# Experimental Demonstration of Continuous-Variable Quantum Key Distribution over 80 km of Standard Telecom Fiber

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# QKD: four main limitations (1/2)

Speed

- Not enough for OTP: not a serious issue
- Physical parameters estimation over large blocks: hardware drifts, latency

Distance

- Asymmetric crypto is not limited
- Trusted nodes are not a good solution: quantum repeaters are required

# QKD: four main limitations (2/2)

Security

- Incomplete security proofs
- Distance between proofs and practical implementations

Deployment

- QKD requires a dark fiber: $$$
- WDM compatibility: lowers QKD extra premium

# Two technologies

| | Discrete variables | Continuous variables |
|---|---|---|
| medium | photon phase/polar. | field amplitude-phase |
| detection | photon counters | coherent detection |
| range | 100 km | 25km |
| rate | 1Mb/s | 10kb/s |
| components | active cooling | standard |
| integration | WDM | WDM |
| security | yes | yes |

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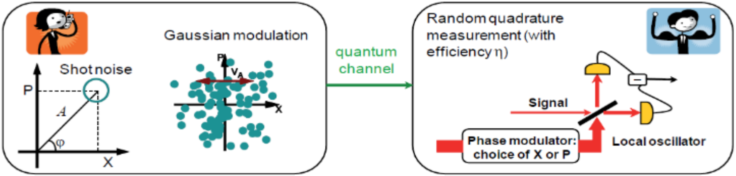
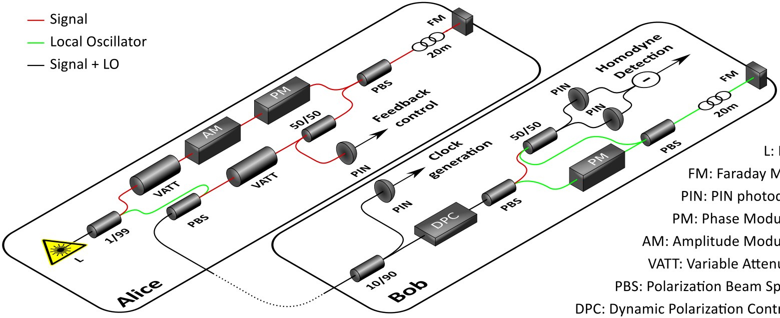
# Gaussian protocol




Losses and excess noise lower the SNR.

# Optical setup




L: Laser
FM: Faraday Mirror
PIN: PIN photodiode
PM: Phase Modulator
AM: Amplitude Modulator
VATT: Variable Attenuator
PBS: Polarization Beam Splitter
DPC: Dynamic Polarization Controller

# Speed limitations

- Delay between classical and quantum signals (200ns)
- Laser pulsed with a tunable frequency (1MHz)
- Data acquisition speed (up to 5MHz)
- Filtering: tradeoff between speed and electronic noise (current cutoff at 10MHz, 100MHz feasible arxiv:1006.1257 Yue-Meng Chi et al.)
- High-speed error correction: LDPC codes (GPU) or polar codes (CPU) (up to 10Mbit/s) (arxiv:1204.5882, P. Jouguet and S. Kunz-Jacques)

# Range limitations

- High error-correction efficiency, even at low SNRs
- Finite-size effects
- Low SNR Alice/Bob synchronization mechanism
- Low-loss LO path
- Excess noise (imperfect relative phase estimation)

New SNR regions allowed by error-correction techniques.

# Channel virtualization

- Idea introduced by Leverrier (Phys. Rev. A 77, 042325 (2008))
- Translates the initial problem into a channel coding problem on a *good* channel
- *Good* means very efficient error-correcting codes available
- Usual suspect: BIAWGNC

# How to improve the efficiency of the multidimensional scheme?

- Improve the approximation between the virtual channel and the target channel
- Improve the efficiency of the codes on the target channel (Phys. Rev. A 84, 062317 (2011), P. Jouguet, S. Kunz-Jacques and A. Leverrier)

# What is a good code for the BIAWGNC?

- A code is designed for a channel **and a SNR**
- Free parameter: the code rate $R = \frac{n-m}{n}$, $m$ the number of parity-check equations, $n$ the length
- Low SNR / Lot of redundancy / Low rate
- Efficiency $\beta\,(SNR) = \frac{R}{C(SNR)}$
- Typical values:
  - Slice reconciliation: $\beta = 90\%$, SNR$= 3$, @30km
  - Multidimensional reconciliation: $\beta = 89\%$, SNR$= 0.5$, @50km

# Set of available codes

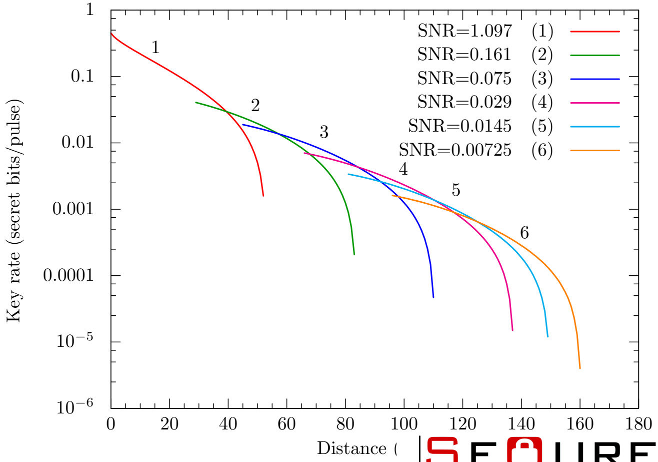
| $\beta$ | $SNR$ |
|---|---|
| 93.6% | 1.097 |
| 93.1% | 0.161 |
| 95.8% | 0.075 |
| 96.9% | 0.029 |
| 96.6% | 0.0145 |
| 95.9% | 0.00725 |

# How to get more flexibility on the SNR?

- Possible to design codes with lower rates
- Not necessary: repetition codes
- Shortening, puncturing
- Optimization on the modulation variance

# Theoretical secret key rate

Parameters: $V_A \in \{1, 100\}$, $T = 10^{-0.2d/10}$, $\xi = 0.01$, $\eta = 0.6$, $V_{elec} = 0.01$

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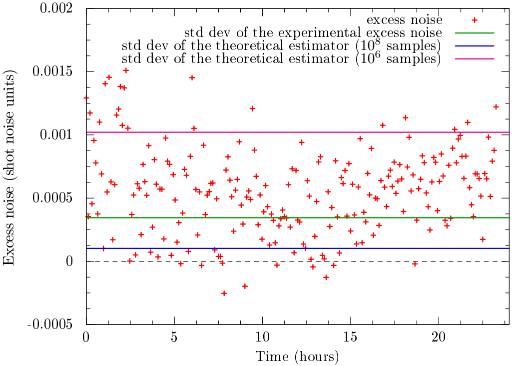
# Finite size effects

- First analysis for discrete modulation protocols in Phys. Rev. A 81, 062343 (2010), Leverrier et al.
- Statistical uncertainty over estimated parameters ($T$, $\xi$)
- $K = \frac{n}{N}(\beta I(x;y) - S^{\epsilon_{PE}}(y;E) - \Delta(n))$
- Extended analysis for Gaussian modulation, including imperfect homodyne detection (efficiency, electronic noise) and shot noise estimation (Phys. Rev. A 86, 032309 (2012), poster 33)
- Main effect: uncertainty on the excess noise $\xi$

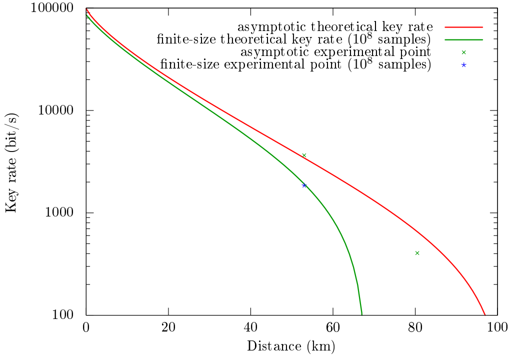
# Experimental results

Parameters: $d = 53$km, $\eta = 0.552$, $V_{elec} = 0.015$, SNR$= 0.17$, $\beta = 94\%$, $\epsilon = 10^{-10}$



# Experimental results

Parameters: $d = 53$km,80km, $\eta = 0.552$, $V_{elec} = 0.015$, SNR=0.17,0.08, $\beta = 94\%$, $\epsilon = 10^{-10}$



# Imperfect preparation

- Thermal noise (Phys. Rev. A 81, 022318 (2010), Usenko and Filip)
- Gaussian modulation: truncated and discretized (finite amount of randomness)
  - Can be taken into account into the security proof (Phys. Rev. A 86, 032309 (2012), poster 33)
  - But a lot of random numbers are required (+ sifting and multidimensional protocol)
- Calibration procedures
  - Calibration of the homodyne detection
  - Calibration of the phase noise



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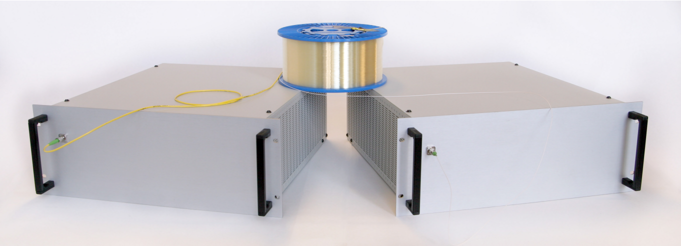
# Summary

- Long distance CVQKD with Gaussian modulation is possible thanks to low SNR error-correction capability
- Computing-power consuming because of decoding close to the threshold
- We use GPU (30$\times$ faster than CPU plus friendly Moore's law)
- Higher secure distance with virtual Gaussian post-selection? (arxiv:1205.6933, J. Fiurasek, N. J. Cerf, arxiv:1206.0936, N. Walk et al.)
- Work on WDM coming

# Enquire about Cygnus



- An **open and customizable** CVQKD research platform
- Tests/demonstrations of integration in optical networks

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