

# Genuine time-bin-encoded quantum key distribution in a turbulent depolarizing free-space channel

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Christopher J. Pugh, Katanya B. Kuntz, Brendon L. Higgins, and Thomas Jennewein

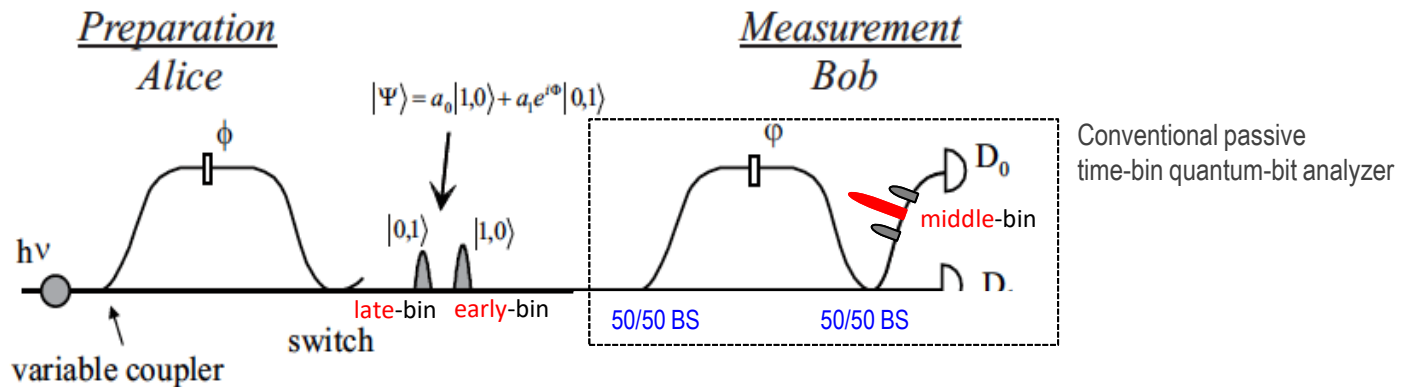
Institute for Quantum Computing  
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# Outline

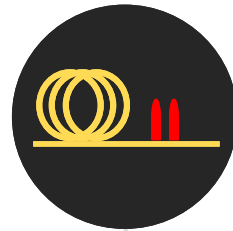
- 1. Time-bin encoding for free-space quantum communication:** motivations and challenges
- 2. Quantum key distribution demonstration**
  - 2-1. in a turbulent free-space channel
  - 2-2. in a depolarizing and turbulent free-space channel
- 3. Summary and outlook**

# Time-bin encoding: versatile for quantum communication in optical fibres



I. Marcikic et al., *Nature* **421**, 509 (2003)

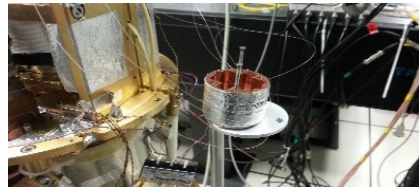
Interference is crucial for time-bin state analysis !



## Commercial QKD system<sup>1</sup>



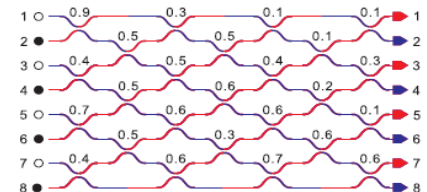
## Fibre-memory storage<sup>2</sup>



## City-wide teleportation<sup>3</sup>



## Boson sampling<sup>4</sup>



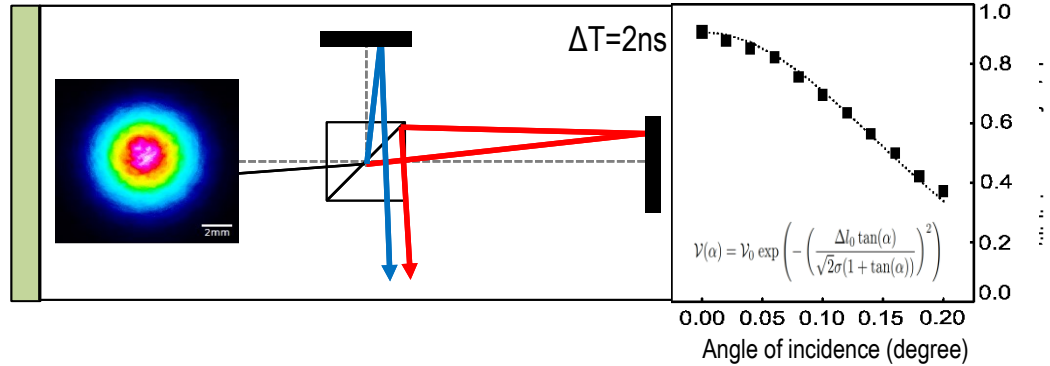
1. Idquantique.com
2. Quantum storage of entangled telecom-wavelength photons in an erbium-doped optical fibre, E. Saglamyurek, et al. *Nat. Photon.* **9**, 83 (2015)
3. Quantum teleportation across a metropolitan fibre network, R. Valivarthi et al., *Nat. Photon.* **10**, 676 (2016)
4. Time-bin-encoded boson sampling with a single-photon device, Y. He et al., *Phys. Rev. Lett.* **118**, 190501 (2017)

# Time-bin encoding: challenges for free-space quantum communication<sup>1</sup>

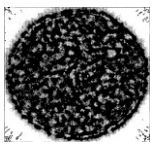
**Beam Wandering**

Angle of Incidence Error  
=  $0.06^\circ$

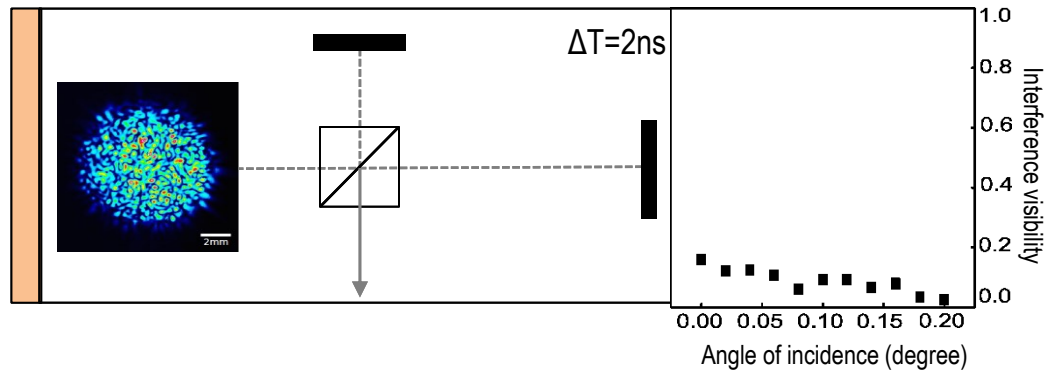
J. P. Bourgoin et al.,  
*Opt. Express* 23, 33437 (2015)



**Wavefront Distortion**



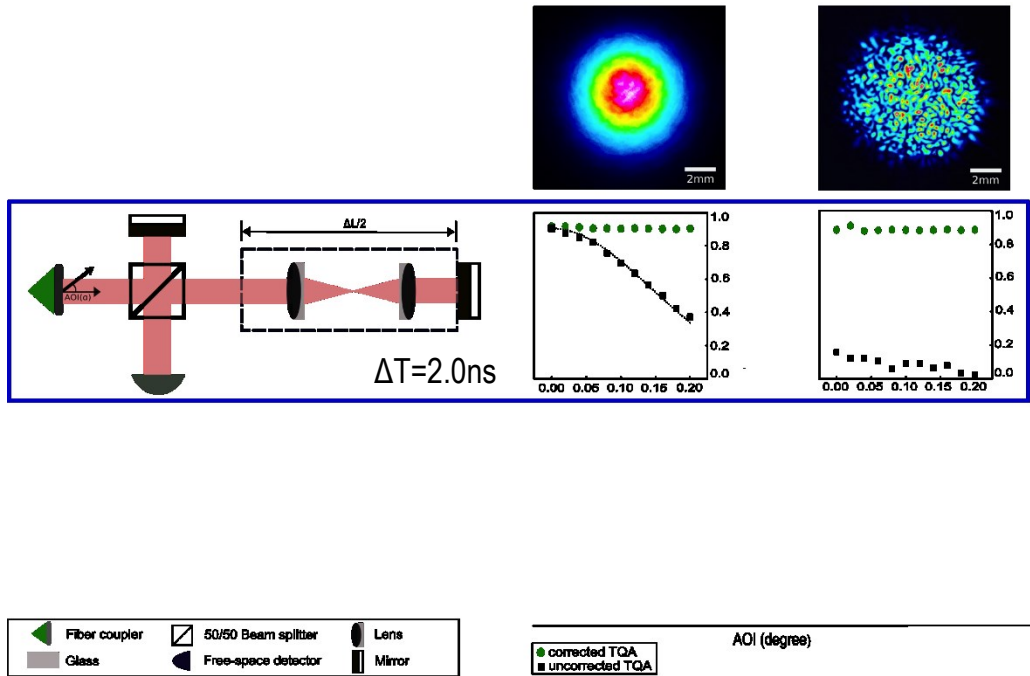
D. L. Fried et al.,  
*App. Opt.* 31, 2865 (1992)



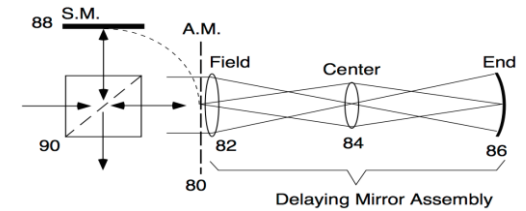
1. Demonstration of analyzers for multimode photonic time-bin qubits, J. Jin et al., arXiv:1509.17490 (2015); *Phys. Rev. A* **97**, 043847 (2018)

# Time-bin encoding: recent progress towards free-space quantum communication

Prior solutions : single-mode-fibre filtering (high loss) / adaptive optics (expensive, challenging)

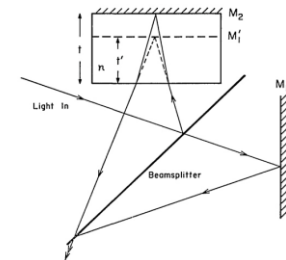


Method 1:  
Imaging optics



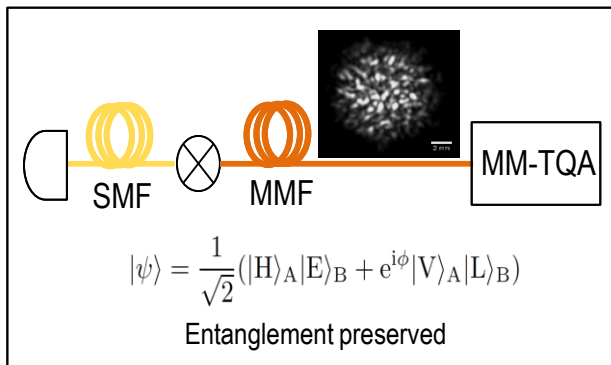
D. J. Erskine, US patent 6115121 (1997)

Method 2:  
Different refractive index

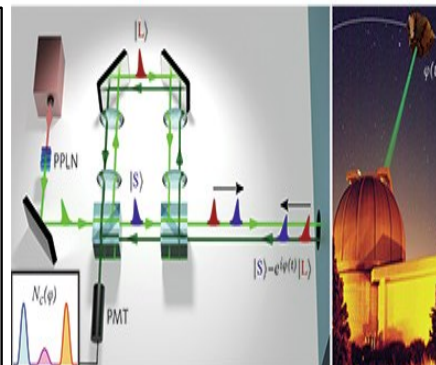


R. L. Hillard et al., JOSA **56**, 362 (1966)

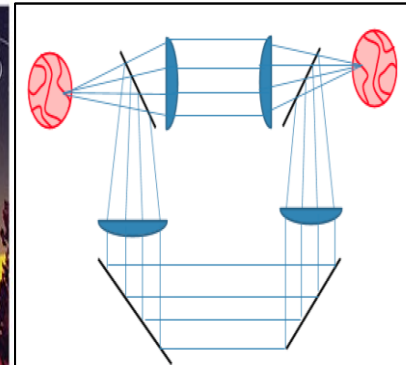
Interference visibility



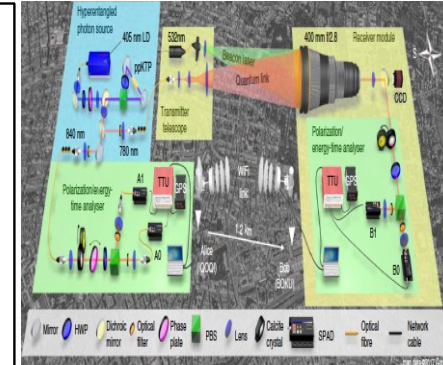
J. Jin et al., arXiv:1509.17490 (2015);  
*Phys. Rev. A* **97**, 043847 (2018)



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

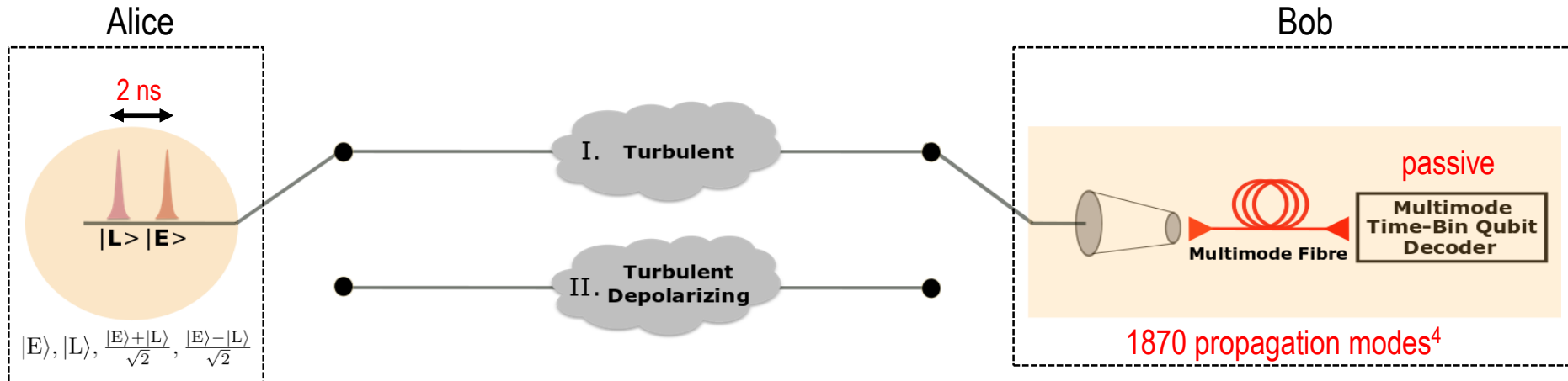


C. Zeithler et al.,  
*Proc. of SPIE* **9739**, 973912 (2016)



F. Steinlechner et al.,  
*Nat. Commun.* **8**, 15971(2017)

# Quantum key distribution: decoy-state BB84 protocol<sup>1-3</sup>



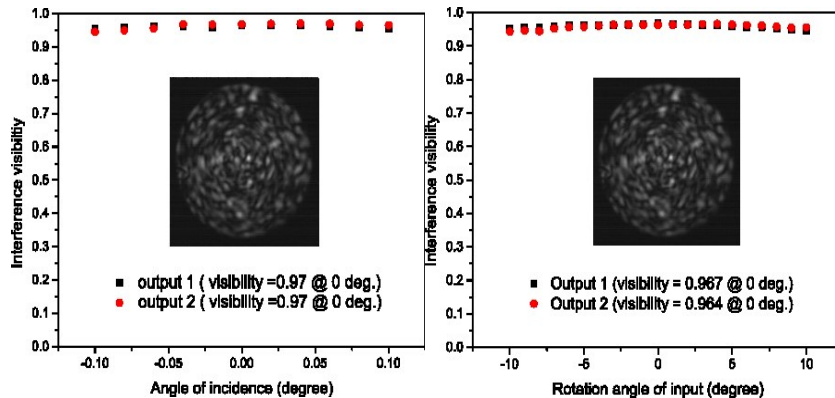
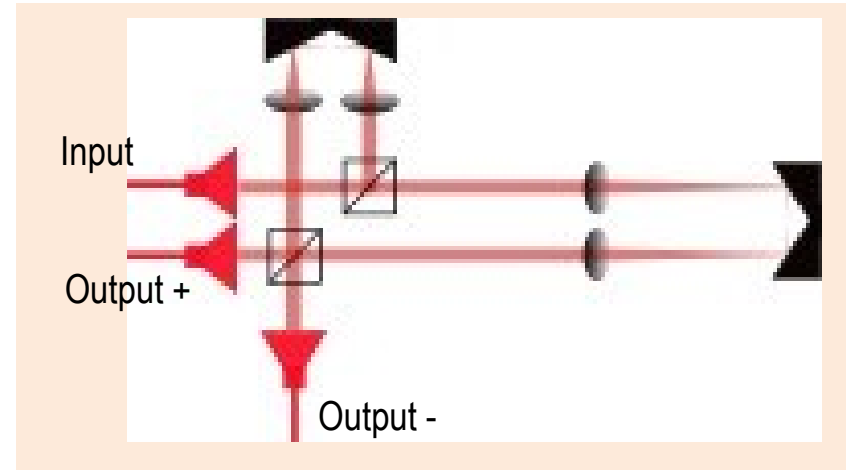
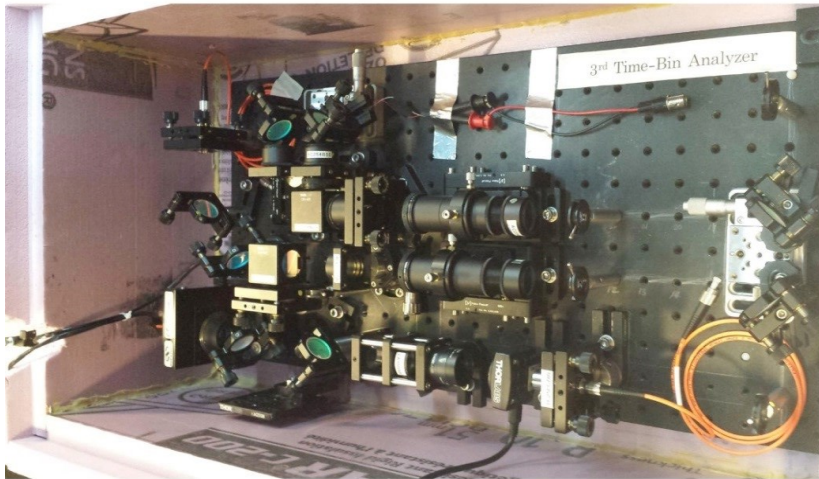
## Classical Postprocessing

01001  
00110

01001  
00110

1. Quantum cryptography, C. H. Bennet and G. Brassard, *Proc. of IEEE Int. Conf. on Computers, Systems and Signal Processing* **175**, 8 (1984)
2. Quantum key distribution with high loss: toward global secure communication, W. -Y. Hwang, *Phys. Rev. Lett.* **91**, 057901 (2003)
3. Practical decoy state for quantum key distribution, X. Ma et al., *Phys. Rev. Lett.* **72**, 012326 (2005)
4. Focusing and scanning light through a multimode optical fiber using digital phase conjugation, I. N. Papadopoulos et al, *Opt. Express* **20**, 10583 (2012)

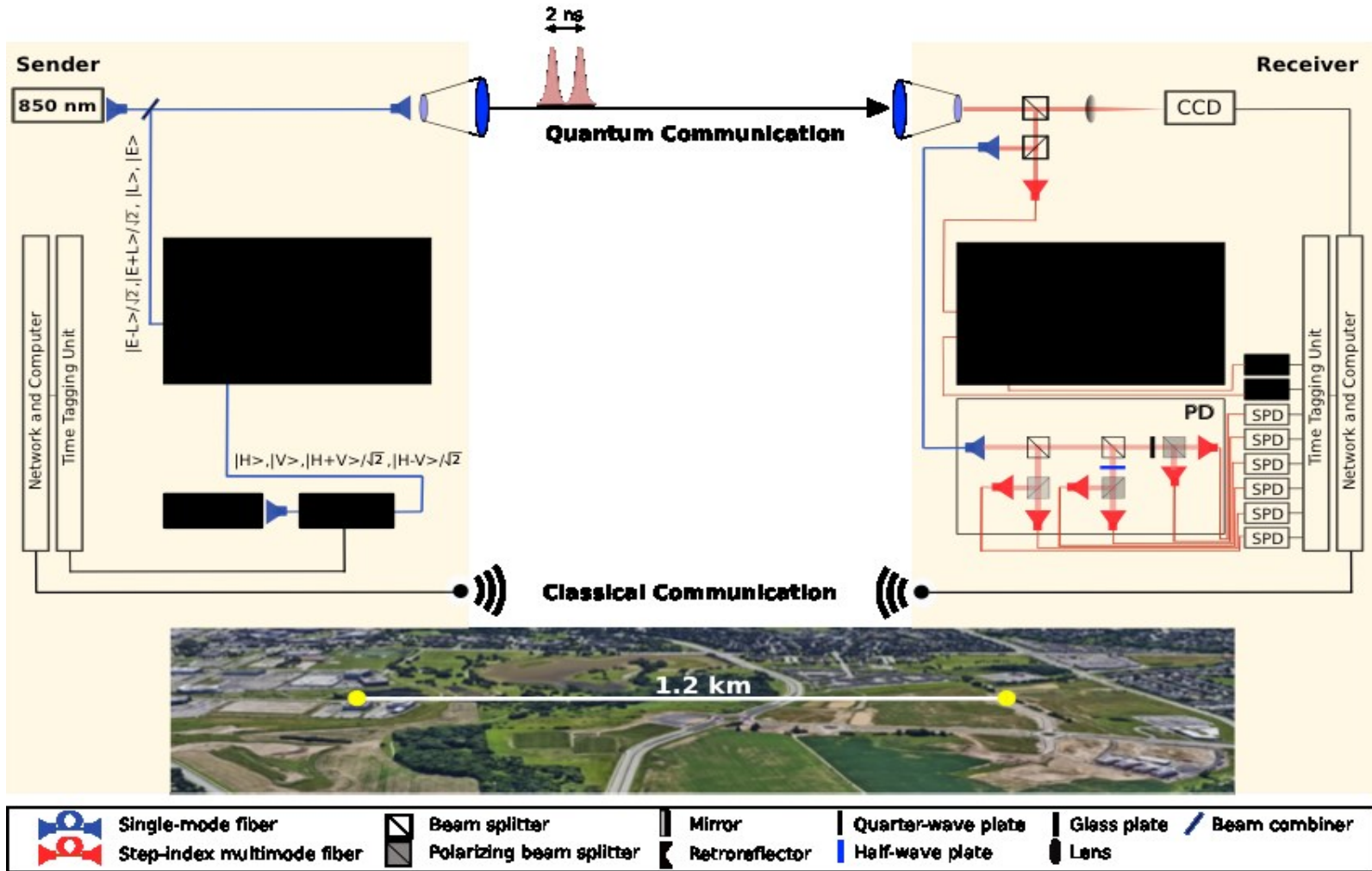
# Quantum key distribution: key component – multimode time-bin qubit analyzer



- ❑ Passive compensation
- ❑ Interference visibility = up to 97 %
- ❑ Throughput = 81 % from input to output coupling
- ❑ Minimized dispersion



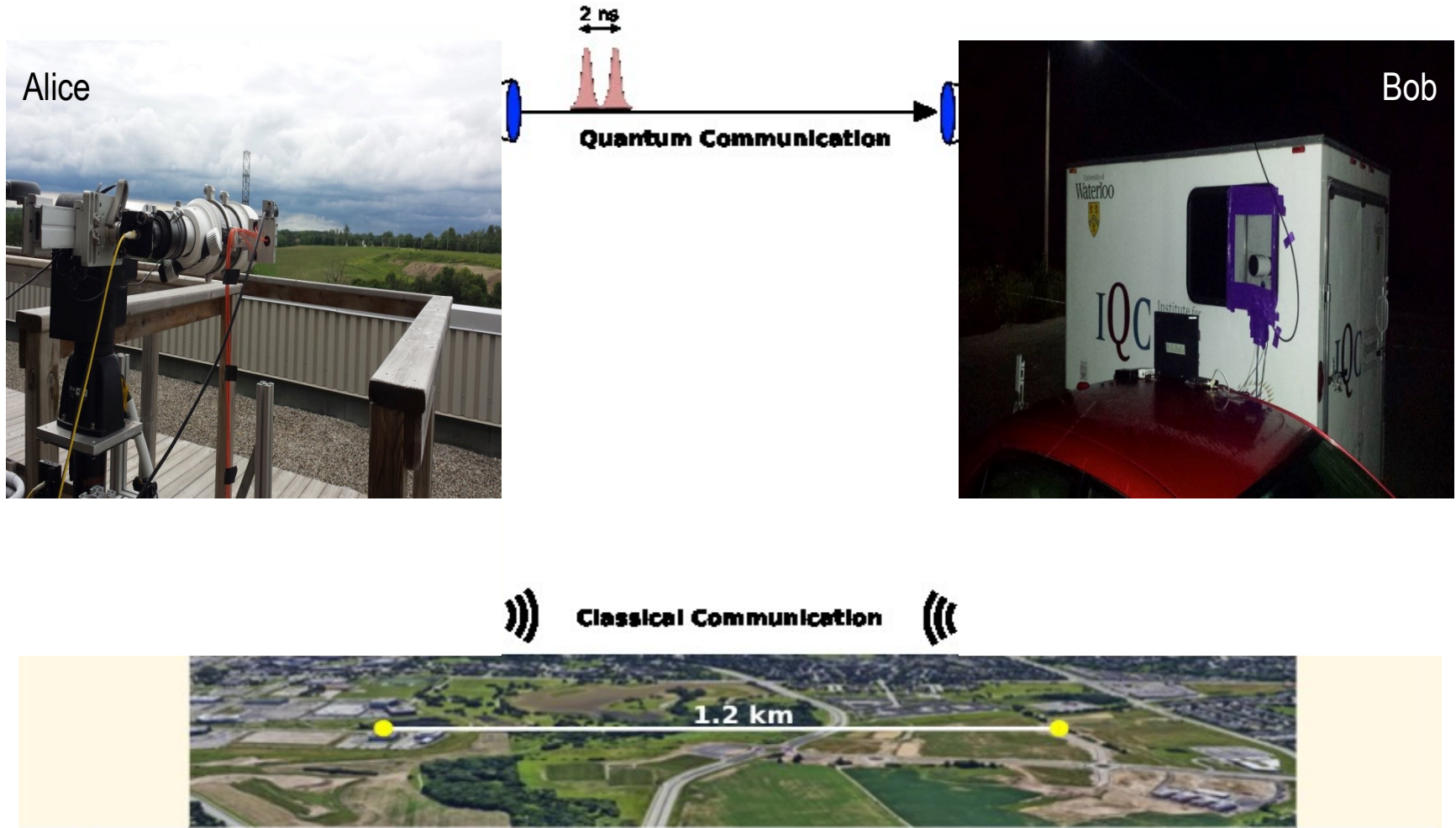
# Quantum key distribution: setup<sup>1</sup>



1. J. Jin et al., paper in preparation

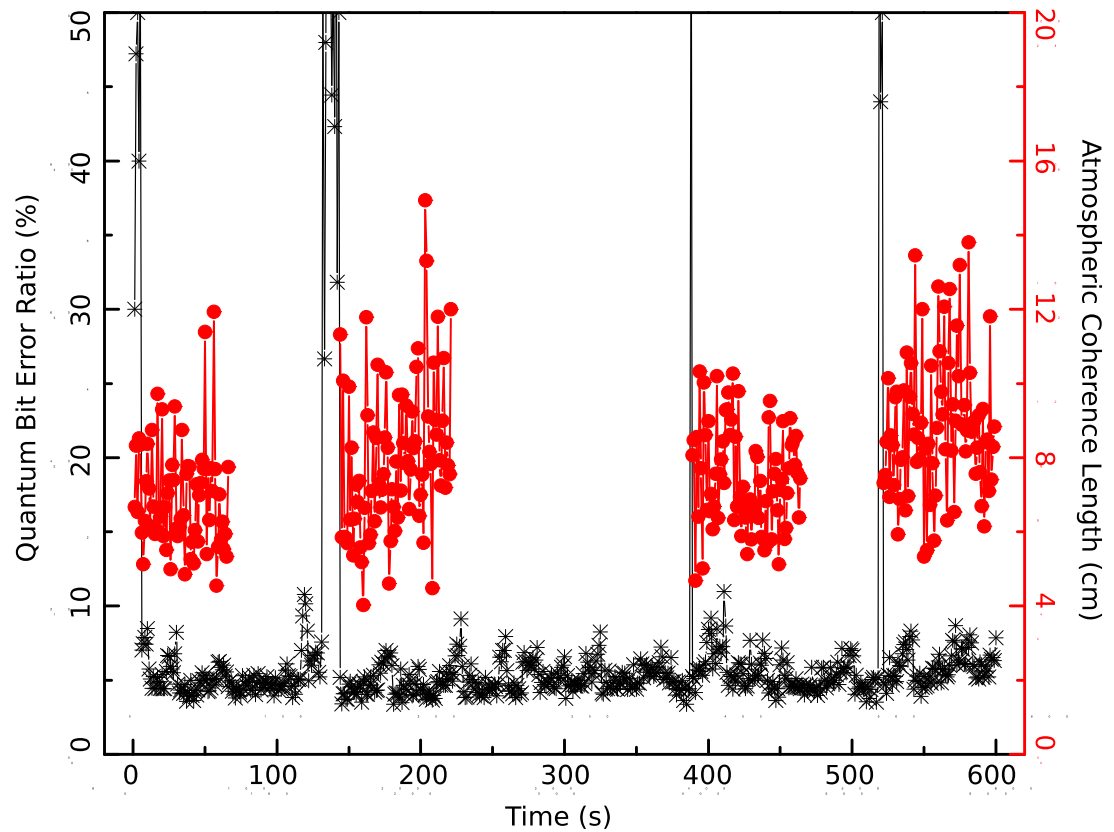
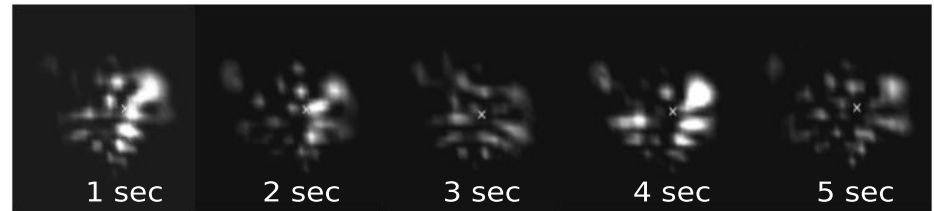


# Quantum key distribution: [setup photos](#)<sup>1</sup>



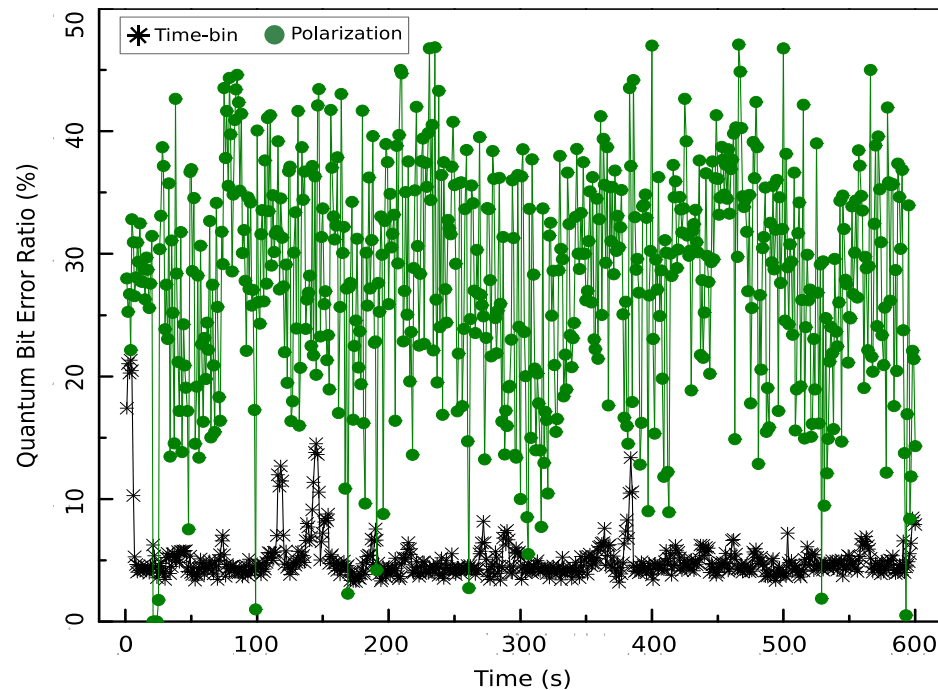
1. J. Jin et al., paper in preparation

# Quantum key distribution: in a turbulent free-space channel<sup>1</sup>

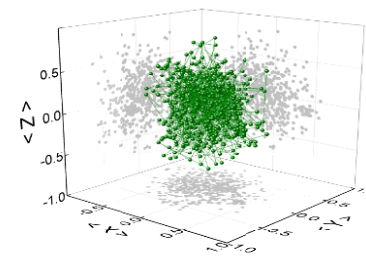
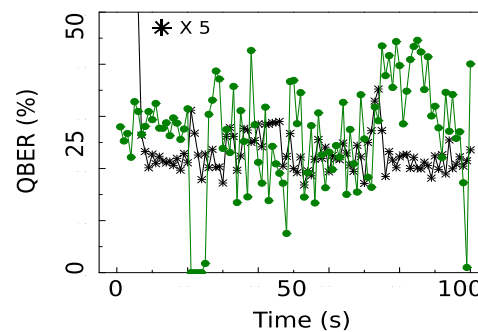


- Mean Coherence Length = 7.83 cm
- Mean Time-Bin QBER = 5.23 %
- Secret Key Rate = 178.9 bits/s

# Quantum key distribution: in a depolarizing and turbulent free-space channel<sup>1</sup>



- ❑ Mean Time-Bin QBER = 4.99 %
- ❑ Secret Key Rate = 167.2 bits/s



1. J. Jin et al., paper in preparation

## Summary

1. Time-bin encoding viable for QKD in a turbulent depolarizing free-space channel
2. Passive multimode time-bin analyzer with
  - high throughput of 81 % from input to output coupling
  - stable interference visibility up to 97 %

## Outlook

1. Time-bin QKD over multi-mode optical fibre
2. Implementation of COW- and DPS-QKD protocols in free space
3. Direct interfacing between fibre and free-space quantum network links
4. Polarizing effects of optics (e.g. lens and mirror) and optical path can be overcome



