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Security proofs for continuous-variable quantum key distribution

Anthony Leverrier

Inria Paris

QCrypt 2020 - virtual

10 August 2020

Disclaimer

- ▶ there won't be any COVID joke, sorry!
- ▶ I won't really talk about experimental stuff
- ▶ I won't talk about the zillion CVQKD protocols out there, only about a couple that are
 - ▶ simple to describe
AND
 - ▶ simple to implement
- ▶ the talk might contain controversial¹ statements such as:

"sure, BB84 is a fine protocol, but it's high time we move to CV protocols!"

¹but nothing too provocative! e.g. I won't talk about the quantum Internet

Outline

Discrete versus continuous variables

- ▶ BB84 vs CVQKD

State-of-the-art for security proofs

- ▶ Gaussian vs discrete modulation of coherent states

Next steps, open questions

- ▶ finite size setting, general attacks

Discrete versus continuous variables

Two natural/simple qkd protocols

BB84

- ▶ so natural that it would have been discovered eventually (much later?), even without B&B
- ▶ distribute copies of $|00\rangle + |11\rangle$
- ▶ measure with $\mathbb{1} = \frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1| + |+\rangle\langle +| + |-\rangle\langle -|)$

CVQKD = THE ∞ -dim generalization

- ▶ distribute copies of $|00\rangle + \lambda|11\rangle + \lambda^2|22\rangle + \dots + \lambda^k|kk\rangle + \dots = e^{\lambda\hat{a}^\dagger\hat{b}^\dagger}|\text{vacuum}\rangle$
- ▶ measure with $\mathbb{1} = \frac{1}{\pi} \int_{\mathbb{C}} |\alpha\rangle\langle\alpha| d\alpha$, with coherent state $|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{k=0}^{\infty} \frac{\alpha^k}{\sqrt{k!}} |k\rangle = e^{\alpha\hat{a}^\dagger}|\text{vacuum}\rangle$
a.k.a. *coherent detection*, *heterodyne* measurement, or *double-homodyne* measurement

alternative for CVQKD

- ▶ measure the quadratures (homodyne detection) \implies the setup of the EPR paper from 1935!²

²formalized much later: Ralph (99), Reid (00), Cerf & al. (01), Grosshans-Grangier (02), Weedbrook & al. (03)...

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Theory vs practice

BB84 in practice: NOT SO SIMPLE!

- ▶ single photons are usually prepared via $|00\rangle + \lambda|11\rangle + \lambda^2|22\rangle + \dots + \lambda^k|kk\rangle + \dots$ and heralding
 - ▶ experimentally-friendlier version of BB84 relies on (phase-randomized) coherent states
- ⇒ same states as in CVQKD! **requires to ~~tweak~~ completely redo the analysis (multi-photon pulses)**
- ▶ photon counters hard to implement replaced by threshold detectors
- ⇒ infinite-dimensional Fock space, same as CVQKD!

CVQKD: pretty much as advertised

- ▶ same states, same measurement as specified (modulo a finite precision issue)
- ▶ P&M version: Alice prepares $|\alpha\rangle$ with $\alpha \sim \mathcal{N}_{\mathbb{C}}(0, \sigma^2)$ (or α from finite set)
- ▶ implementations today closely match the original protocols

my personal (provocative) view:

BB84 was nice to launch the field of quantum crypto, but the future belongs to CV!

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ok... are there any drawbacks to CVQKD?

of course not!

More challenging theory³

- ▶ ∞ dimension (same is kind of true for implementations of DVQKD)
- ▶ continuous-valued AND unbounded measurement operators
- ▶ quality of the correlations measured via *covariance matrix (unbounded)*, not QBER or CHSH score
⇒ conceptual difficulties, but rather *clean problems*

Experimental performance: seems *less robust to loss* than DV

- ▶ losses are filtered out for DV: discard the no-click events⁴
- ▶ all pulses are there for CV, but noisier ⇒ harder to estimate the channel parameters precisely
- ▶ very large blocks required for long distance

³modern DVQKD protocols are also very complex!

⁴modulo some assumptions on the detectors (as demonstrated by Vadim Makarov!)

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P&M version of CVQKD

- ▶ Alice sends $|\alpha_1\rangle, \dots, |\alpha_n\rangle$
 - ▶ α_k either Gaussian variable or element from a finite set (e.g. $\{\pm\alpha, \pm i\alpha\}$)
- ▶ Bob measures with heterodyne detection: gets $\beta_1, \dots, \beta_n \in \mathbb{C}$.
 - ▶ typical model: $\beta = t\alpha + \gamma$ with fixed *attenuation* t and Gaussian noise $\gamma \sim \mathcal{N}_{\mathbb{C}}(0, 1 + t^2\zeta)$
 - ▶ $t \sim 0.1$ at 100km
 - ▶ ζ is the *excess noise*: $10^{-3} - 10^{-2}$ in implementations \implies hard to measure precisely
- ▶ classical postprocessing (essentially identical to DV)
 - ▶ key map: from Bob's data (reverse reconciliation⁵)

$$\beta_1, \dots, \beta_n \rightarrow x_1, \dots, x_n \in \{0, 1\}$$

- ▶ parameter estimation: covariance matrix of α, β
(informally, want to estimate t, ζ) \implies *the most challenging part*
- ▶ privacy amplification

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CV or DV?

- ▶ photons live in ∞ -dimensional Fock space: why encode information on some qubit space?
- ▶ the simplest states to prepare are coherent (= Gaussian) states! (already used in telecom industry)
- ▶ coherent (heterodyne) detection is needed for the whole telecom industry: huge incentives!
- ▶ more natural/efficient to encode information in phase-space: continuous variables!
- ▶ what about DI / MDI /TF QKD? those don't really work with CV... Well, they're only needed because we don't quite know how to implement vanilla BB84 :-)

\implies *qubits are good for computing, less for communicating* classical information

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State-of-the-art for security proofs

QKD as a tomography problem

Goal

get sufficient correlations between A and B to upper bound on Eve's information about \vec{x} :

- ▶ composable security: $H_{\min}^{\epsilon}(X_1, \dots, X_N | E)_{\rho_{AXE}^{(n)}}$
- ▶ asymptotic bound⁶: $H(X_1 | E)_{\rho_{AXE}}$ (single channel use)

major difficulty already for collective attacks in the asymptotic limit: ρ_{AXE} is a pure

- ▶ 4-qubit state for BB84: 16 parameters
- ▶ 4-mode state in $\text{Span}(|i, j, k, \ell\rangle : i, j, k, \ell \in \mathbb{N})$ for CVQKD; even truncating the Fock space to 10 photons/mode gives more than 10^4 parameters

One (only?) useful tool: von Neumann entropy maximized by Gaussian states $S(\rho) \leq S(\rho_G)$

QKD version: $\chi(\beta, E)_{\rho} \leq \chi(\beta, E)_{\rho_G}$ (ρ_G the Gaussian state with same covariance matrix as ρ)

\implies asymptotic security against collective attacks for protocols with Gaussian modulation

[Wolf, Giedke, Cirac PRL 2005] [Garcia-Patron, Cerf PRL 2006] [Navascues, Grosshans, Acin PRL 2006]

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Last few years

- ▶ Gaussian modulation: essentially solved!
- ▶ discrete modulation: still very open, and somewhat pressing issue!

Gaussian modulation: $\alpha \sim \mathcal{N}_{\mathbb{C}}(0, \sigma^2)$

2 approaches to prove security against general attacks:

Entropic uncertainty relation [Furrer & al. PRL 2012]

- ▶ discretize $\implies X_{\delta}, P_{\delta}$
- ▶ $H_{\min}^{\epsilon}(X_{\delta}|E)_{\rho^n} + H_{\max}^{\epsilon}(P_{\delta}|B)_{\rho^n} \geq -\log \frac{\delta^2}{2\pi} S_0^{(1)}\left(1, \frac{\delta^2}{4}\right)^2$

but protocol requires squeezed states, bound not believed to be tight

Gaussian de Finetti [AL PRL 2017]

crucial fact: protocol is symmetric wrt $U(n)$ (instead of S_n for BB84) \implies stronger de Finetti

- 1 symmetrize in phase-space \implies restrict to $\rho^n = \rho_G^{\otimes n}$
- 2 equipartition property: $H_{\min}^{\epsilon}(X_{\delta}|E)_{\rho_G^{\otimes n}} \approx nH(X_{\delta}|E)_{\rho_G}$
- 3 $H(X_{\delta}|E)_{\rho_{\text{Gauss}}} = H(X_{\delta}) - \chi(X_{\delta}; E)_{\rho_G}$
- 4 estimation of CM \implies upper bound on $\chi(X_{\delta}; E)_{\rho_G}$

missing element: finite precision of measurements

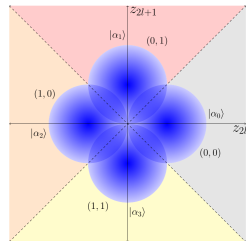
Discrete modulation

Lorenz & al. (2004), Namiki, Hirano (2006), Zhao & al. (2009), AL, Grangier (2009), Sych, Leuchs (2010), Bradler, Weedbrook (2017)...

- ▶ easier to implement: same as coherent telecom industry
 - ▶ better for error correction
- ⇒ huge interest from industry, H2020 CiViQ

theory is more complicated

- ▶ EUR don't help (coherent states)
- ▶ $U(n)$ -symmetry is broken ⇒ no Gaussian de Finetti, unclear how to perform PE
- ▶ non-Gaussian E-B protocol: pb for bounding vN entropy
⇒ even asymptotic collective attacks are nontrivial!



Very recent finite-size analysis of a 2-state protocol

[Matsuura & al. arXiv : 2006.04661]

- ▶ mapping to a qubit protocol, but 2 states aren't sufficient to get very good performance
- ▶ unclear how to extend to 4 states or more

Two recent results on the 4-state protocol

asymptotic security for collective attacks, assuming channel parameters are known

main idea: convex optimization to bound Holevo information / conditional vN entropy

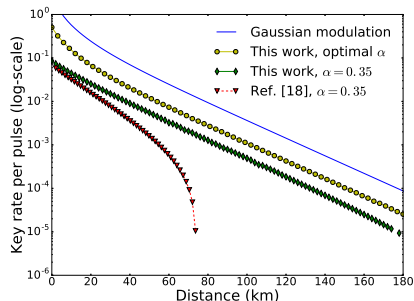
Ghorai, Grangier, Diamanti, AL PRX 19

- ▶ SDP to bound $f(\rho) = \text{tr}((\hat{q}_A \hat{q}_B - \hat{p}_A \hat{p}_B)\rho)$
+ Gaussian optimality
- ▶ pro: simple optimization, can be extended to larger constellations
- ▶ con: bounds are not tight

Lin, Upadhyaya, Lütkenhaus PRX 19: better (for now)

- ▶ SDP to bound $H(X|E)$ directly: $f(\rho) = D(\mathcal{G}(\rho) || \mathcal{Z}[\mathcal{G}(\rho)])$
- ▶ pro: much tighter key rate
- ▶ con: nonlinear objective function, optimization more involved (follows techniques from Coles & al. Nat. Comm. 16)

$$\begin{aligned} & \text{minimize } f(\rho) \\ & \text{subject to } \rho \succeq 0 \\ & \text{tr}(\rho \hat{O}_{PM}) = o_{PM} \\ & \text{tr}(\rho) = 1 \end{aligned}$$



(from Lin & al. 2019)

Limitations of these 2 works

- ▶ only numerical results
- ▶ the true SDP cannot be solved directly because of ∞ dim \implies heuristic truncation of Hilbert space
 - ▶ seems ok, but no proof
 - ▶ see recent work by Upadhyaya & al. (poster # 92)
- ▶ only deal with ideal detection
 - ▶ rather easy to patch with approach from Ghorai & al. (still won't be tight)
 - ▶ harder for Lin & al. (see poster # 28)
- ▶ parameter estimation is ignored!
- ▶ what about larger constellations? the results from Ghorai & al. should get much tighter

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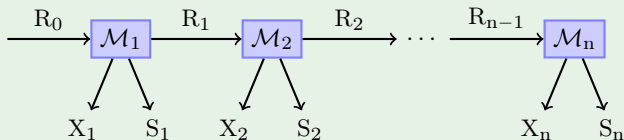
- ▶ finite size setting, general attacks

Next steps, open questions

Going further: security against general attacks, finite-size setting?

a potential approach: the entropy accumulation theorem [Dupuis, Fawzi, Renner 2016]

- ▶ gives tight bounds for DV QKD
- ▶ successfully applied to device-independent QKD [Arnon-Friedman & al. 2018]



- ▶ $H_{\min}^\epsilon(X_1 \cdots X_n | ES^n)_{\rho^n} \geq n \min_{\sigma} H(X_1 | ES_1)_{\sigma} - O(\sqrt{n})$

difficulties to adapt EAT to CV:

- ▶ requires some test. Seems much harder to define than for DV: should be related to covariance matrix, but not clear how
- ▶ test depends on some unbounded continuous outcome

The real difficulty: unbounded variables

Given $x_1, \dots, x_n \in \mathbb{R}$ i.i.d. from unknown distribution with $\langle x \rangle = 0$, estimate $\langle x^2 \rangle$

random sampling doesn't work, e.g.,

$$x_i = \begin{cases} 0 & \text{with prob } 1 - \varepsilon \\ \pm C & \text{with prob } \varepsilon/2 \end{cases}$$

$\implies \langle x^2 \rangle = C^2\varepsilon$ but requires to sample a fraction $\geq 1 - \varepsilon$

Solution: rotational symmetry

- ▶ apply random $R \in O(n)$ to \vec{x} : $\vec{x} \rightarrow R\vec{x}$,
- ▶ sample first k coordinates
- ▶ concentration of measure gives tight bounds

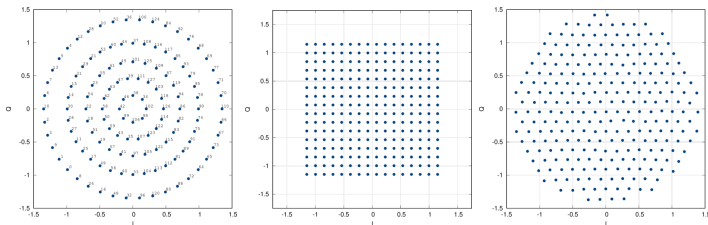
\implies bound on CM for protocols with Gaussian modulation \implies security against collective attacks [AL PRL 2015]

Unclear how to perform PE for discrete modulation at the moment...

unless restricted attack setting (e.g. Papanastasiou, Pirandola arXiv:1912.11418)

Optimal constellation?

- ▶ infinitely precise Gaussian modulation isn't physical \implies finite constellations
- ▶ 2 or 3 states aren't enough to get good performance
- ▶ 4 states are ok, but larger constellations should allow for larger variance
 - ▶ improved asymptotics: key rate $\times 10$?
 - ▶ better for PE, for finite-size
 - ▶ "easy" for telecom industry



- ▶ previous results should extend there but unclear how tractable will be the numerics
- ▶ very large constellations might allow for continuity-type arguments (Kaur, Guha, Wilde arXiv:1901.10099)

Conclusion and perspectives

Conclusion and perspectives

- ▶ CV are well-suited to large-scale deployment of QKD:
 - compatible with telecom industry standards
- ▶ security is quite involved (infinite dimension, unbounded variables, discretization, truncation...) but *not more than for modern DVQKD protocols*, and with *cleaner problems*?

challenges for theorists

- ▶ is it possible to apply entropy accumulation?
- ▶ how to perform parameter estimation without rotation symmetry? (for discrete modulation)
- ▶ what is better: 4 states or large constellations?

Thanks!

