Twin field QKD with discrete phase randomisation

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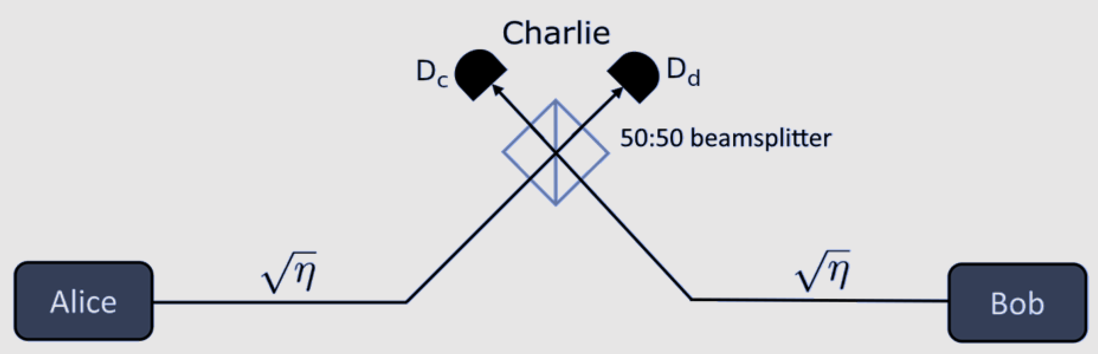
Twin-Field QKD

- **Twin-field QKD** offers **improved key-rate scaling** with channel loss, opening the way for **distance records**.



- Many practical variants with weak laser sources: sending-or-not sending, phase-matching…
- Almost all use the **decoy-state method**, which requires users to generate **phase-randomised coherent states**.

Continuous phase randomisation (CPR)

- **Key assumption** of the decoy state method: the phase is randomised **continuously** and **uniformly**.

$$\frac{1}{2\pi}\int_0^{2\pi} \left|\sqrt{\mu}e^{i\theta}\middle\rangle\!\middle\langle\sqrt{\mu}e^{i\theta}\right| d\theta = \sum_{n=0}^{\infty} p_{n|\mu}\,|n\rangle\!\langle n|$$

- However, this is **hard to achieve in practice**!
- Two methods:
  - **Passive randomisation**: Turning the laser on and off. But there are **correlations** between one pulse and the next.
  - **Active randomisation**: Using a phase modulator. But this approach randomized over a **discrete** set.
- Both methods may have **security loopholes**…

BB84 with DPR

- The security of decoy-state BB84 with discrete phase randomisation (DPR) has been considered in [Cao14].
- There, the authors show that a DPR coherent state can be decomposed as

$$\sum_{n=0}^{M-1} \left|\sqrt{\mu}e^{\frac{2\pi n}{M}}\middle\rangle\!\middle\langle\sqrt{\mu}e^{\frac{2\pi n}{M}}\right| = \sum_{n=0}^{M-1} p_{n|\mu}\,|\lambda_n^{\mu}\rangle\!\langle\lambda_n^{\mu}|$$

where the states $|\lambda_n^{\mu}\rangle$ have a small dependency on μ. The yield probabilities for two states arising from different intensities can be bounded by the **trace distance** bound

$$|Y_n^{\mu} - Y_n^{\nu}| \leq \sqrt{1 - |\langle\lambda_n^{\nu}|\lambda_n^{\mu}\rangle|^2}$$

- Thanks to this, the security of the protocol can be proved, in combination with linear programming techniques.
- Results show that the performance is close to CPR with only ten random phases.

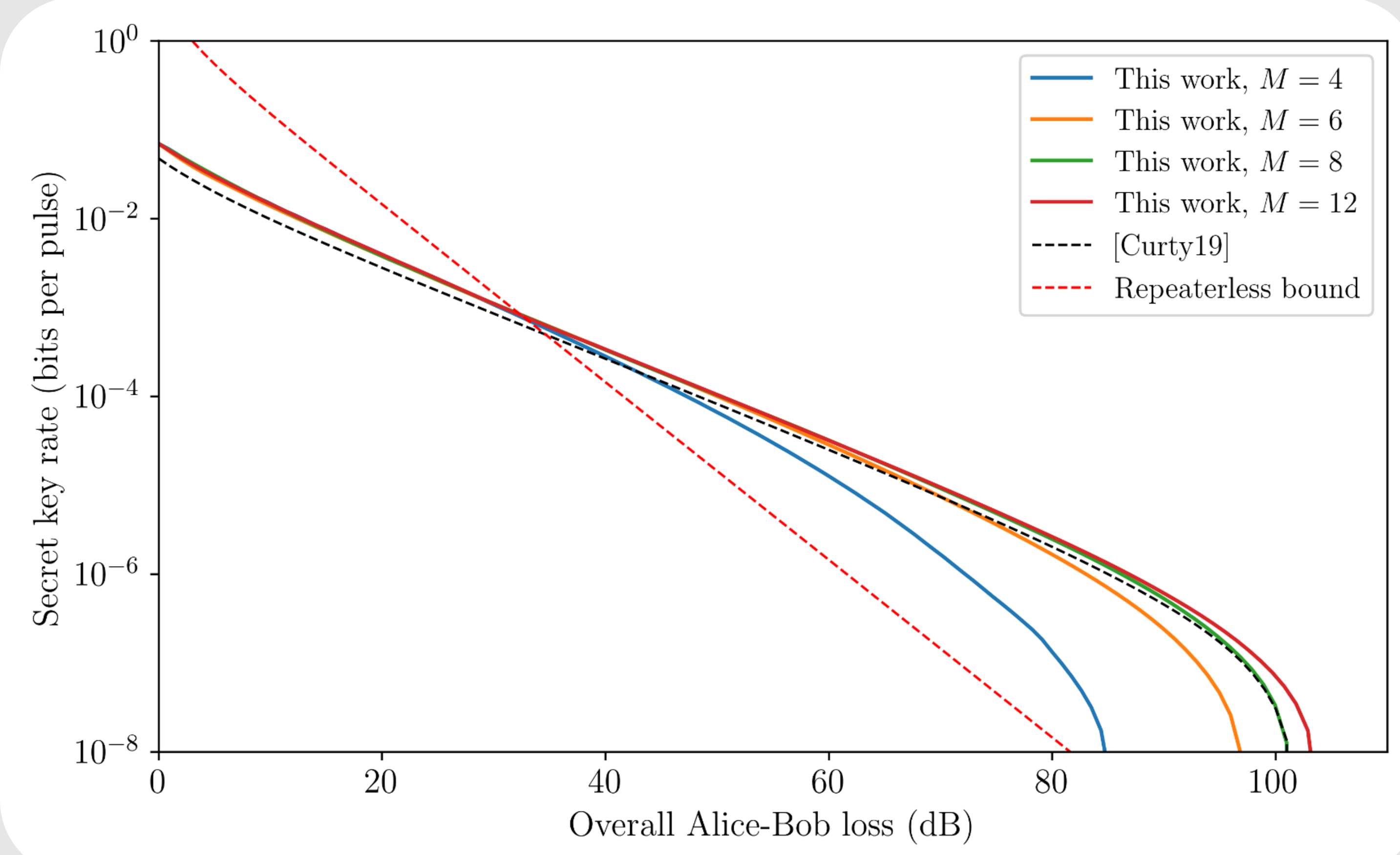
TF-QKD with DPR

- Using similar ideas, we **propose** a TF-QKD variant that relies exclusively on **discrete phase randomisation.**
- It has a similar setup as in [Curty19], but the phase of test mode emissions is randomised discretely rather than continuously.
- Because of DPR, it is very difficult to find an analytical expression for the phase-error rate.

Numerical security analysis

- The linear programming approach of [Cao14] doesn't work well here.
- Instead, we express a bound on the phase-error rate as the solution of a **semidefinite program** (SDP), where the constraints use the data from the test mode emissions.
- For this, we modify the approach proposed in [Primaatmaja, 19], which can prove the security of any discretely modulated MDI-QKD type protocol using semidefinite programming.
- In principle, their results should be directly applicable here. However, the number of constraints is $O(n^4)$, where n is the number of pure states sent by each user. The large number of states sent here makes this approach unfeasible.
- Instead, we use a far smaller number of constraints, mostly based on the **trace distance bound**.

Results



- Remarkably, we obtain **better results** than [Curty19]!
- The key reason is that, using DPR, we can **postselect** the test mode rounds in which the users used the same (or opposite) phases. We can use the postselected data to obtain a **better estimate** for the **phase-error rate**.
- This post-selection is not possible using CPR, as Alice and Bob have infinitely many phase choices, and they will never use exactly the same phase.

Conclusions

- Most TF-QKD variants rely on the emission of laser pulses with a **continuous random phase**, which is difficult to achieve in practice.
- We propose a TF-QKD variant that relies on **discrete phase randomisation**.
- The use of discrete randomisation allows to perform a test mode **phase post-selection**.
- Because of this, our proposal obtains **higher secret key rates** than a similar protocol based on continuous randomisation.

References

[Curty19] Curty, M., Azuma, K., & Lo, H. K. (2019). Simple security proof of twin-field type quantum key distribution protocol. *npj Quantum Information, 5(1)*, 1-6.
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[Primaatmaja19] Primaatmaja, I. W., Lavie, E., Goh, K. T., Wang, C., & Lim, C. C. W. (2019). Versatile security analysis of measurement-device-independent quantum key distribution. *Physical Review A, 99(6)*, 062332.

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