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Proof-of-principle test of coherent-state continuous-variable quantum key distribution through turbulent atmosphere

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Atmospheric free-space or fiber-optical channel?

- Suffer from atmospheric effects (turbulence)
- Channel fading

✓Quickly deployable

✓Require only a line-of-sight location of the stations

vs

✓Stable and predictable transmittance

✓Noise is characterizable and in some cases can be negligible

- Requires prepared and ad justed network
- Higher cost

Fading channel

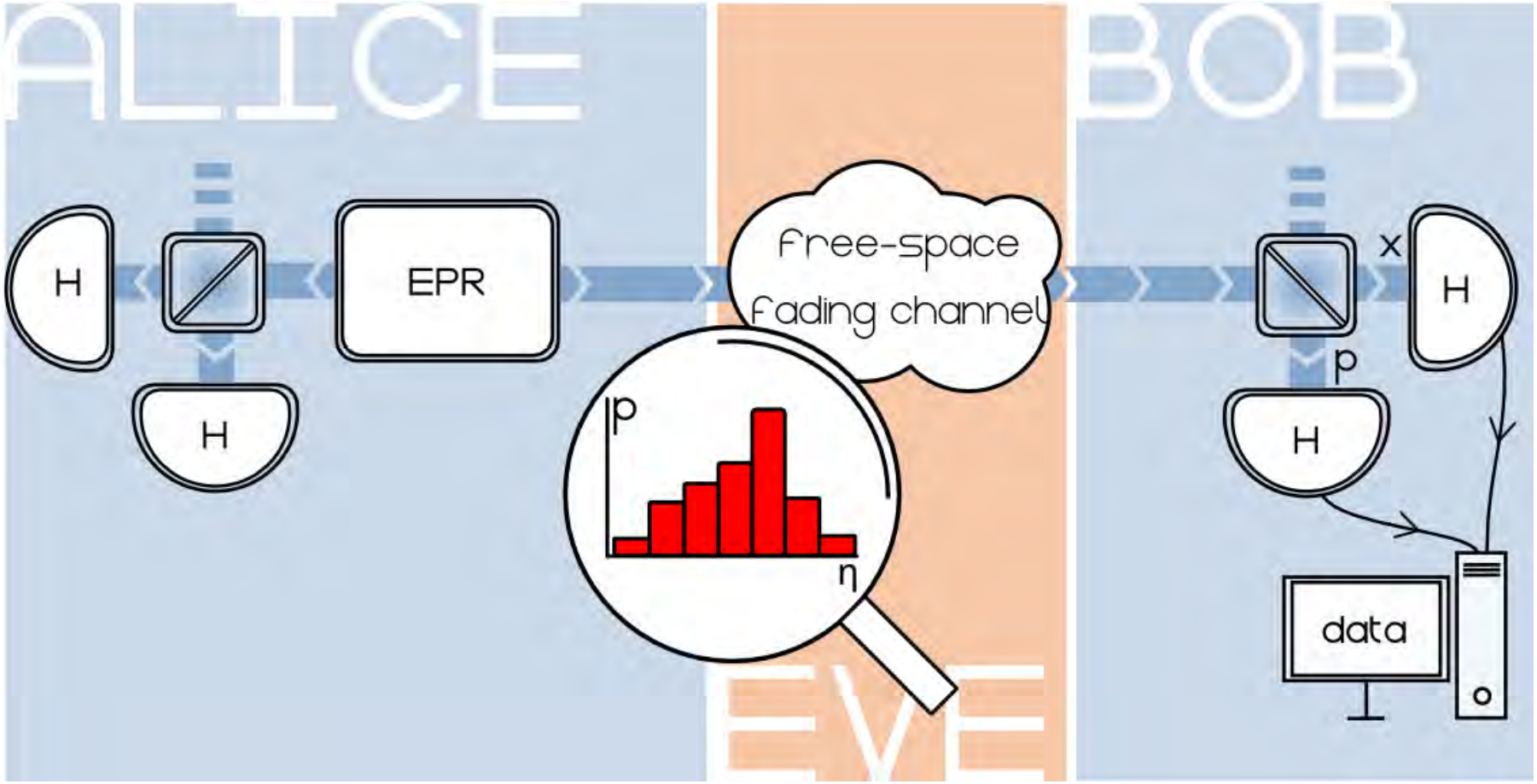
[1] Usenko et al., New. J. Phys. 14,093048 (2012)

[2] Dong et al., Phys. Rev. A 82, 012312 (2010)

Evolution of Gaussian state after single sub-channel (relatively stable transmittance window).

$$\gamma_{AB} = \begin{pmatrix} V\mathbb{I} & \sqrt{V^2-1}\sigma_Z \\ \sqrt{V^2-1}\sigma_Z & V\mathbb{I} \end{pmatrix} \rightarrow \gamma_{AB}^{i} = \begin{pmatrix} V\mathbb{I} & \sqrt{\eta_i}\sqrt{V^2-1}\sigma_Z \\ \sqrt{\eta_i}\sqrt{V^2-1}\sigma_Z & (V\eta_i + 1 - \eta_i + \chi)\mathbb{I} \end{pmatrix}$$

Fading channel



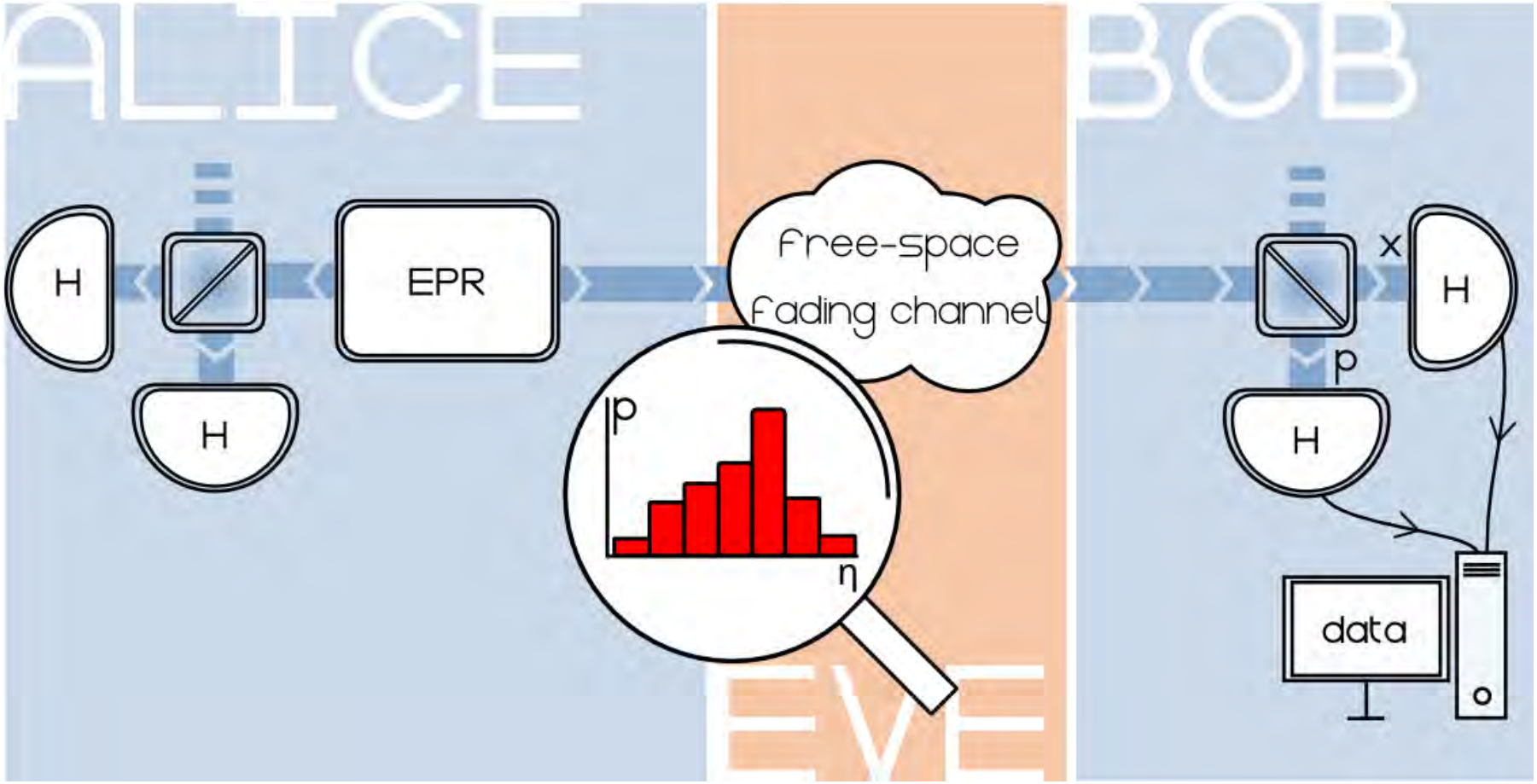
[1] Usenko et al., New. J. Phys. 14,093048 (2012)

[2] Dong et al., Phys. Rev. A 82, 012312 (2010)

The overall state after fading channel is the mixture of states after individual sub-channels.

$$\gamma_{AB}^{i} = \begin{pmatrix} V\mathbb{I} & \sqrt{\eta_i}\sqrt{V^2-1}\sigma_Z \\ \sqrt{\eta_i}\sqrt{V^2-1}\sigma_Z & (V\eta_i + 1 - \eta_i + \chi)\mathbb{I} \end{pmatrix} \Rightarrow \gamma'_{AB} = \begin{pmatrix} V\mathbb{I} & \langle\sqrt{\eta}\rangle\sqrt{V^2-1}\sigma_Z \\ \langle\sqrt{\eta}\rangle\sqrt{V^2-1}\sigma_Z & (V\langle\eta\rangle + 1 - \langle\eta\rangle + \chi)\mathbb{I} \end{pmatrix}$$

Fading channel



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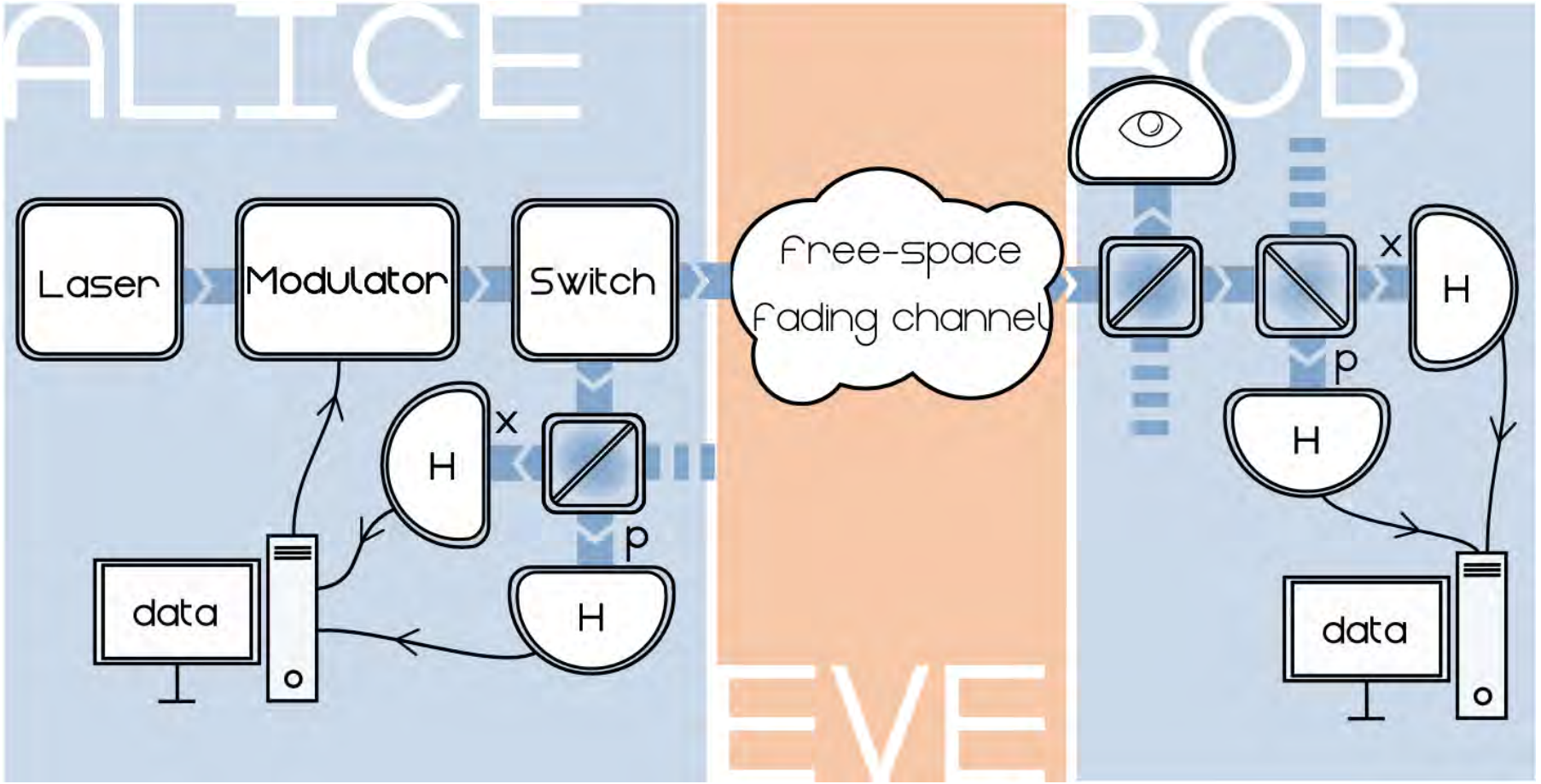
[2] Dong et al., Phys. Rev. A 82, 012312 (2010)

Channel can be considered as a non-fading with transmittance $\langle\sqrt{\eta}\rangle^2$ and excess noise caused by fading $\varepsilon_f = Var(\sqrt{\eta})(V-1)$. The variance of the signal mode after channel becomes $V_B' = \langle\sqrt{\eta}\rangle^2(V-1) + \varepsilon_f + \chi + 1$.

ε_f - variance dependent noise!

Setup sketch. Key rate.



R_{col} - key rate

β – post-processing efficiency

I_{AB}- mutual information between trusted parties

χ_E - Holevo bound

V_X - state variance

$V_{X|Y}$ - conditional state variance

C_{XY}- correlations

$$R_{col} = \beta I_{AB} - \chi_E; \quad I_{XY} = \frac{1}{2}\log_2\left[\frac{V_X}{V_{X|Y}}\right]; \quad V_{XY} = V_X - \frac{C_{XY}^2}{V_B};$$

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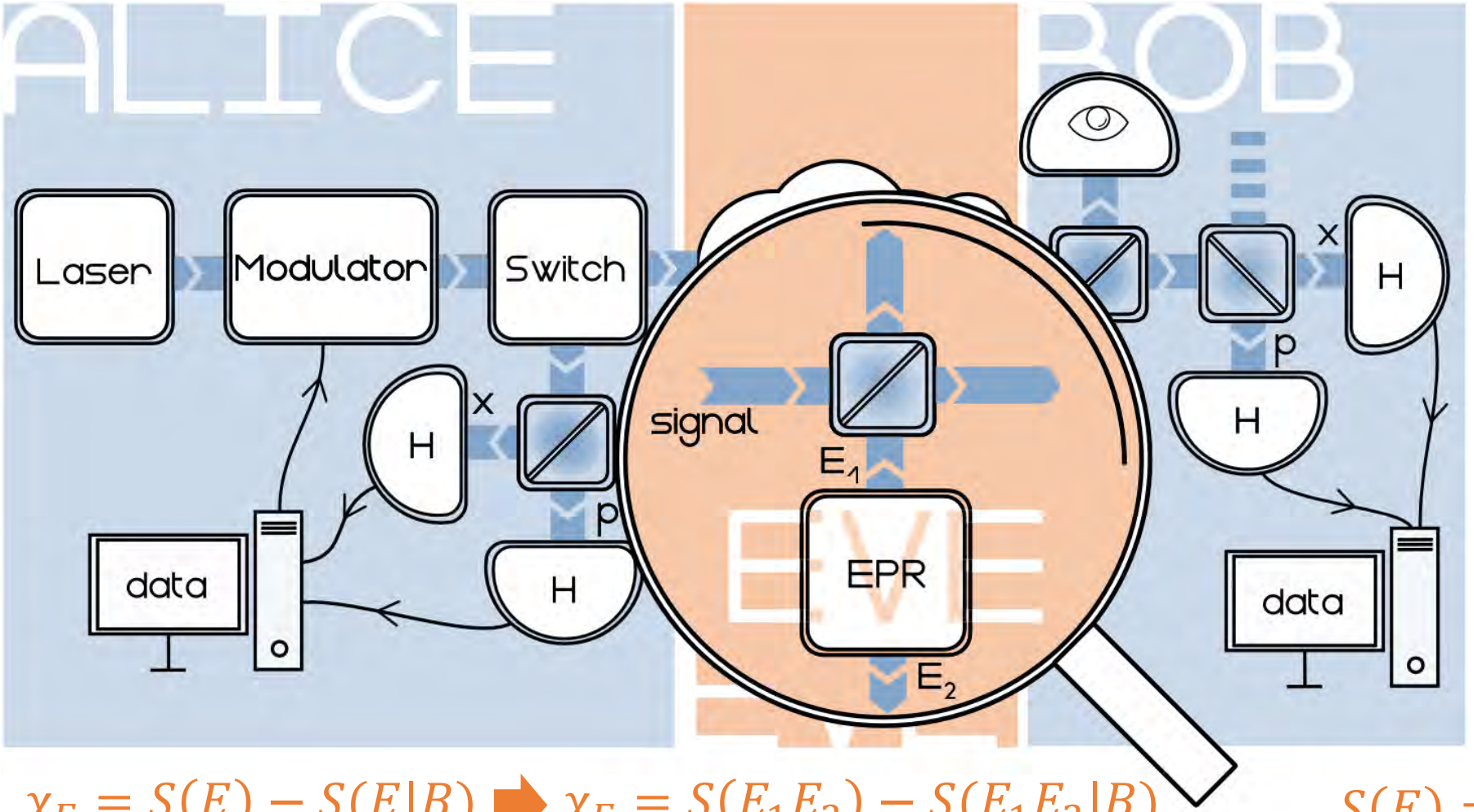
Setup sketch. Eve.



χ_E - Holevo bound

$S(X)$ - Von Neumann entropy

$G(x)$ - bosonic entropy function

λ_i - covariance matrix symplectic eigenvalues

$$\chi_E = S(E) - S(E|B) \Rightarrow \chi_E = S(E_1E_2) - S(E_1E_2|B)$$

$$G(x) = (x+1)\log_2[x+1] - x\log_x x$$

$$S(E) = \sum_{i=1}^{N} G\left(\frac{\lambda_i - 1}{2}\right)$$

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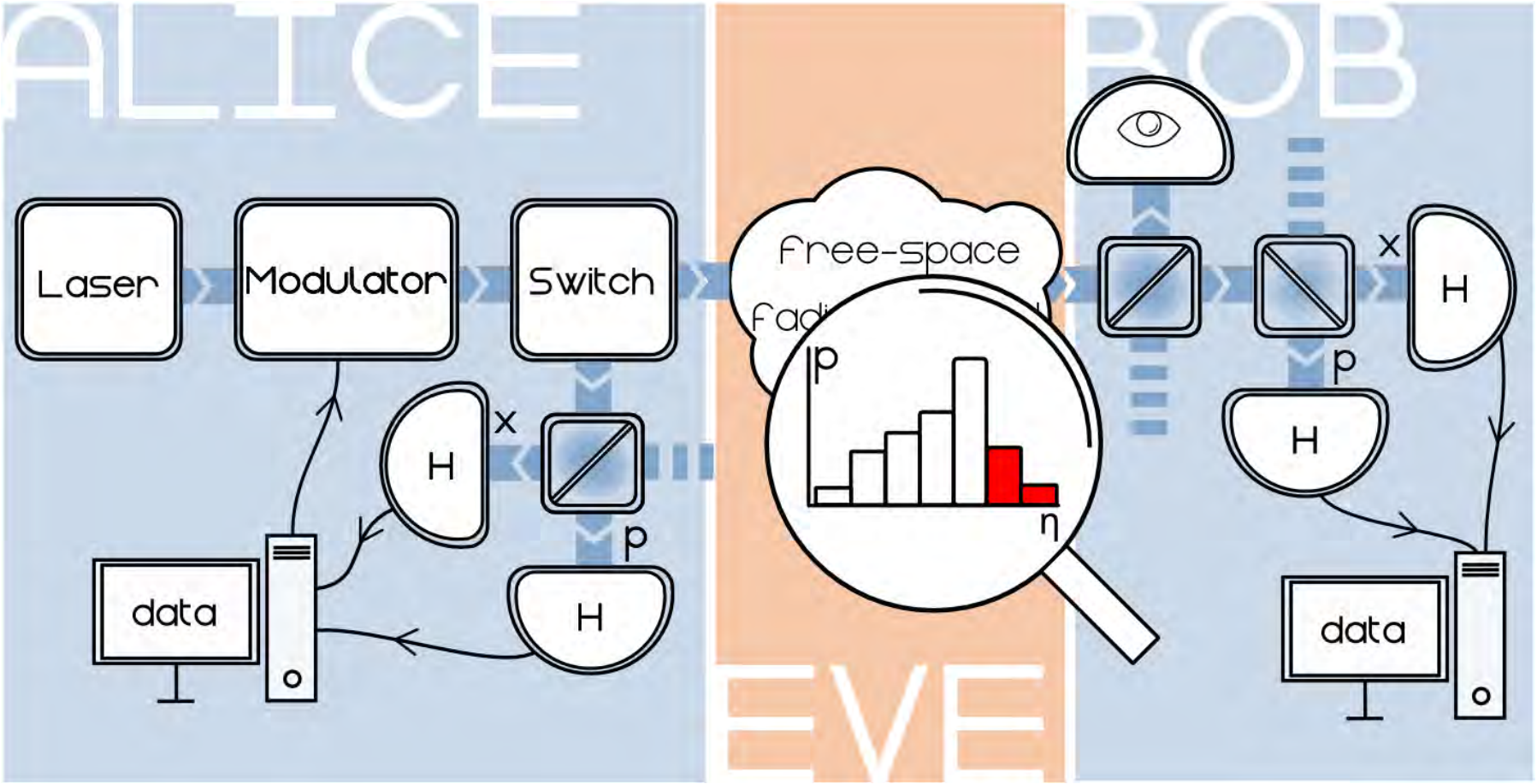
Setup sketch. Post-selection.



We create post-selected state by choosing a subset of channel transmittance distribution.

This allows us maximize lower bound of the secure key rate of the coherent-state CV QKD protocol.

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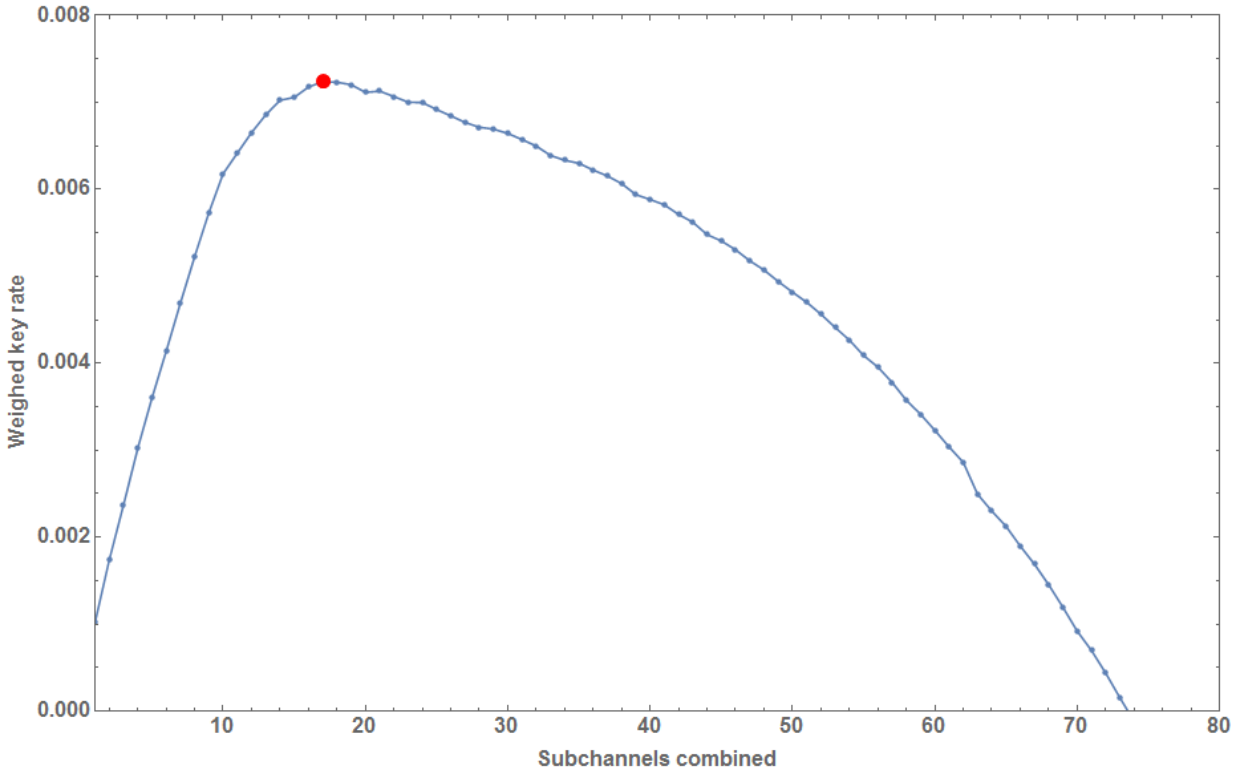
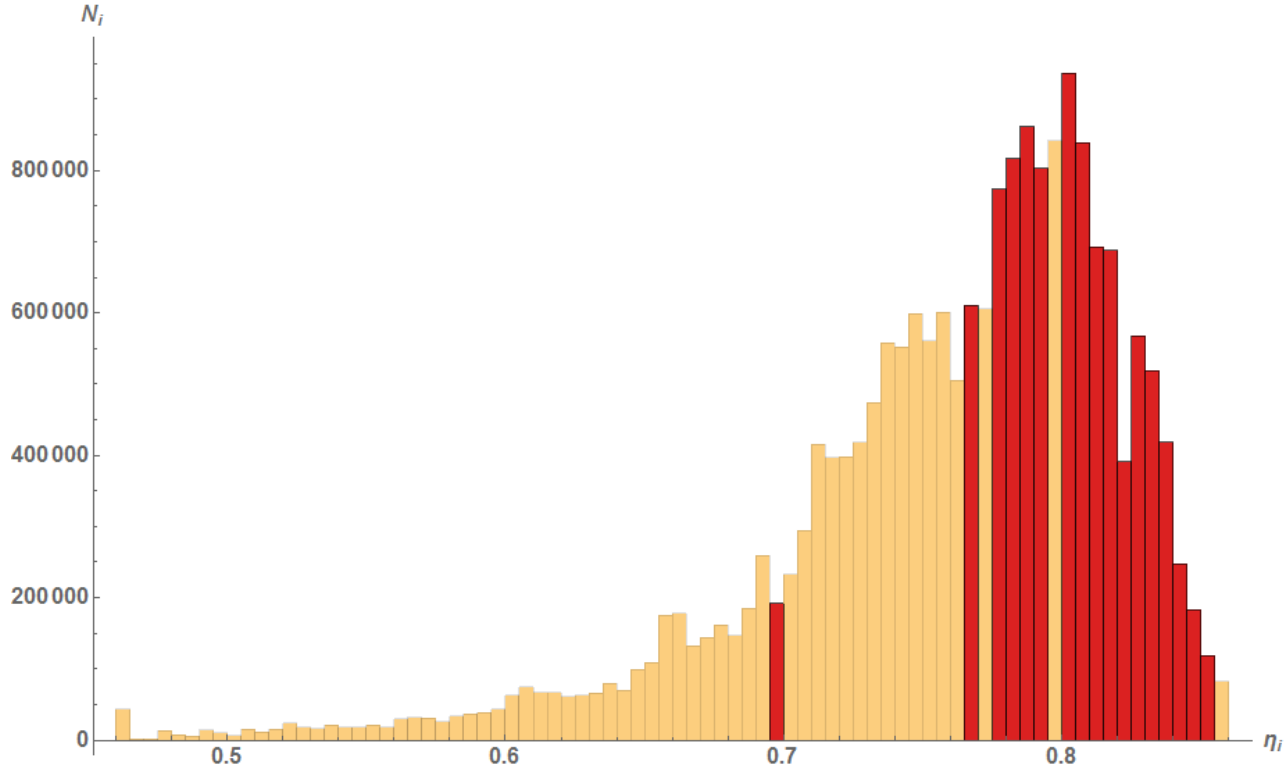
Results. Vm=0.51

Key rate for the post-selected state



Atmospheric channel transmittance distribution



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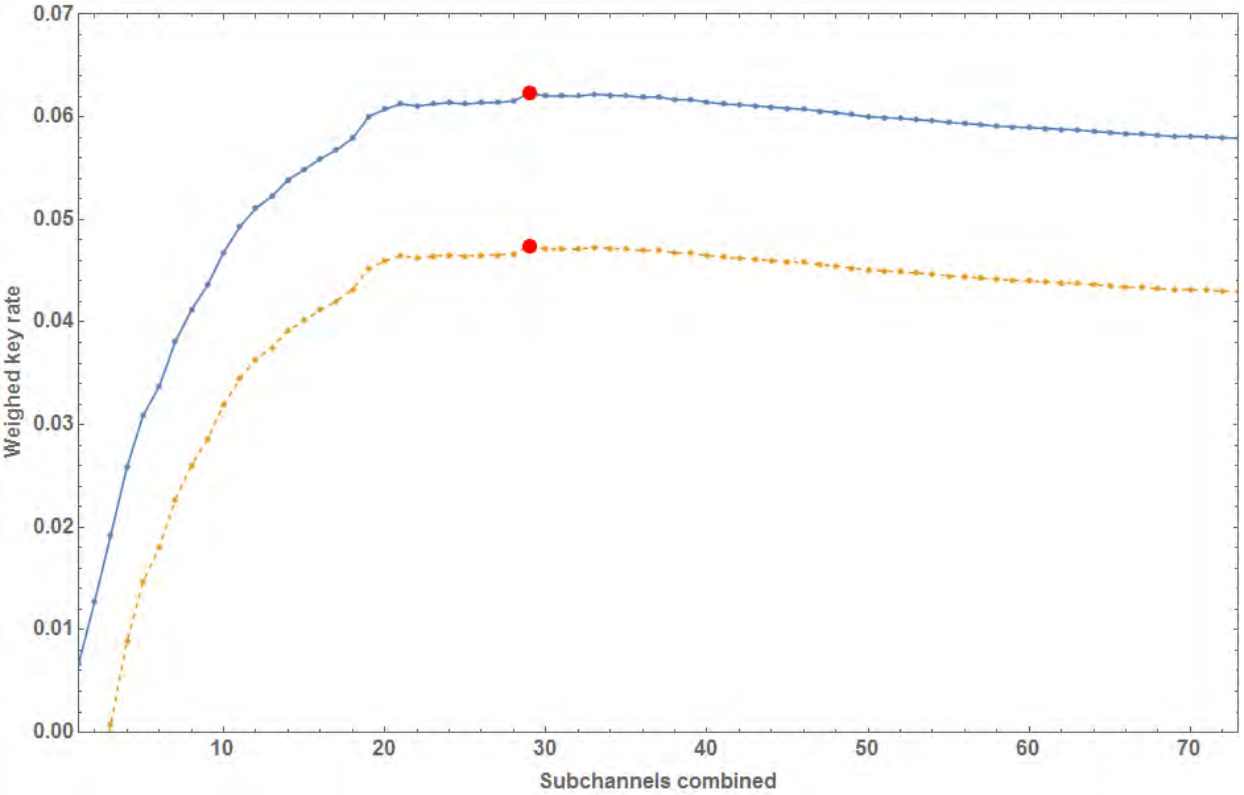
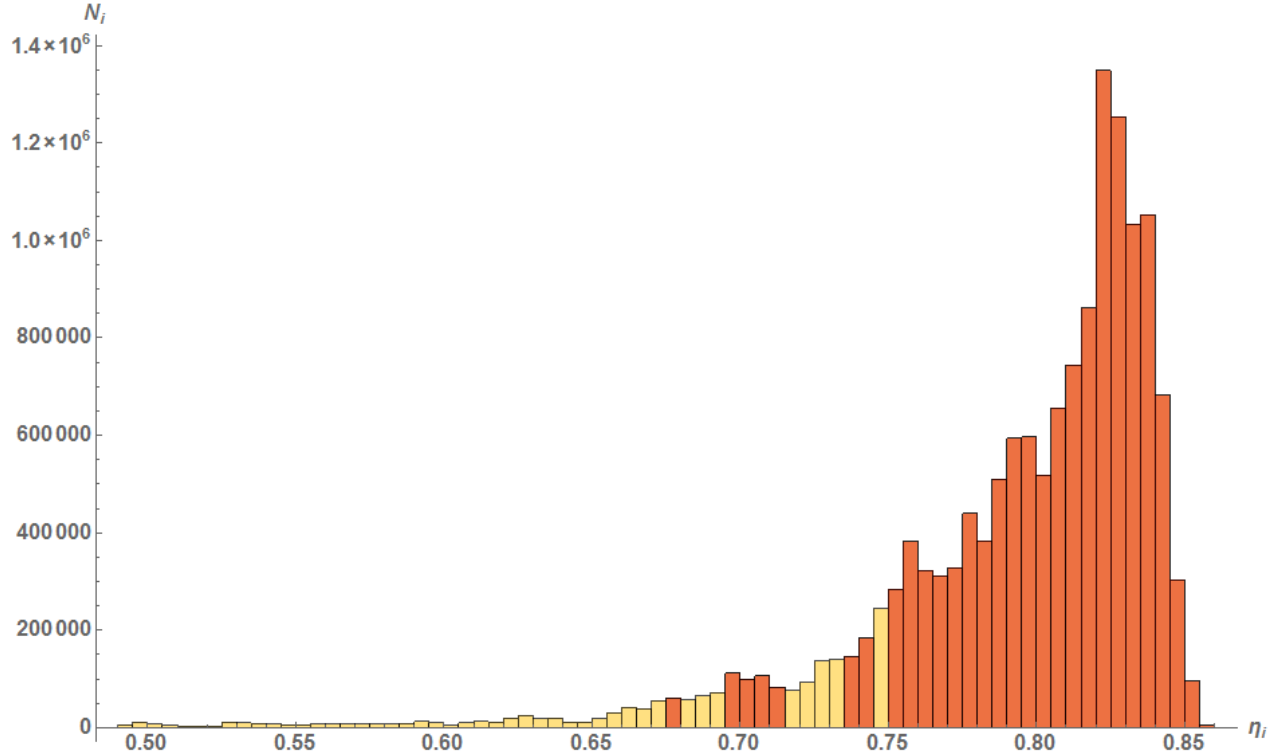
Results. Vm=1.44

Key rate for the post-selected state



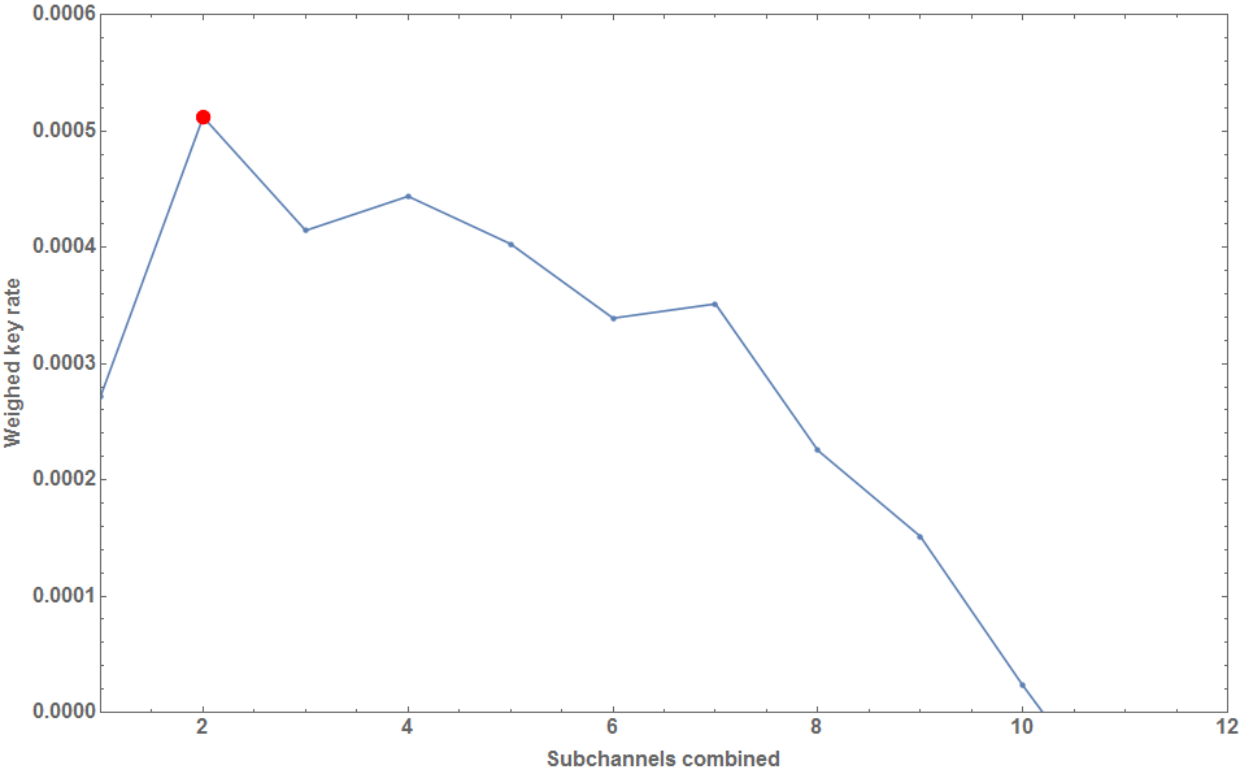
Atmospheric channel transmittance distribution



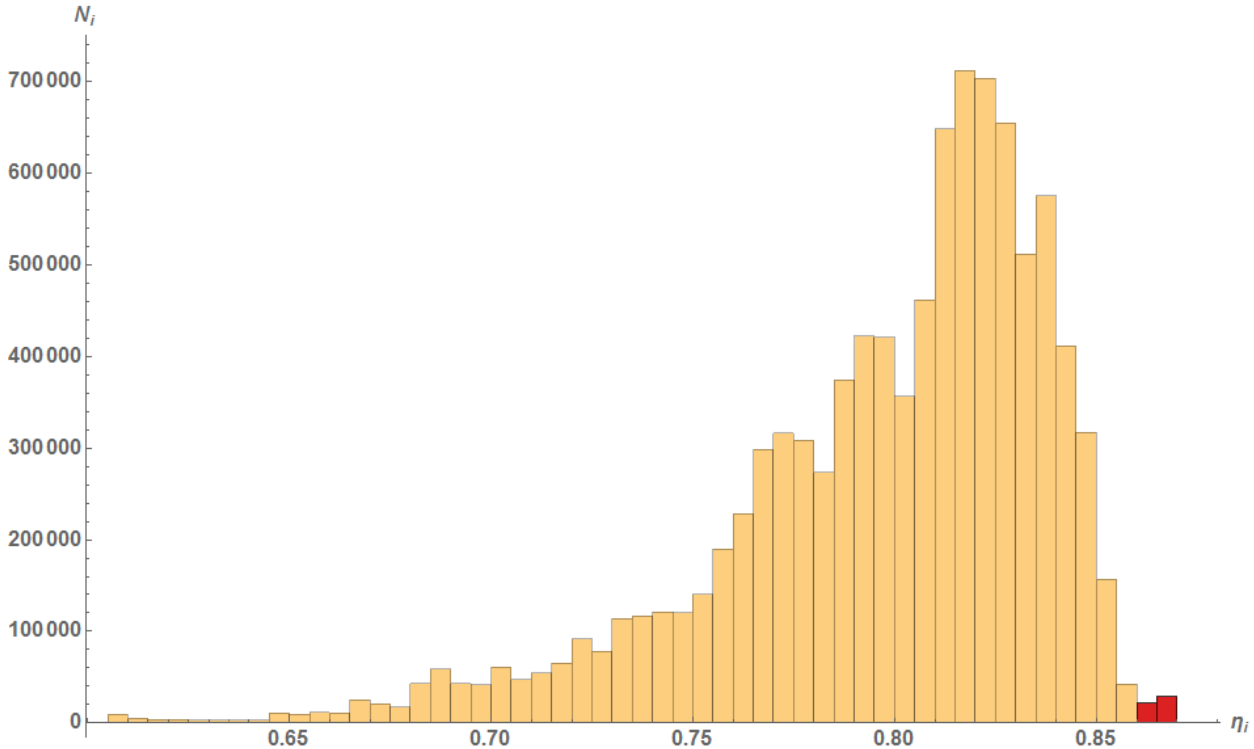
[3] Leverrier, Grosshans, Grangier, Physical Review A 81, 062343 (2010).

Results. Vm=3.6

Key rate for the post-selected state



Atmospheric channel transmittance distribution



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Conclusions

- We have demonstrated the possibility to perform continuous-variable quantum key distribution over the real atmospheric channel with the transmittance fluctuations
- Considering the optimal state modulation coherent-state protocol can overcome finite-size effects and limited post-processing efficiency
- The post-selection of sub-channels can quantitatively improve the key rate and even restore it
- The post-selection can be advantageous even for optimal modulation considering more turbulent atmospheric channels

Further steps

- Compensation of beam wandering effects in atmospheric free-space channels

  [Preparing publication]

- Side channels effects in CV QKD

  [Derkach, Usenko, Filip, Phys. Rev. A **93**, 032309 (2016)]

- Source attacks, multimode modulation effects and advantages of coherent-state protocol in CV QKD

  [Preparing publication]

Thank you!