Quantum limits of optical communication with macroscopic states of light

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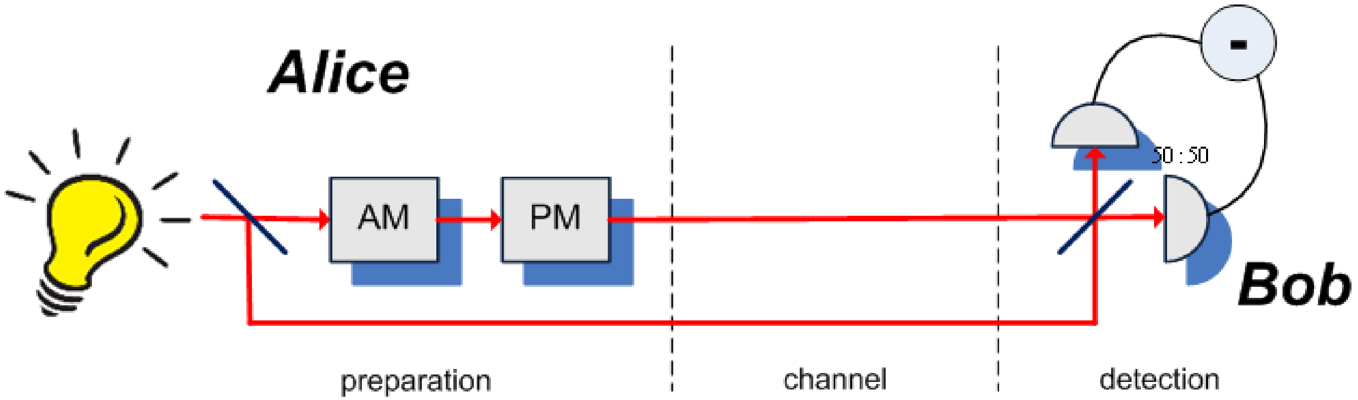
Outline

- CV optical/quantum communication
- **Quantum-inspired methods (decoupling of side channels)**
- **Homodyne detection of macroscopic states**
- **Effect of macroscopic properties on mutual info/entanglement**
- **Role of detector unbalancing**
- Summary

CV optical communication



Alice

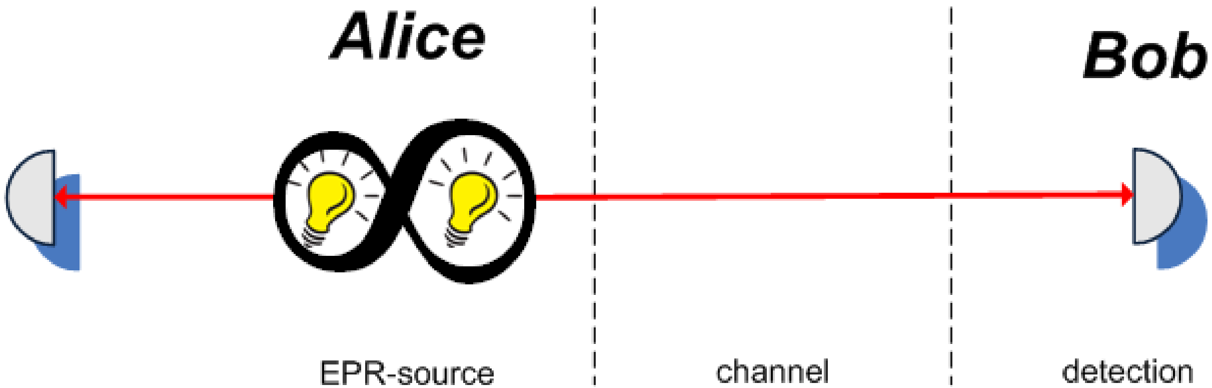
- prepares a squeezed/coherent state
- applies quadrature displacement
- sends to the channel

Bob

- performs homodyne detection

Figures of merit: mutual information/SNR/channel capacity

CV entanglement sharing



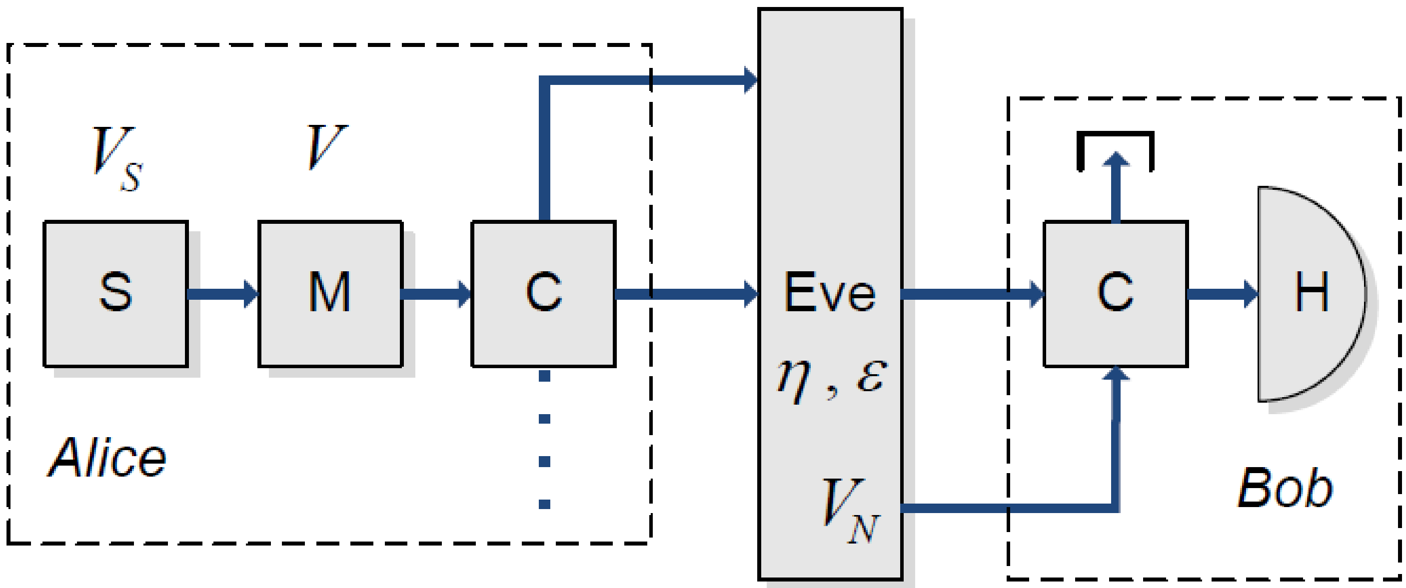
Alice and Bob share an entangled resource

Motivation: benchmarking [Killoran & Lutkenhaus, PRA 83, 052320 (2011)]

Figures of merit: Logarithmic negativity etc

Quantum-inspired methods

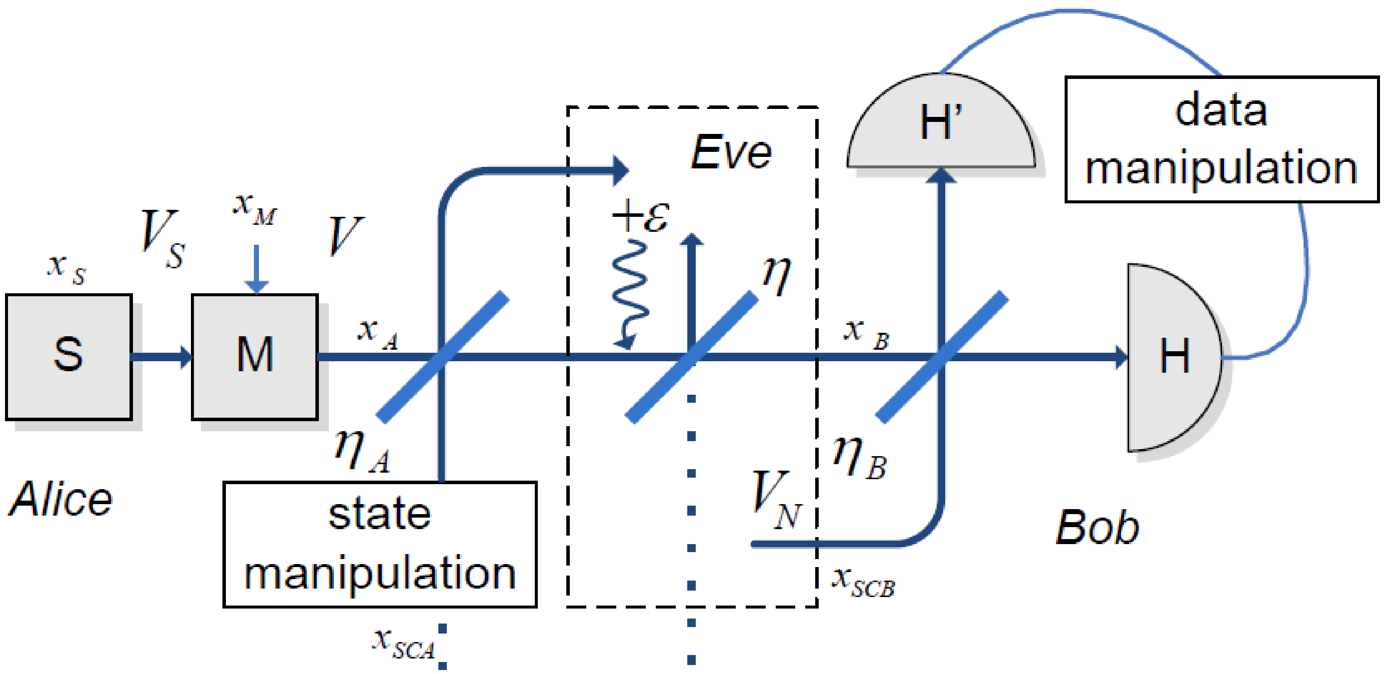
Decoupling of side-channels in CV QKD



[I. Derkach, VCU, R. Filip, PRA, in print (2016)]

Quantum-inspired methods

Decoupling of side-channels in CV QKD



Receiver side-channel monitoring and data manipulation:

$$\Delta x = g x_B^{'} - g^{'} x_{SCB}^{'}$$

[I. Derkach, VCU, R. Filip, PRA, in print (2016)]

Quantum-inspired methods

Decoupling of side-channels in CV QKD

$$x'_B = \sqrt{\eta_D}(x_B\sqrt{\eta_B} + x_{SCB}\sqrt{1-\eta_B}) + x_1\sqrt{1-\eta_D}$$

$$x'_{SCB} = \sqrt{\eta_D}(-x_B\sqrt{1-\eta_B} + x_{SCB}\sqrt{\eta_B}) + x_2\sqrt{1-\eta_D}$$

$$\Delta x = x_B\sqrt{\eta_D}(g\sqrt{\eta_B} + g'\sqrt{1-\eta_B}) + x_{SCB}\sqrt{\eta_D}(g\sqrt{1-\eta_B} - g'\sqrt{\eta_B}) + \sqrt{1-\eta_D}(gx_1 - g'x_2)$$

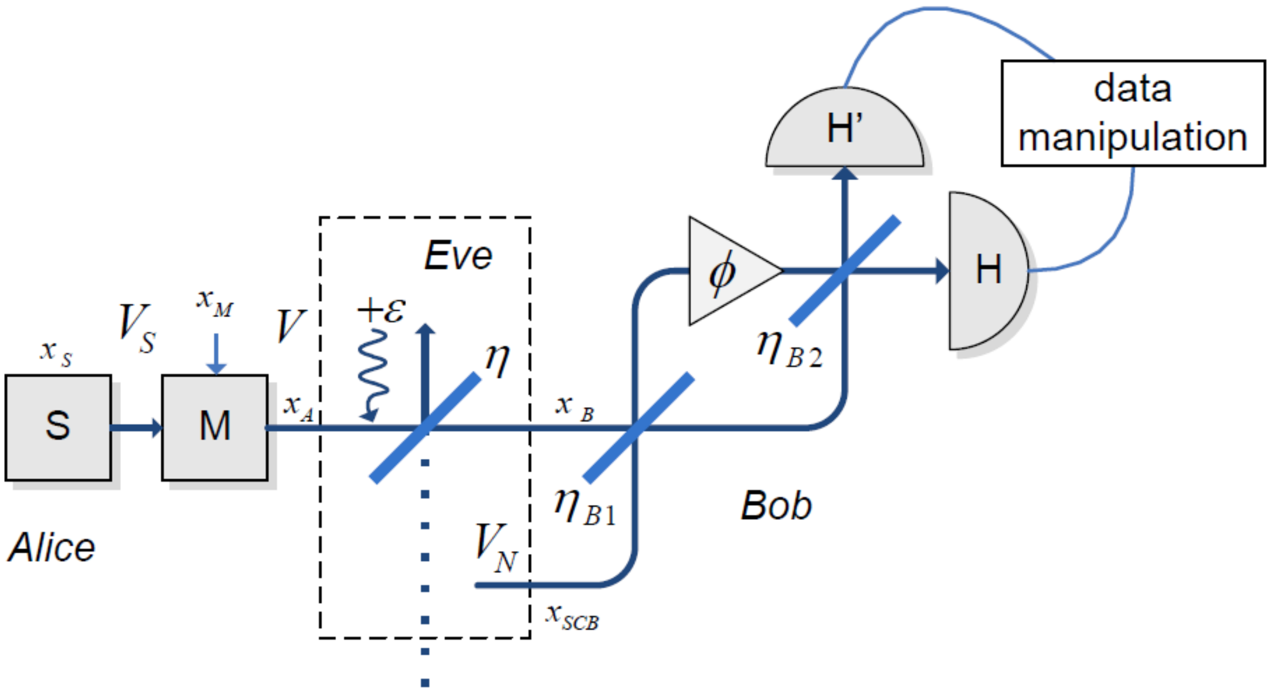
Optimal monitoring: $g = \sqrt{\eta_B}$, $g' = \sqrt{1-\eta_B}$

$$\boxed{\Delta x = x_B\sqrt{\eta_D} + \sqrt{1-\eta_D}(x_1\sqrt{\eta_B} - x_2\sqrt{1-\eta_B})}$$

[I. Derkach, VCU, R. Filip, PRA, in print (2016)]

Quantum-inspired methods

Decoupling of side-channels in CV QKD:
interferometric coupling



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Quantum-inspired methods

Decoupling of side-channels in CV QKD:
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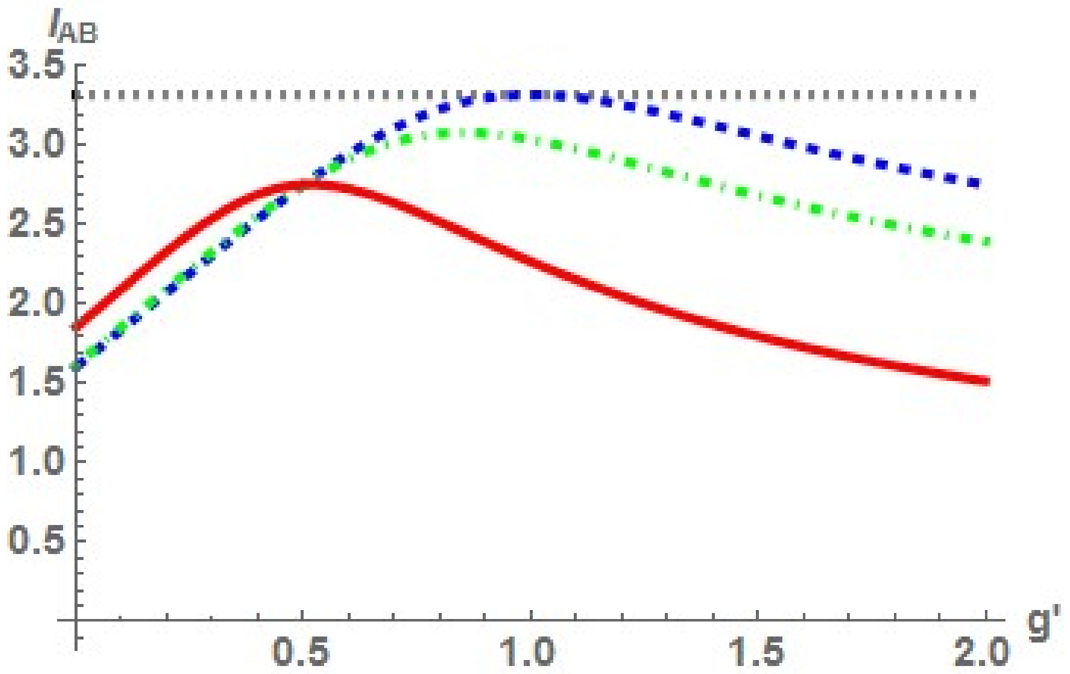


[I. Derkach, VCU, R. Filip, PRA, in print (2016)]

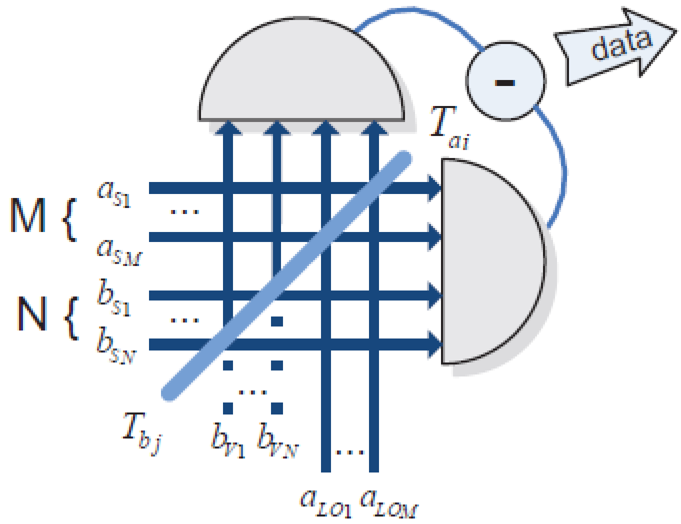
now let’s consider…

Macroscopic squeezed / entangled states of light:

- Heavily multimode
- Highly intense

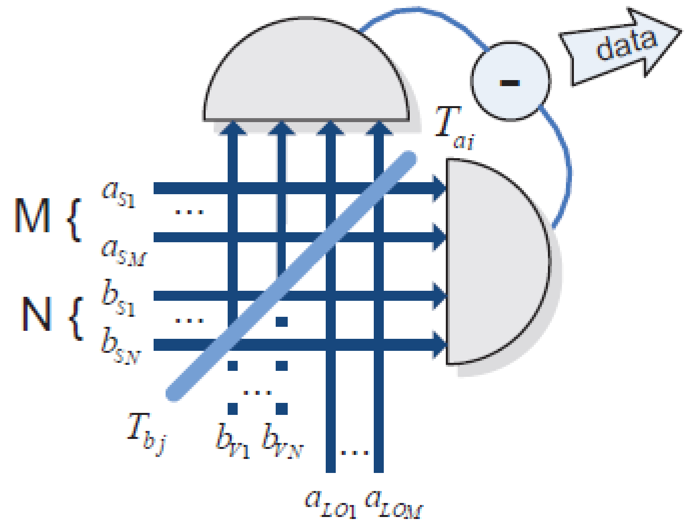
[Iskhakov, Chekhova, and Leuchs, PRL 102, 183602 (2009)]

Homodyning of macroscopic states



$$\begin{pmatrix} a'_{S_i} \\ a'_{LO_i} \end{pmatrix}_{out} = \begin{pmatrix} \sqrt{T_{a_i}} & \sqrt{1-T_{a_i}} \\ -\sqrt{1-T_{a_i}} & \sqrt{T_{a_i}} \end{pmatrix} \begin{pmatrix} a_{S_i} \\ a_{LO_i} \end{pmatrix}$$

Homodyning of macroscopic states



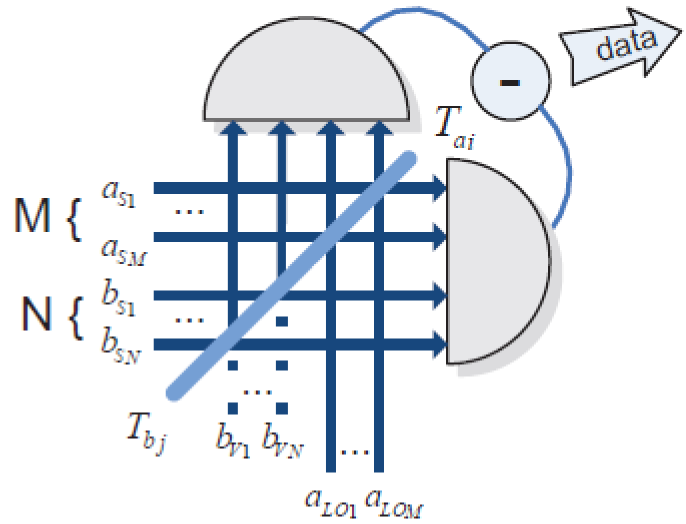
Measured photon numbers:

$$n_1 = \sum_i^M a'^\dagger_{S_i} a'_{S_i} + \varepsilon \sum_j^N b'^\dagger_{S_j} b'_{S_j} \quad \text{and} \quad n_2 = \sum_i^M a'^\dagger_{LO_i} a'_{LO_i} + \varepsilon \sum_j^N b'^\dagger_{V_j} b'_{V_j}$$

$$n_1 = \sum_i^M \left[T_{a_i} a^\dagger_{S_i} a_{S_i} + \sqrt{T_{a_i}(1-T_{a_i})}\left(a^\dagger_{S_i} a_{LO_i} + a^\dagger_{LO_i} a_{S_i}\right) + (1-T_{a_i}) a^\dagger_{LO_i} a_{LO_i} \right] +$$

$$+ \varepsilon \sum_j^N \left[T_{b_j} b^\dagger_{S_j} b_{S_j} + \sqrt{T_{b_j}(1-T_{b_j})}\left(b^\dagger_{S_j} b_{V_j} + b^\dagger_{V_j} b_{S_j}\right) + (1-T_{b_j}) b^\dagger_{V_j} b_{B_j} \right]$$

Homodyning of macroscopic states

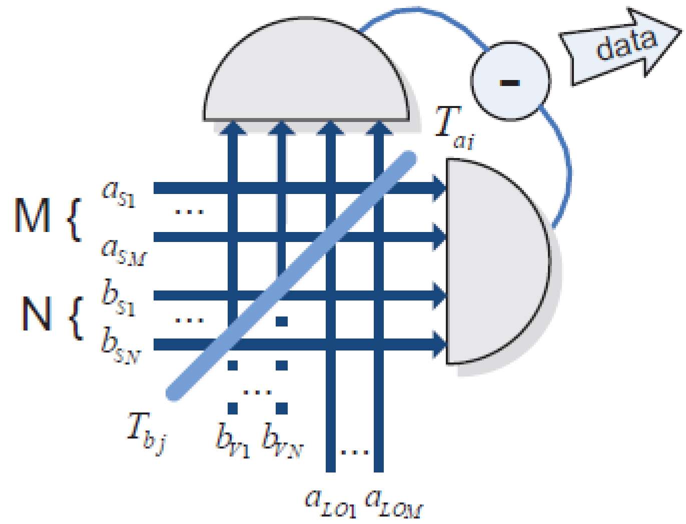


Measured photon numbers:

$n_1 = \sum_i^M a'^{\dagger}_{S_i} a'_{S_i} + \varepsilon \sum_j^N b'^{\dagger}_{S_j} b'_{S_j}$ and $n_2 = \sum_i^M a'^{\dagger}_{LO_i} a'_{LO_i} + \varepsilon \sum_j^N b'^{\dagger}_{V_j} b'_{V_j}$

$$n_2 = \sum_i^M \left[(1 - T_{a_i}) a^{\dagger}_{S_i} a_{S_i} - \sqrt{T_{a_i}(1 - T_{a_i})} (a^{\dagger}_{S_i} a_{LO_i} + a^{\dagger}_{LO_i} a_{S_i}) + T_{a_i} a^{\dagger}_{LO_i} a_{LO_i} \right] +$$
$$+ \varepsilon \sum_j^N \left[(1 - T_{b_j}) b^{\dagger}_{S_j} b_{S_j} - \sqrt{T_{b_j}(1 - T_{b_j})} (b^{\dagger}_{S_j} b_{V_j} + b^{\dagger}_{V_j} b_{S_j}) + T_{b_j} b^{\dagger}_{V_j} b_{B_j} \right]$$

Homodyning of macroscopic states



1. BALANCED DETECTION

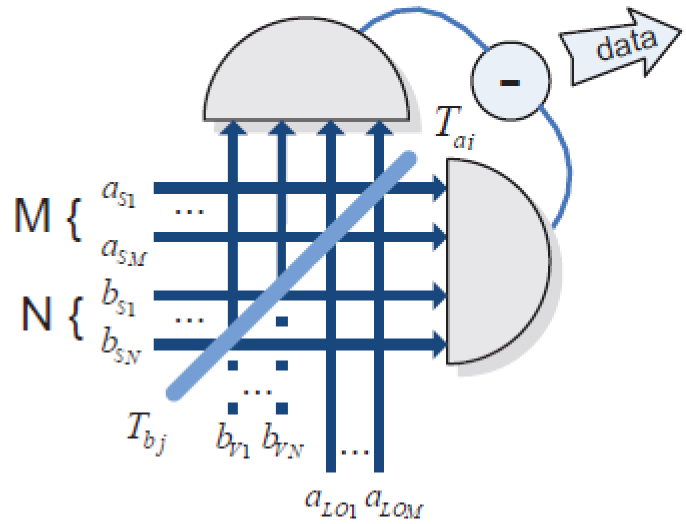
$$n_1 = \sum_i^M a_{S_i}'^\dagger a_{S_i}' + \varepsilon \sum_j^N b_{S_j}'^\dagger b_{S_j}'$$ and $$n_2 = \sum_i^M a_{LO_i}'^\dagger a_{LO_i}' + \varepsilon \sum_j^N b_{V_j}'^\dagger b_{V_j}'.$$

Difference photocurrent: $\Delta_i = \alpha \sum_i^M x_i + \varepsilon \sum_j^N (b_{S_j}^\dagger b_{V_j} + b_{V_j}^\dagger b_{S_j}).$

Normalized variance: $\boxed{Var(\Delta_i)_{norm} = Var(X) + \varepsilon_{tot}^2 \bar{n},}$

where $\bar{n} \equiv \langle b_{s_j}^\dagger b_{s_j} \rangle$ and $\varepsilon_{tot}^2 = \dfrac{N\varepsilon^2}{M\alpha^2}.$

Homodyning of macroscopic states



2. UNBALANCED 2-MODE CASE $\Delta_i \propto n_1 - g n_2$

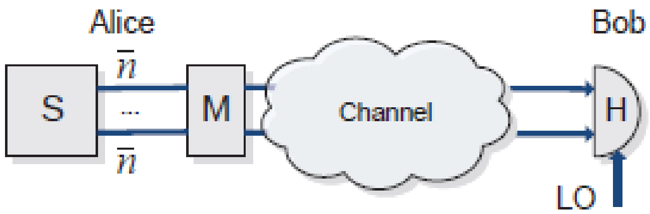
Normalized variance:

$$Var(\Delta_i)^{(unb)}_{norm} = Var(X) + \frac{\varepsilon^2_{tot}}{T_a(1-T_a)}\left[T_b(1-T_b)\bar{n} + (T_b - T_a)^2 Var(n)\right]$$

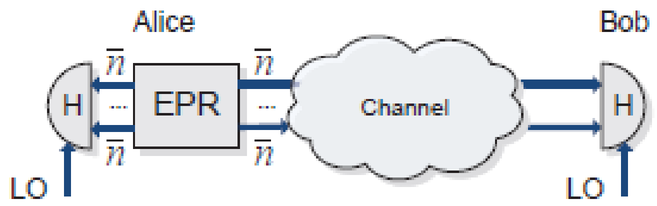
with $g = \frac{T_a}{1-T_a}$ in order to compensate fluctuations in the main signal mode.

Applications

OPTICAL COMMUNICATION / RESOURSE SHARING

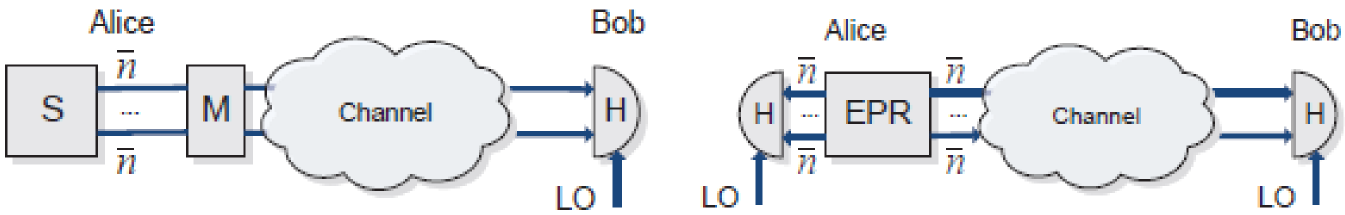


prepare-and-measure



entanglement-based

Applications



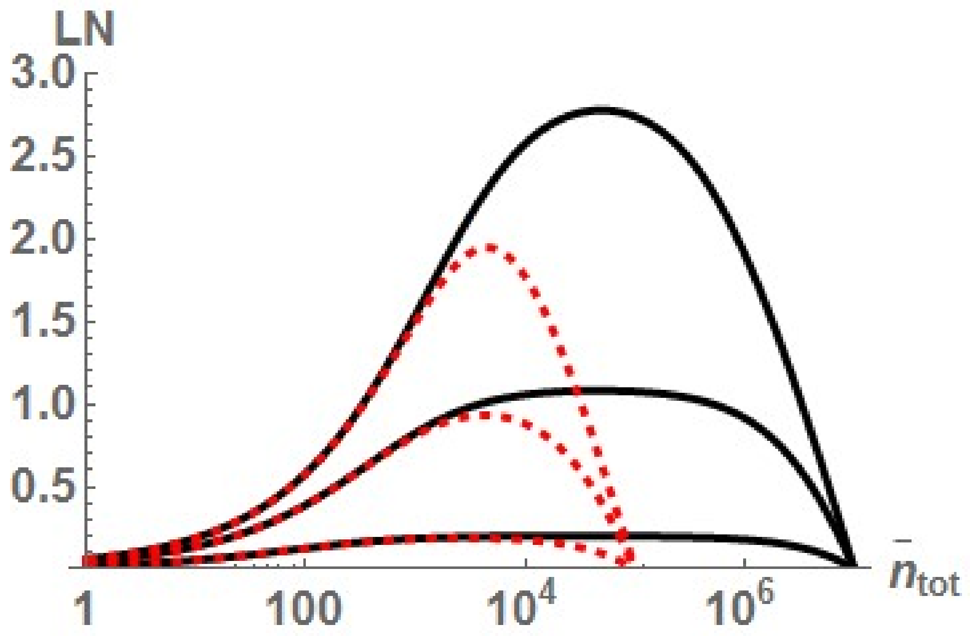
1. DETECTION OF SQUEEZING AND ENTANGLEMENT

Squeezing is lost at $\bar{n} = (1 - V_S)/\varepsilon_{tot}^2$

e.g. $V_S = -10$ dB upon $\varepsilon_{tot} = 10^{-2}$ is lost at $\bar{n} \approx 10^4$

Entanglement is lost at $\bar{n} = \dfrac{1}{\varepsilon_{tot}^2 (1 + \varepsilon_{tot}^2/4)}$ approx. $\bar{n} = \varepsilon_{tot}^{-2}$.

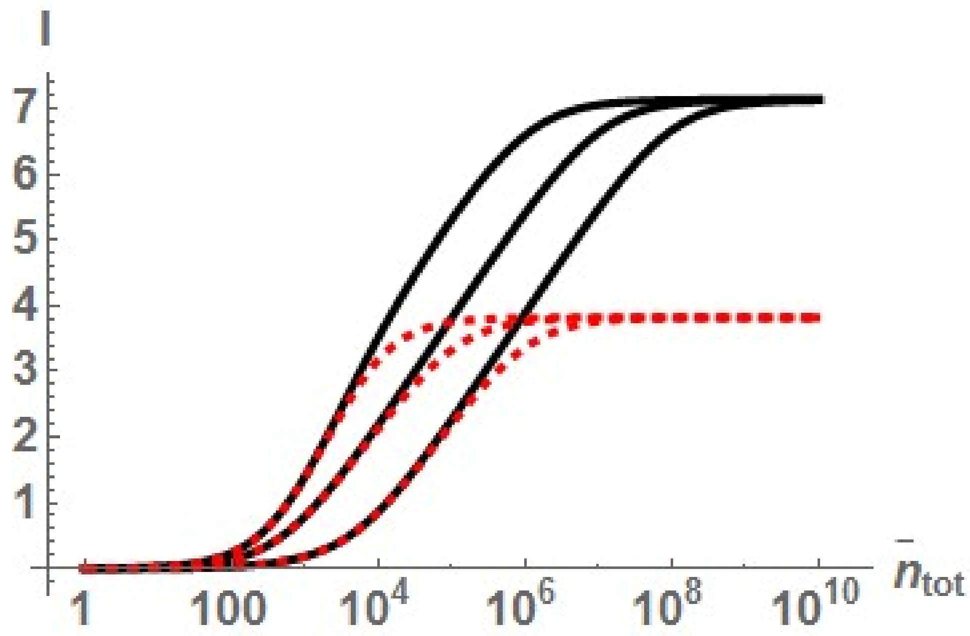
Entanglement sharing with macro states



Logarithmic negativity vs total mean photon number at 10^3 modes; $\varepsilon_{tot} = 10^{-2}$(solid lines), $\varepsilon_{tot} = 0.1$ (dashed red lines). Channel transmittance: 10%,50%,90% (top to bottom).

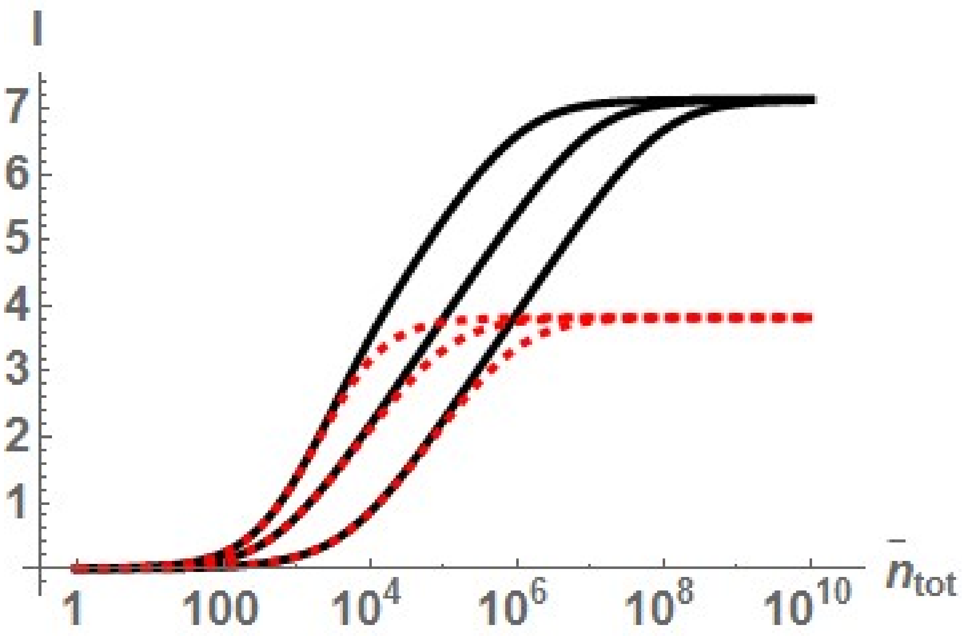
[VCU, L. Ruppert, and R. Filip, Opt. Exp. 23 31534 (2015)]

Optical communication with macro states



Mutual info vs total mean photon number at 10^3 modes; $\varepsilon_{tot} = 10^{-2}$(solid lines), $\varepsilon_{tot} = 0.1$ (dashed red lines). Channel transmittance: 10%,50%,90% (top to bottom).

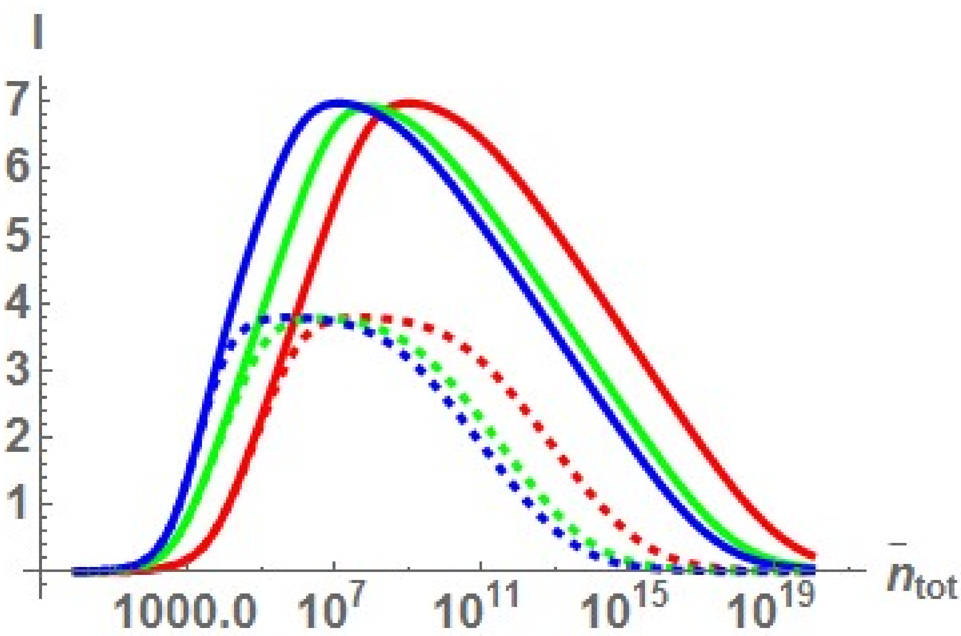
Optical communication with macro states



$$\boxed{I \propto Log\left(1+\frac{2}{\varepsilon_{tot}^{2}}\right)}$$

Mutual info vs total mean photon number at 10^3 modes; $\varepsilon_{tot} = 10^{-2}$(solid lines), $\varepsilon_{tot} = 0.1$ (dashed red lines). Channel transmittance: 10%,50%,90% (top to bottom).

Optical communication with macro states role of unbalancing



Mutual info vs total mean photon number at 10^3 modes; $\epsilon_{tot} = 10^{-2}$ (solid lines), $\epsilon_{tot} = 0.1$ (dashed lines). Channel transmittance: 10%,50%,90% (RGB). Homodyne coupling is unbalanced by 1%.

Suppression of noise

The noise concerned with the macro nature of the signal can be suppressed by the increase of the LO power.

It was successfully tested at MPL in Erlangen.

Summary

- Signal brightness together with mode mismatch result in the excess noise, proportional to the mean photon number in the signal;
- Such noise leads to a trade-off between entanglement and brightness/squeezing and to saturation of mutual information;
- Unbalancing leads to the noise proportional to the photon-number variance;
- Noise due to unbalancing leads to a trade-off between mutual information and brightness;
- The impact of noise concerned with the macroscopic nature of the signal can be suppressed by mode selection and/or increase of power of the local oscillator.

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Thank you for attention!

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