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QUANTUM KEY DISTRIBUTION WITH CONTINUOUS VARIABLES

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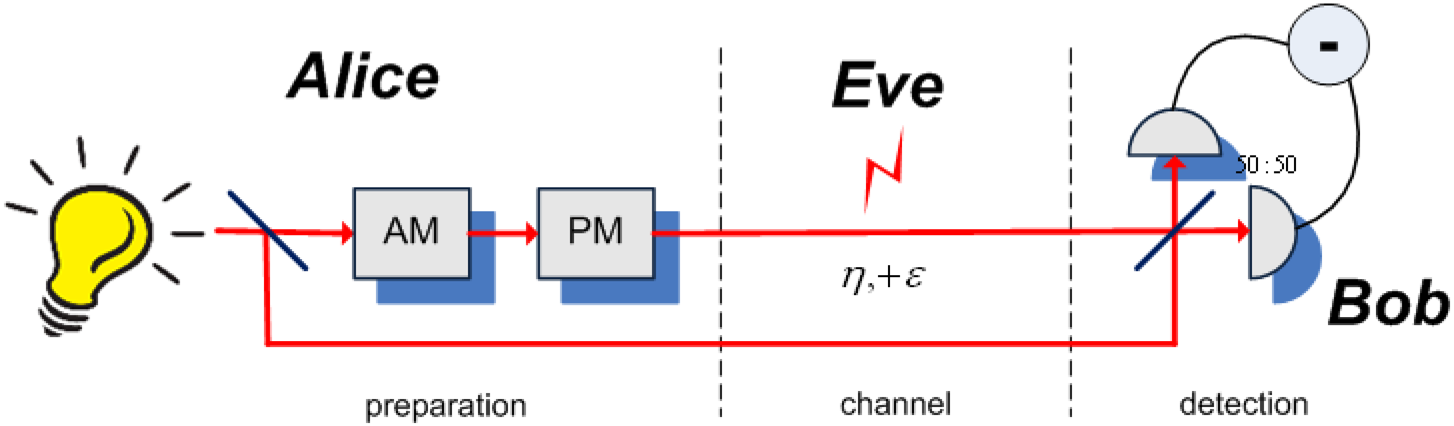
Department of Optics, Palacký University,
Olomouc, Czech Republic

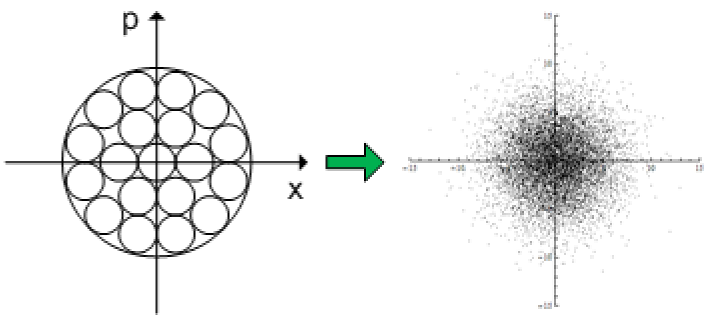
UPOL, 2012

Outline

- Security analysis
- Squeezed-state protocol implementation
- Fading channels
- Summary

CV Quantum Key Distribution



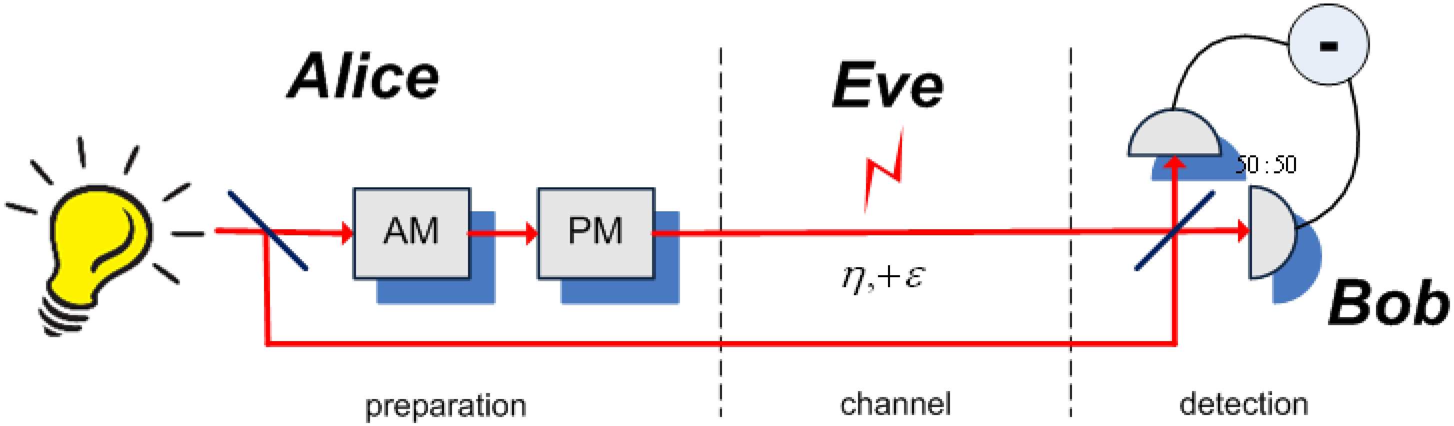


Coherent states-based protocol:

Laser source, modulation

F. Grosshans and P. Grangier. PRL 88, 057902 (2002); F. Grosshans et al., Nature 421, 238 (2003)

CV Quantum Key Distribution

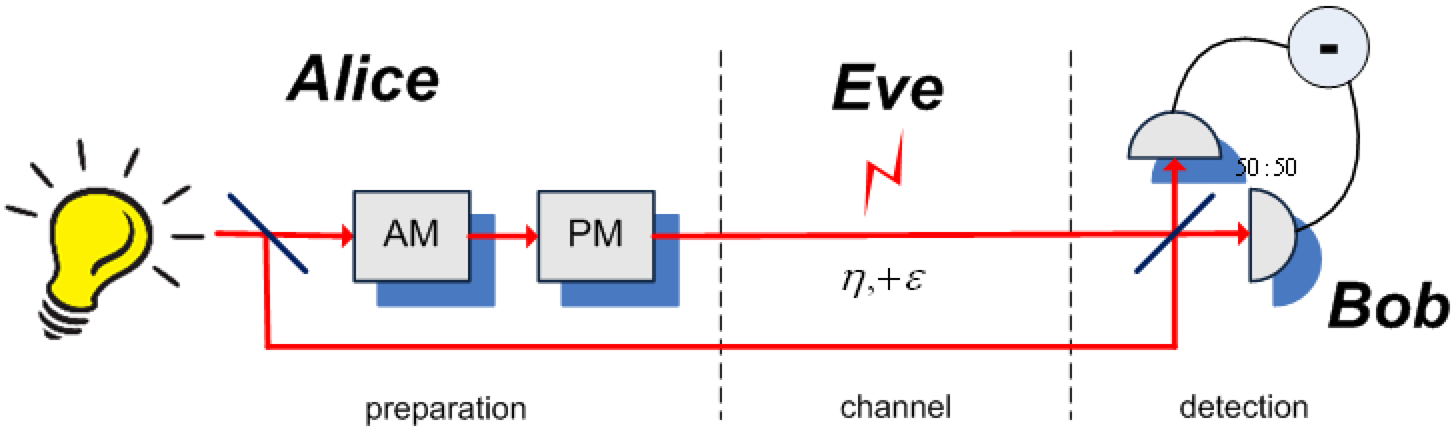


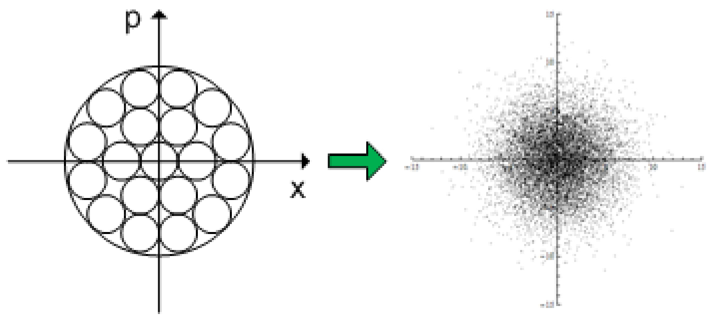
- Alice generates two Gaussian random variables {**a,b**}
- Alice prepares a coherent state, displaced by {**a,b**}
- Bob measures a quadrature, obtaining **a** or **b**
- Bases reconciliation
- Error correction, privacy amplification

Achievements: 25 km, 2 kbps
J. Lodewyck et al., PRA 76, 042305 (2007)

New: 80 km
P.Jouguet et al., arXiv:1210.6216 (2012)

CV Quantum Key Distribution





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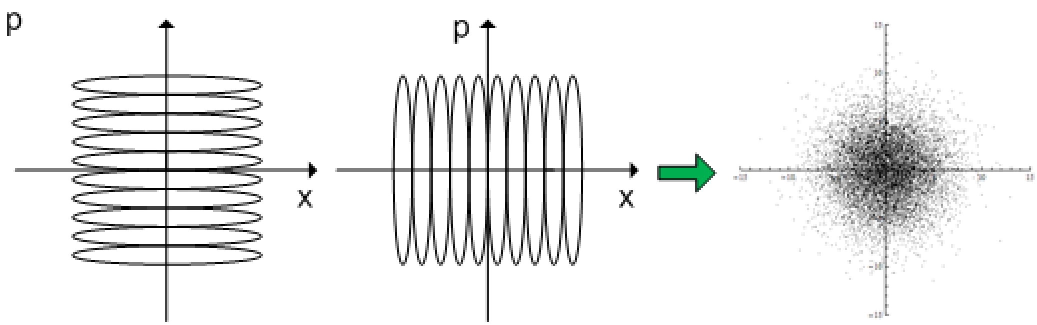
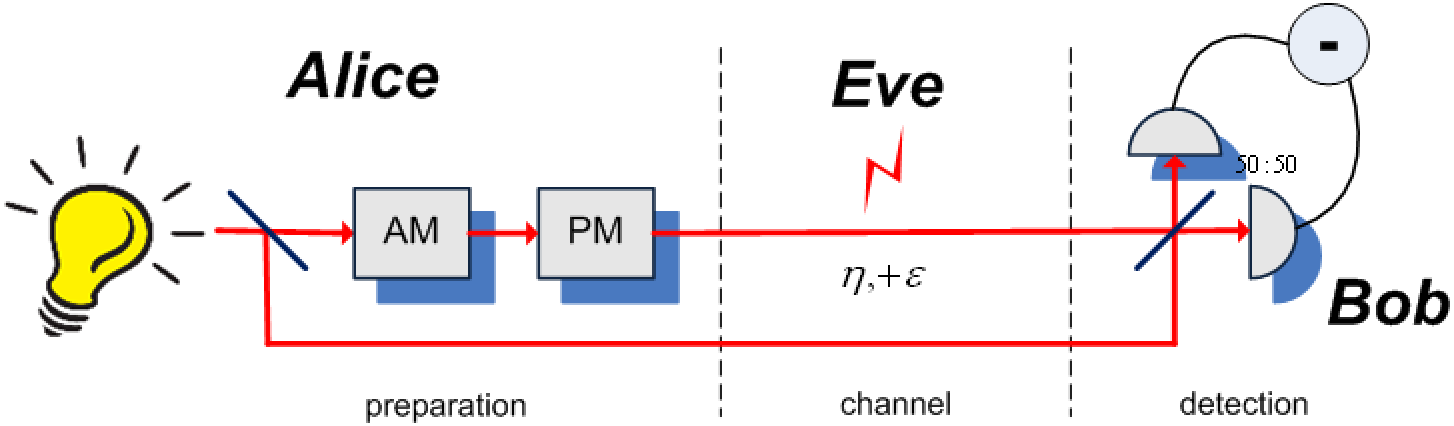
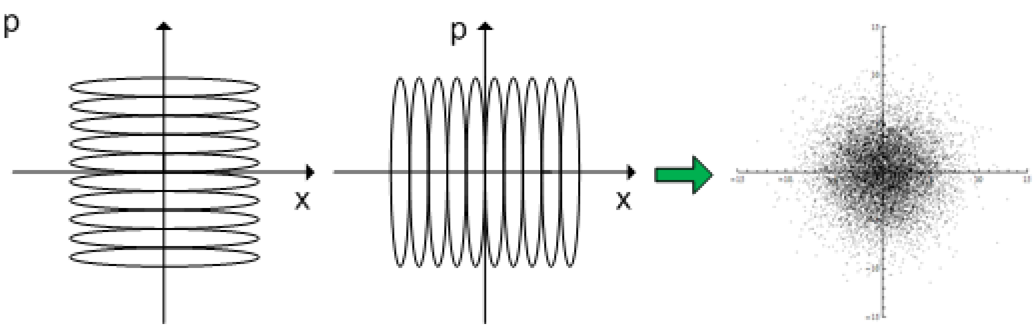


Squeezed states-based protocol:
Squeezed source, modulation
N. J. Cerf, M. Levy, and G. Van Assche, PRA 63, 052311 (2001)

CV Quantum Key Distribution

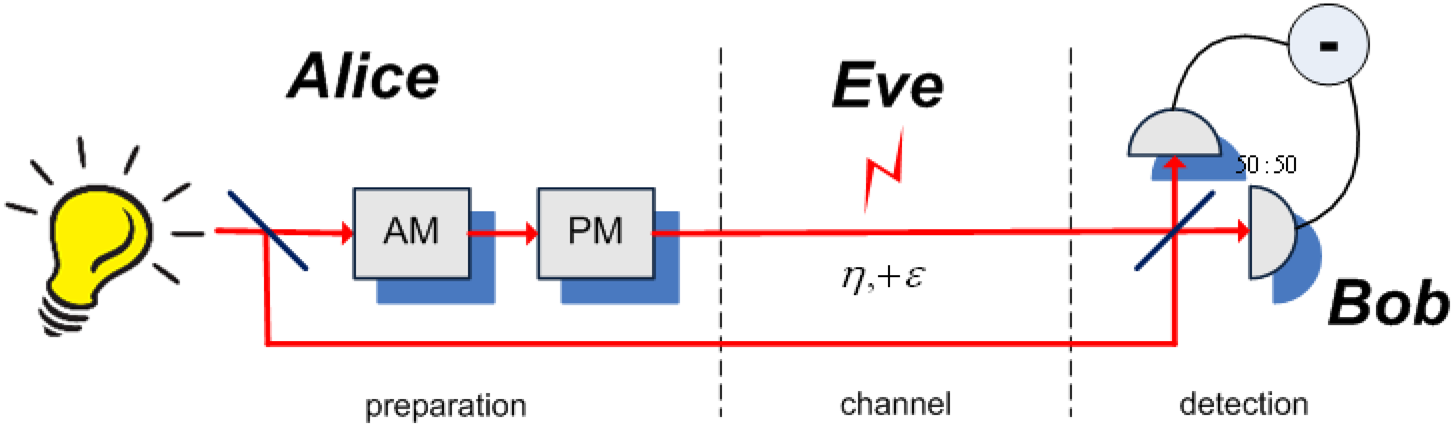


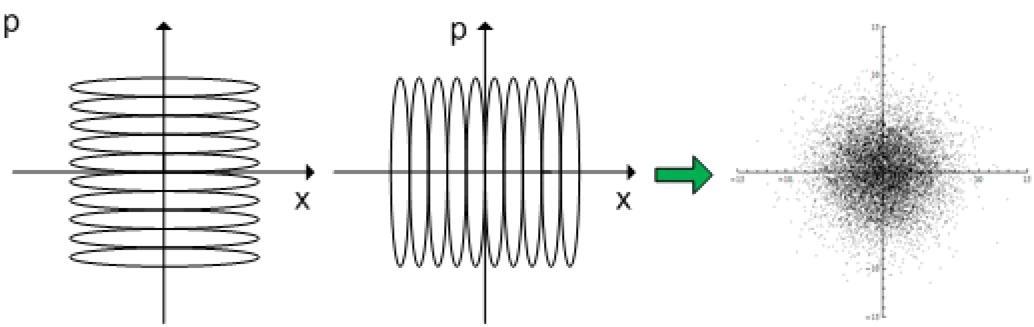


Squeezed states-based protocol:
Squeezed source, modulation
N. J. Cerf, M. Levy, and G. Van Assche, PRA 63, 052311 (2001)

- Alice generates a Gaussian random variable **a**
- Alice prepares a squeezed state, displaced by **a** in squeezed direction
- Bob measures a quadrature
- Bases reconciliation
- Error correction, privacy amplification

CV Quantum Key Distribution





Squeezed states-based protocol:
Squeezed source, modulation
N. J. Cerf, M. Levy, and G. Van Assche, PRA 63, 052311 (2001)

- Was not implemented,
- investigated for high squeezing only

Extremality of Gaussian states

Wolf-Giedke-Cirac theorem. If *f* satisfies:

1. Continuity in trace norm (if $\|\rho_{AB}^{(n)} - \rho_{AB}\|_1 \rightarrow 0$ when $n \rightarrow \infty$, then $f(\rho_{AB}^{(n)}) \rightarrow f(\rho_{AB})$
1. Invariance over local "Gaussification" unitaries $f(U_G^\dagger \otimes U_G^\dagger \, \rho_{AB}^{\otimes N} \, U_G \otimes U_G) = f(\rho_{AB}^{\otimes N})$
2. Strong sub-additivity $f(\rho_{A_{1\ldots N}B_{1\ldots N}}) \leq f(\rho_{A_1 B_1}) + \ldots + f(\rho_{A_N B_N})$

Then , for every bipartite state ρ_{AB} with covariance matrix γ_{AB} we have

$$\boxed{f(\rho_{AB}) \leq f(\rho_{AB}^G)}$$

[*M. M. Wolf, G. Giedke, and J. I. Cirac. Phys. Rev. Lett. 96, 080502 (2006)]*

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[*M. M. Wolf, G. Giedke, and J. I. Cirac. Phys. Rev. Lett. 96, 080502 (2006)]*

Consequence:

Gaussian states maximize the information leakage.
Covariance matrix description is enough to prove security

[R. Garcıa-Patron and N.J. Cerf. Phys. Rev. Lett. 97, 190503, (2006);
M. Navascus, F. Grosshans and A. Acin, Phys. Rev. Lett. 97, 190502 (2006)]

CV Quantum key distribution: security

Collective attacks: $\boxed{I = I_{AB} - \chi_{BE}}$

Holevo quantity: $\chi_{BE} = S_E - \int P(B) S_{E|B} dB$, $\boxed{\chi_{BE} = S(\rho_E) - S(\rho_{E|B})}$

(*Renner, Gisin, Kraus, Phys. Rev. A 72, 012332, 2005)*

computation: $S_E = \sum_i G\left(\frac{\lambda_i - 1}{2}\right)$, $G(x) = (x+1)\log_2(x+1) - x\log_2 x$

λ_i - symplectic eigenvalues of the covariance matrix γ_E ,

similarly for $\gamma_E^{x_B} = \gamma_E - \sigma_{BE}(X\gamma_B X)^{MP}\sigma_{BE}^T$

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In case of channel noise – purification by Eve:

$$S(\rho_E) = S(\rho_{AB}) \qquad S(\rho_{E|B}) = S(\rho_{A|B})$$

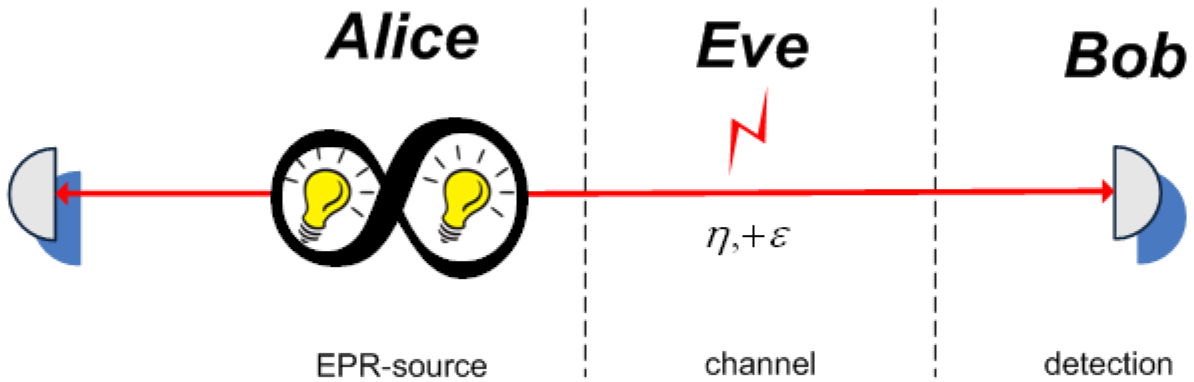
$$\gamma_A^{x_B} = \gamma_A - \sigma_{AB}(X\gamma_B X)^{MP}\sigma_{AB}^T \qquad X = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Framework: EPR-based set-up

Two-mode squeezed vacuum state:

$$|x\rangle\rangle = \sqrt{(1-x^2)}\sum_n x^n\,|n,n\rangle\rangle$$

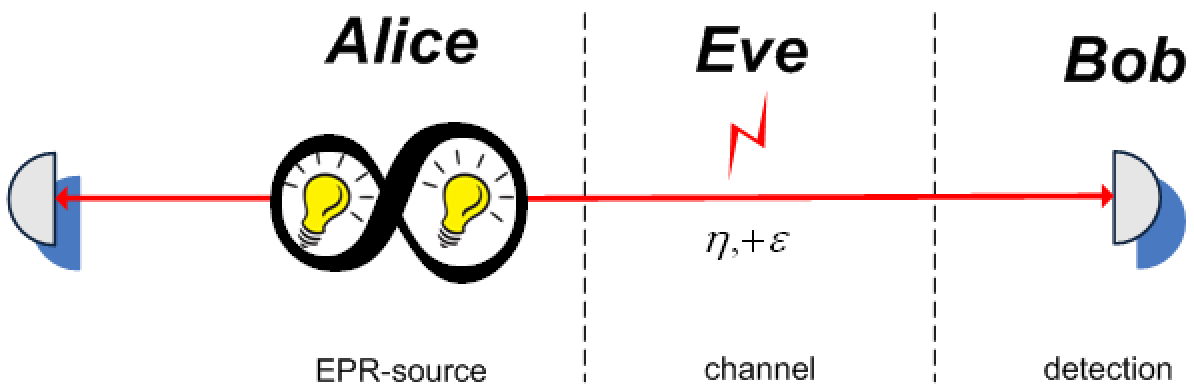
$$x \in \mathbb{C} \text{ and } 0 \leq |x| \leq 1$$



Framework: EPR-based set-up

Equivalent entanglement-based scheme:

- Homodyne at Alice = squeezed state preparation



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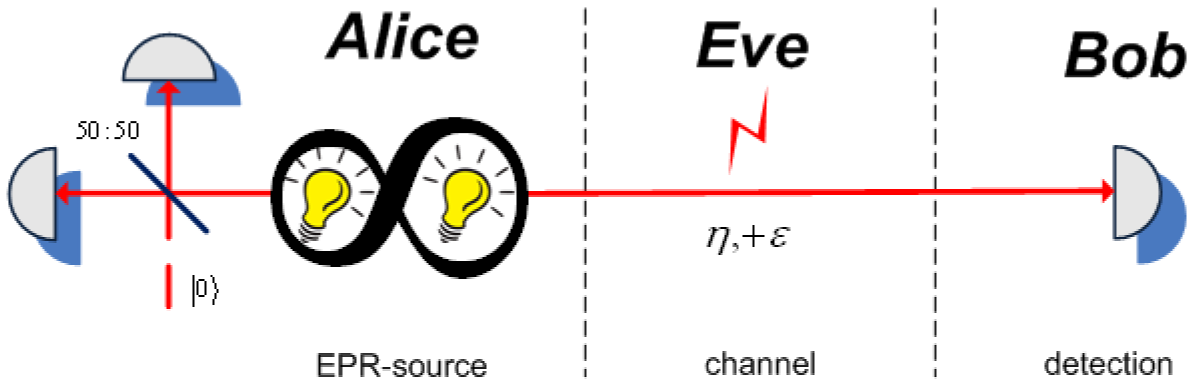

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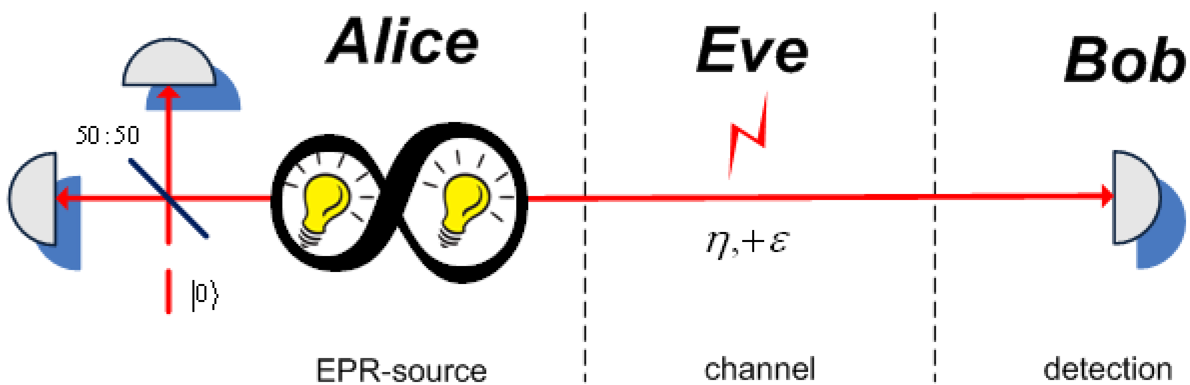
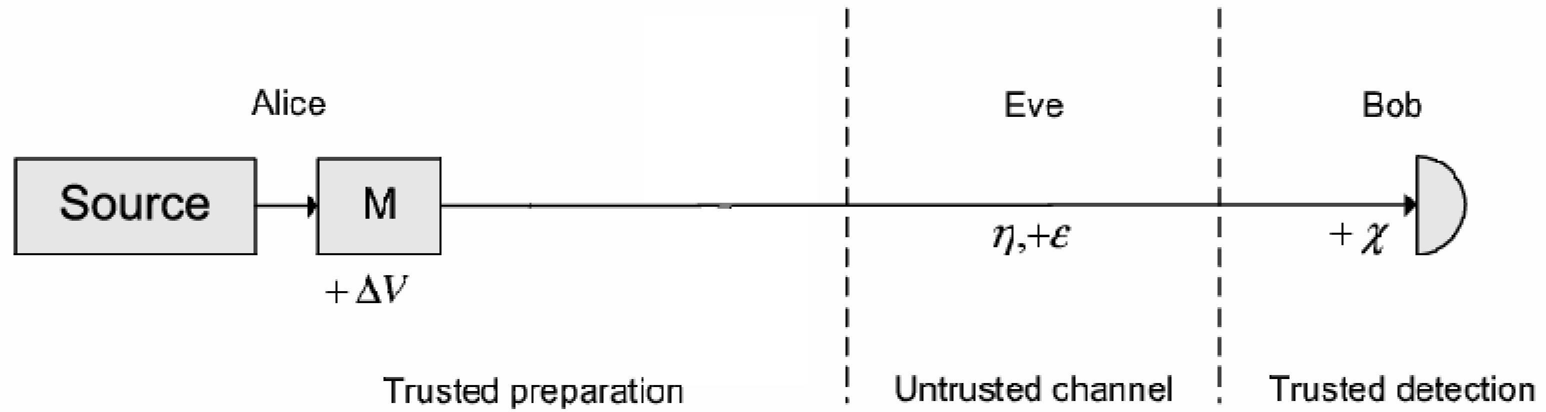


Advantages:

- Complete theoretical description;
- Scalability.

Influence of noise

<u>Distinguishing the noise types:</u> **trusted** (preparation ΔV and detection χ noise) and **untrusted** (channel noise ε)



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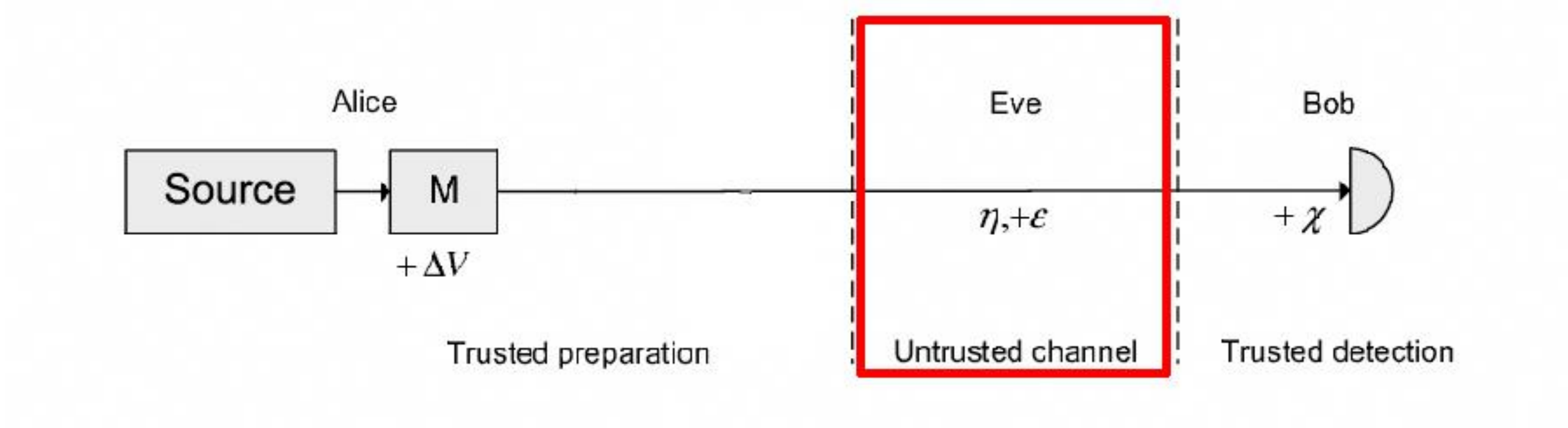
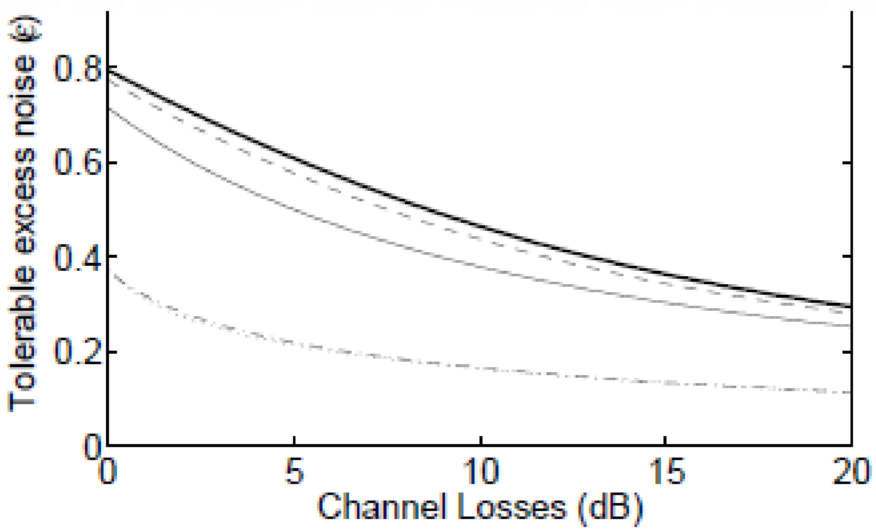


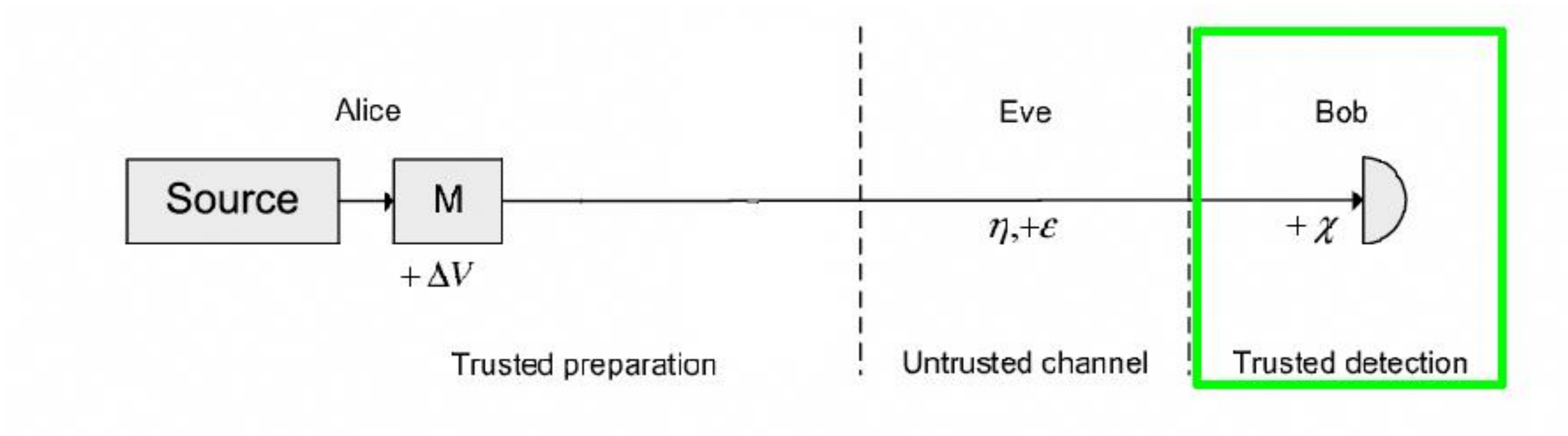


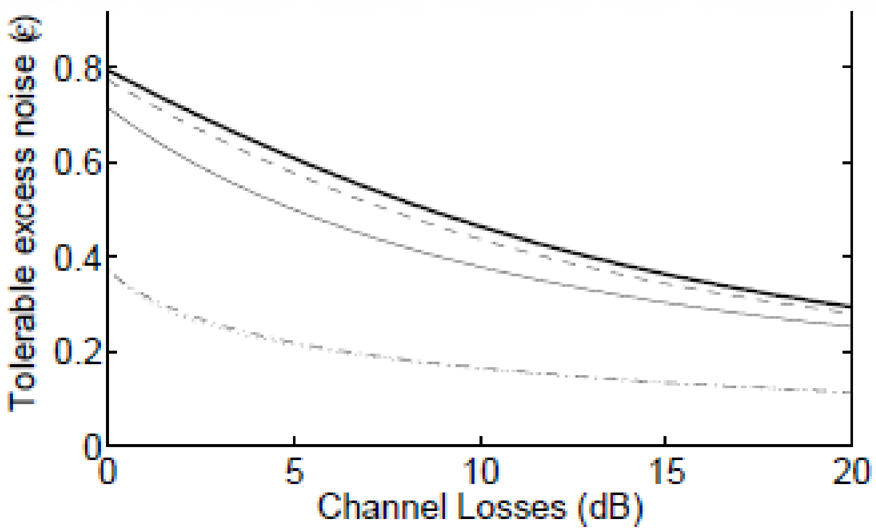
Untrusted noise limits security.

◀Typical dependence of maximum tolerable channel excess noise versus loss

Influence of noise

Distinguishing the noise types: **trusted** (preparation ΔV and detection χ noise) and **untrusted** (channel noise ε)





Trusted detection noise improves (!) security.

◀Typical dependence of maximum tolerable channel excess noise versus loss

R. Garcia-Patron, N. Cerf, PRL 102 120501 (2009)

Influence of noise

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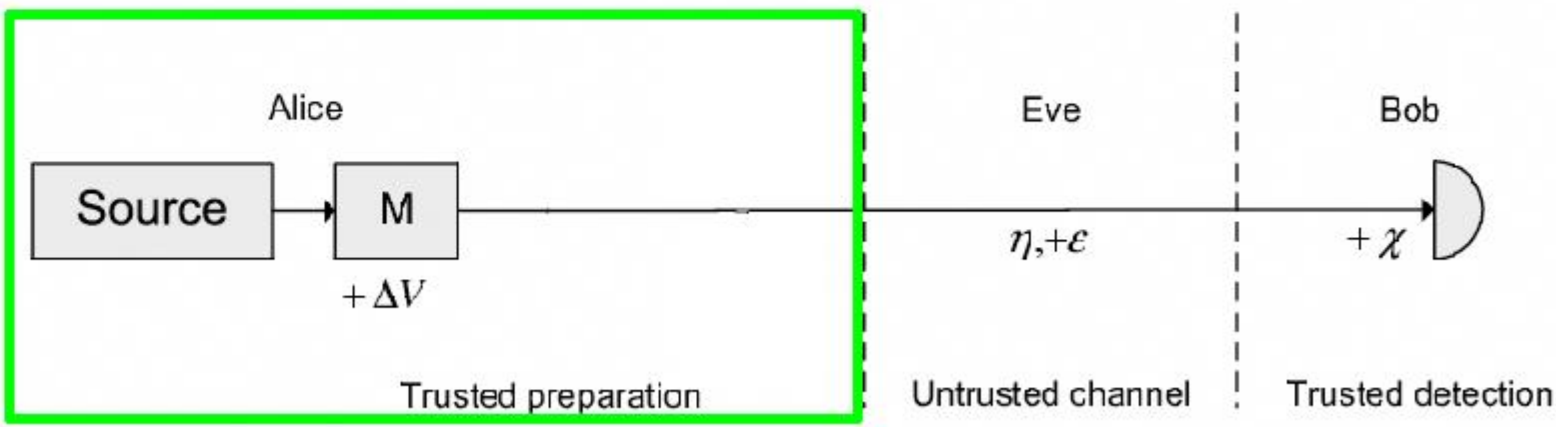
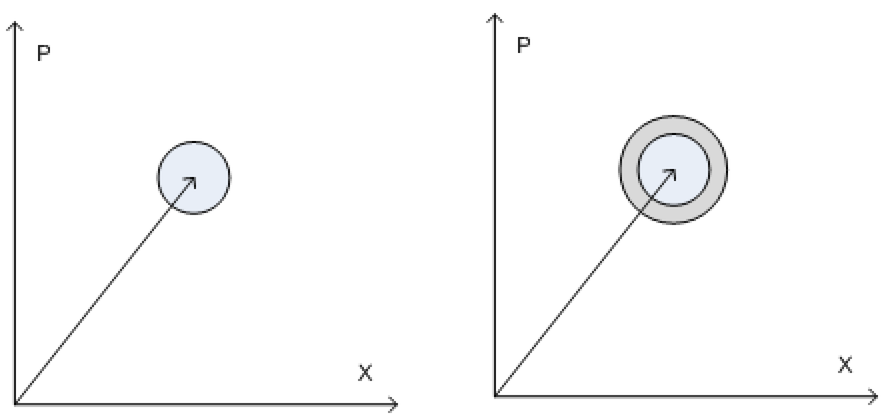


Trusted preparation noise. Coherent states: phase-insensitive excess noise



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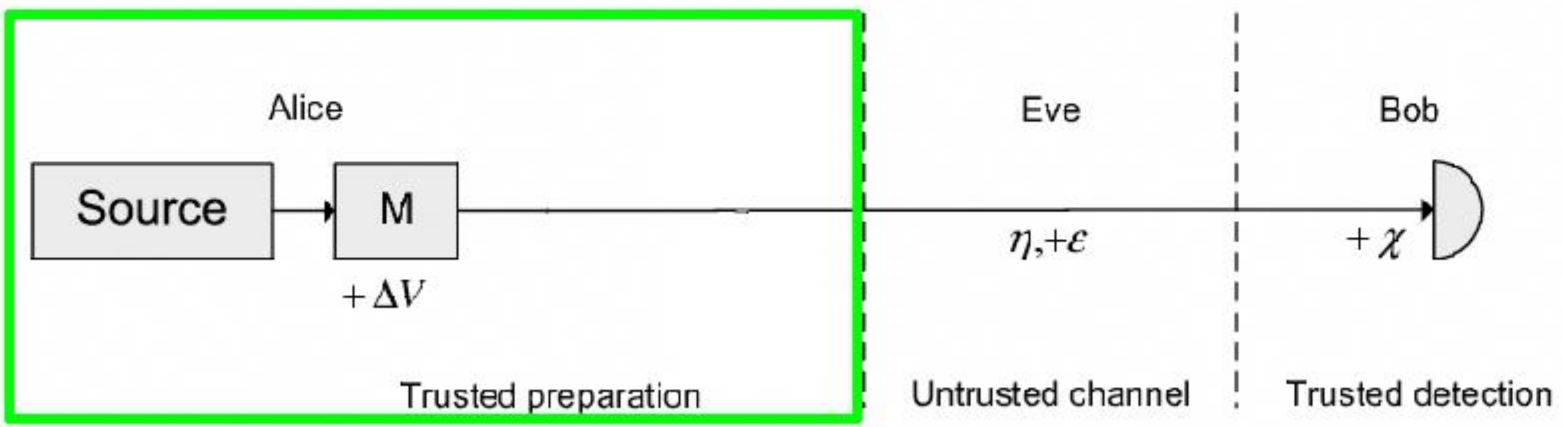


Trusted preparation noise. Coherent states: phase-insensitive excess noise

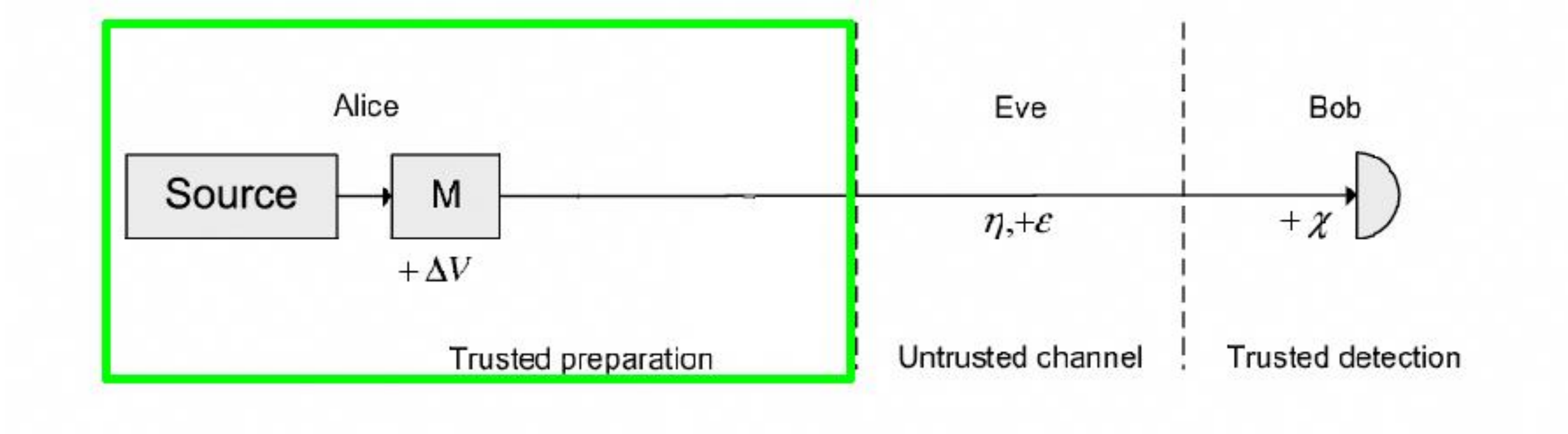
Is security breaking:

$$\boxed{\Delta V_{I,\max} = \frac{1}{1-\eta}}$$

η - channel transmittance

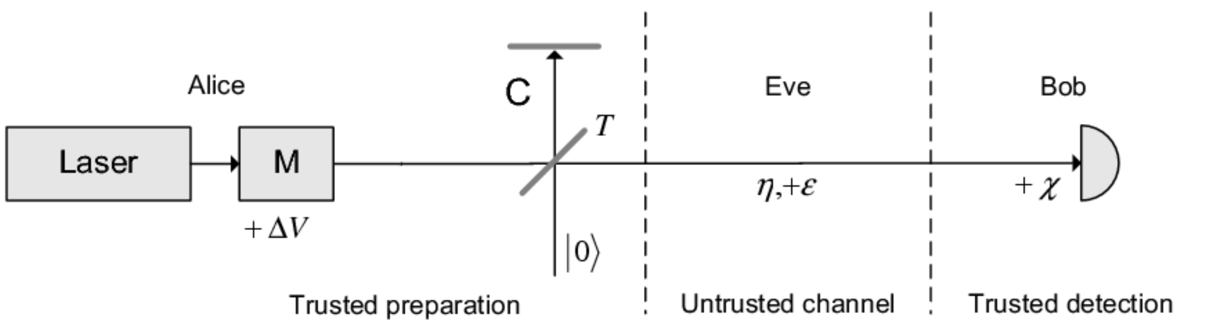
Influence of noise

Distinguishing the noise types: **trusted** (preparation ΔV and detection χ noise) and **untrusted** (channel noise ε)



Trusted preparation noise. Coherent states: phase-insensitive excess noise

Purification:



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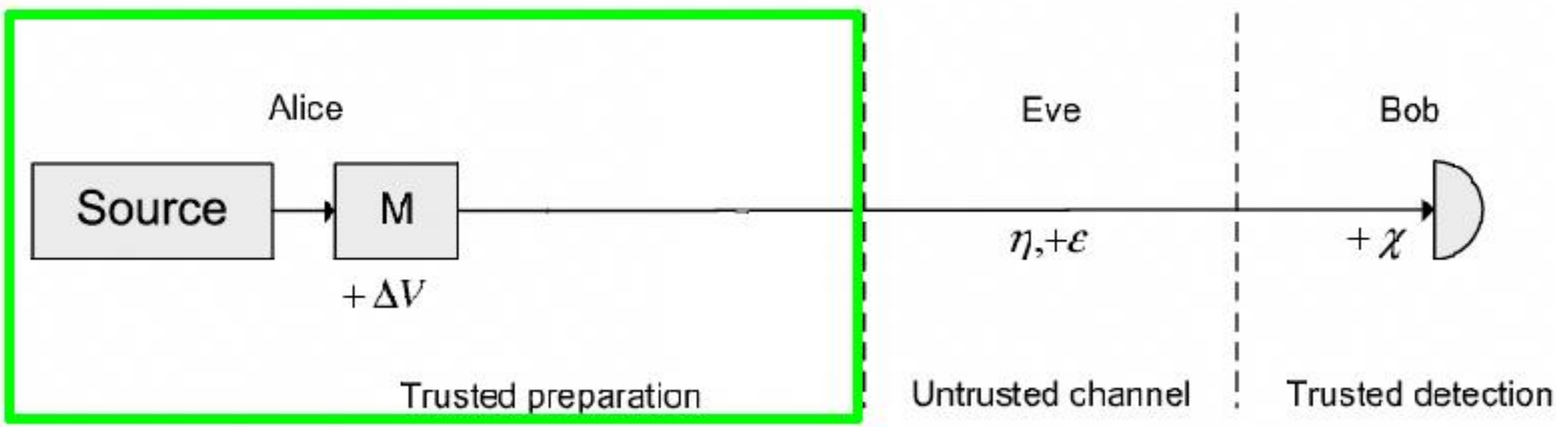


Trusted preparation noise. Coherent states: phase-insensitive excess noise

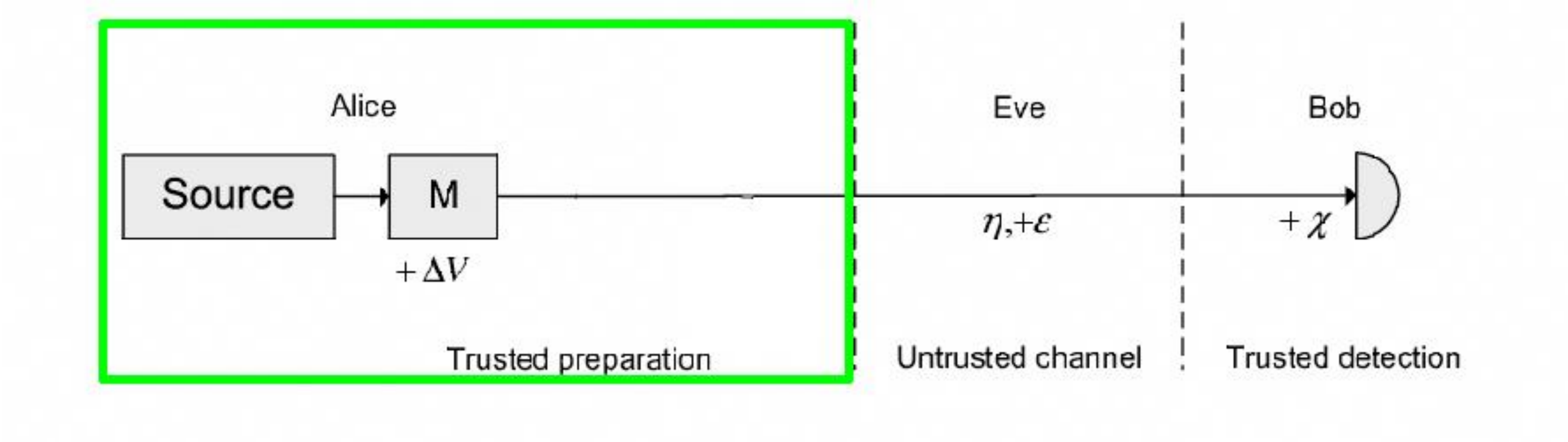
Purification restores security:

$$\Delta V_{I,max} = \frac{1}{T(1-\eta)}$$

*[V. U., R. Filip, Phys. Rev. A **81**, 022318 (2010) / arXiv:0904.1694]*

Influence of noise

Distinguishing the noise types: **trusted** (preparation ΔV and detection χ noise) and **untrusted** (channel noise ε)



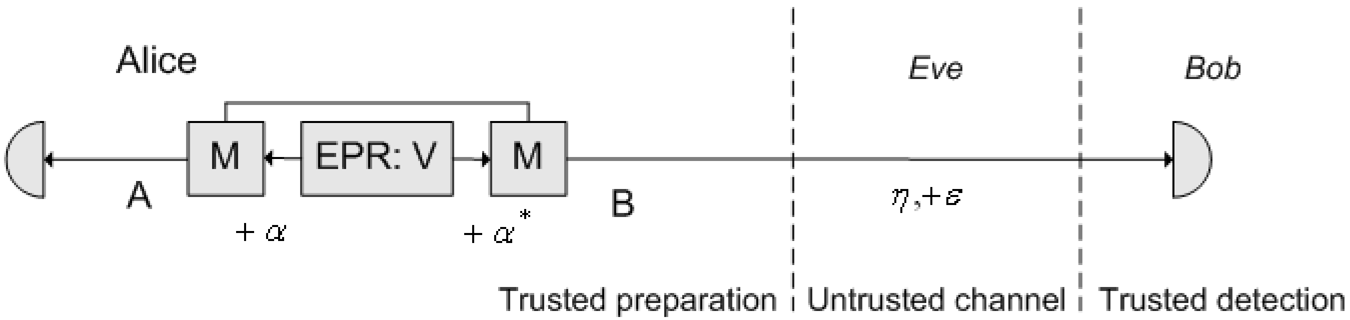
Trusted preparation noise. Coherent states: phase-insensitive excess noise

What if noise is correlated?

Additional classical correlations

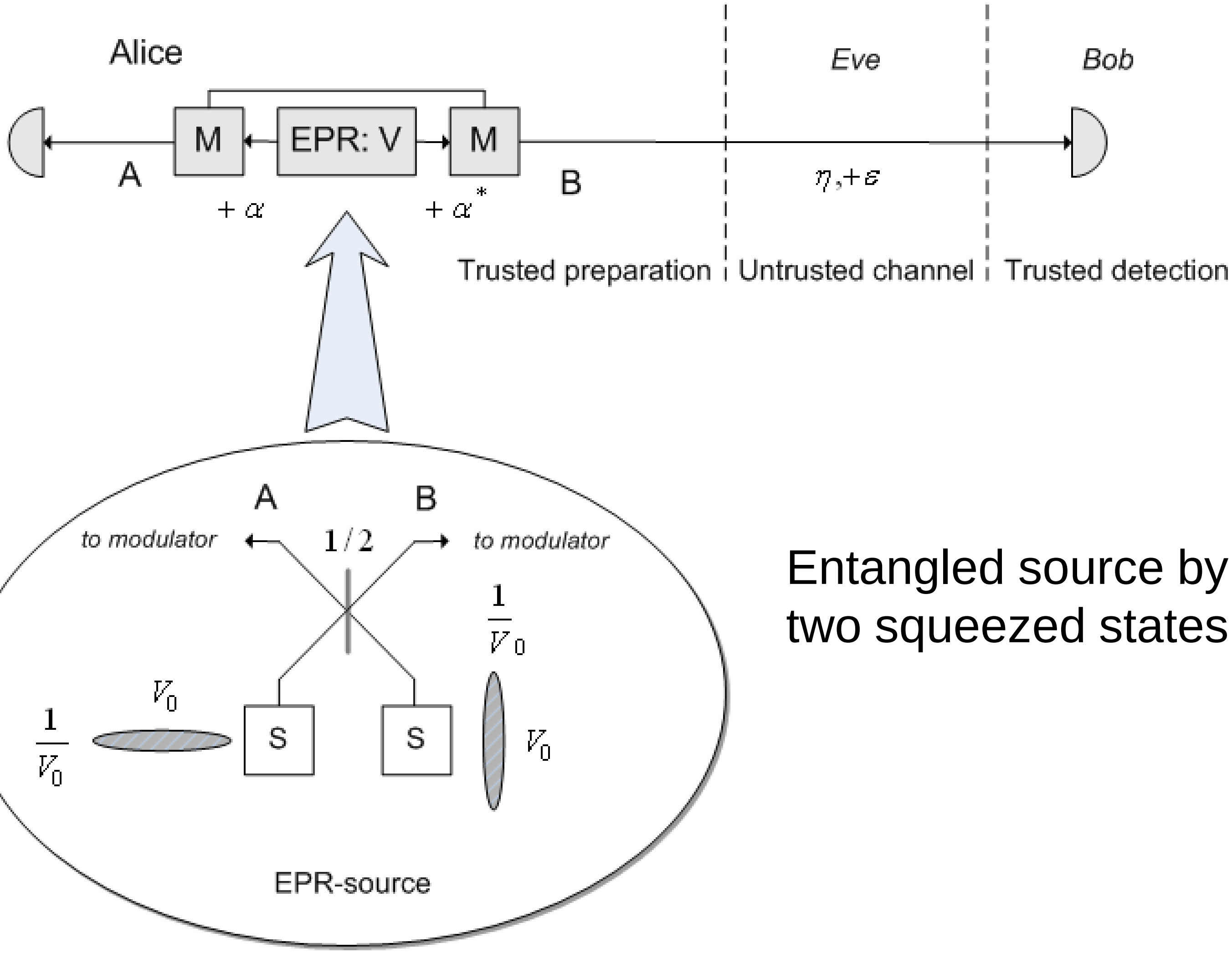
Project realized while visiting DTU, Lyngby

Additional classical correlations



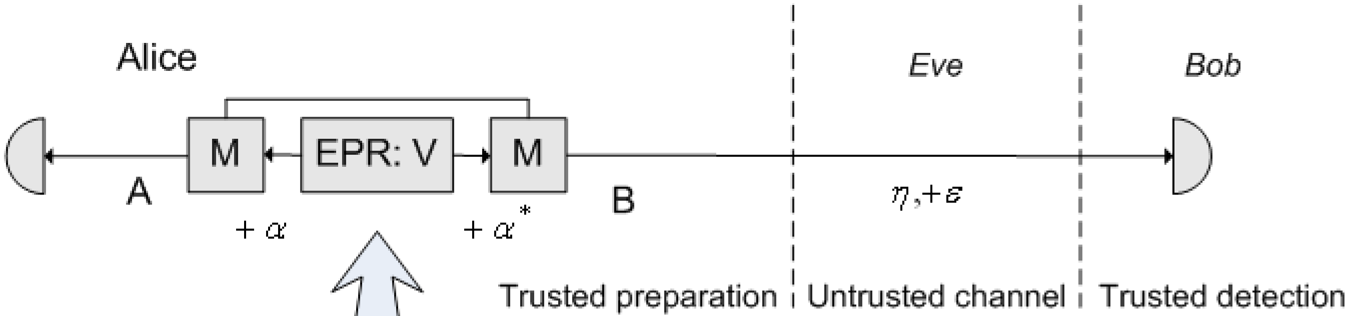
Turning noise to correlations: additional modulator

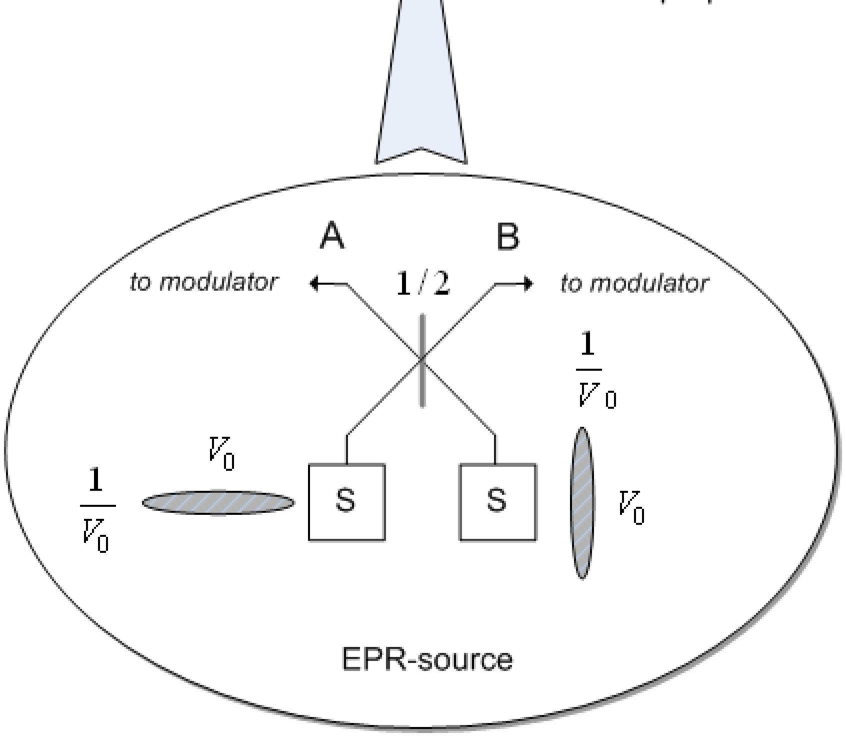
Additional classical correlations

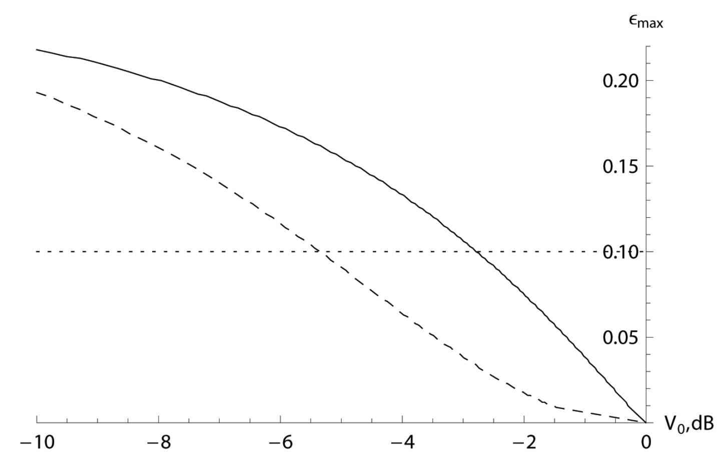


Entangled source by coupling of two squeezed states

Additional classical correlations

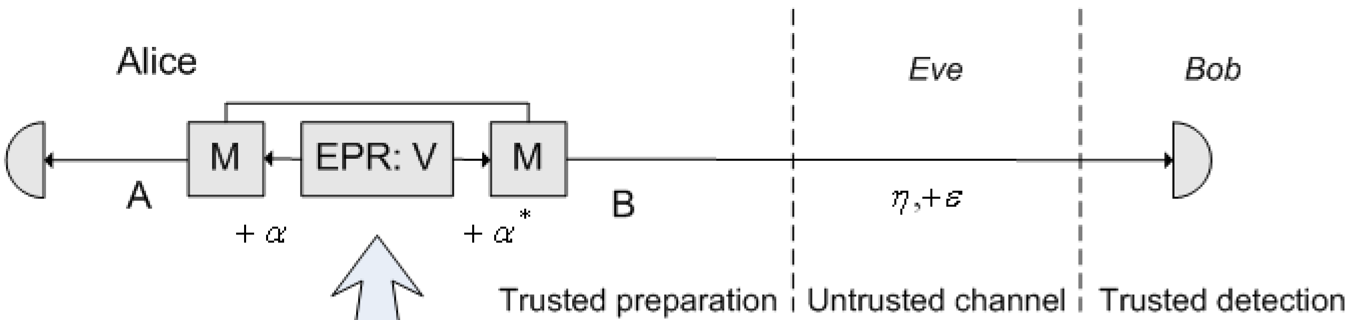


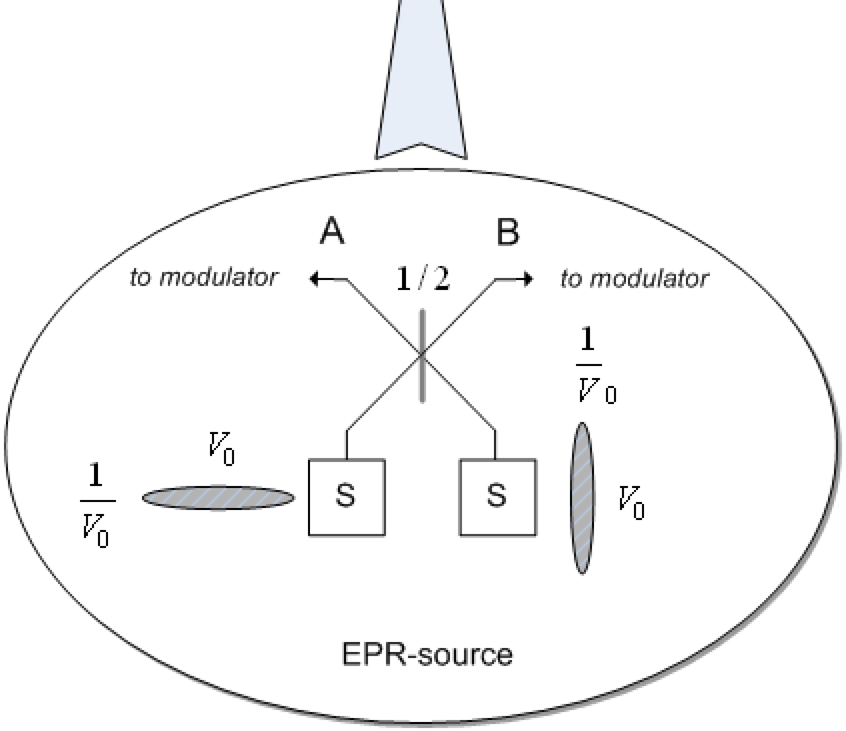


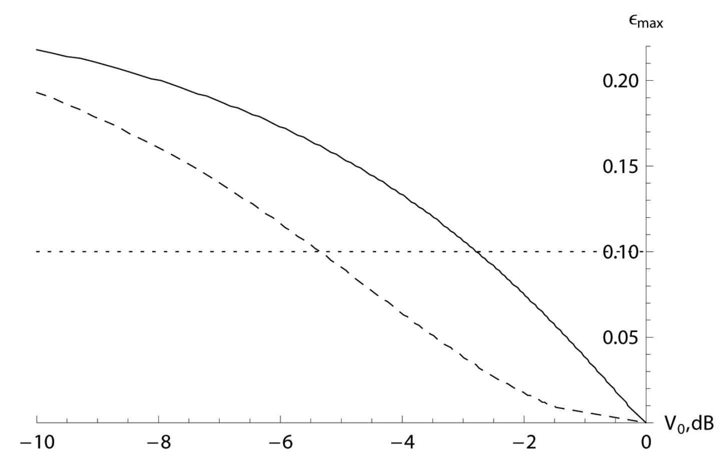


Additional modulation of squeezed states (i.e., additional classical correlations) makes scheme more robust to the channel excess noise.

Additional classical correlations

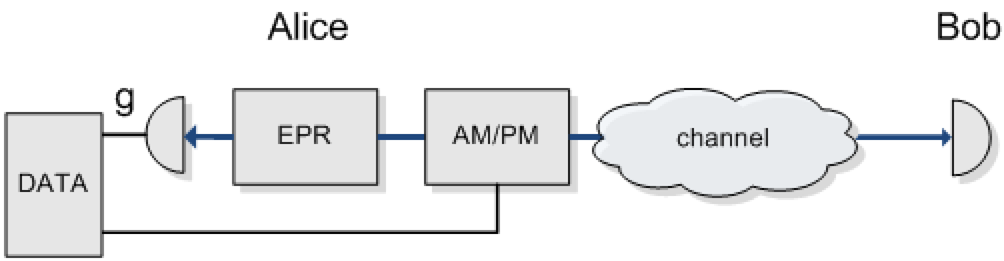






*[V. U. and R. Filip, New J. Phys., **13**, 113007, (2011) / arXiv:1111.2311]*

Super-optimized protocol



Alice applies gain factor to her data:

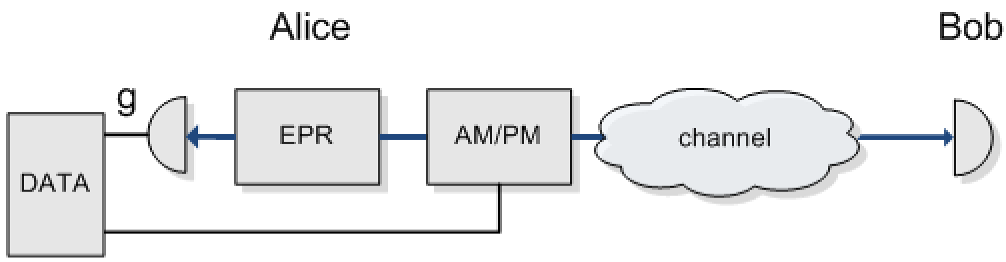
$$x'_A = g x_A + x_M$$

Covariance and correlation matrices:

$$\gamma_A = \left[g^2 \frac{1}{2}\left(\frac{1+V_0^2}{V_0} + \Delta V_0\right) + \Delta V\right]\mathbb{I}$$

$$\sigma_{AB} = \left[g \frac{1}{2}\left(\frac{1-V_0^2}{V_0} + \Delta V_0\right) + \Delta V\right]\sigma_z$$

Super-optimized protocol



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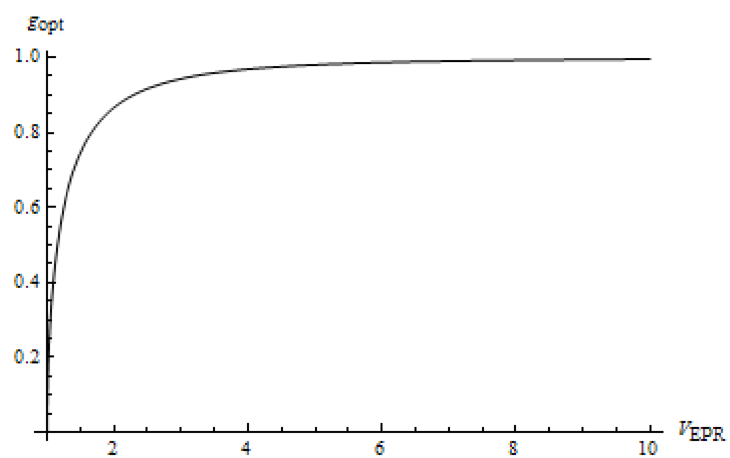
Optimal gain:

$$g_{opt} = \frac{\sqrt{V_{EPR}{}^2 - 1}}{V_{EPR}} \equiv \frac{C_{EPR}}{V_{EPR}}$$



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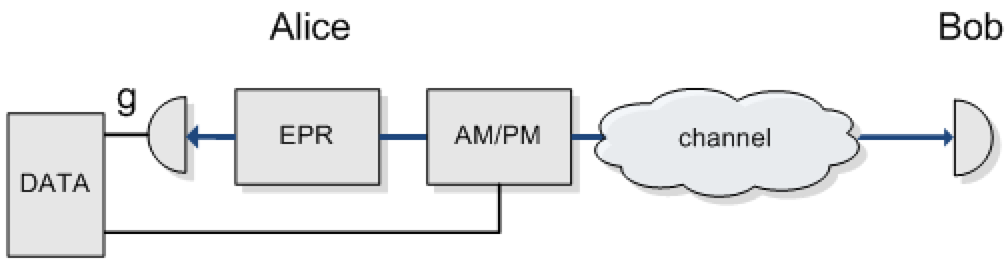
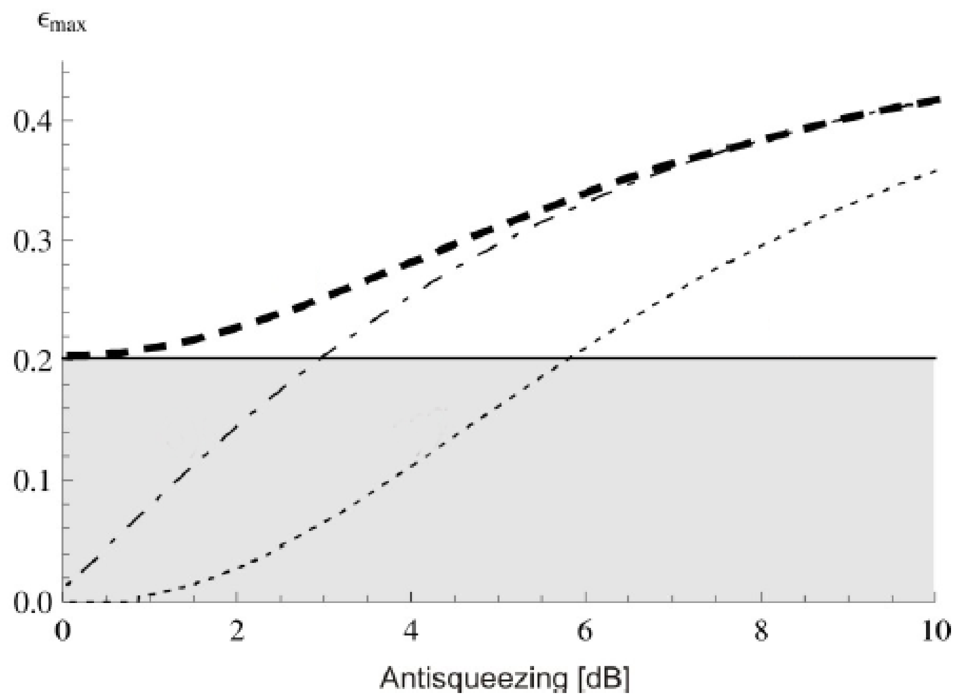
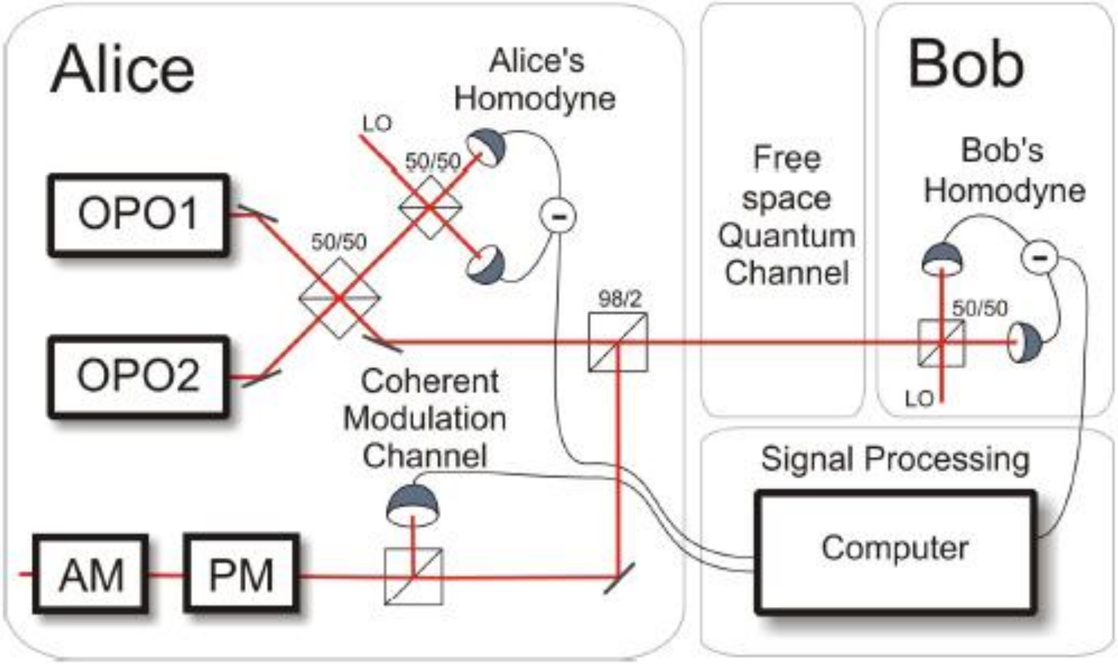




The protocol overcomes the coherent-state protocol upon any degree of squeezing

Proof-of-principle

Performed at the Denmark Technical University, Lyngby
(NLQO group, Prof. Ulrik Andersen)



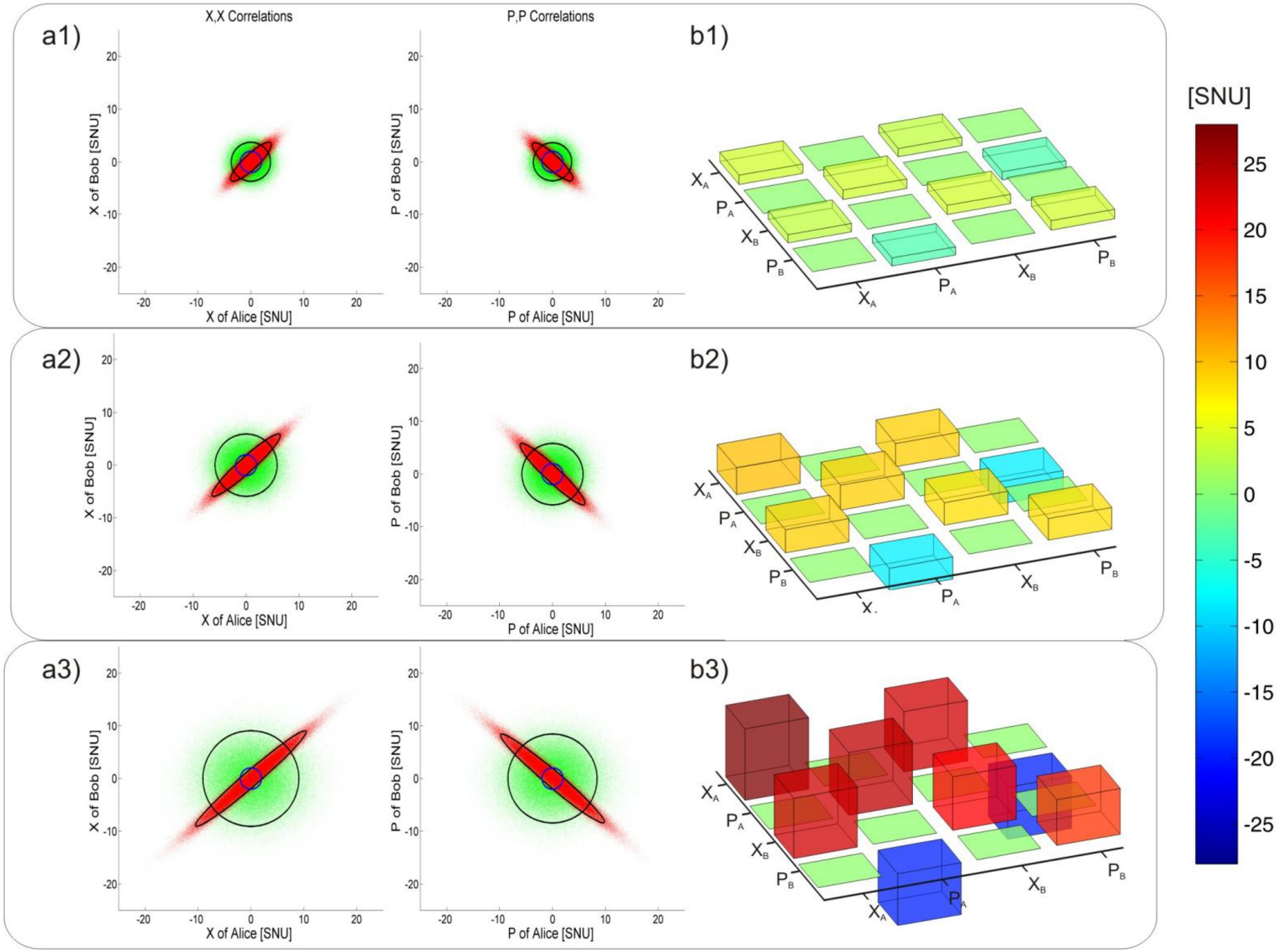
Sketch of the set-up

Proof-of-principle

No modulation

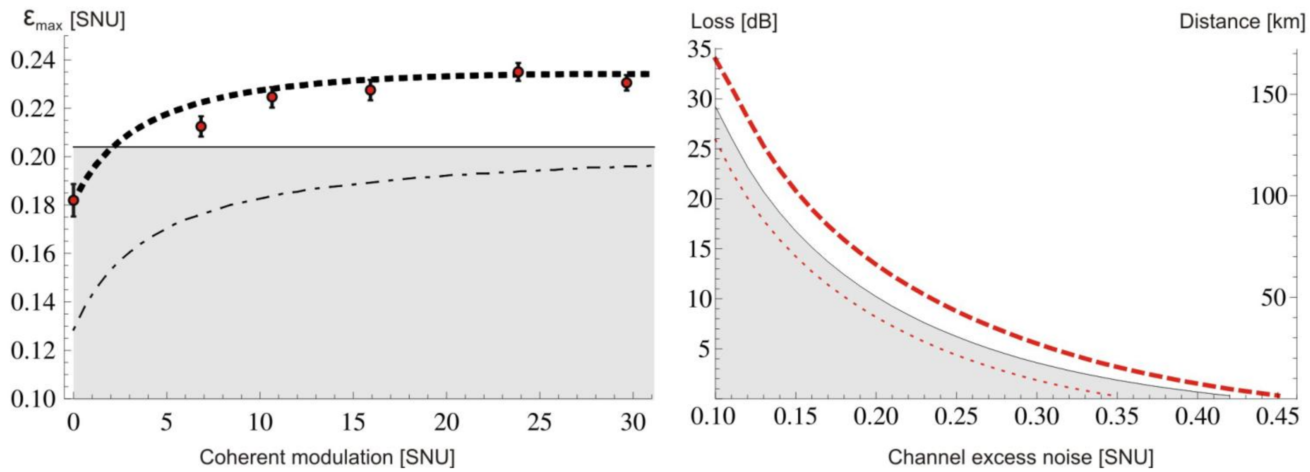
3.6 SNU

23.8 SNU



Raw quadrature data (left); covariance matrices (right)

Proof-of-principle



Untrusted channel simulation results: the squeezed-state protocol with the obtained states outperforms any coherent-state protocol (in tolerable noise and distance)

L. Madsen, V. U., M. Lassen, R. Filip, U. Andersen, Nature Communications 3, 1083 (2012)

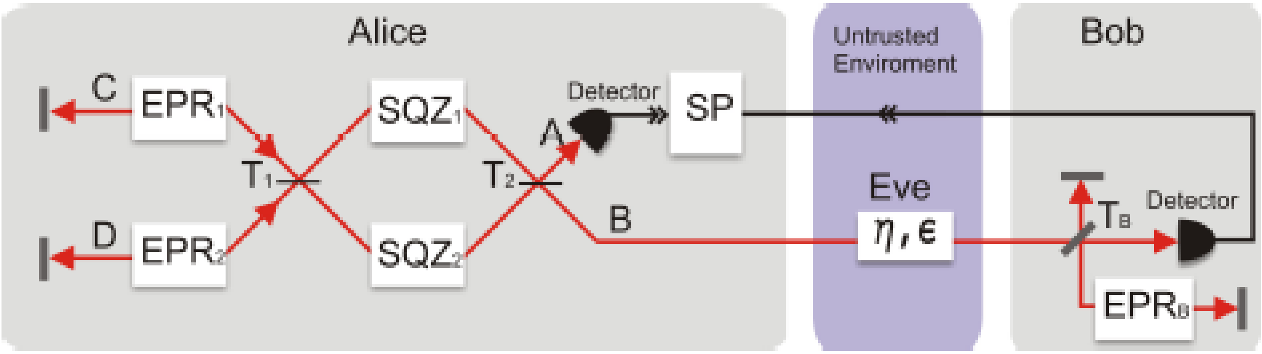
Proof-of-principle

Arbitrary (experimentally obtained) state purification using Bloch-Messiah reduction (*Braunstein, PRA 71, 055801, 2005*)

Experimental covariance matrix:

$$\gamma_{AB} = \begin{pmatrix} V_A^x & & & \\ 0 & V_A^p & & \\ C_{AB}^x & 0 & V_B^x & \\ 0 & C_{AB}^p & 0 & V_B^p \end{pmatrix}$$

Equivalent scheme:



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Equivalent matrix:

$$\gamma'_{ABCD} = \begin{pmatrix} V_A^x & & & & & & & \\ 0 & V_A^p & & & & & & \\ C_{AB}^x & 0 & V_B^x & & & & & \\ 0 & C_{AB}^p & 0 & V_B^p & & & & \\ C_{AC}^x & 0 & C_{BC}^x & 0 & V_C & & & \\ 0 & C_{AC}^p & 0 & C_{BC}^p & 0 & V_C & & \\ C_{AD}^x & 0 & C_{BD}^x & 0 & C_{CD}^x & 0 & V_D & \\ 0 & C_{AD}^p & 0 & C_{BD}^p & 0 & C_{CD}^p & 0 & V_D \end{pmatrix}$$

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$$\gamma_{AB} = \begin{pmatrix} V_A^x & & & \\ 0 & V_A^p & & \\ C_{AB}^x & 0 & V_B^x & \\ 0 & C_{AB}^p & 0 & V_B^p \end{pmatrix}$$

Equivalent matrix:

$$\begin{aligned}
V_A^x &= -2at_1t_2 + \frac{T_2(V_2+d)}{s_1^2} + \frac{(1-T_2)(V_1-d)}{s_2^2}\\
V_B^x &= 2at_1t_2 + \frac{T_2(V_1-d)}{s_2^2} + \frac{(1-T_2)(V_2+d)}{s_1^2}\\
V_A^p &= -2bt_1t_2 + T_2s_1^2(V_2+d) + (1-T_2)s_2^2(V_1-d)\\
V_B^p &= 2bt_1t_2 + T_2s_2^2(V_1-d) + (1-T_2)s_1^2(V_2+d)\\
C_{AB}^x &= at_1(1-2T_2) + t_2\left(\frac{V_1-d}{s_2^2} - \frac{V_2+d}{s_1^2}\right)\\
C_{AB}^p &= bt_1(1-2T_2) + t_2\left(s_2^2(V_1-d) - s_1^2(V_2+d)\right)
\end{aligned}$$

with

$$s_{1(2)} = \exp r_{1(2)}; t_{1(2)} = \sqrt{T_{1(2)}(1-T_{1(2)})}; a = (V_1-V_2)/(s_1s_2); b = (V_1-V_2)s_1s_2,$$
$$d = T_1(V_1-V_2).$$

Bits of knowledge

- One should check cross-correlations in covariance matrix
- Optimal gain is independent on channel parameters
- One can effectively purify any two-mode Gaussian state
- Improper mode matching causes preparation noise

Environment

- Attenuating channels (fiber-optical links)
- Channels with the excess noise (fiber links+noise)
- Fluctuating channels (atmospheric links)

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The task

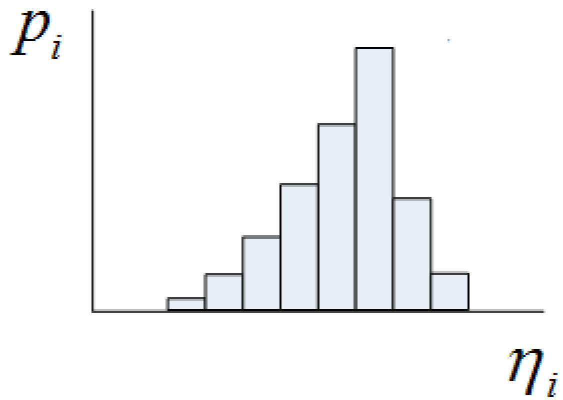
We investigate the effect of **fluctuating channels** on the **entanglement** and **security** of the **Gaussian states** of light.

CV QKD over fading channels

Project realized while visiting MPI, Erlangen
group of prof. Gerd Leuchs

Fading channels

Described by the distributions of transmittance values $\{\eta_i\}$
and respective probabilities $\{p_i\}$



Fading is typically observed in atmospheric channels, where it is caused by the turbulence effects.

Fading channels

Initial two-mode covariance matrix:

$$\gamma_{AB}^{0} = \begin{pmatrix} \gamma_A & \sigma_{AB} \\ \sigma_{AB} & \gamma_B \end{pmatrix}$$

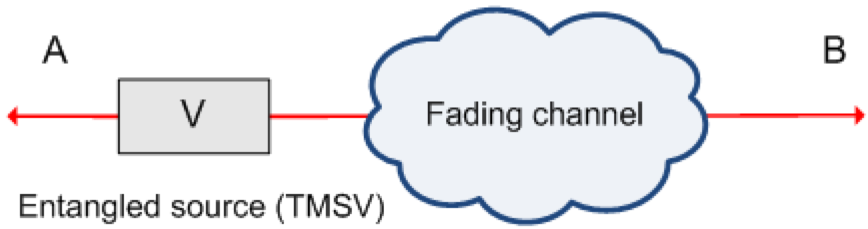
Effect of an *i*-th channel:

$$\gamma_{AB}^{i} = \begin{pmatrix} \gamma_A & \sqrt{\eta_i}\sigma_{AB} \\ \sqrt{\eta_i}\sigma_{AB} & \eta_i\gamma_B + [1-\eta_i]\mathbb{I} \end{pmatrix}$$

Effect of the fading channel:

$$\gamma_{AB} = \begin{pmatrix} \gamma_A & \langle\sqrt{\eta}\rangle\sigma_{AB} \\ \langle\sqrt{\eta}\rangle\sigma_{AB} & \langle\eta\rangle\gamma_B + [1-\langle\eta\rangle]\mathbb{I} \end{pmatrix}$$

Fading channels: effect on entanglement



Initial two-mode squeezed-vacuum state:

$$\gamma_{AB} = \begin{pmatrix} V\mathbb{I} & \sqrt{V^2-1}\sigma_z \\ \sqrt{V^2-1}\sigma_z & V\mathbb{I} \end{pmatrix}$$

After a fading channel:

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

Is equivalent to a fixed channel with variance-dependent excess noise:

$$\boxed{\gamma'_{AB} = \begin{pmatrix} V\mathbb{I} & \langle\sqrt{\eta}\rangle\sqrt{V^2-1}\sigma_z \\ \langle\sqrt{\eta}\rangle\sqrt{V^2-1}\sigma_z & \langle\sqrt{\eta}\rangle^2(V-1) + \epsilon_f + \chi + 1)\mathbb{I} \end{pmatrix}}$$

where $\epsilon_f = Var(\sqrt{\eta})(V-1)$ and $Var(\sqrt{\eta}) = \langle\eta\rangle - \langle\sqrt{\eta}\rangle^2$

Fading channels: effect on entanglement

Purity (Gaussian mixedness): $p(\gamma_{AB}) = 1/\sqrt{Det\gamma_{AB}}$

After a fading channel:

$$p(\gamma'_{AB}) = \frac{1}{Var(\sqrt{\eta})V(V-1) + V(1-\langle\sqrt{\eta}\rangle^2) + \langle\sqrt{\eta}\rangle^2}$$

For arbitrarily strong fading: $p(\gamma_{AB}) = 4/(V+1)^2$

Fading channels: effect on entanglement

Entanglement measure: logarithmic negativity $E_{LN}(\gamma) = max[0, -ln(\tilde{\lambda}_-)]$

Quantifies to which extent PT covariance matrix fails to be positive;
Is the upper bound on the distillable Gaussian entanglement.

$\tilde{\lambda}_-$ - smallest symplectic eigenvalue of the PT covariance matrix (smallest of eigenvalues of $|i\Omega\tilde{\gamma}|$)

In our case entanglement is broken by:

$$Var(\sqrt{\eta})_{max,ent} = 2\langle\sqrt{\eta}\rangle^2/(V-1)$$

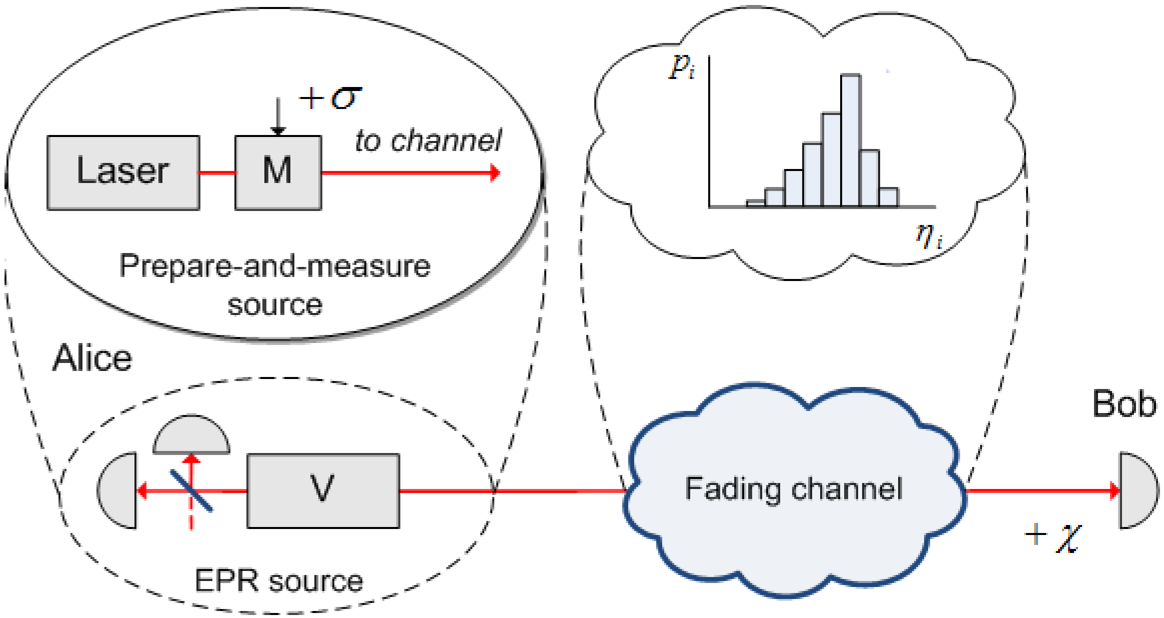
If excess noise is present, then

$$Var(\sqrt{\eta})_{max,ent} = \frac{2(\langle\sqrt{\eta}\rangle^2 - 1) - \chi + \sqrt{4(1+\langle\sqrt{\eta}\rangle^2)^2 + \chi^2}}{2(V-1)}$$

- high source variance → even small fading is harmful
- low source variance → entanglement is robust

Fading channels: effect on QKD

Equivalent entanglement-based scheme:



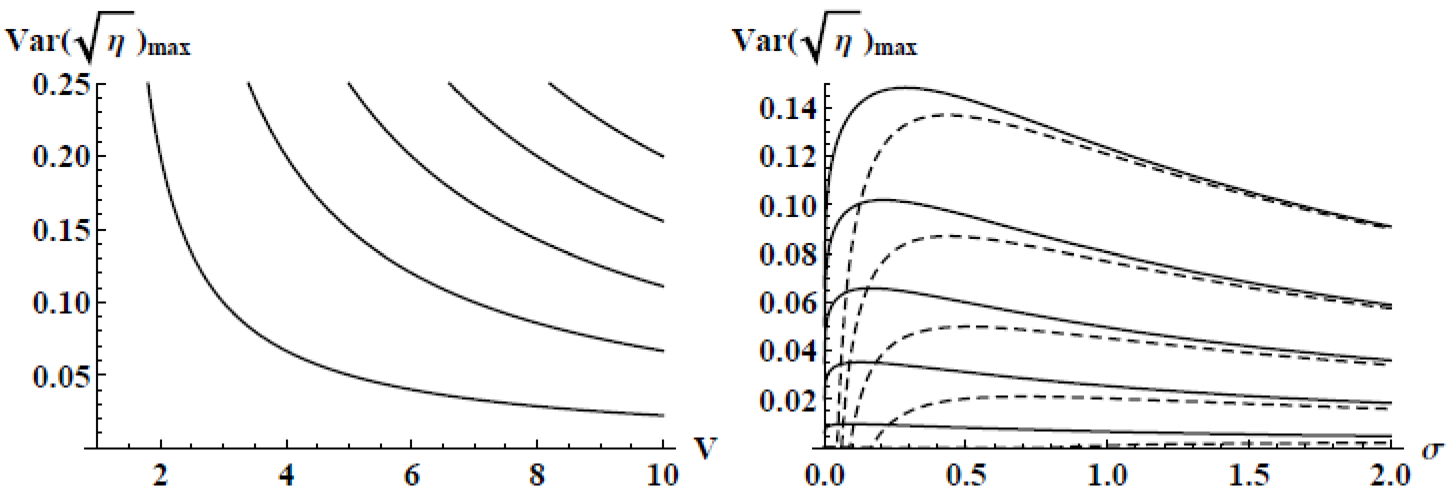
Effect of a fading channel upon individual attacks:

$$Var(\sqrt{\eta})_{max,ind} = \frac{\langle\sqrt{\eta}\rangle^2\sigma - 2(\sigma+1)(\chi+1) + \sqrt{\langle\sqrt{\eta}\rangle^4\sigma^2 + 4(\sigma+1)^2}}{2\sigma(\sigma+1)}$$

Where $\sigma = V - 1$ - modulation variance

Fading channels: effect on QKD

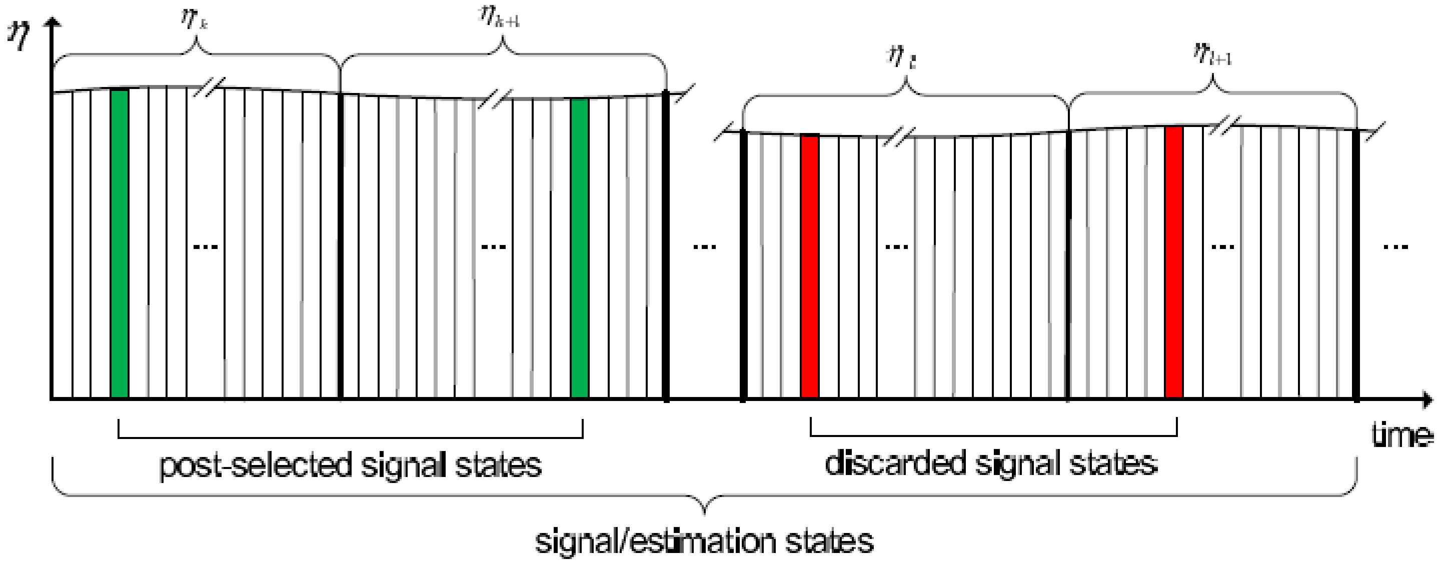
Entanglement (left) and security against the collective attacks (right):



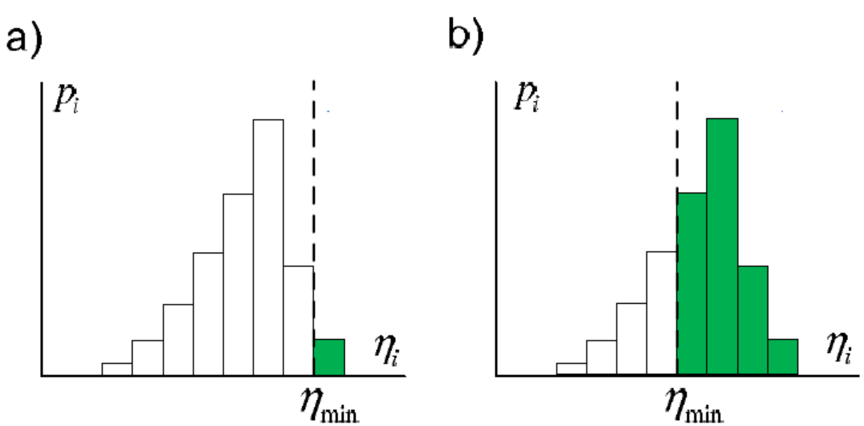
solid lines: no excess noise
dashed lines: excess noise $\chi = 1.2 \cdot 10^{-2}$

Post-selection of sub-channels

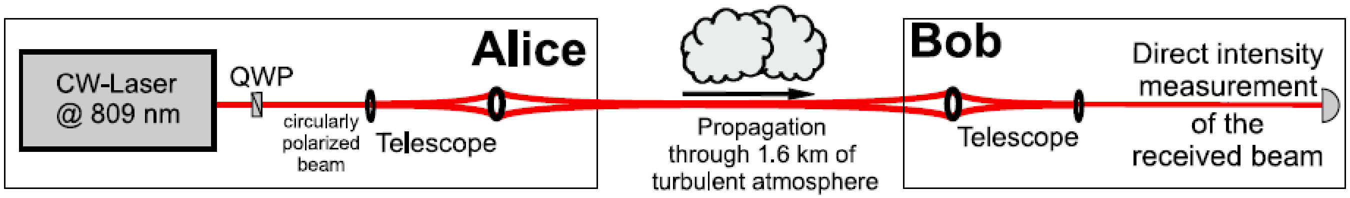
Post-selection time-flow:



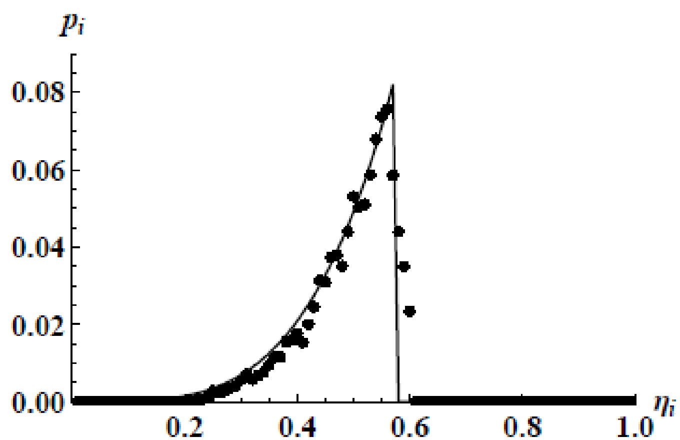
Post-selection of a single / multiple subchannels:



Real fading channel



Transmittance distribution obtained from a 1.6 km atmospheric link in Erlangen

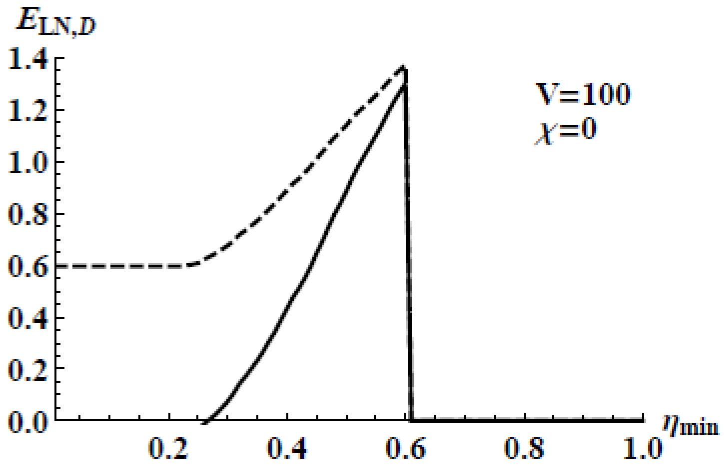


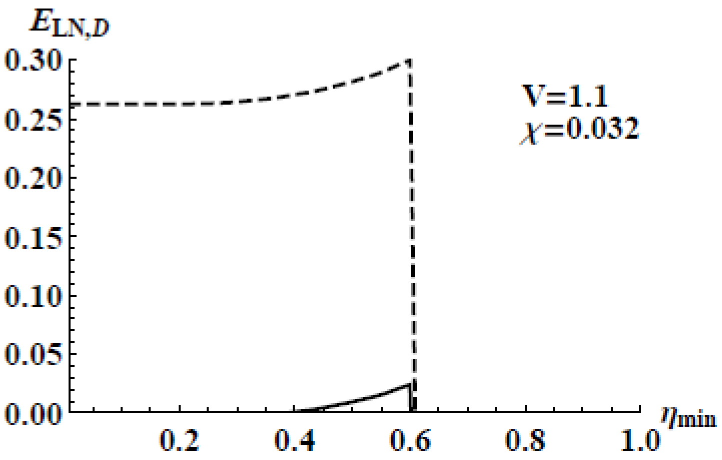
Sampling rate 150 kHz, bin size $\Delta\eta = 0.01$

Experimental distribution is well fitted by the log-normal one with $\sigma_b = 0.6$,$W/a = 1.5$ and additional attenuation of 25%.

Channel is characterized by $\langle\sqrt{\eta}\rangle^2 \approx 0.492$ and $Var(\sqrt{\eta}) \approx 3 \cdot 10^{-3}$

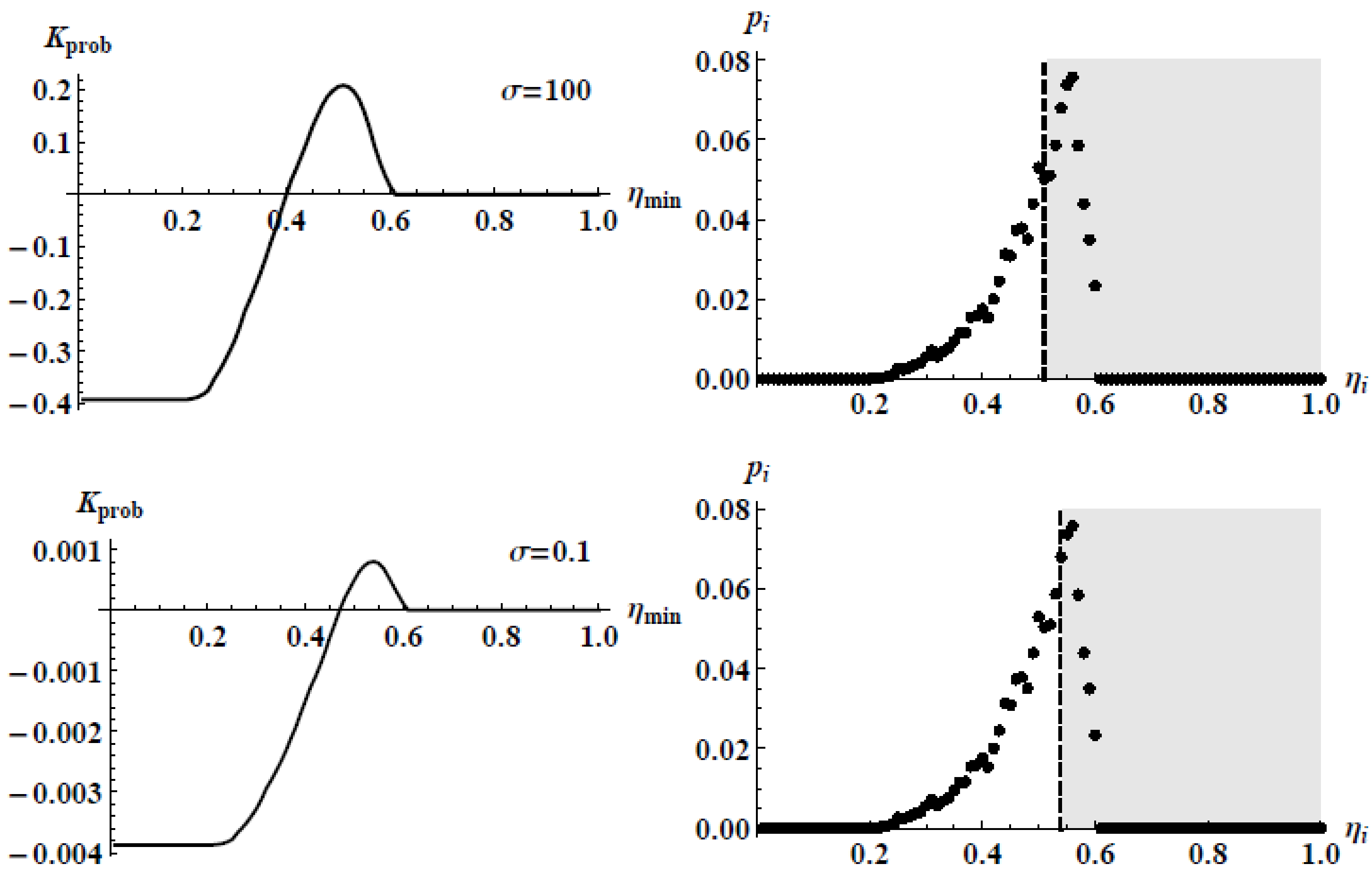
Real fading channel





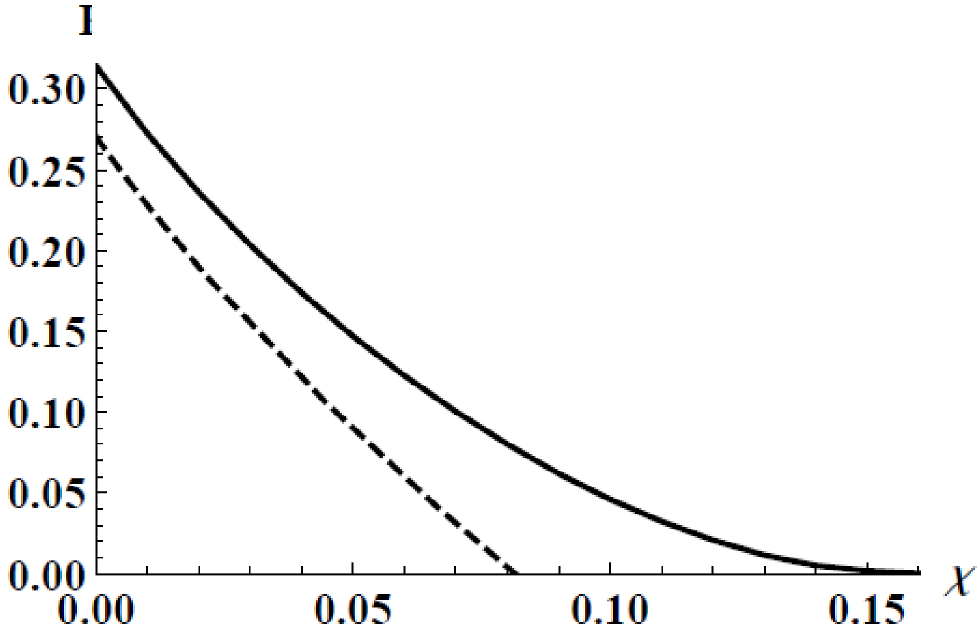
Effect of post-selection after the real fading channel on the entanglement in terms of logarithmic negativity (dashed)
and conditional entropy (solid line) for high (left) and low
state variance (right).

Real fading channel



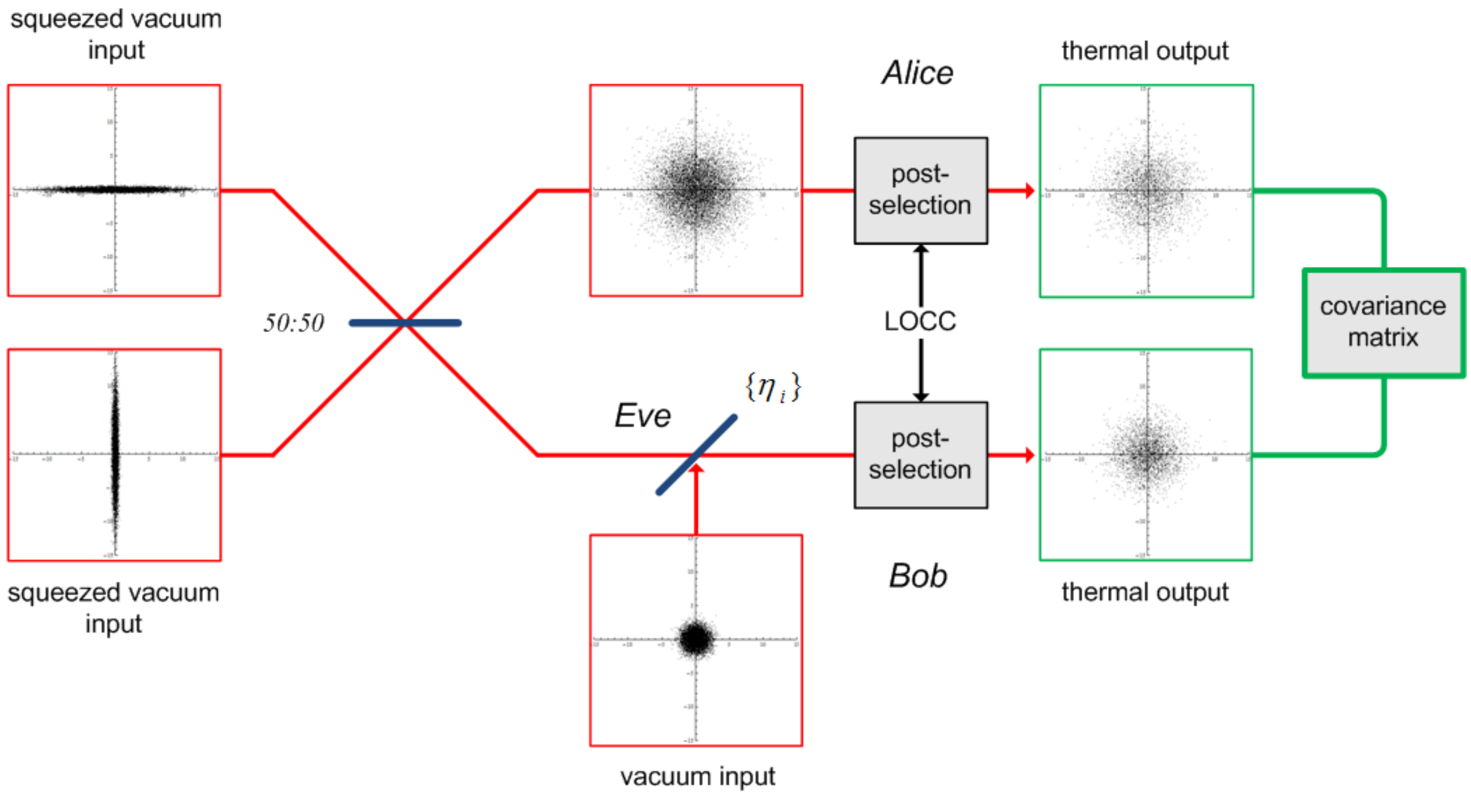
Effect of post-selection after the real fading channel on the security of the coherent-state protocol in terms of the weighted key rate (left). Corresponding optimal PS region is given at the right. Noise $\chi = 3.2 \cdot 10^{-2}$

Real fading channel



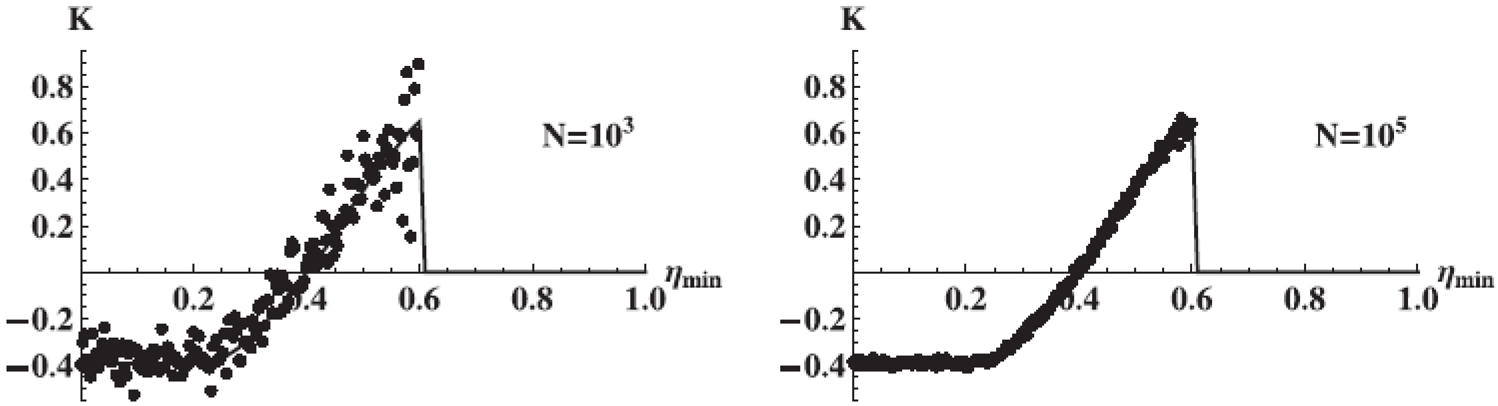
Secure key rate versus given excess noise upon optimized modulation and optimized post-selection (solid line) and upon optimized modulation and no post-selection (dashed line).

Finite-size effects



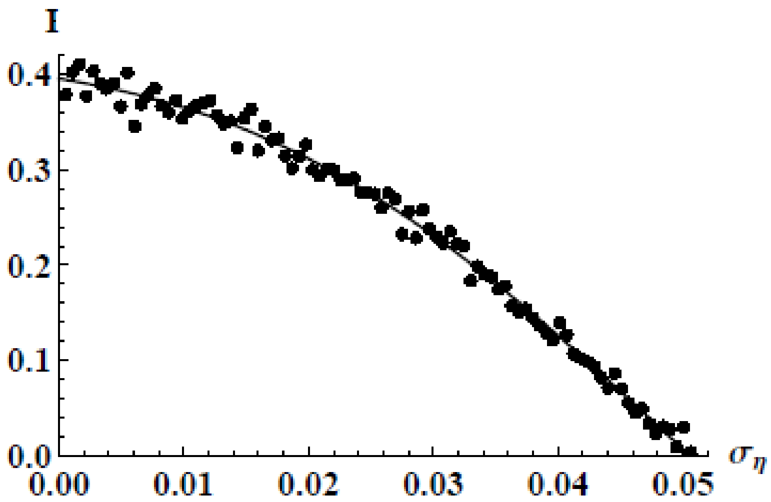
Scheme for numerical modeling of the fading and post-selection effects.

Finite-size effects



Effect of the finite ensemble size on the key rate upon post-selection.

Finite-size effects



Effect of the imperfect estimation on the key rate upon optimal post-selection and limited ensemble size.

[V. U., B. Heim, Ch. Peuntinger, Ch. Wittmann, Ch. Marquardt, G. Leuchs, R. Filip, New J. Phys., 14, 093048 (2012)]

Bits of knowledge

- Beam-wandering is dominant in short-distance free-space channels
- Temperature gradients drastically increase turbulence
- One can numerically model CV entanglement
- Fixed “pessimistic” decrease of actual transmittance is less dangerous than fading of transmittance around measured value

Summary

- Additional correlated modulation improves security region of a squeezed CV QKD protocol;

- Super-optimized protocol uses advantage of both coherent and squeezed protocols, gaining from any degree of squeezing;

- States with higher variance are strongly affected by fading channels

- Post-selection of sub-channels restores security and entanglement after the fluctuating atmospheric channels

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Thank you for attention!

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