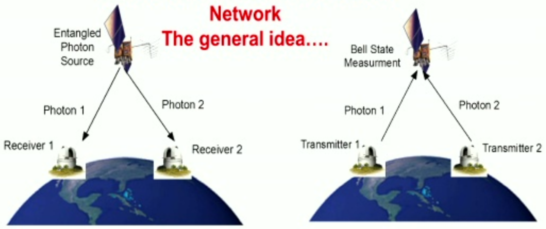
Intercontinental Quantum Secured Network
The general idea….



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- Detector independent QKD: H.K. Lo, PRL, 2012

QuEST aims at demonstrating uplink based QKD – never been shown before globally.

- **Uplink allows for photon source to be at the ground based lab.**
- **More flexibility with changing the source even after the satellite has been launched.**
- **Can include quantum memory components also after satellite launch.**

1. Liao, S.K., et al.: Satellite-to-ground quantum key distribution. Nature. 549(7670), 43–47 (2017)
2. Chen, Y.A., et al.: An integrated space-to-ground quantum communication network over 4,600 kilometres. Nature. 589(7841), 214–219 (2021)
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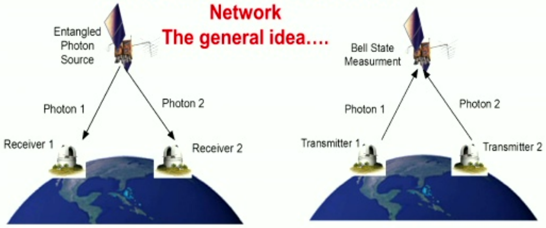
- Current means of securing communications using public key cryptography stand to be compromised with the advent of algorithmic breakthroughs including quantum computing.
- Secure quantum communications thus becomes the need of the hour.
- The security should be operational across long distances, between countries and beyond.
- Using a satellite as a trusted node is a novel means towards long distance secure quantum communications.

QuEST is India's first project on satellite based quantum communications (Sep 2017 -). Started at a time when the field was not that popular, its achievements have played a major role towards putting India on the global map for quantum communications research.

The Chinese satellite demonstrated down link based QKD[1,2,3].

Intercontinental Quantum Secured Network
The general idea….



From GEO, almost half the Earth is visible.

- Quantum Repeater: N. Sangouard, C. Simon, et al, Rev. Mod.Phys, 2011
- Detector independent QKD: H.K. Lo, PRL, 2012

QuEST aims at demonstrating uplink based QKD – never been shown before globally.

- **Uplink allows for photon source to be at the ground based lab.**
- **More flexibility with changing the source even after the satellite has been launched.**
- **Can include quantum memory components also after satellite launch.**
- **Tremendous scope for novel, first-in-the-world science.**

1. Liao, S.K., et al.: Satellite-to-ground quantum key distribution. Nature. 549(7670), 43–47 (2017)
2. Chen, Y.A., et al.: An integrated space-to-ground quantum communication network over 4,600 kilometres. Nature. 589(7841), 214–219 (2021)
3. Yin, J., et al.: Entanglement-based secure quantum cryptography over 1,120 kilometres. Nature. 582(7813), 501–505 (2020)

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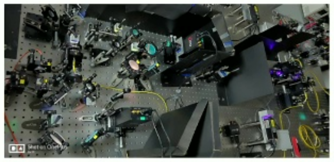
Quantum Experiments using Satellite technology (QuEST-ISRO), RRI-ISRO

RRI

2017-

Overall milestones achieved so far



1. **An in-lab (free-space) experimental implementation of the B92 protocol has been achieved and reported. This is India's first reported end to end free space QKD experiment, published in internationally peer reviewed journal. The protocol established globally competitive keyrate of 51± 0.5 KHz and a QBER of 4.79±0.01% - *Physical Review Applied* 14 024036, 2020.**

2. **First demonstration** of quantum key distribution **between two buildings using an atmospheric free space channel** in India (February 2021), using Entanglement (**https://www.rri.res.in/quic/qkdactivities.php**).

3. **First demonstration** of quantum key distribution between a **stationary source** and a **moving receiver platform** in India (March 2023), (**https://timesofindia.indiatimes.com/home/science/rri-moves-step-closer-to-ground-to-satellite-based-secure-quantum-communications/articleshow/99167615.cms?from=mdr**)

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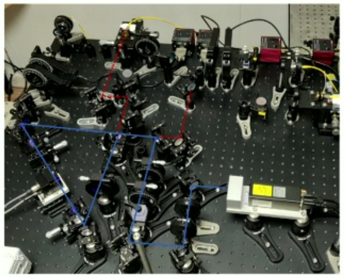
qkdSim

QKD experimenter's toolkit



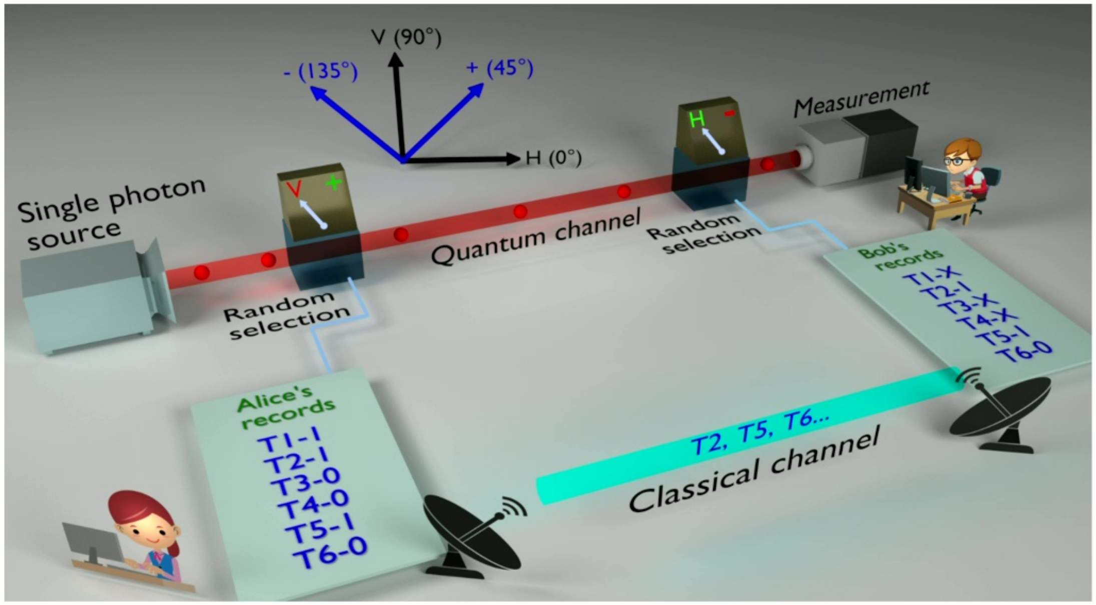
4. *R. Chatterjee, S. Chatterjee, B. C. Sanders, and U. Sinha, "An experimenter's toolkit for simulating quantum key distribution protocol implementations",* **Indian Patent Application No. 202141023697 (2021)** [**Novel software development for QKD with device and process imperfections**].

5. *S. Chatterjee and U. Sinha, "Methods and a system for optimizing performance of a quantum key distribution (QKD) protocol"*, **Indian Patent Application No.: 202341035230 (May, 2023)** [**Novel software development for improving QKD performance parameters**].

6. **Novel entanglement based QKD protocol using a new resource friendly, measurement-based passive feedback mechanism method to mitigate scrambling of polarisation of photons for satellite-based QKD, *Communications Physics* (Nature Publishing Group) 6, Article number: 116 (2023).**

7. **Estimating the link budget of satellite-based quantum key distribution (QKD) for uplink transmission through the atmosphere, S.Behera, U.Sinha, submitted 2023.**

QKD: polarization-encoded B92 protocol

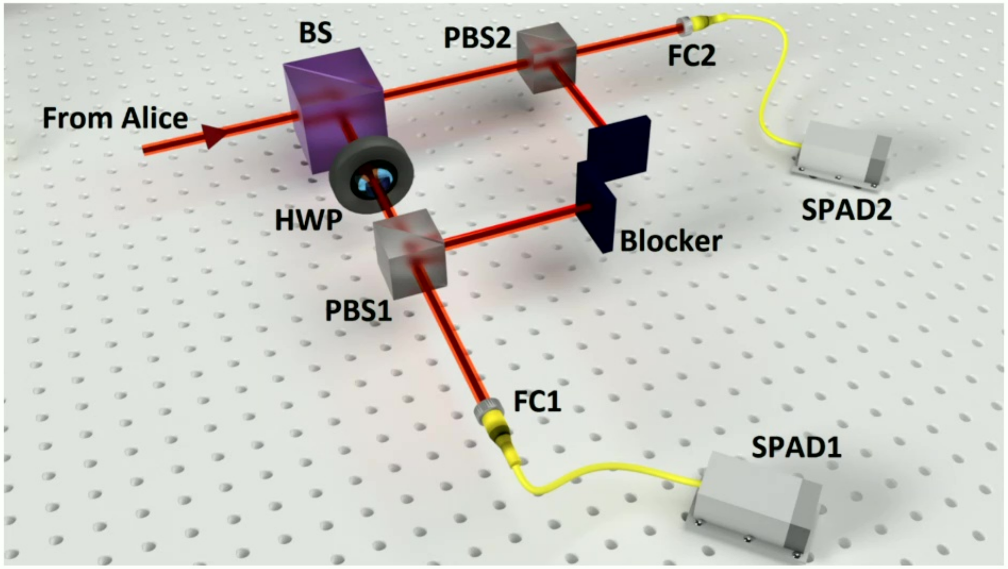


Single photon generation

QPV 2023

C. H. Bennett, Phys. Rev. Lett. **68**, 3121 (1992).

Schematic of B92 experimental setup: Bob's module



Components:
BS: 50-50 non-polarizing beamsplitter
HWP: half-wave plate
PBS1, PBS2: polarizing beamsplitters
FC1, FC2: fibre couplers
SPAD1, SPAD2: single photon avalanche detector

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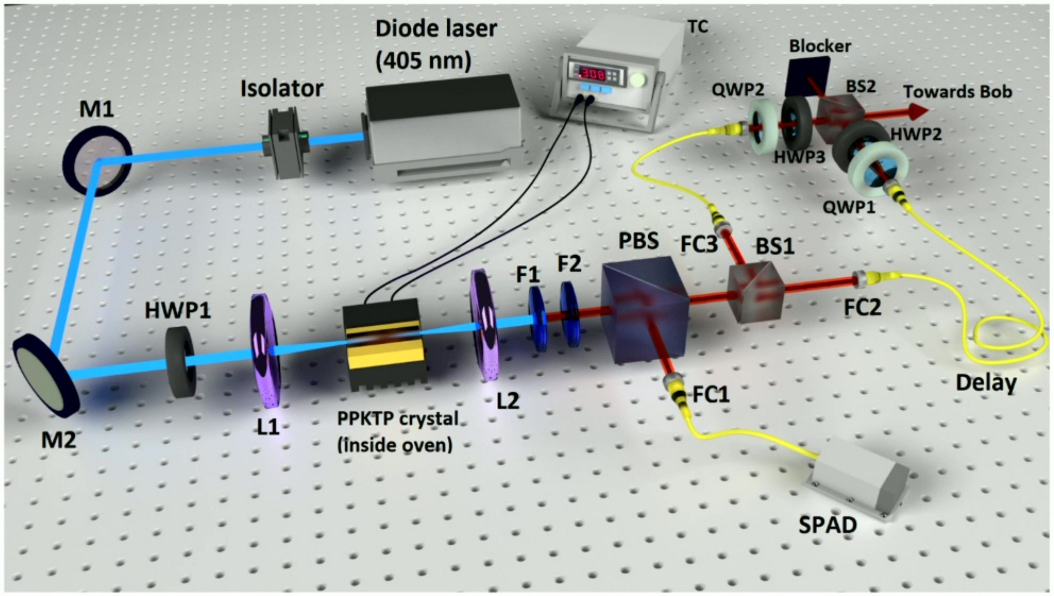
R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders, and U. Sinha, Phys. Rev. App. **14**, 024036 (2020).

Schematic of B92 experimental setup: Alice's module



- Heralded single photon using SPDC (continuous pumping)
- Passive quantum randomness

Eavesdropping attacks:

1) PNS type attack
2) Attacks based on active random basis selection

R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders, and U. Sinha, Phys. Rev. App. **14**, 024036 (2020).

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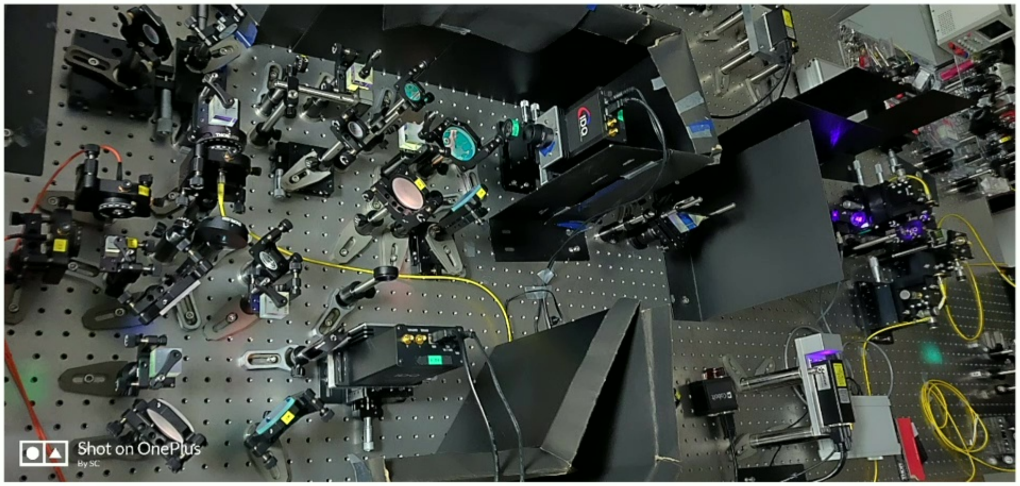
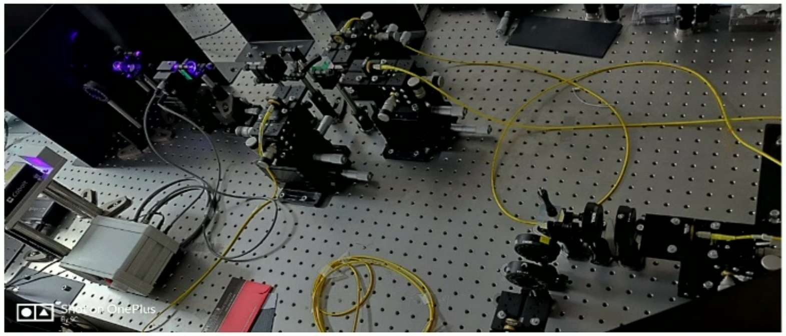
Snapshots of the actual B92 setup

RRI

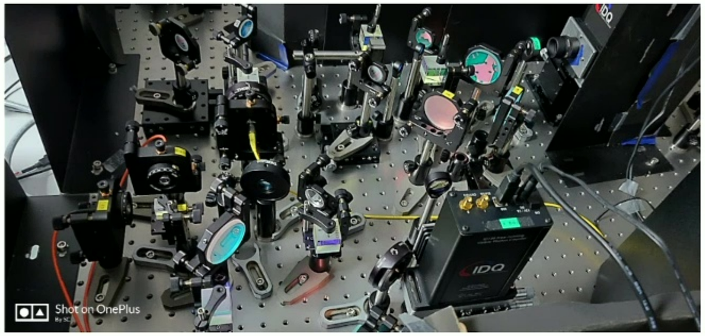
Combined setup



Alice's setup



Bob's setup



R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders, and U. Sinha, Phys. Rev. App. **14**, 024036 (2020).

Why B92?

Novelties in the experimental demonstration of B92:

1) Use of heralded single-photon from spontaneous parametric down-conversion (SPDC) process

Most of the previous experimental works used weak coherent pulse (WCP) to perform the B92 protocol, which creates a threat to the security. An eavesdropper can implement a photon-number splitting (PNS) type attack on the protocol, as the probability of the presence of multi-photons in a WCP is significant. On the other hand, heralded single-photon pulse generated from the SPDC process (with low pump power) typically has a very low probability of multi-photon generation, compared to WCP. So, our experimental setup is advantageous in terms of security.

2) Use of true randomness

In most of the experiments, the source of randomness for Alice while preparing random polarization states is a pseudo-random number generator. In our setup, we use a symmetric non-polarizing beam-splitter, where the choice of 'which path' to take, can be considered 'truly' random for the case of a single photon.

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3) Correlating polarization with the temporal degree of freedom

In our B92 experiment, we implement a novel approach of correlating temporal degrees of freedom with the polarization of the photons. In this scenario, Alice encodes each photon with a randomly selected polarization basis as well as a correlated time delay. For example, 'V' photons always have a time delay $\Delta\tau$, whereas '+45' photons have no time delay. So, while Bob measures polarization, Alice measures time-delay in the post-processing stage. This modification in the setup makes the protocol tolerant to external noise.

4) High key-rate and low QBER

We report a key-rate of 51 ± 0.5 kbit/sec and bit error rate (QBER) of $4.79 \pm 0.01\%$ respectively. To our knowledge, the reported key-rate is the highest value, achieved in a heralded single-photon based B92 setup. Also, the QBER is lower than the security threshold value of 4.8%.

Competing QKD simulation toolkits in literature

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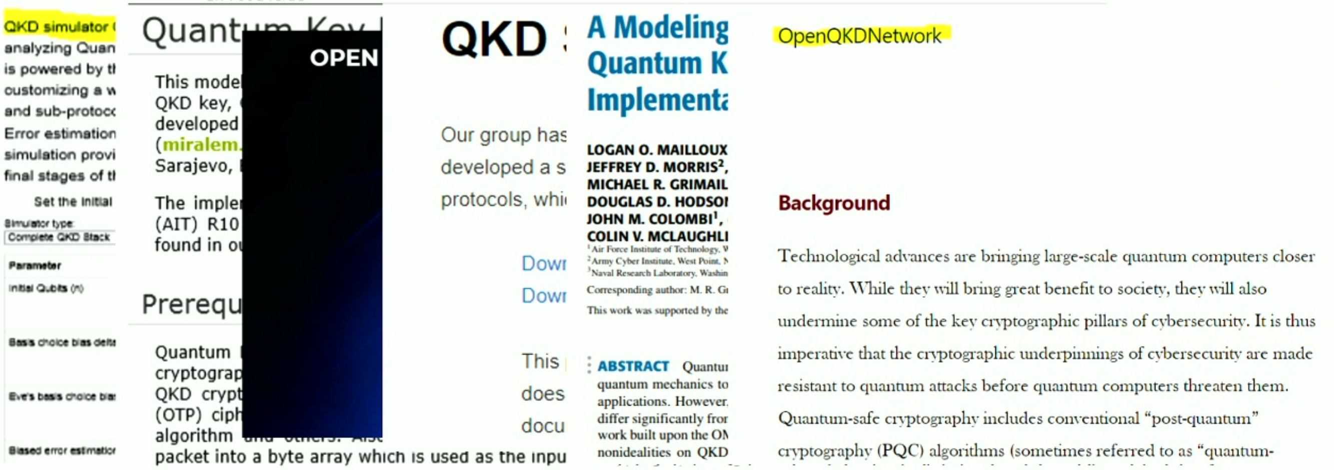
- With QKD becoming commercially viable, advanced engineer techniques are being proposed.
- Direct testing of these techniques in an optical setup is not very cost effective.
- A simulator that can accurately pre-evaluate the performance of these setups/designs.



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LOGAN O. MAILLOUX
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DOUGLAS D. HODSON
JOHN M. COLOMBI[1],
COLIN V. MCLAUGHLI
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[2] Army Cyber Institute, West Point, N
[3] Naval Research Laboratory, Washin
Corresponding author: M. R. Gr
This work was supported by the

ABSTRACT Quantum
quantum mechanics to
applications. However,
differ significantly fror
work built upon the OM
nonidealities on QKD

OpenQKDNetwork

Background

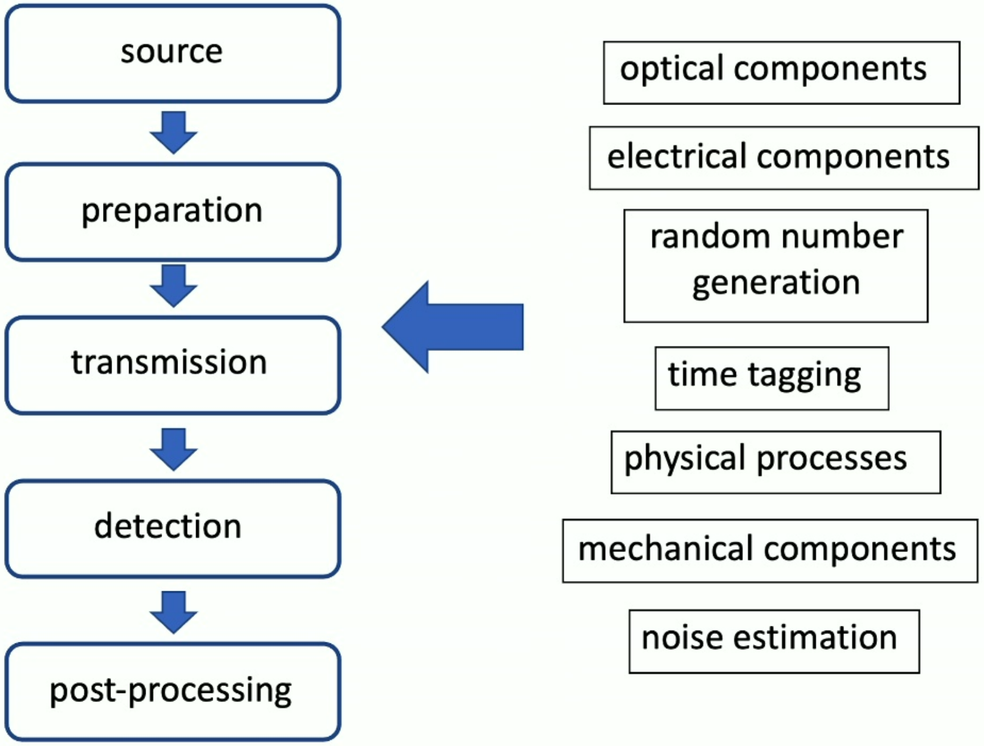
Technological advances are bringing large-scale quantum computers closer to reality. While they will bring great benefit to society, they will also undermine some of the key cryptographic pillars of cybersecurity. It is thus imperative that the cryptographic underpinnings of cybersecurity are made resistant to quantum attacks before quantum computers threaten them. Quantum-safe cryptography includes conventional "post-quantum" cryptography (PQC) algorithms (sometimes referred to as "quantum-

Missing requirements:

- Quick and precise simulation of physical processes.
- Consideration of experimental non-idealities.

In-house developed QKD simulation toolkit

QKD architecture



source

preparation

transmission

detection

post-processing

optical components

electrical components

random number generation

time tagging

physical processes

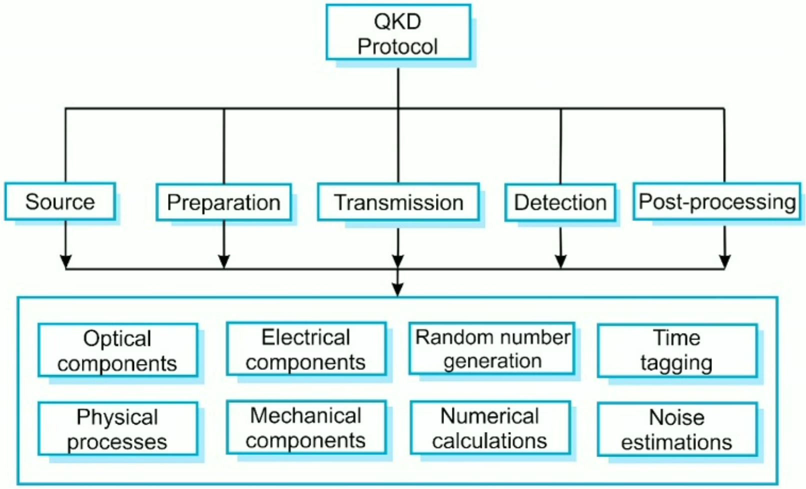
mechanical components

noise estimation

R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders, and U. Sinha, Phys. Rev. App. **14**, 024036 (2020).
R. Chatterjee, S. Chatterjee, B. C. Sanders, and U. Sinha, Indian Patent Application No. 202141023697 (2021).

• qkdSim: QKD experimenter‘s simulation kit

- With QKD becoming commercially viable, advanced engineer techniques are being proposed.
- Direct testing of these techniques in an optical setup is not very cost effective.
- ‘qkdSim’ helps in quick accommodation and testing of these techniques by enabling simulation of QKD protocols considering *physical process models*, *realistic imperfection* and *experimental non-idealities*.
- We have tested its prototype’s performance with an in-lab (free-space) implementation of B92 protocol.



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R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders, and U. Sinha*, Physical Review Applied* **14** 024036, 2020

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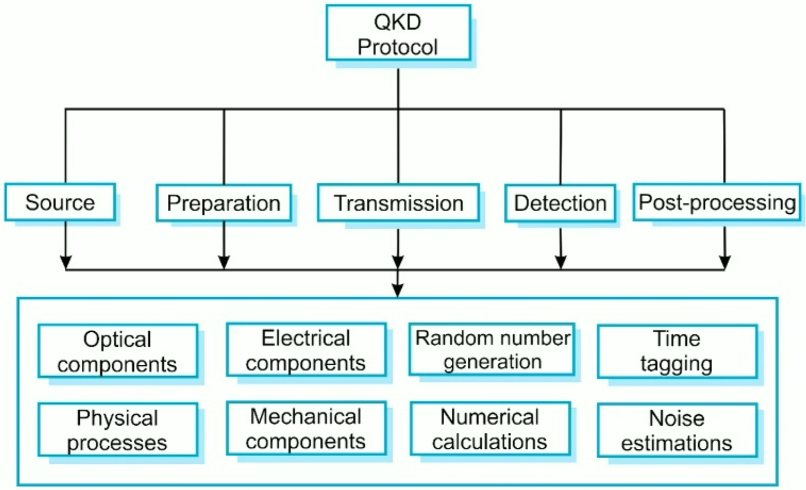


QKD Protocol

Source

Preparation

Transmission

Detection

Post-processing

Optical components

Electrical components

Random number generation

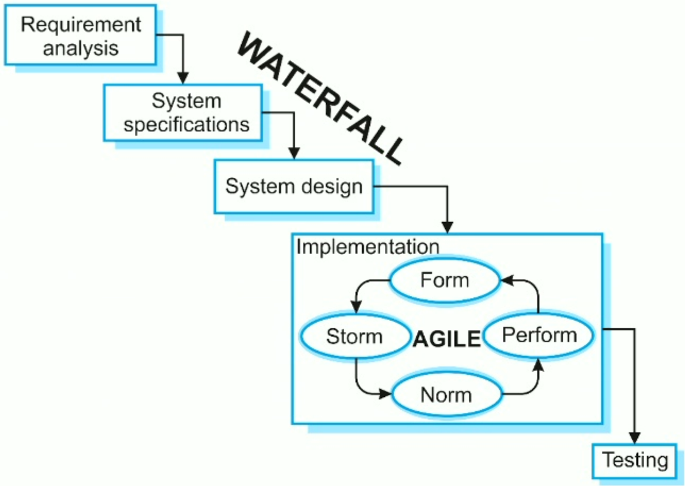
Time tagging

Physical processes

Mechanical components

Numerical calculations

Noise estimations



Requirement analysis

System specifications

System design

Implementation

Form

Storm

AGILE

Perform

Norm

Testing

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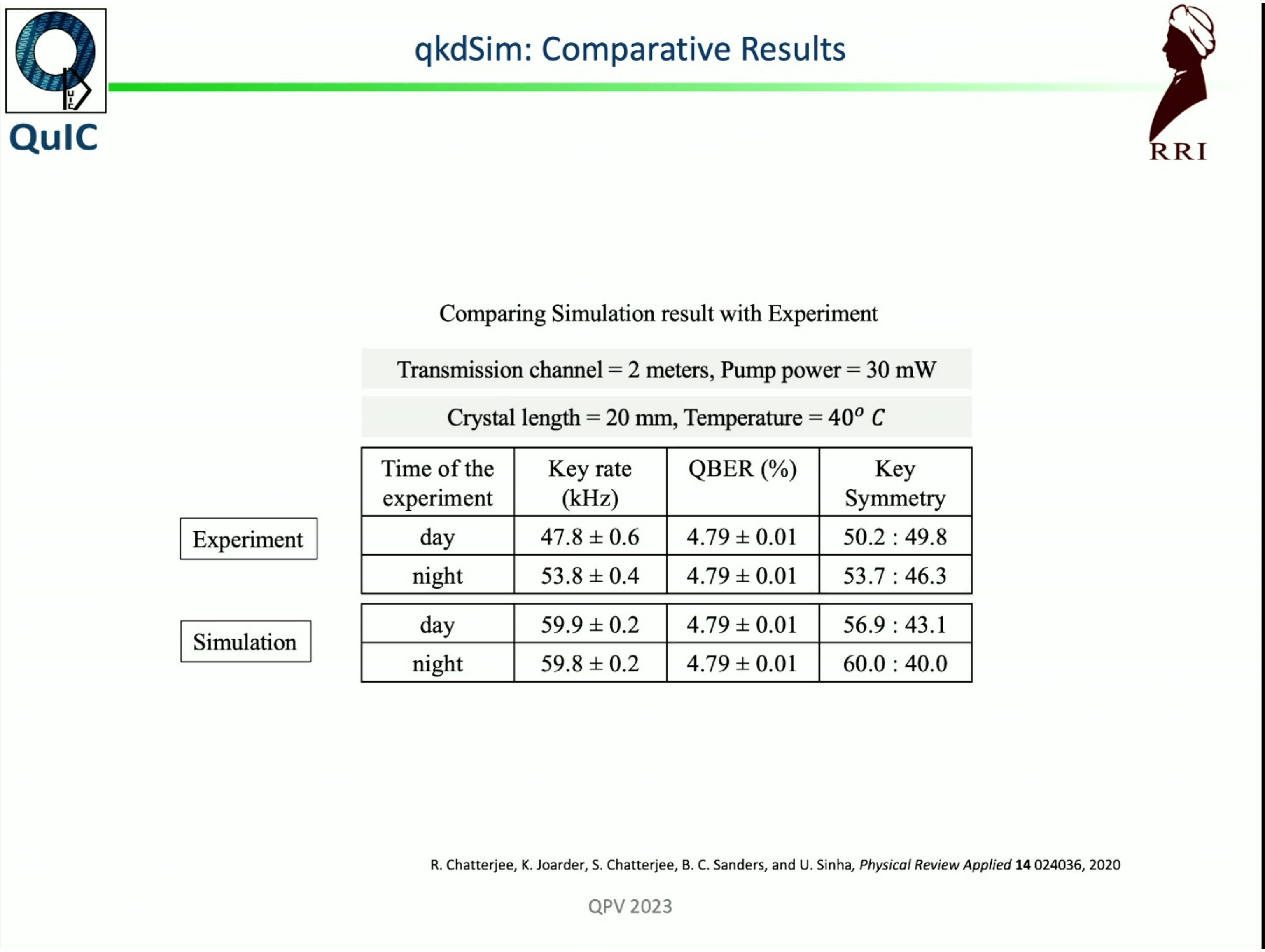
R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders, and U. Sinha, *Physical Review Applied* **14** 024036, 2020



qkdSim: Comparative Results

Comparing Simulation result with Experiment

Transmission channel = 2 meters, Pump power = 30 mW

Crystal length = 20 mm, Temperature = $40^o\ C$

	Time of the experiment	Key rate (kHz)	QBER (%)	Key Symmetry
Experiment	day	47.8 ± 0.6	4.79 ± 0.01	50.2 : 49.8
	night	53.8 ± 0.4	4.79 ± 0.01	53.7 : 46.3
Simulation	day	59.9 ± 0.2	4.79 ± 0.01	56.9 : 43.1
	night	59.8 ± 0.2	4.79 ± 0.01	60.0 : 40.0

R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders, and U. Sinha, *Physical Review Applied* **14** 024036, 2020

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B92 implementational novelties & highlights

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SPDC-based B92 implementation	Key rate [Kbps]	QBER [%]	Transmission channel length [m]
J. Wilson et al. (2016)	31.6	10.5	0.4
R. Chatterjee et al. (2020)	53.8	4.79	2

THIS STORY IS FROM JUNE 29, 2020

RRI researcł communicat

Chethan Kumar | TNN | Jun 29, 202

Presenting qkdSim: a QKD experimer experimentalists figuring out the mos

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K. S. Jayaraman
doi:10.1038/nindia.2020.117 Publi

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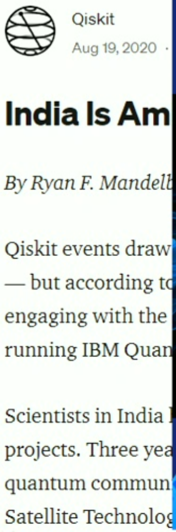

Qiskit
Aug 19, 2020 ·

India Is Am

By Ryan F. Mandelb

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Scientists in India projects. Three yea quantum commun Satellite Technolog

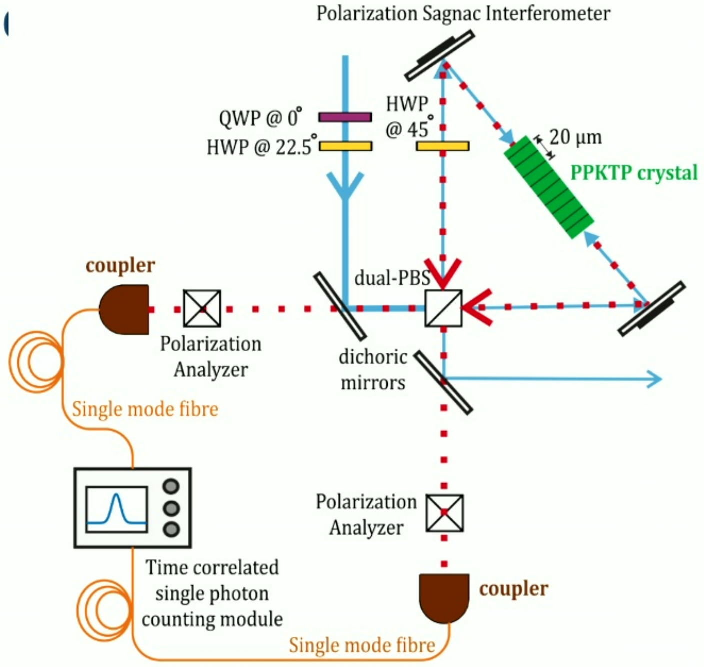
20. RRI ACHIEVES FIRST SUCCESSFUL IMPLEMENTATION OF A HIGHLY SECURE EFFICIENT QUANTUM CRYPTOGR C SCHEME

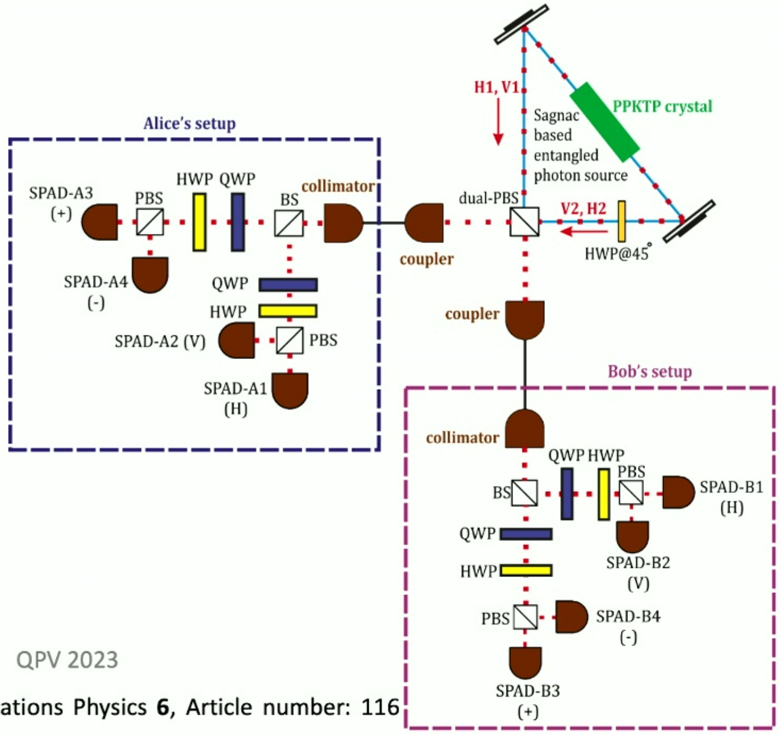
The QuIC lab he first successful n India of a hi ent Quantum Cr eme for an end to end D under the RRI-ISRO Quantum Experiments using Technology". The lab has also ne up with an end-to-end simulation toolkit named as "qkdSim" to ensure safety in secure quantum communication platforms, a first of its kind that enables Quantum Key Distribution Protocol (QKD) experimentalists to obtain a realistic estimate of the result from an experimental setup meant to demonstrate a QKD protocol. They have also performed an experiment in collaboration with HRI Allahabad that demonstrates a novel quantum state estimation tool opening up a new paradigm in quantum state estimation.

DST's 20 major success stories of 2020

J. Wilson et al., Quant. Comm. & Quant. Imag. XIV, Vol. 9980, ISOP, 99800U (2016).
R. Chatterjee, K. Joarder, S. Chatterjee, B. C. Sanders, and U. Sinha, Phys. Rev. App. **14**, 024036 (2020).

In-lab BBM92 protocol implementation





S. Chatterjee, K. Goswami, R. Chatterjee, and U. Sinha, Communications Physics **6**, Article number: 116 (2023)

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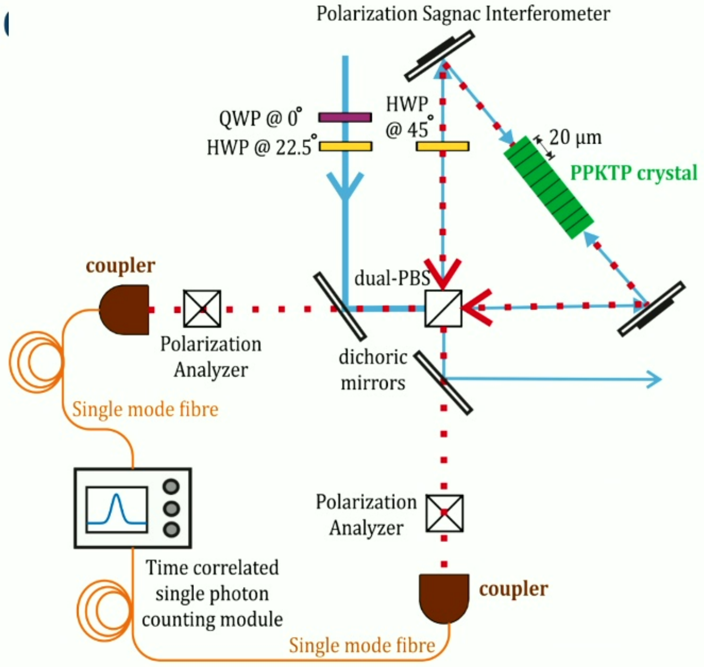
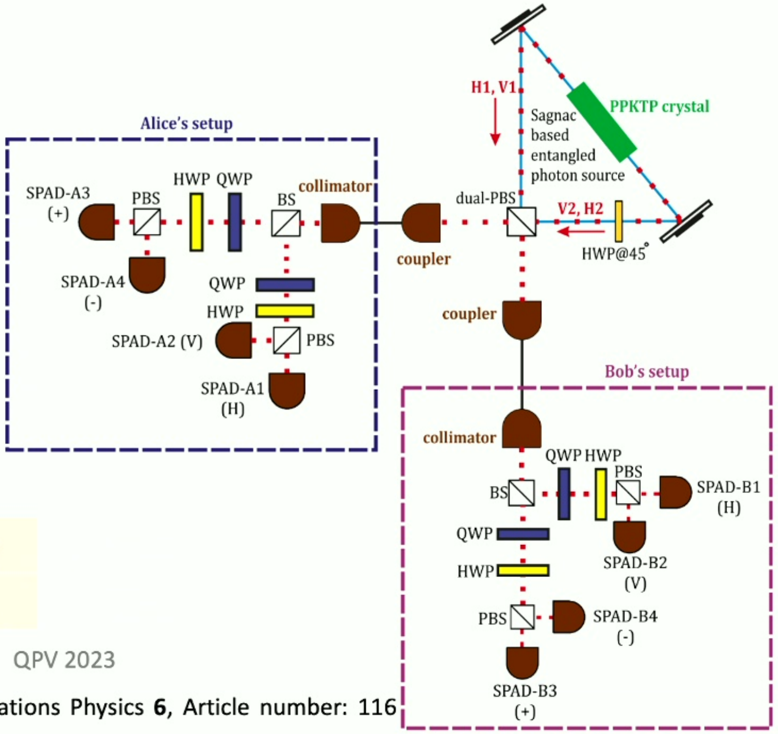


Source performance metrics:

Fidelity	Concurrence	Purity
94%	92%	91%



Protocol performance metrics:

Key rate	QBER	Key symmetry
96.1 [Kbps]	10.3 [%]	50.04 : 49.96

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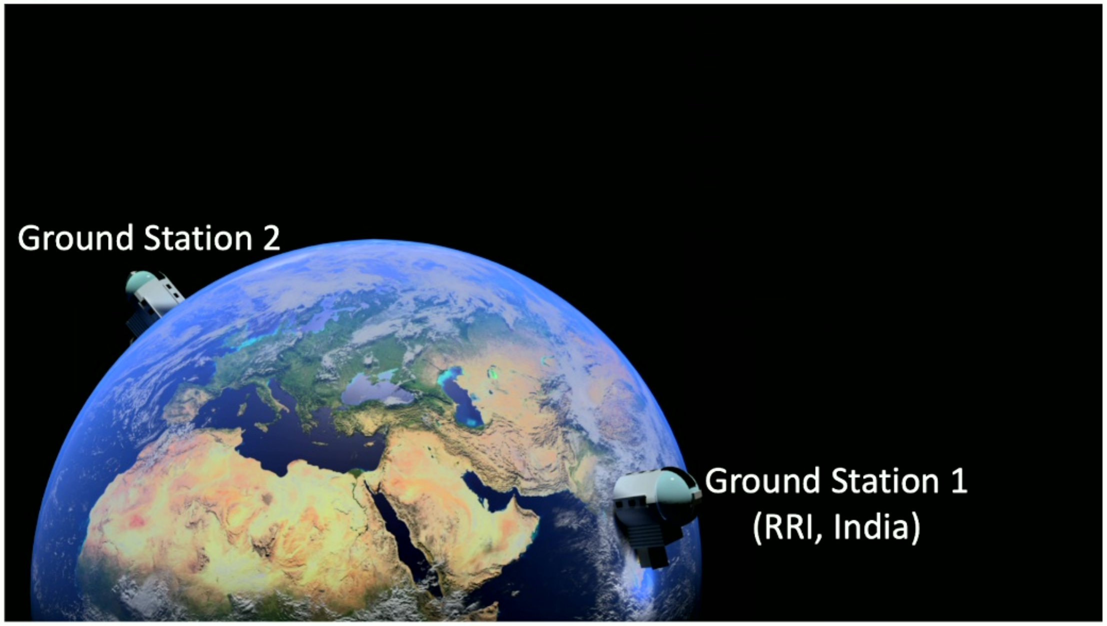
S. Chatterjee, K. Goswami, R. Chatterjee, and U. Sinha, Communications Physics **6**, Article number: 116 (2023)

A novel technique...



❑ **Conventionally, active feedback-based mechanism are employed for real-time polarization tracking.**

❑ **Long-distance QKD implementation, in which polarization of light is commonly used degree of freedom, is becoming increasingly important.**

❑ **A significant challenge:**
  - ❖ **photon-polarization gets affected due to birefringence in fibre-based implementations.**
  - ❖ **Variation of reference frames due to satellite movement in long-haul demonstrations.**

S. Chatterjee, K. Goswami, R. Chatterjee, and U. Sinha, Communications Physics **6**, Article number: 116 (2023)

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A novel technique...

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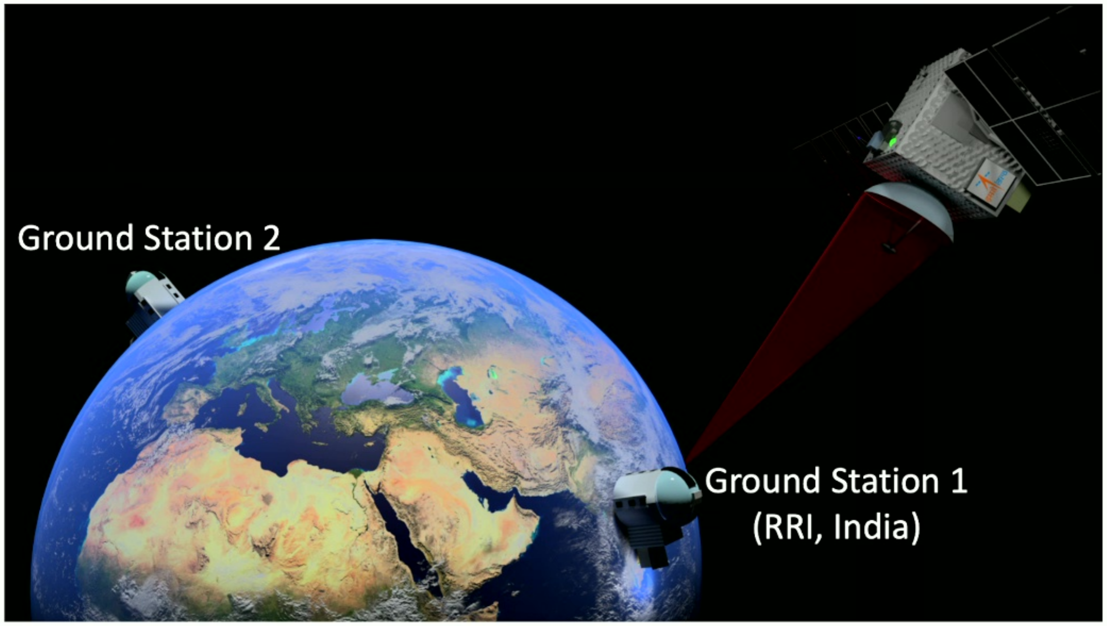

- ❑ **Conventionally, active feedback-based mechanism are employed for real-time polarization tracking.**
- ❑ **We employ a polarization bases compensation method that obviates the need for active polarization tracking in satellite-QKD implementations.**

Our method's performance is independent of any local polarization rotation.

- ❑ **Long-distance QKD implementation, in which polarization of light is commonly used degree of freedom, is becoming increasingly important.**
- ❑ **A significant challenge:**
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S. Chatterjee, K. Goswami, R. Chatterjee, and U. Sinha, Communications Physics **6**, Article number: 116 (2023)

Concept

Conventional (active) methods of polarization tracking:

- Stochastic algorithm to dynamically compensate for any polarization fluctuations.
- Robotized polarization correction based on an active control system

Our approach without an active feedback:

- Perform a quantum state tomography at the output and obtain the reconstructed the density matrix.
- Evaluate the optimal measurement bases choice that leads to a high (anti-) correlation in outcomes.

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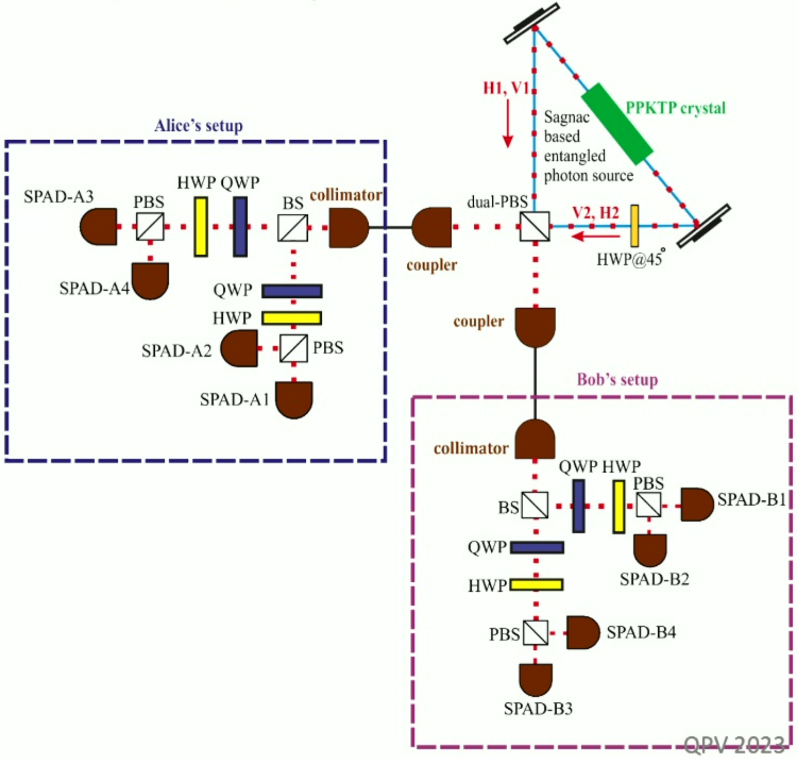
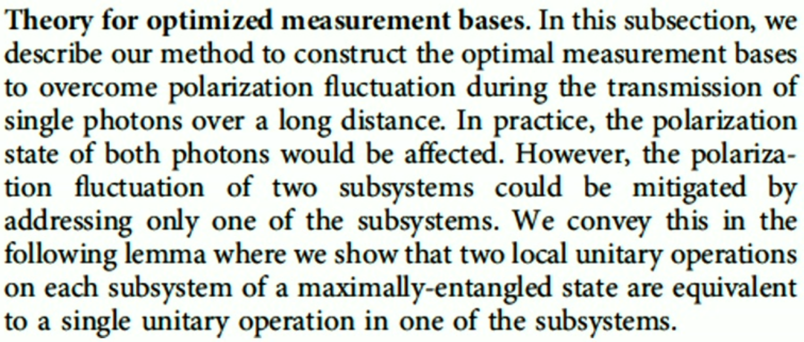


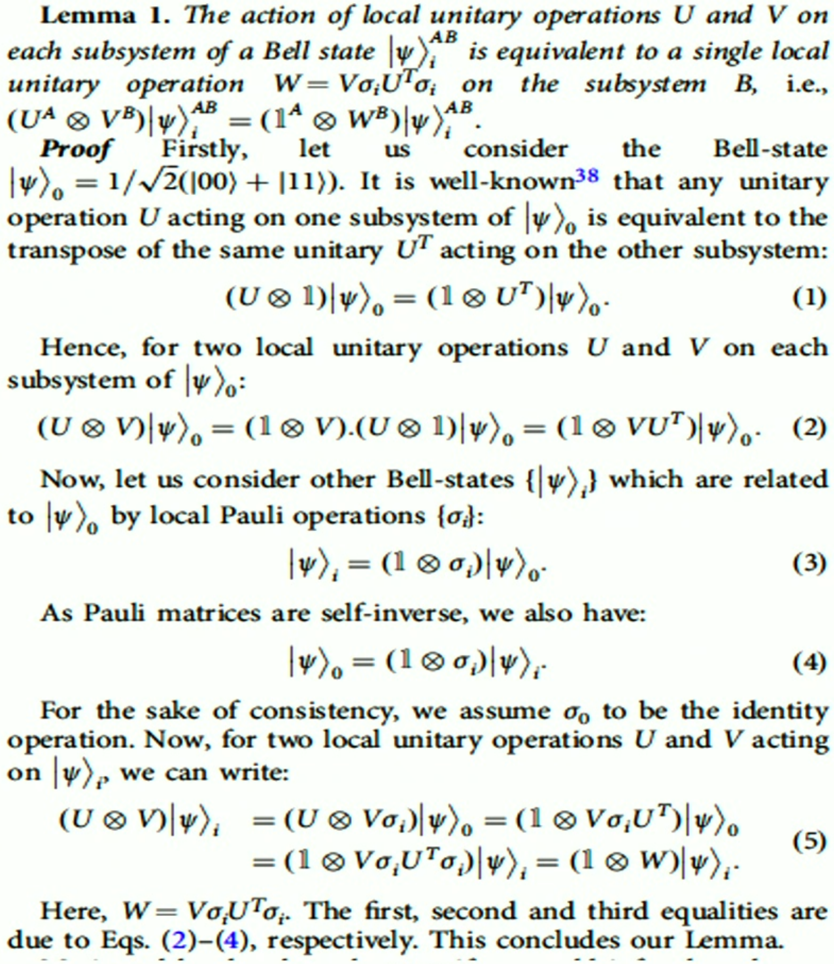
Our approach without an active feedback:

- Perform a quantum state tomography at the output and obtain the reconstructed the density matrix.
- Evaluate the optimal measurement bases choice that leads to a high (anti-) correlation in outcomes.
- Achieve the best trade-off between the key rate, QBER, and balanced key symmetry.

S. Chatterjee, K. Goswami, R. Chatterjee, and U. Sinha, Communications Physics **6**, Article number: 116 (2023)



Theory for optimized measurement bases. In this subsection, we describe our method to construct the optimal measurement bases to overcome polarization fluctuation during the transmission of single photons over a long distance. In practice, the polarization state of both photons would be affected. However, the polarization fluctuation of two subsystems could be mitigated by addressing only one of the subsystems. We convey this in the following lemma where we show that two local unitary operations on each subsystem of a maximally-entangled state are equivalent to a single unitary operation in one of the subsystems.



Lemma 1. *The action of local unitary operations U and V on each subsystem of a Bell state $|\psi\rangle_i^{AB}$ is equivalent to a single local unitary operation $W = V\sigma_i U^T \sigma_i$ on the subsystem B,* i.e., $(U^A \otimes V^B)|\psi\rangle_i^{AB} = (\mathbb{1}^A \otimes W^B)|\psi\rangle_i^{AB}$.

Proof Firstly, let us consider the Bell-state $|\psi\rangle_0 = 1/\sqrt{2}(|00\rangle + |11\rangle)$. It is well-known[38] that any unitary operation U acting on one subsystem of $|\psi\rangle_0$ is equivalent to the transpose of the same unitary U^T acting on the other subsystem:

$$(U \otimes \mathbb{1})|\psi\rangle_0 = (\mathbb{1} \otimes U^T)|\psi\rangle_0. \tag{1}$$

Hence, for two local unitary operations U and V on each subsystem of $|\psi\rangle_0$:

$$(U \otimes V)|\psi\rangle_0 = (\mathbb{1} \otimes V).(U \otimes \mathbb{1})|\psi\rangle_0 = (\mathbb{1} \otimes VU^T)|\psi\rangle_0. \tag{2}$$

Now, let us consider other Bell-states $\{|\psi\rangle_i\}$ which are related to $|\psi\rangle_0$ by local Pauli operations $\{\sigma_i\}$:

$$|\psi\rangle_i = (\mathbb{1} \otimes \sigma_i)|\psi\rangle_0. \tag{3}$$

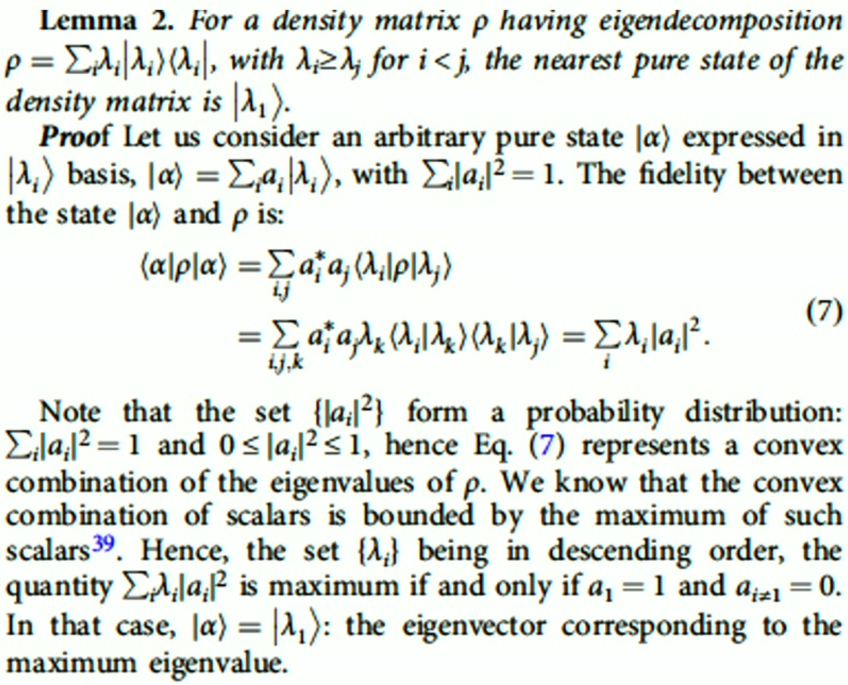
As Pauli matrices are self-inverse, we also have:

$$|\psi\rangle_0 = (\mathbb{1} \otimes \sigma_i)|\psi\rangle_i. \tag{4}$$

For the sake of consistency, we assume σ_0 to be the identity operation. Now, for two local unitary operations U and V acting on $|\psi\rangle_i$, we can write:

$$\begin{aligned}(U \otimes V)|\psi\rangle_i &= (U \otimes V\sigma_i)|\psi\rangle_0 = (\mathbb{1} \otimes V\sigma_i U^T)|\psi\rangle_0 \\ &= (\mathbb{1} \otimes V\sigma_i U^T \sigma_i)|\psi\rangle_i = (\mathbb{1} \otimes W)|\psi\rangle_i.\end{aligned} \tag{5}$$

Here, $W = V\sigma_i U^T \sigma_i$. The first, second and third equalities are due to Eqs. (2)–(4), respectively. This concludes our Lemma.

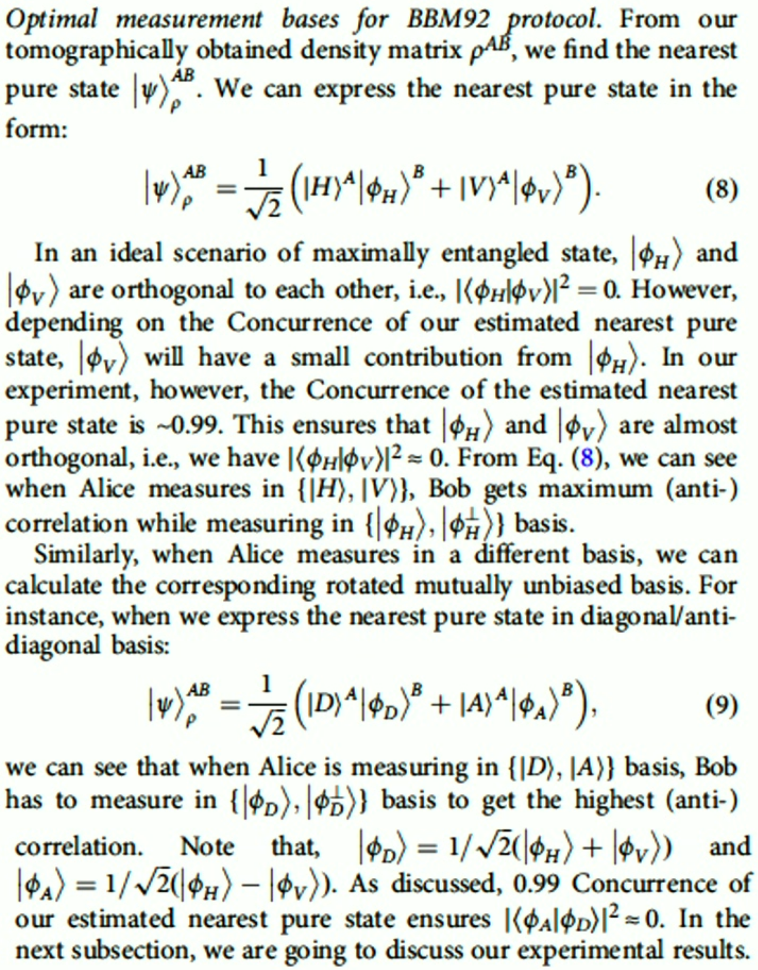


Lemma 2. *For a density matrix* ρ *having eigendecomposition* $\rho = \sum_i \lambda_i |\lambda_i\rangle\langle\lambda_i|$, *with* $\lambda_i \geq \lambda_j$ *for* $i < j$, *the nearest pure state of the density matrix is* $|\lambda_1\rangle$.

Proof Let us consider an arbitrary pure state $|\alpha\rangle$ expressed in $|\lambda_i\rangle$ basis, $|\alpha\rangle = \sum_i a_i |\lambda_i\rangle$, with $\sum_i |a_i|^2 = 1$. The fidelity between the state $|\alpha\rangle$ and ρ is:

$$\begin{aligned} \langle\alpha|\rho|\alpha\rangle &= \sum_{i,j} a_i^* a_j \langle\lambda_i|\rho|\lambda_j\rangle \\ &= \sum_{i,j,k} a_i^* a_j \lambda_k \langle\lambda_i|\lambda_k\rangle\langle\lambda_k|\lambda_j\rangle = \sum_i \lambda_i |a_i|^2. \end{aligned} \tag{7}$$

Note that the set $\{|a_i|^2\}$ form a probability distribution: $\sum_i |a_i|^2 = 1$ and $0 \leq |a_i|^2 \leq 1$, hence Eq. (7) represents a convex combination of the eigenvalues of ρ. We know that the convex combination of scalars is bounded by the maximum of such scalars[39]. Hence, the set $\{\lambda_i\}$ being in descending order, the quantity $\sum_i \lambda_i |a_i|^2$ is maximum if and only if $a_1 = 1$ and $a_{i \neq 1} = 0$. In that case, $|\alpha\rangle = |\lambda_1\rangle$: the eigenvector corresponding to the maximum eigenvalue.



Optimal measurement bases for BBM92 protocol. From our tomographically obtained density matrix ρ^{AB}, we find the nearest pure state $\left|\psi\right\rangle_{\rho}^{AB}$. We can express the nearest pure state in the form:

$$\left|\psi\right\rangle_{\rho}^{AB}=\frac{1}{\sqrt{2}}\left(|H\rangle^{A}\left|\phi_{H}\right\rangle^{B}+|V\rangle^{A}\left|\phi_{V}\right\rangle^{B}\right). \tag{8}$$

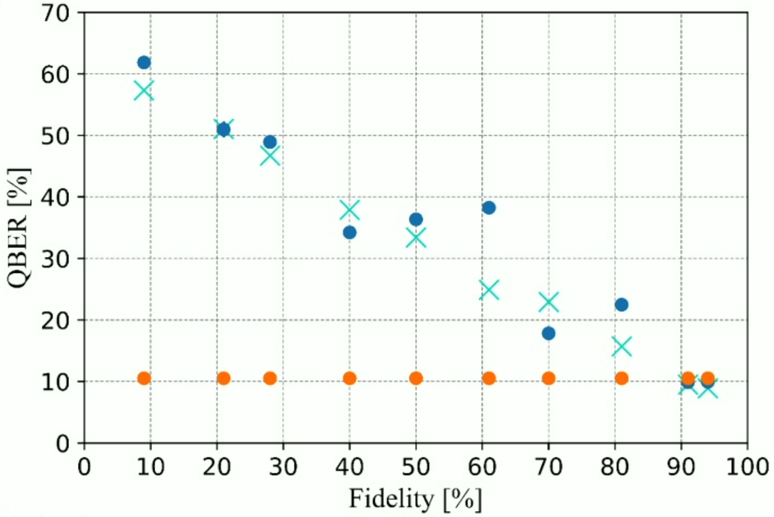
In an ideal scenario of maximally entangled state, $\left|\phi_{H}\right\rangle$ and $\left|\phi_{V}\right\rangle$ are orthogonal to each other, i.e., $|\langle\phi_{H}|\phi_{V}\rangle|^{2}=0$. However, depending on the Concurrence of our estimated nearest pure state, $\left|\phi_{V}\right\rangle$ will have a small contribution from $\left|\phi_{H}\right\rangle$. In our experiment, however, the Concurrence of the estimated nearest pure state is ~0.99. This ensures that $\left|\phi_{H}\right\rangle$ and $\left|\phi_{V}\right\rangle$ are almost orthogonal, i.e., we have $|\langle\phi_{H}|\phi_{V}\rangle|^{2}\approx 0$. From Eq. (8), we can see when Alice measures in $\{|H\rangle,|V\rangle\}$, Bob gets maximum (anti-) correlation while measuring in $\{\left|\phi_{H}\right\rangle,\left|\phi_{H}^{\perp}\right\rangle\}$ basis.

Similarly, when Alice measures in a different basis, we can calculate the corresponding rotated mutually unbiased basis. For instance, when we express the nearest pure state in diagonal/anti-diagonal basis:

$$\left|\psi\right\rangle_{\rho}^{AB}=\frac{1}{\sqrt{2}}\left(|D\rangle^{A}\left|\phi_{D}\right\rangle^{B}+|A\rangle^{A}\left|\phi_{A}\right\rangle^{B}\right), \tag{9}$$

we can see that when Alice is measuring in $\{|D\rangle,|A\rangle\}$ basis, Bob has to measure in $\{\left|\phi_{D}\right\rangle,\left|\phi_{D}^{\perp}\right\rangle\}$ basis to get the highest (anti-) correlation. Note that, $\left|\phi_{D}\right\rangle=1/\sqrt{2}(\left|\phi_{H}\right\rangle+\left|\phi_{V}\right\rangle)$ and $\left|\phi_{A}\right\rangle=1/\sqrt{2}(\left|\phi_{H}\right\rangle-\left|\phi_{V}\right\rangle)$. As discussed, 0.99 Concurrence of our estimated nearest pure state ensures $|\langle\phi_{A}|\phi_{D}\rangle|^{2}\approx 0$. In the next subsection, we are going to discuss our experimental results.

Results



- Unoptimized QBERs (blue dots) measured in conventional measurement bases.
- Unoptimized QBERs (orange dots) measured in optimized measurement bases.

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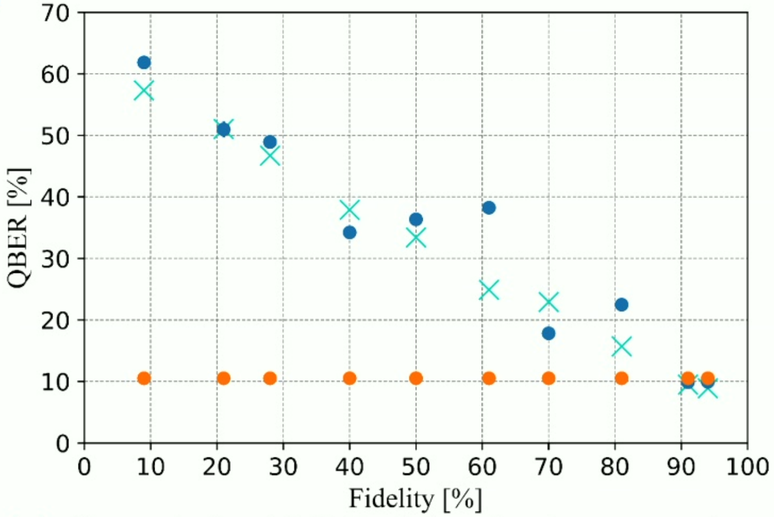
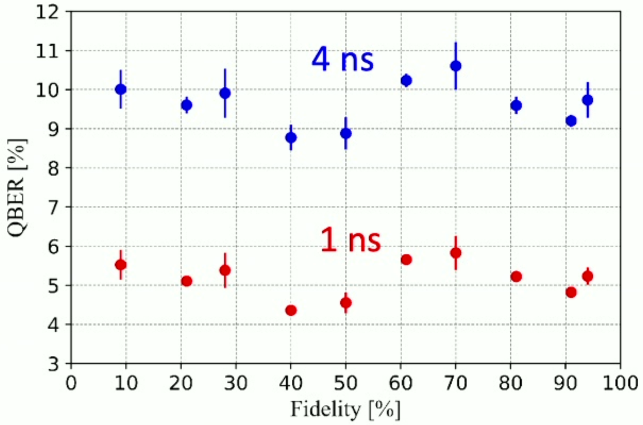
Results





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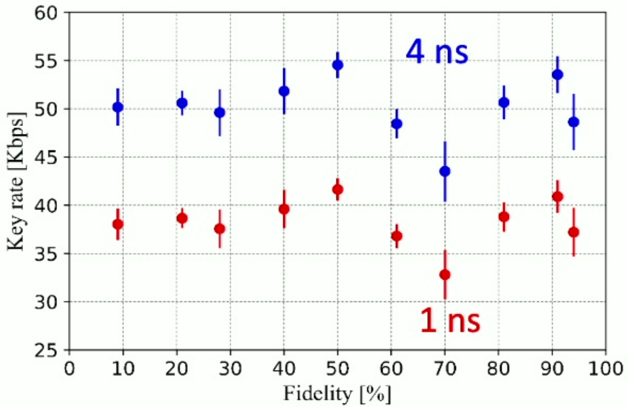
- Unoptimized QBERs (cyan crosses) measured in Pauli bases – chosen to provide best SNR.



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Simulating long distance results from real data

Losses for different humidity and temperature

	200 m			300 m			500 m		
RH\T	*288*	*293*	*298*	*288*	*293*	*298*	*288*	*293*	*298*
50%	.968	.966	.965	.926	.92	.914	.886	.873	.861
70%	.967	.966	.965	.926	.92	.914	.886	.873	.861
90%	.967	.966	.965	.925	.918	.913	.885	.872	.86

≈ 0.97 ≈ 0.92 ≈ 0.87

Table for losses, in terms of attenuation factor, at different distances. The rows represent relative humidity and the columns represent temperature in Kelvin. We observe that the losses are almost independent of the relative humidity and temperature.

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QuIC

Usefulness

RRI

- Our method addresses important practical challenges in QKD demonstrations: correcting the polarization of light which gets inevitably affected during long distance transmission.
- Active control systems having more parts than the raw system, are more prone to faults over our method, which can lead to instability of the (closed) stabilization loop.
- Our method is cost-effective as the conventional active feedback system-based polarization tracking techniques are resource intensive, resulting in additional maintenance cost.

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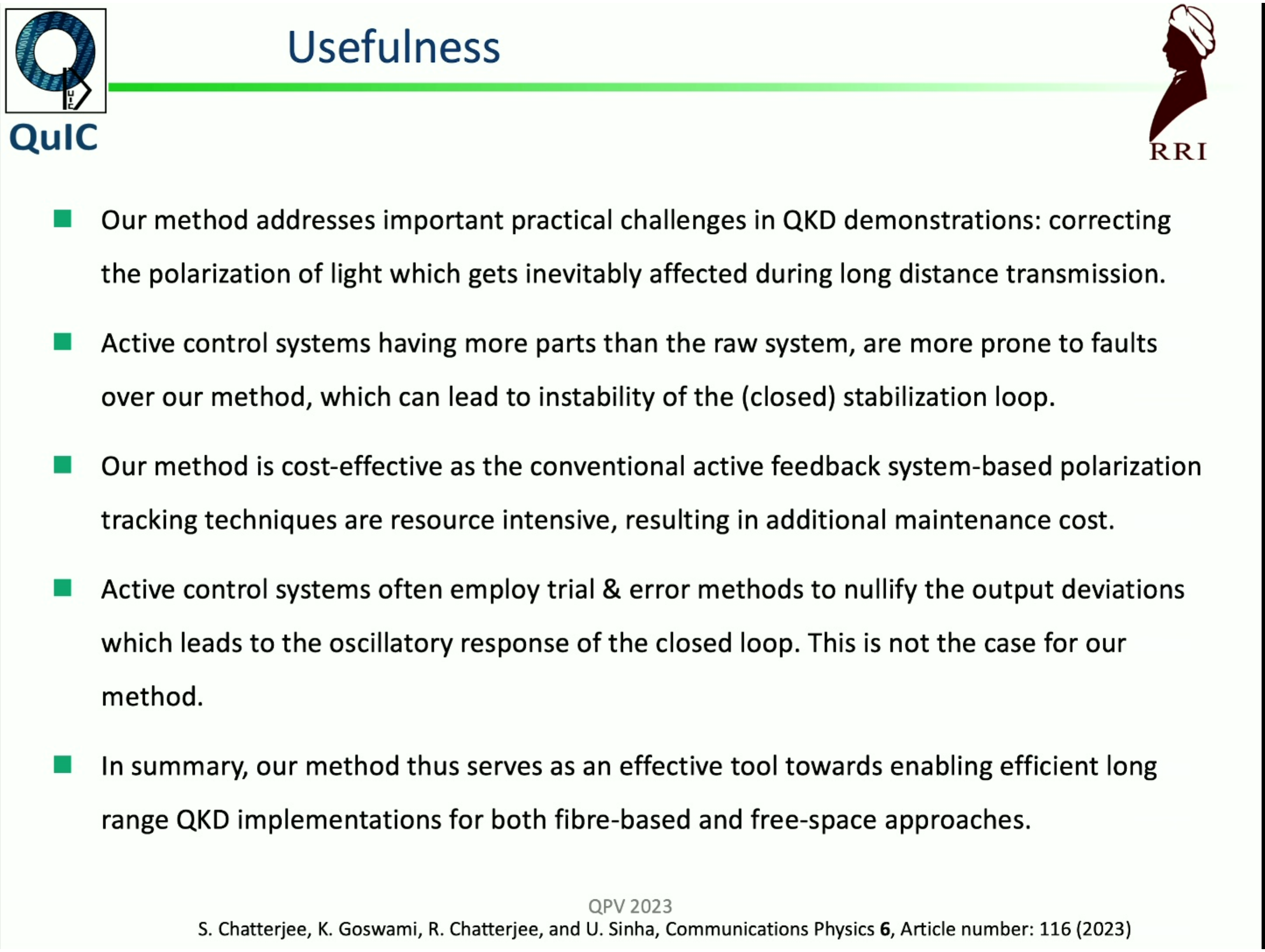

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- In summary, our method thus serves as an effective tool towards enabling efficient long range QKD implementations for both fibre-based and free-space approaches.

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Free space quantum communications through an atmospheric channel

QuIC

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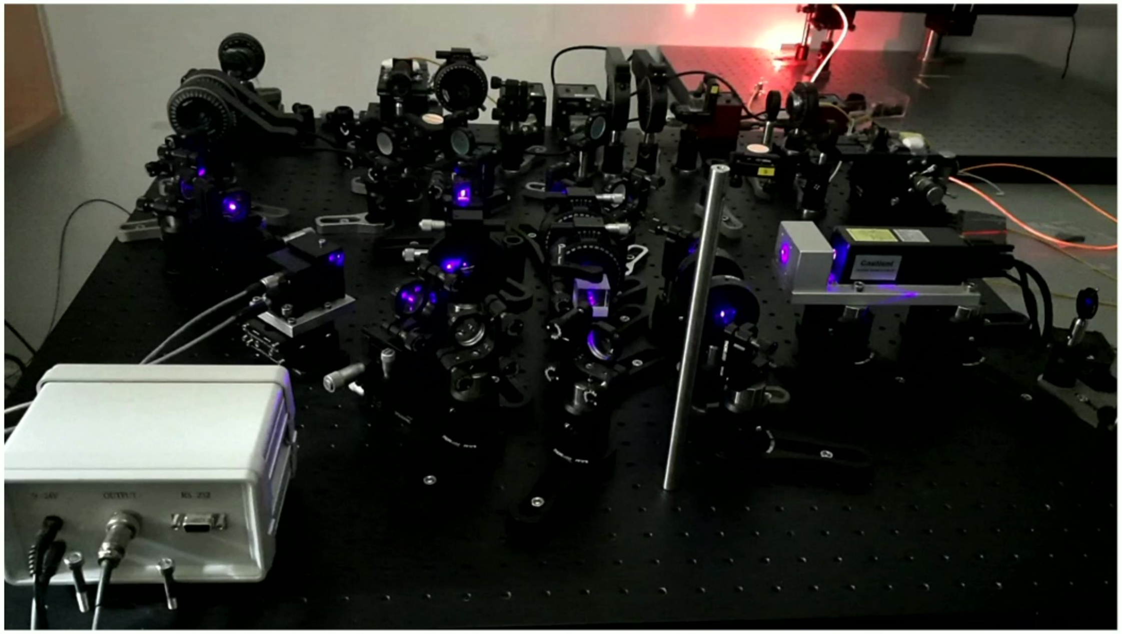
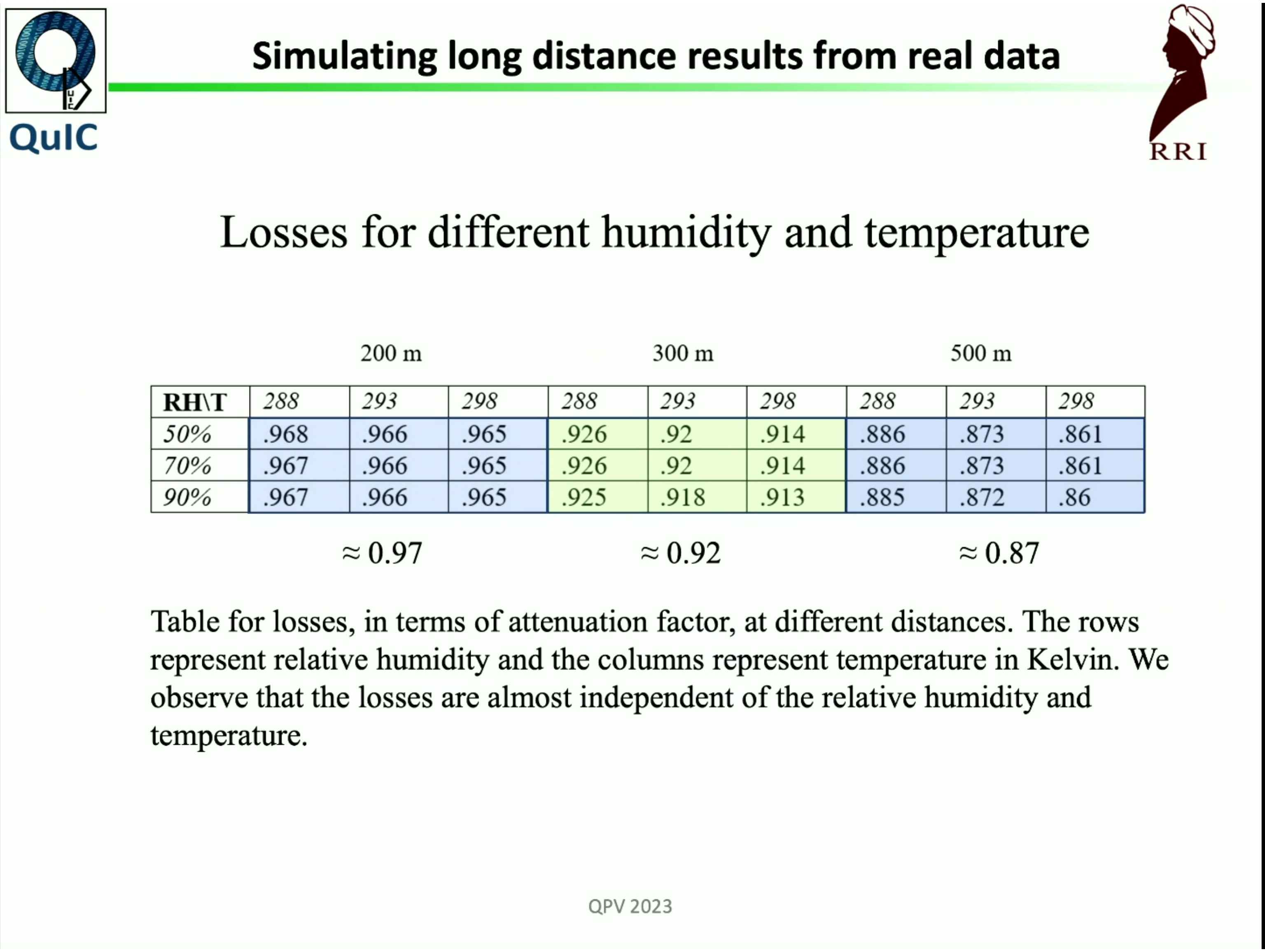


Free space quantum communications through an atmospheric channel



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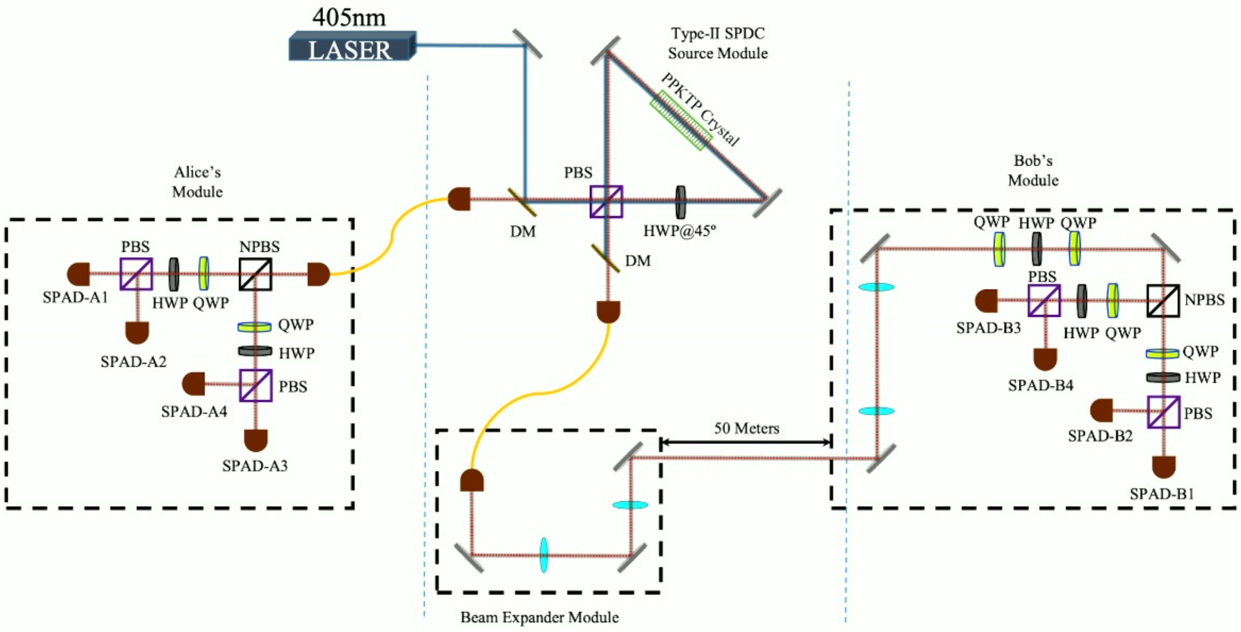

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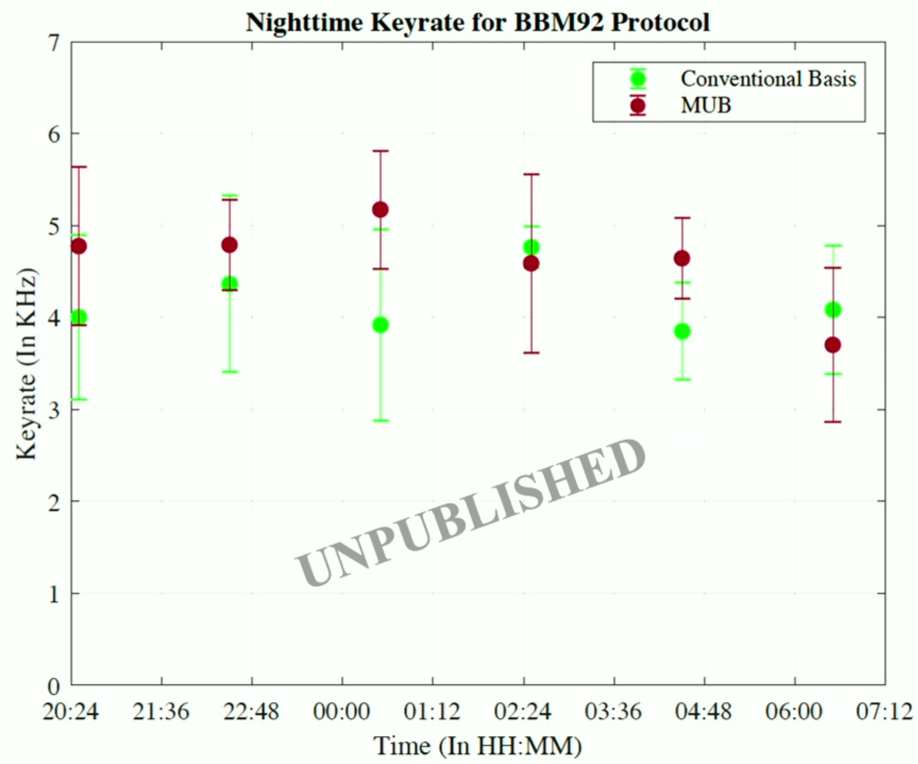

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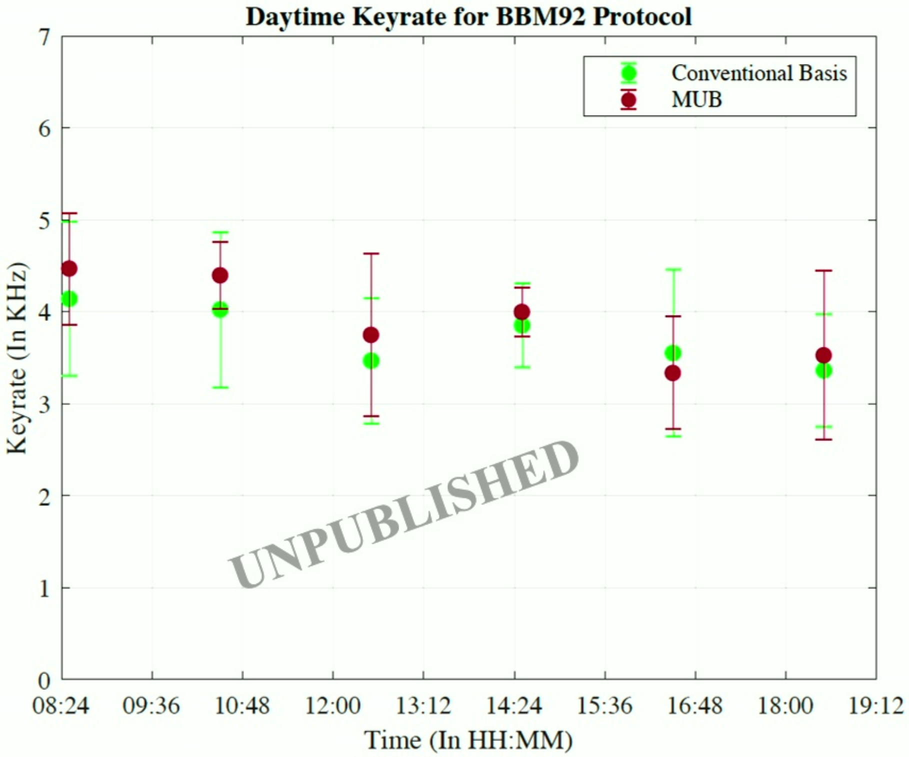

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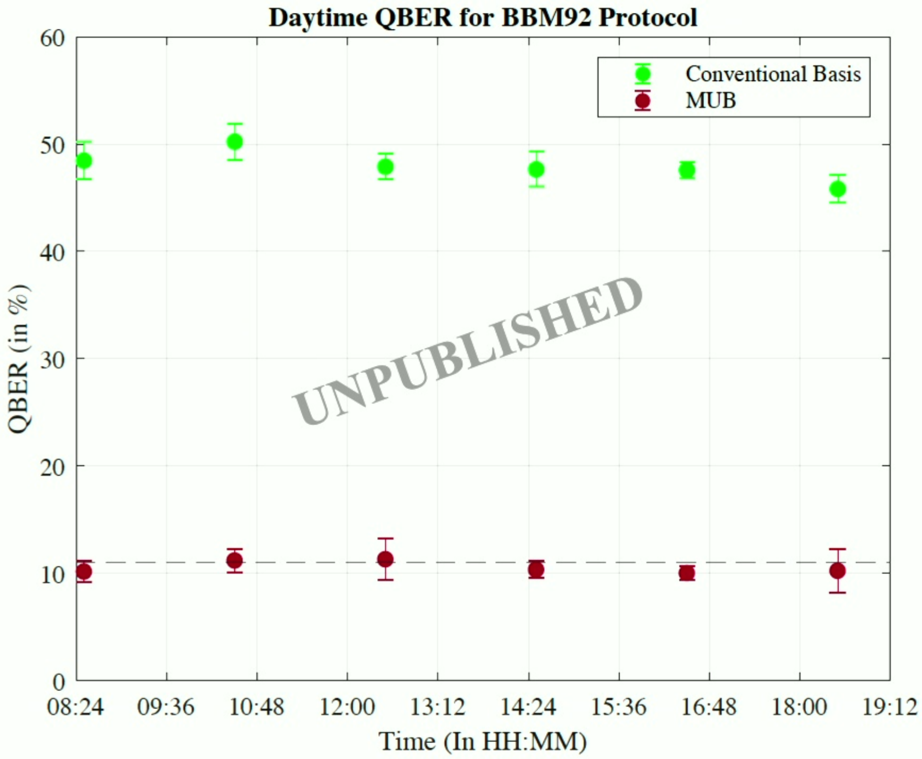

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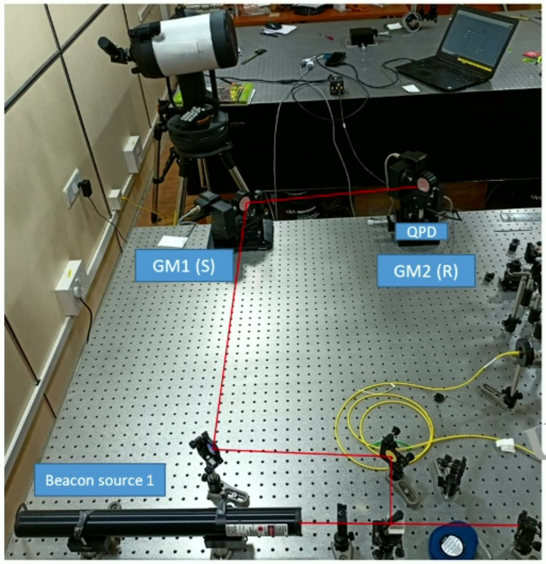
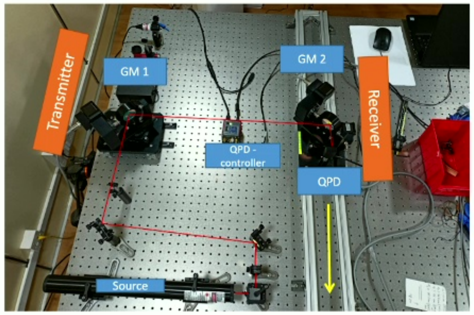
Experimental setup

- ➢ **Using two gimbal mirror on a translational stage and single beacon in a closed loop setup**

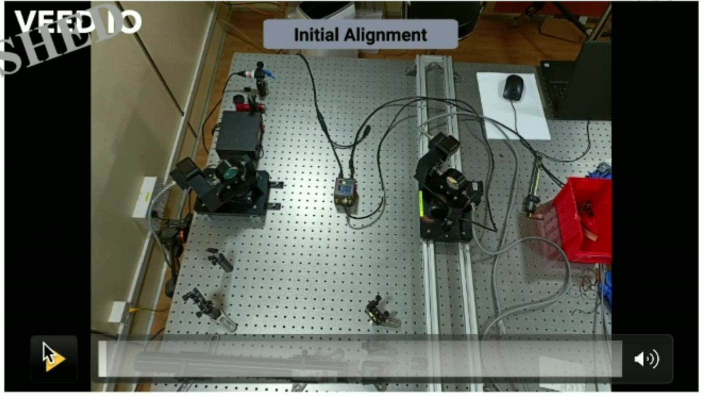


- GM 2 is mounted on a translational stage and displacement is introduced using the micrometer drive.
- Pointing and tracking is observed up to a displacement of 25mm

- ➢ **Transmitter gimbal stationed and receiver gimbal moved on rail of length 1 meter.**



Video



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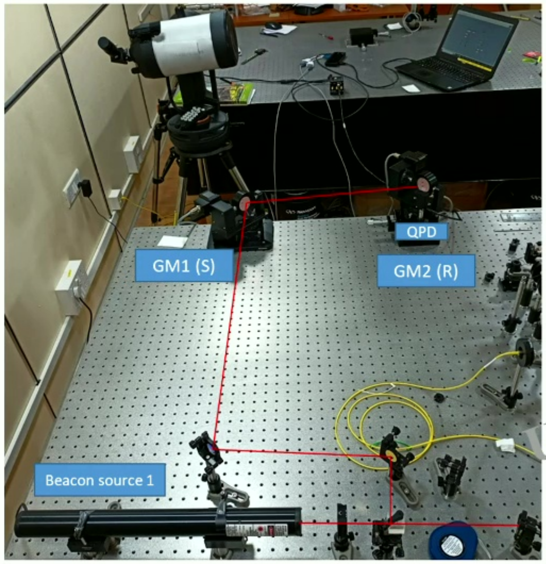

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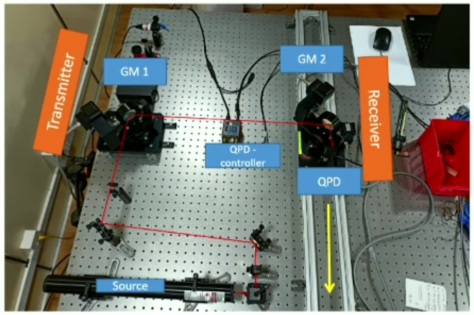
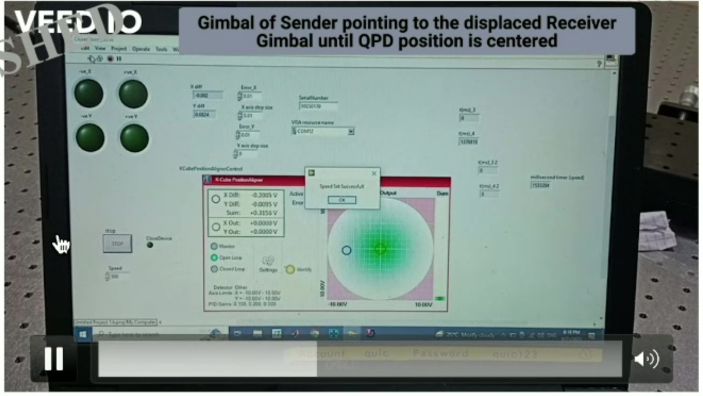


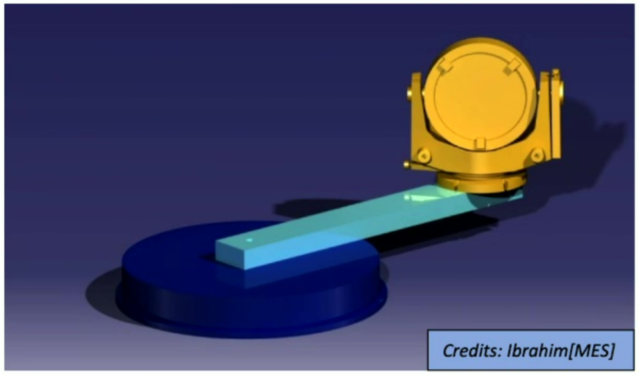
Video



Gimbal of Sender pointing to the displaced Receiver Gimbal until QPD position is centered

Feedback demonstration of moving receiver on circular motorized arm

Schematic


Credits: Ibrahim[MES]

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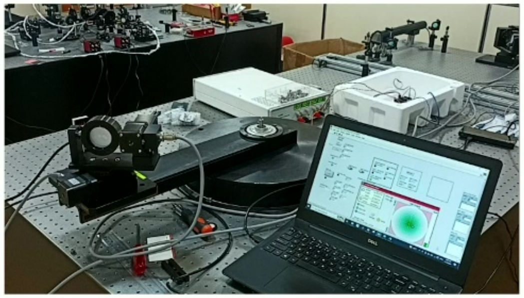
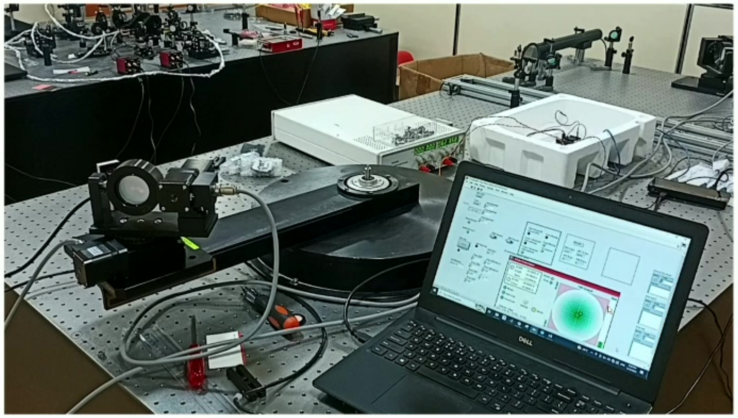




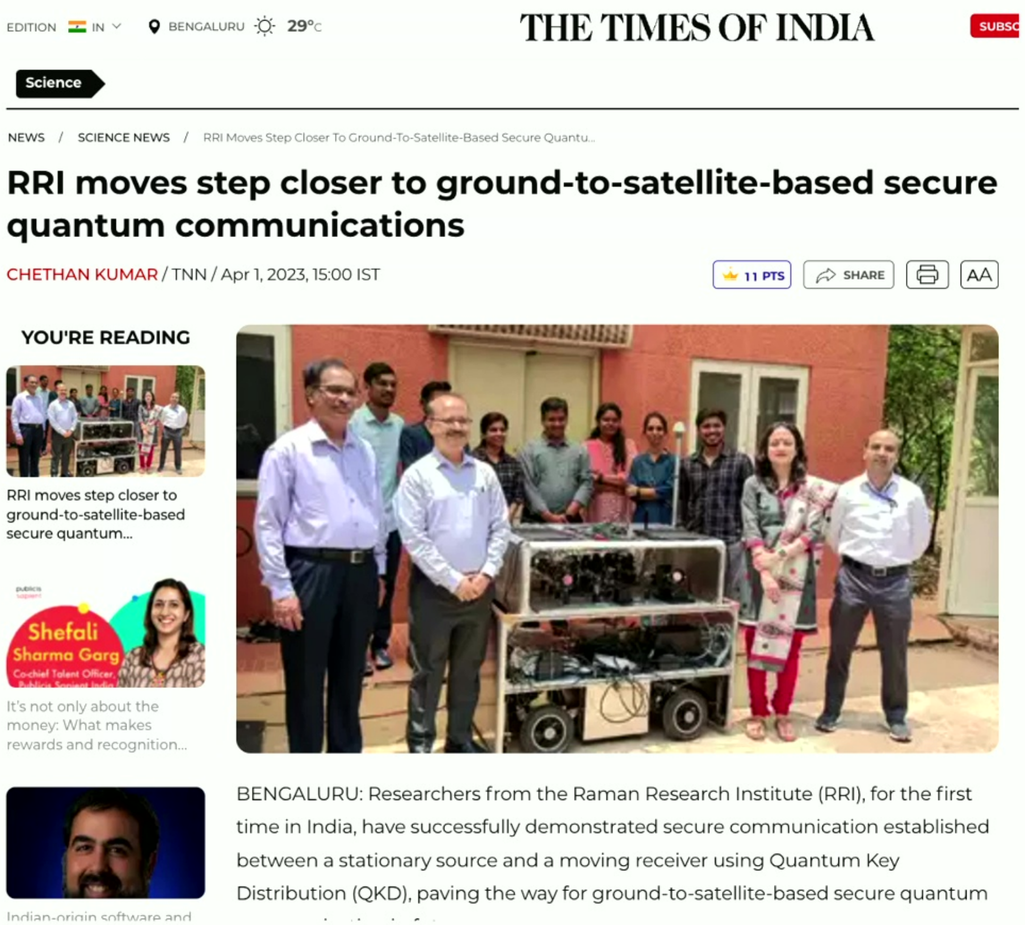
Video

Moving receiver platform developed with the help from Mechanical Engineering Services (MES) at RRI.

Moving receiver platform developed with the help from Mechanical Engineering Services (MES) at RRI.

QuIC

RRI



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