How to harness high-dimensional temporal entanglement for QKD

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Motivation:

QKD connections face several challenges:

- Quantum repeaters not available yet
- Exponential loss in fibres
- Free-space links are limited to operation times with very low background-noise (nighttime)

⇒ High-Dimensional Entanglement

- Analyses of such setups were primarily heuristic and relied on assumptions

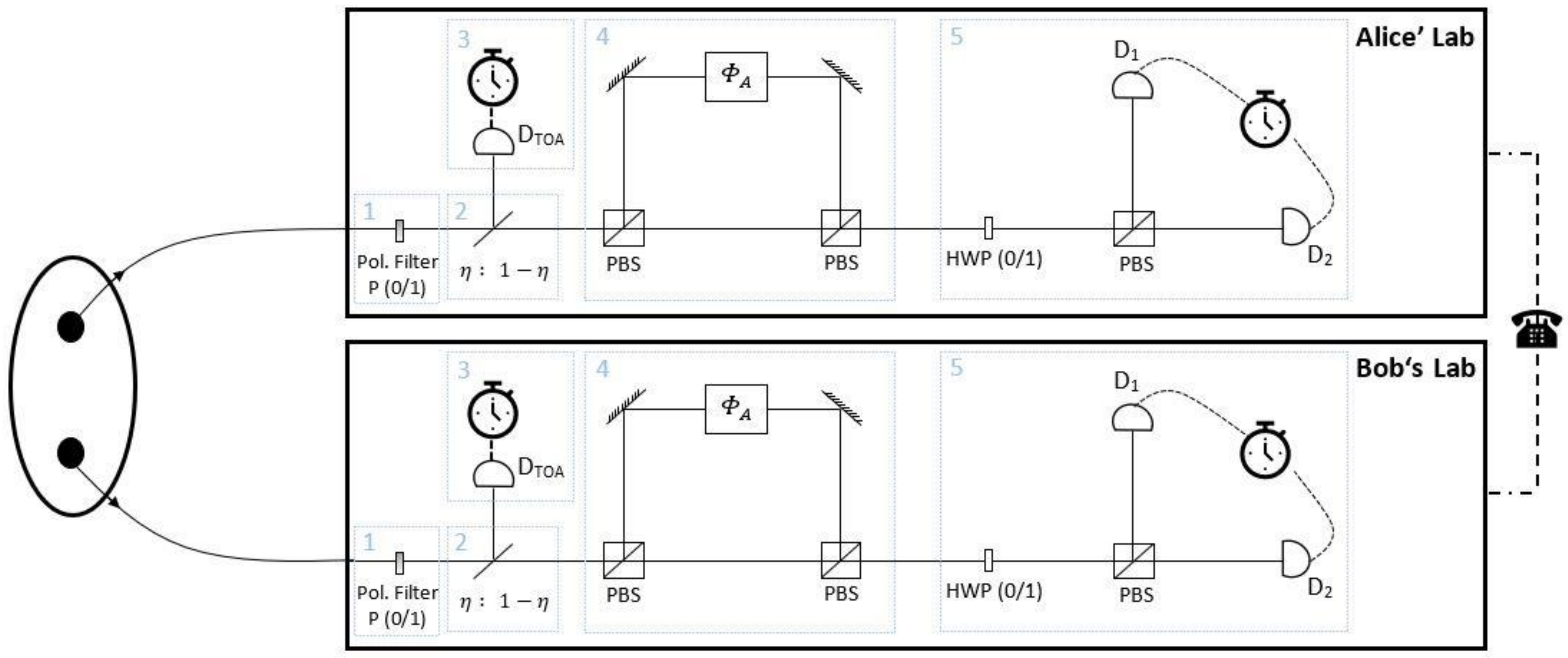

Figure 1: Sketch of the analysed setup. A source produces entangled photons which are measured by Alice and Bob either in Time-of-Arrival (3) or Time-Superposition (4,5) basis. The polarisation filter (1) can be either inserted or removed.

Setting and Problem:

- A source produces entangled photon pairs in $(\mathcal{H}_{\text{Pol}} \otimes \mathcal{H}_T)^{\otimes 2}$
- Alice and Bob measure in two settings:
  I. Time-of-Arrival (ToA)
  II. Time-Superposition (TSUP) between neighboring time-bins

  and record clicks.
- The interpretation of the measurements and their meaning for the time-part depend on the polarization degree of freedom.
- Previous analyses assumed that time and polarization are
  a) independent from each other and
  b) that the polarisation degree is unaffected by noise,

  which is unjustified.

$$|\Psi^{\text{eff}}_{\text{target}}\rangle := \sum_{p\in\mathcal{P}} c_p\,|p\rangle \otimes \frac{1}{\sqrt{d}}\sum_{k=0}^{d-1}|kk\rangle$$

$$\mathrm{TT}(i,j) := \mathrm{Tr}\left[\rho\left(M^A(i)\otimes M^B(j)\right)\right],$$

$$\mathrm{SS}_{a,b}(i,j) := \mathrm{Tr}\left[\rho\left(\tilde{M}^A_a(i,\phi^A)\otimes \tilde{M}^B_b(j,,\phi^B)\right)\right],$$

$$\mathrm{TS}_b(i,j) := \mathrm{Tr}\left[\rho\left(M^A(i)\otimes \tilde{M}^B_b(j,\phi^B)\right)\right],$$

$$\mathrm{ST}_a(i,j) := \mathrm{Tr}\left[\rho\left(\tilde{M}^A_a(i,\phi^A)\otimes M^B(j,\phi^B)\right)\right],$$

Results:

- We propose [1] a new protocol that makes use of an additional polarization filter (1) with target state

$$|\Psi_{\text{new}}\rangle = |DD\rangle \otimes \frac{1}{\sqrt{d}}\sum_{k=0}^{d-1}|kk\rangle$$

- and compare it a protocol analysed earlier, relying on (a) and (b) with target state

$$|\Psi_{\text{old}}\rangle = \frac{|HH\rangle + |VV\rangle}{\sqrt{2}} \otimes \frac{1}{\sqrt{d}}\sum_{k=0}^{d-1}|kk\rangle$$

- Our solution removes both (a) and (b) while improving the noise-resistance and easing the practical complexity of the experiment simultaneously.
- We develop a realistic noise-model and compare the asymptotic secure key rates of both protocols, using a recent numerical method [*Quantum 7, 1019 (2023)*].
- The tolerance against solar photons increases by a factor of 1.75, which promises to shift operation times towards daytime [see also *PRX 13, 021001 (2023)*].

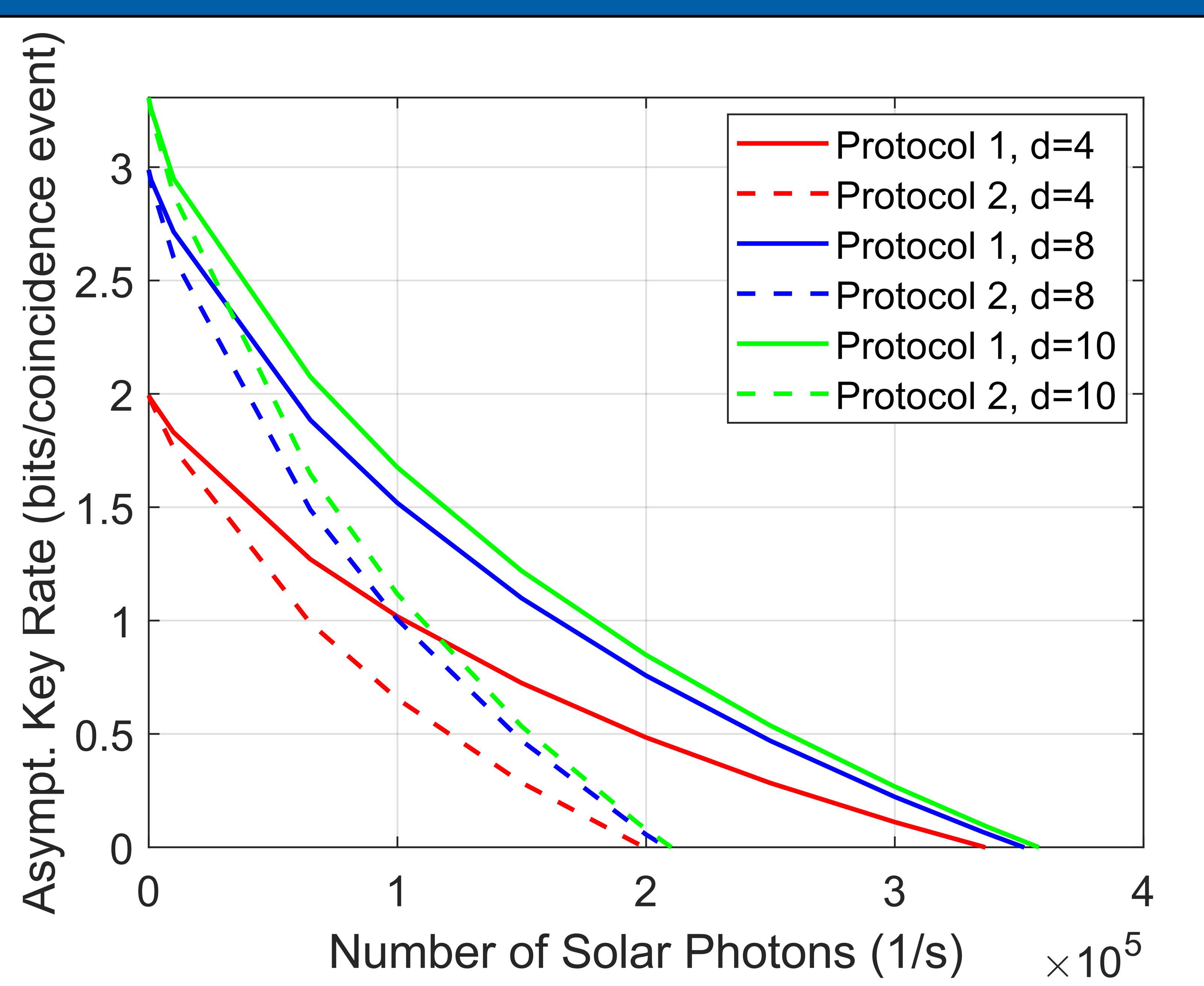

Figure 2: Asymptotic secure key rate vs. solar photons per second for $T = 5.4\times 10^{-9},\ p_{\text{Loss}} = 99.7\%,\ \eta_{\text{det}} = 90\%,\ r_{\text{dark}} = 100/s,\ r_{\text{pair-prod}} = 0.1/T.$

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This work has received funding from the Horizon-Europe research and innovation programme under grant agreement No 101070168 (HyperSpace).

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Preprint available:

[1] A. Bergmayr, F. Kanitschar, M. Pivoluska and M. Huber, How to harness temporal entanglement, using limited interferometry setups, arXiv:quant-ph/2308.04422 (2023)

SCAN ME!