Towards secure QKD with testable assumptions on modulation devices

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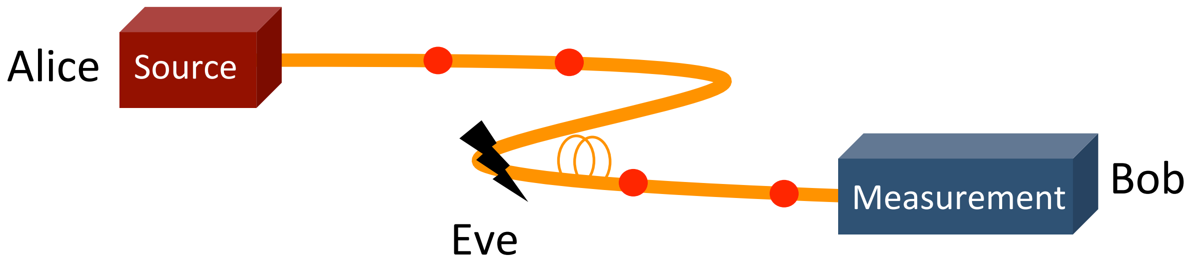
[4]*NTT Basic Research Laboratories*

Practical security of QKD

➢ **The security of most existing implementations of QKD has not been rigorously established yet. Why?**

➡ Security proofs so far make ideal assumptions on the users' devices.



Source imperfections

Realistic imperfections, even major imperfections such as **modulation errors**, are not taken into account in most of security proofs.

Detector blinding attacks

L. Lydersen *et al*., Nat. Photonics **4**, 686 (2010).

Time-shift attacks

Y. Zhao et al., Phys. Rev. A **78**, 042333 (2008).

Detector control

I. Gerhardt *et al,* Nat. Commun. **2**, 349 (2011).

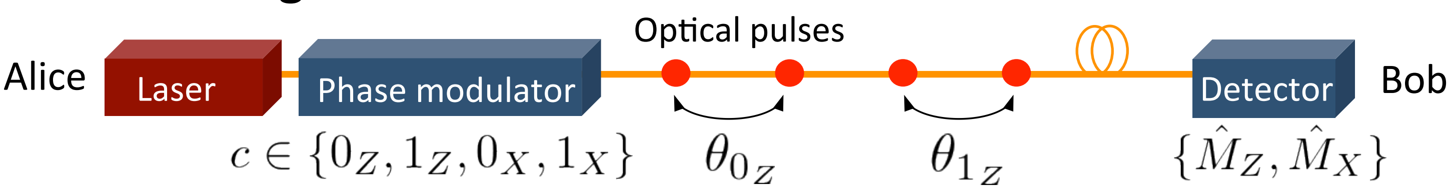
➡ Measurement-device-independent (MDI) QKD

H. K. Lo *et al,* Phys. Rev. Lett. **108**, 130503(2012).

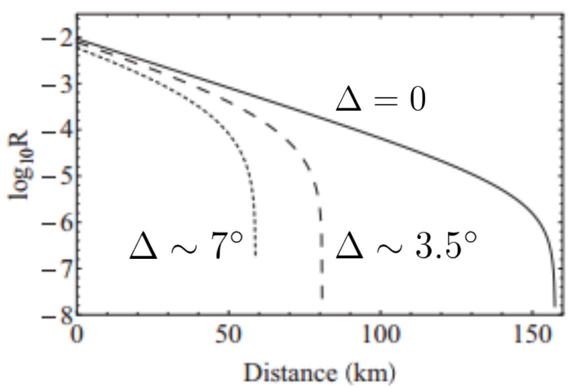
GLLP security proof

- **Phase-encoding BB84**

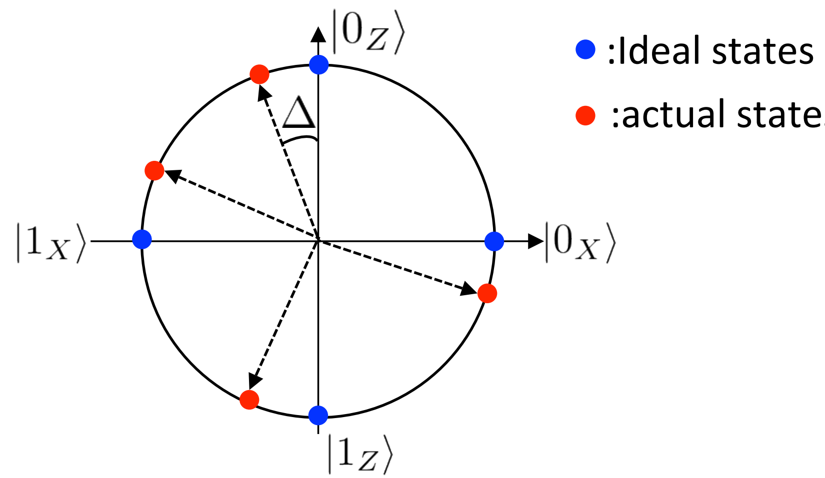
D. Gottesman *et al.*, Quant. Inf. Comput. **4**, 325 (2004).



<u>GLLP analysis</u>



<u>Qubit space of 2 consecutive pulses</u>

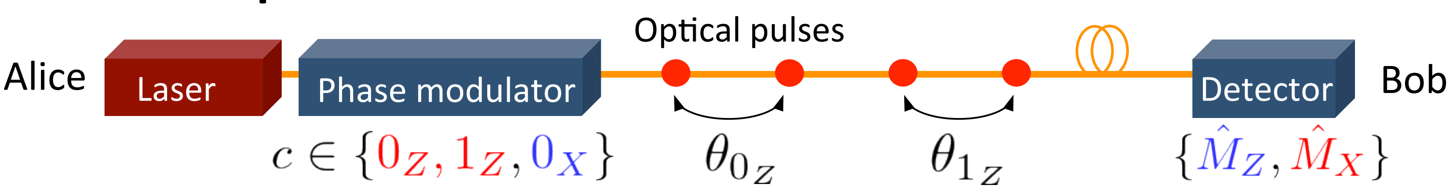


Even under the small phase modulation errors, the achievable distance and the key rate drastically decrease.

Loss-tolerant protocol

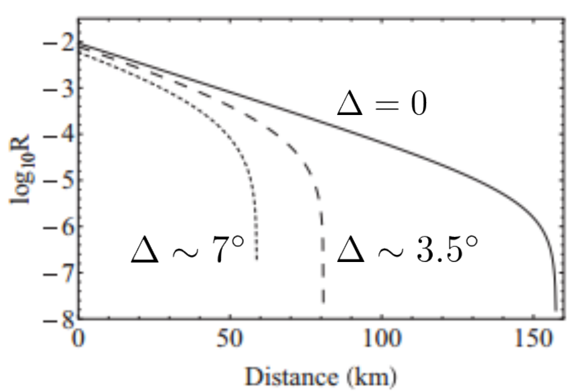
- **Loss-tolerant protocol**

K. Tamaki *et al*., Phys. Rev. A **90**, 052314 (2014).

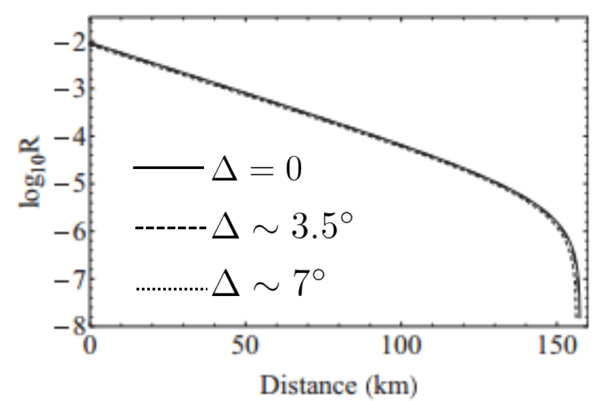


The main idea:
Utilizing the "basis mismatched events" to estimate Eve's leaked information.

GLLP analysis



Loss-tolerant protocol



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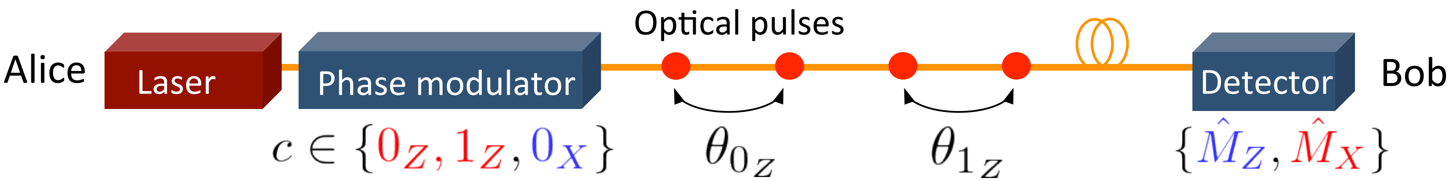
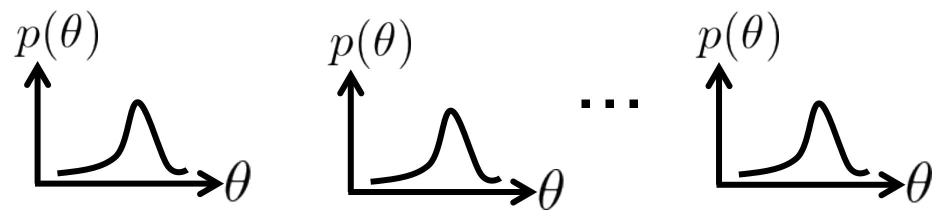


The LT protocol assumes that the phase modulation errors follow **IID**.

IID distribution on modulation device



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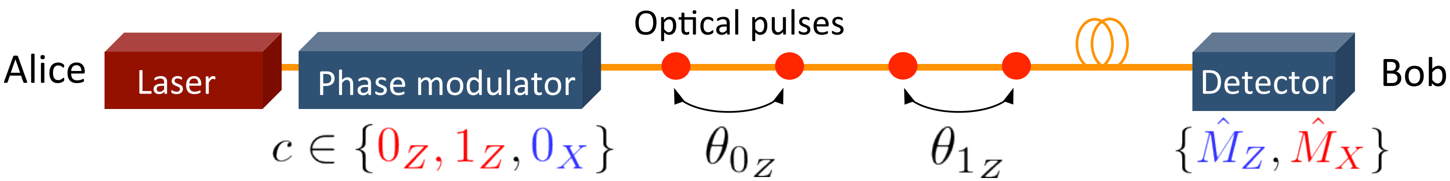

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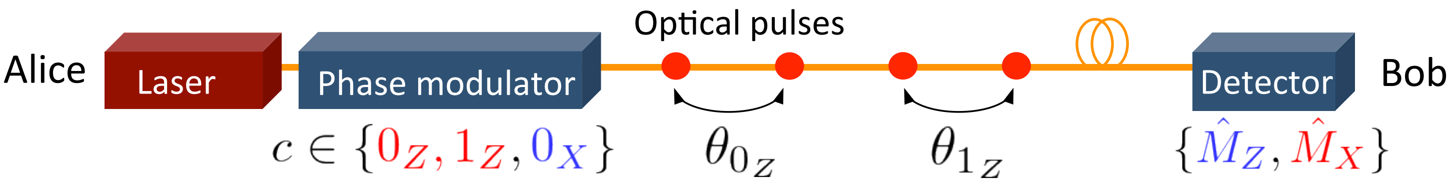

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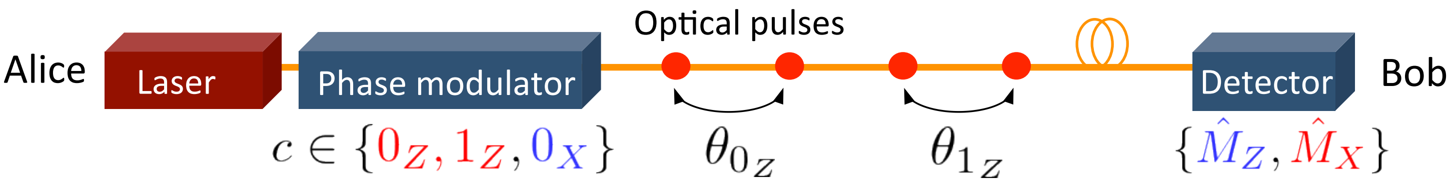

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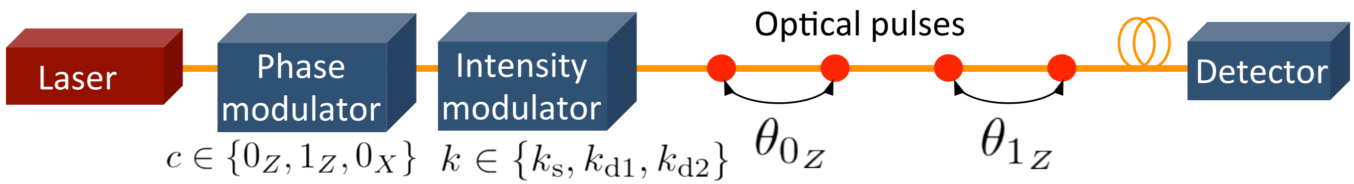
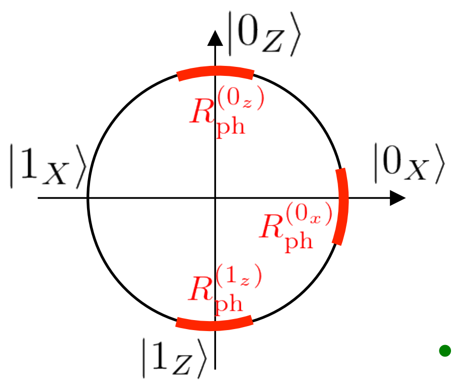
Towards secure QKD with testable assumptions on modulation devices (see arXiv soon!)

Characterization of modulation devices

- **Loss-tolerant protocol**



Phase modulator:



All the pulses emitted with c

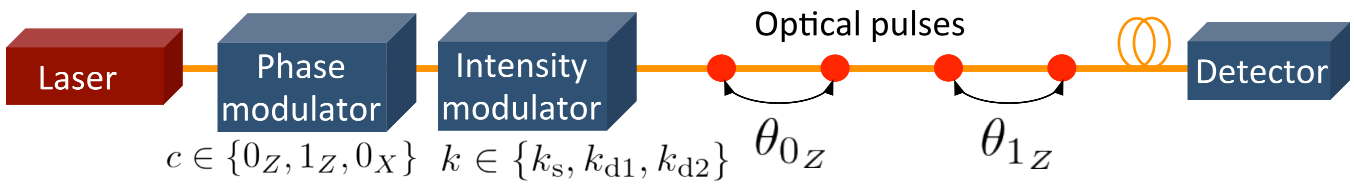
$$\Pr\left[\left|\{i_c|\theta_{i_c} \in R_\mathrm{ph}^{(c)}\}\right| \geq N_c - \delta_c\right] \geq 1 - \epsilon_c$$

Phase interval | Tagged pulses | Failure probability

- Untagged signal: Pulse whose phase lies in the interval
- Tagged signal: Pulse whose phase does not lie in the interval

Characterization of modulation devices

- **Loss-tolerant protocol**



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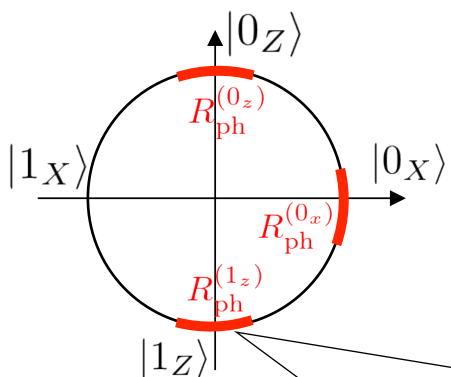


$$\Pr\left[|\{i_c|\theta_{i_c} \in R_{\rm ph}^{(c)}\}| \geq N_c - \delta_c\right] \geq 1 - \epsilon_c$$

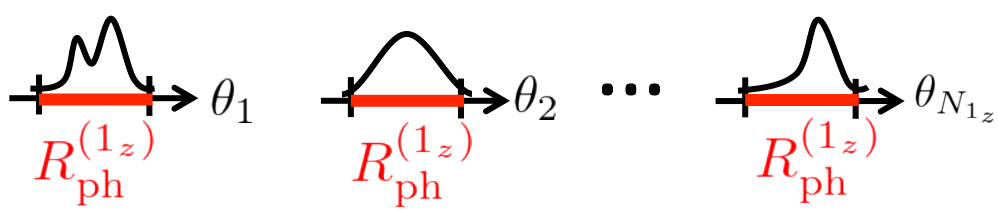
All the pulses emitted with c (N_c)

Phase interval ($R_{\rm ph}^{(c)}$)

Tagged pulses (δ_c)

Failure probability (ϵ_c)

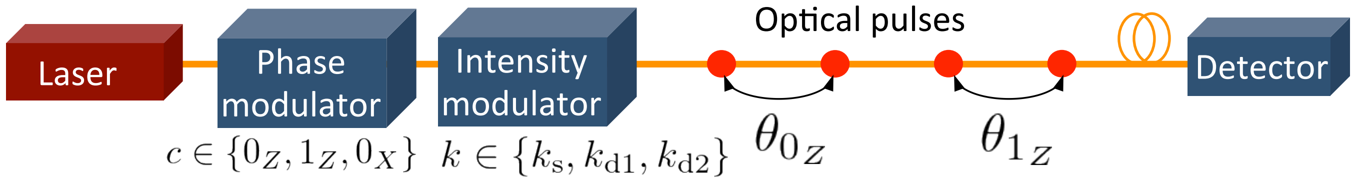
- Non-IID modulation errors are accommodated.



- Intervals are potentially testable in experiments.

Characterization of modulation devices

- **Loss-tolerant protocol**



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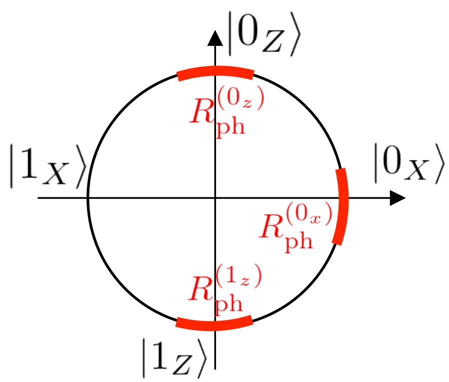

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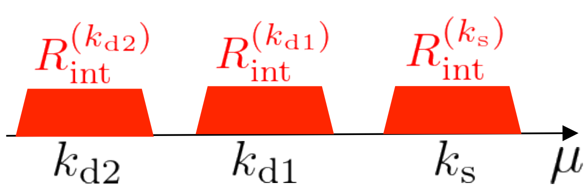
$$\Pr\left[|\{i_c|\theta_{i_c} \in R_{\rm ph}^{(c)}\}| \geq N_c - \delta_c\right] \geq 1 - \epsilon_c$$

Phase interval | Tagged pulses | Failure probability

Intensity modulator:



All the pulses emitted with k

$$\Pr\left[|\{i_k|\mu_{i_k} \in R_{\rm int}^{(k)}\}| \geq N_k - \delta_k\right] \geq 1 - \epsilon_k$$

Intensity interval | Tagged pulses | Failure probability

- Tagged events occur independently of k

Simulation results

Finite-key length

see arXiv soon!

- **Secure key length against coherent attacks:**

$$\ell \geq S_1^{\mathrm{u}}\Big(1 - h(e_{\mathrm{ph}}^{\mathrm{u}})\Big) - \lambda_{\mathrm{EC}}$$

Number of Z-basis detected events from untagged single-photon emissions

Leaked information for the untagged single-photon emissions

Bits exchanged in reconciliation

- **Estimation for the parameters:**

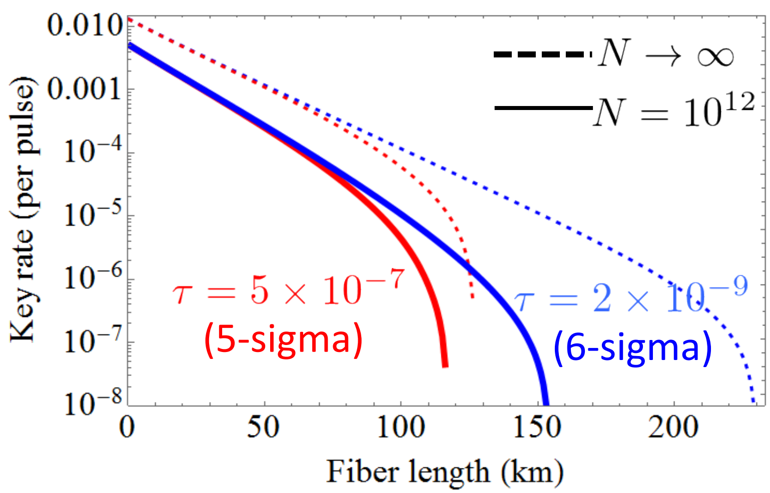
M. Curty *et al*., Nat. Commun., **5**, 3732 (2014).

S_1^{u} : Extend the "decoy-state method" based on our intensity interval assumption.

$e_{\mathrm{ph}}^{\mathrm{u}} := \frac{N_{\mathrm{ph}}^{\mathrm{u}}}{S_1^{\mathrm{u}}}$: Phase error rate for the untagged single photon emissions among the Z-basis untagged single-photon emissions.

Key rate against distance

- **Key rate**=key length per signal transmission.
- Secrecy parameter $\epsilon_{\mathrm{s}} = 10^{-10}$
- Correctness $\epsilon_{\mathrm{cor}} = 10^{-10}$
- Loss in the optical fiber=0.2dB/km
- Detection efficiency=46%, dark count=1.5×10^{-8} Y-L. Tang *et al.*, Phys. Rev. Lett. **113**, 190501 (2014).



Modulation devices

Phase interval: F. Xu *et al.*, PRA **92**, 032305 (2015).

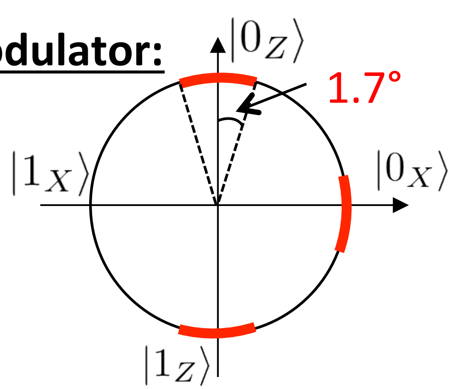
$$R_{\mathrm{ph}} = [\theta_c - 1.7°, \theta_c + 1.7°]$$

Intensity interval (±3%):

$$R_{\mathrm{int}} = [\mu(1-0.03), \mu(1+0.03)]$$

τ=Probability (per pulse) of being outside the interval

Phase modulator:



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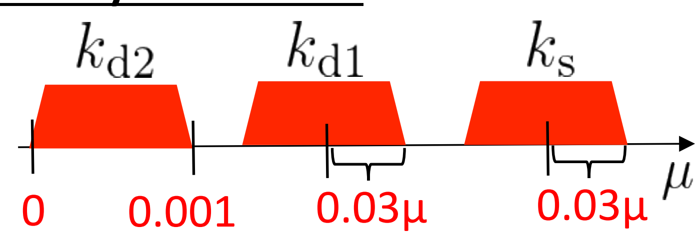

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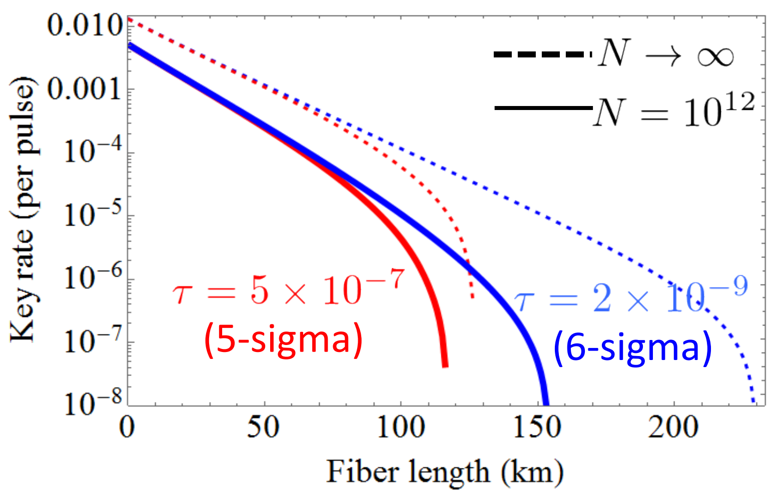

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Notice

1) If τ increases, the number of pulses that do not lie within the intervals also increases. The *tagged signals* become problematic especially in the *high loss regime*.

2) If the intervals are guaranteed by 5-sigma confidence level, more than 100km secure QKD is possible within reasonable number of signal transmissions.

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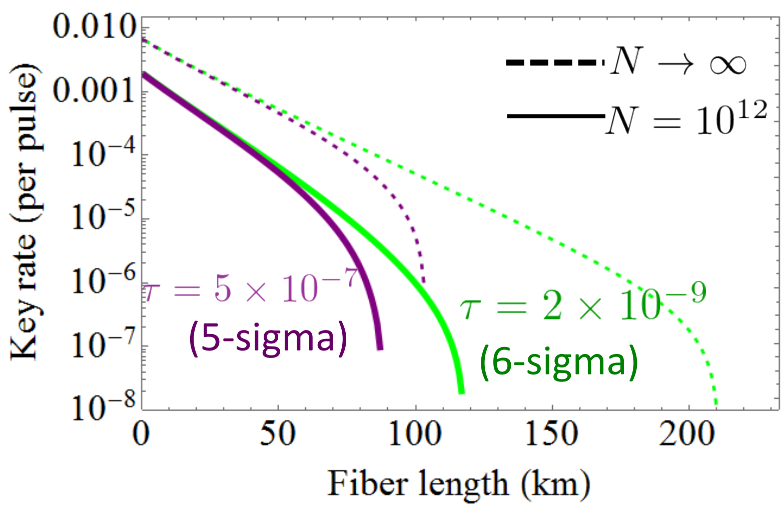

Modulation devices

Phase interval: F. Xu *et al.,* PRA **92**, 032305 (2015).

$$R_{\mathrm{ph}} = [\theta_c - 1.7^\circ, \theta_c + 1.7^\circ]$$

Intensity interval (±5%):

$$R_{\mathrm{int}} = [\mu(1-0.05), \mu(1+0.05)]$$

τ =Probability (per pulse) of being outside the interval

Notice

Even if we assume ±5% intensity fluctuations with guaranteeing the 5-sigma confidence level, secure QKD over about 90 km is possible with a reasonable number of signal transmissions.

Conclusions & Outlook

- **Device characterizations on modulation devices:**
  1. Remove the **IID assumption**.
  2. **Intervals** are the sufficient condition and **no detailed characterization is needed**, such as an error distribution and the independence among the actual phases and intensities.

- **High performance:**
  Long distant secure QKD is possible up to (with $N = 10^{12}$ pulse emissions)

$$\ell \sim 90\mathrm{km}$$

  with realistic assumptions on the modulation devices of

  $\pm 5\%$ intensity and $\pm 1.7^\circ$ phase intervals.

- **Experimental scheme for the characterization:**
  How to guarantee the phase and intensity intervals are important future works.

- **Application to another QKD setting:**
  To apply our theory to another setting, say the MDI setting.