Threats to quantum cryptography in presence of losses

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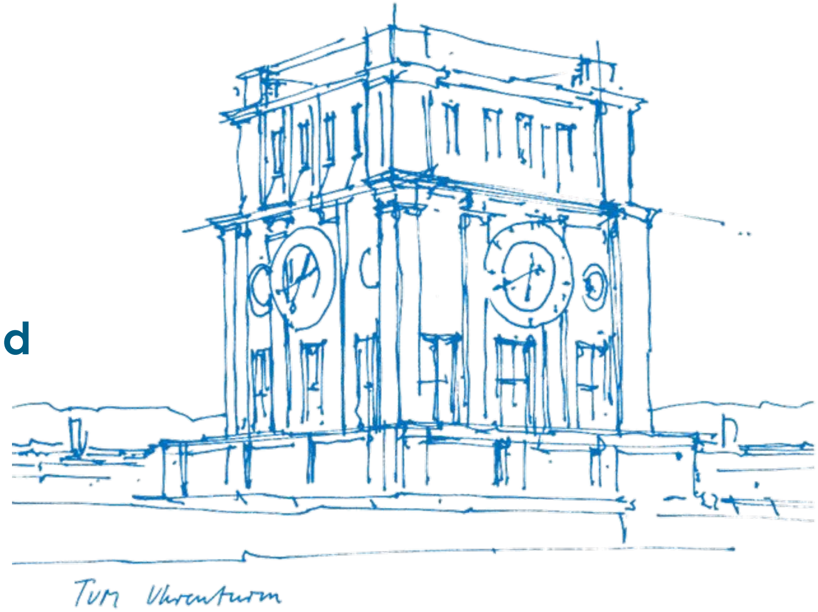


Contents

- Theoretical Quantum Systems Design (TQSD)
  - Research activities
- Problems of direct transmission
  - Qubit, transmission and transducer limit
- Quantum crypto background
  - Public key, authentication, oblivious transfer
- Vulnerabilities
  - Public key, authentication, oblivious transfer
- Mitigation
  - Quantum teleportation via entanglement distribution

Theoretical Quantum Systems Design (TQSD)

- Working group in **Technische Universität München (TUM)** for **theoretical foundations of quantum system** design.

- Research agenda
  - **Emulation** of future hybrid quantum communication networks.
  - Quantum system design, in particular the interaction of the **different resources** that can be used for **high data rates** and **reliable** communication.
  - Investigating new potential use cases enabled by adding quantum communication resources, especially, **entanglement-assisted communication**.
  - **Secure** message transmission over quantum channels.

TQSD current projects

- Q.TOK
  - Quantum **token-based authentication** and secure data storage
  - In collaboration with 7 memory projects in **Grand Challenge of Quantum Communication**.
- QD-CamNetz
  - Working on a **quantum internet demonstrator** with three nodes
  - Joint project with TU Dresden
- QuaPhySI
  - Investigating quantum technologies for **Physical Layer Service Integration**
- and more

Qubit limits

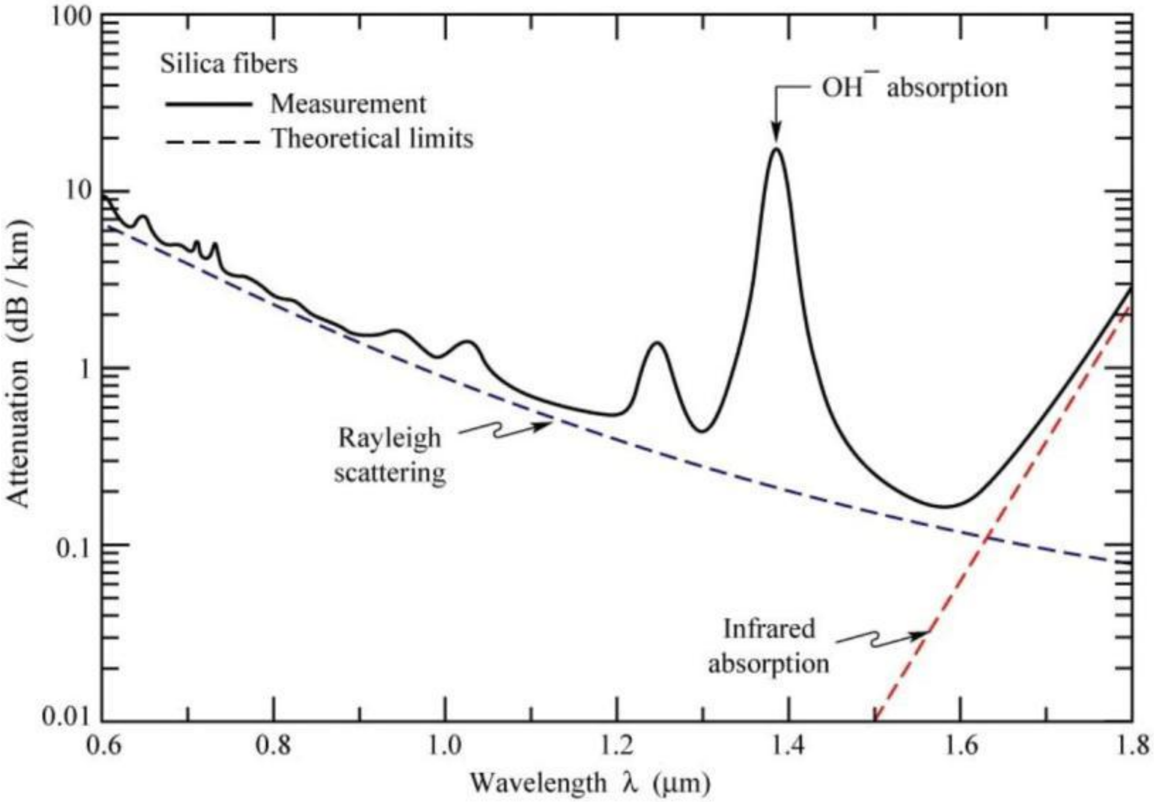
- Constraints from quantum mechanics
  - No measurement without state altercation
  - No cloning
  - No copy and retransmission.
- The sender may not know the qubit to send.
  - For BB84 QKD, the sender may know the qubit state.
  - For quantum money, the owner can't know.
- Sometimes nobody knows the qubit state.
  - E.g. QPUF-based quantum token.
  - Prevents malicious cloning but the loss from a link failure is irrevocable.

Transmission Limits: Losses & Absorption

- Losses due to bending
- Impurities, splicing, and connections lead to absorption/scattering
- Intrinsic absorption in every material
- Dependent on implementation, absorption may effect qubit loss in transmission

Transmission Limits: Absorption

- e.g. Absorption in standard SiO_2 fibres



Transmission Limits: Dispersion and Broadening Effects

- Wavelength dependency of refractive index/propagation speed
- In reality nonzero spectral linewidth of signal pulse (thermal & intrinsic effects)
- Thus temporal broadening of pulses
- Wavelength dependency of optical hardware may lead to loss
- Degraded indistinguishability of photons => failure rate of quantum operations

Transduction Limits

- Losses in conversion from flying to stationary qubit
- Highly dependent on implementation
- Most often light-matter interaction
- Described by cavity quantum electrodynamics (QED)
- Two-level system (TLS) in resonator cavity as stationary qubit
- Light entering cavity as flying qubit

Crypto background

- Public-key **encryption** and digital **signature**
- Identity **Authentication**
- **1-2 Oblivious Transfer** : Alice has two messages **{m0,m1}**, Bob **chooses one** to receive. They **DO NOT TRUST** each other
  - Alice cannot guess Bob's choice
  - Bob cannot learn the other message

Vulnerability: Public-key encryption

- Public-key scheme, based on qubit rotations*
  - **classical message** encrypted through a **quantum public key**
  - yields a **quantum ciphertext**
  - receiver decrypts via a **classical private key**
- Key-pair generation
  - **Example** (using 4-bits numbers):
    - **private_key = { 7, 1, 2, 12} (random)**
    - Consider angles **{7/16 *Pi, 1/16 *Pi, 2/16 *Pi, 12/16 *Pi}**
    - Get 4 qubits in |**0>** state, rotate them by the above angles
- Encryption
  - Rotate public-key qubits by 0 or Pi
- Decryption
  - Apply inverse (w.r.t key-gen phase) rotations

**Nikolopoulos, Georgios M. "Applications of Single-Qubit Rotations in Quantum Public-Key Cryptography." Physical Review A, vol. 77, no. 3, Mar. 2008. Crossref, https://doi.org/10.1103/physreva.77.032348.*

Vulnerability: Public-key encryption and digital signature

- Problems of quantum keys
  - with enough copies, adversaries can learn the private key
  - receiver must make sure there is a limited number of copies at all times
  - what if a public key is lost? (while encrypting, while sending it…)

	Assumed: Benign Loss	**Assumed: Malicious Steal**
Reality: Benign Loss	Receiver re-sends the key to the honest user who lost it	Receiver refuses retransmission, honest user can no longer send an encrypted message
Reality: Malicious Steal	Attackers gain more copies of the key, and later leak the private key	Receiver refused retransmission, successfully prevents an attack

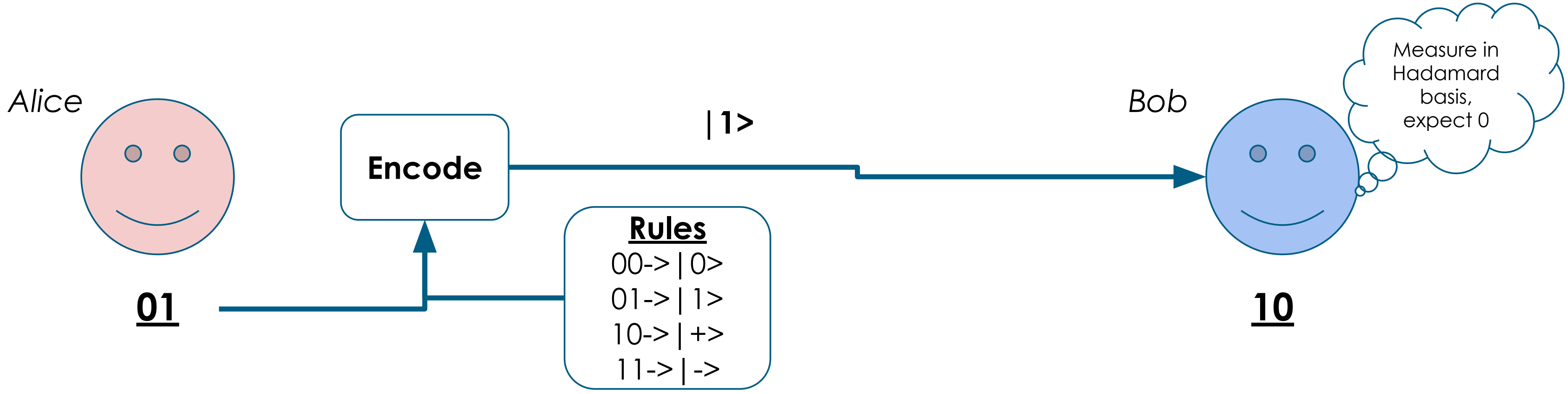
Vulnerability: Public-key encryption and digital signature

- Similar problem in quantum digital signature scheme by Gottesman and Chuang*
- Other protocols under investigation

**Gottesman, Daniel, and Isaac Chuang. "Quantum digital signatures." arXiv preprint quant-ph/0105032 (2001).*

Vulnerability: Authentication

- Consider (a simplified version of) this protocol by Hong et al*.
  - Alice and Bob **pre-share a classical key**
  - Alice maps every two bits of her key to one of the BB84 states **{|0>,|1>,|+>,|->}**
  - Bob measures and compares according to his bits
  - **Example**



*Hong, Chang ho, et al. "Quantum identity authentication with single photon." Quantum Information Processing 16 (2017): 1-20.

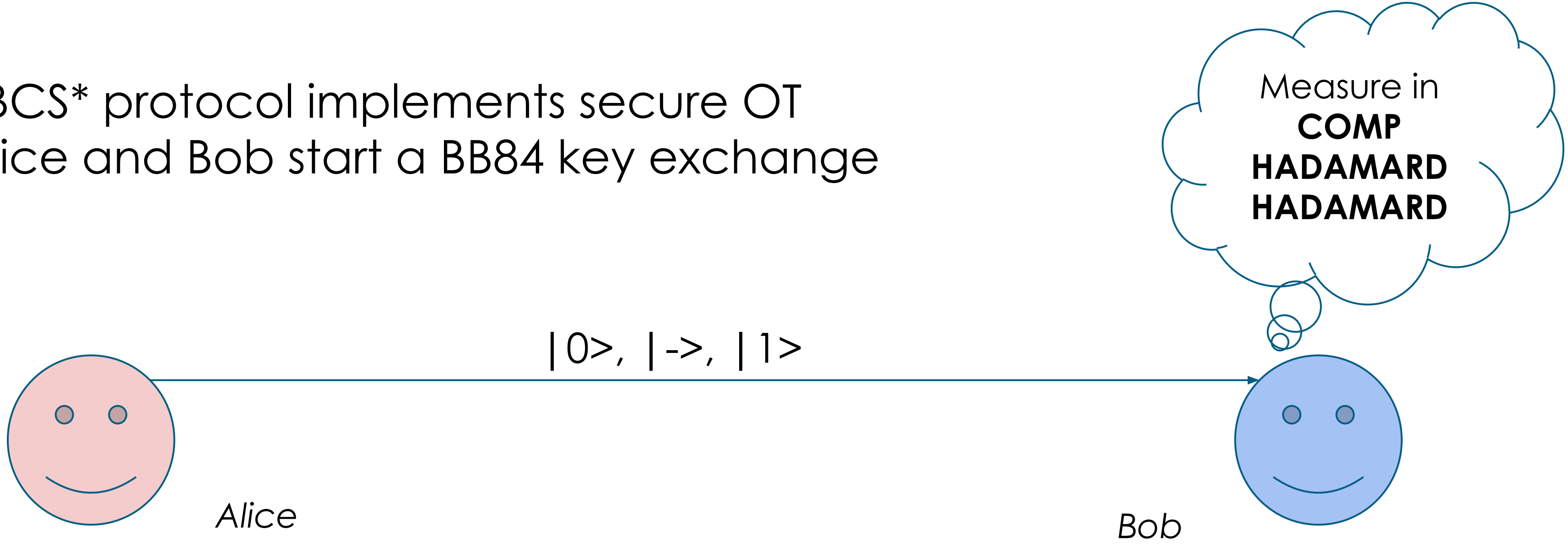
Vulnerability: Authentication

- Multiple copies of the same qubit leak the corresponding key
  - what if a qubit is lost?

	Assumed: Benign Loss	**Assumed: Malicious Steal**
Reality: Benign Loss	Alice resends the qubit to Bob, who can verify her key	Alice will not allow Bob to verify her identity, authentication failed
Reality: Malicious Steal	Attackers gain more copies of the qubit, and later leak the private key bit	Alice avoids an attack

Vulnerability: Oblivious transfer

- BBCS* protocol implements secure OT
- Alice and Bob start a BB84 key exchange



RandBits() = **<u>0,1</u>**,1

<u>0,1</u>,0

- The rest is classical post-processing and communication
- Bob didn't guess some bases in some positions, won't learn both messages

**Bennett, Charles H., et al. "Practical quantum oblivious transfer." Annual international cryptology conference. Berlin, Heidelberg: Springer Berlin Heidelberg, 1991.*

Vulnerability: Oblivious transfer

- What if the qubits are lost?

	Assumed: Benign Loss	Assumed: Malicious Claim
Reality: Benign Loss	Alice resends the qubits to Bob, so that the protocol may continue	Alice will not resend the qubits, threatening the protocol's correctness.
Reality: Malicious Claim	Bob gains more copies of the qubits, possibly learning corresponding key bits	Alice avoids an attack by Bob trying to guess both messages

- Fortunately, there is a simple mitigation
  - Alice just replaces lost qubits with new random qubits (random value and basis)
  - Negligible overhead, preserves security

Mitigations

- Some protocols are **inherently immune**
  - BBCS for OT, Kanamori et al*'s authentication
- For some protocols, **teleportation** mitigates the threat
  - Error happens when sharing entanglement -> still recoverable
  - Following the procedure suggested in **RFC9340**
- Use of **decoy states**
  - First proposed **by Hwang* for QKD**
  - Hong et al. propose their use to detect eavesdroppers.
  - Active adversaries are still a threat, requires information on the channel

**Y. Kanamori, Seong-Moo Yoo, D. A. Gregory and F. T. Sheldon, "On quantum authentication protocols," GLOBECOM '05. IEEE Global Telecommunications Conference, 2005., St. Louis, MO, USA, 2005, pp. 5 pp.-, doi: 10.1109/GLOCOM.2005.1577930.*

*Hwang, Won-Young (1 July 2003). "Quantum Key Distribution with High Loss: Toward Global Secure Communication". *Physical Review Letters*. 91 (5): 057901

Thanks for your attention.

Transduction Limits

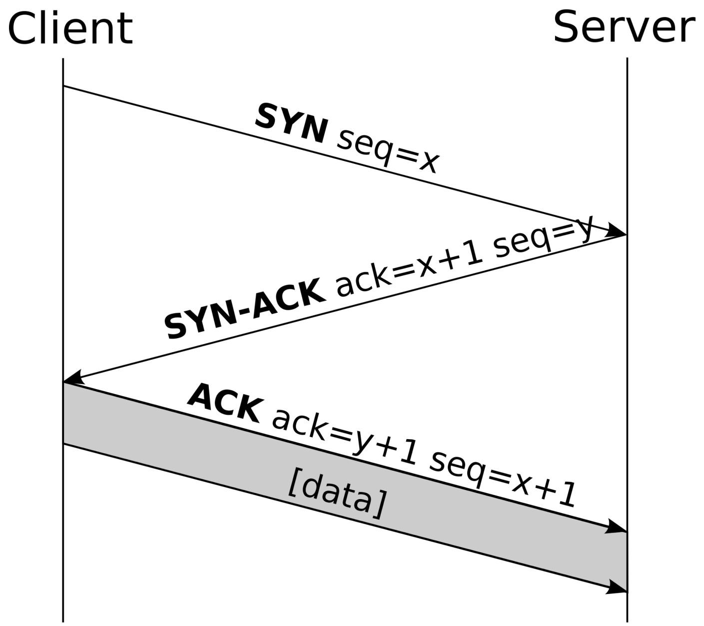
- System dynamics described via:
  - **Emitter decay rate γ**: TLS decay in the cavity mode, approx. by lifetime τ of TLS excited state via $\gamma \approx 1/\tau$
  - **Cavity loss rate κ**: rate of photons exiting cavity, depends on quality factor Q of resonator via $\kappa \propto 1/Q$
  - **Coupling strength g_0 between TLS and photon**, depends on mode volume V_0 of resonator: $g_0 \propto \sqrt{1/V_0}$.
- Different cavity designs with different Q and V_0, like micropillars or photonic crystals, etc.
- Different TLS like quantum dots (QD), vacancy centres, etc.

Crypto Primitives

- **Public-key crypto:** generate a public and private key
  - Anybody can **use the public key to encrypt** a message
  - Only you can **use the private key to decrypt** it
- **Digital signature:** generate a public and private key
  - Only you can **sign a message** with your **private key**
  - Anybody can **verify** your signature with the **public key**

Retransmissions in classical communication

- Messages are lost in modern telecom
- **TCP/IP** stack designed to tolerate losses
- Classically, the solution is simple: **retransmit**
  - Before sending a message, always duplicate it
  - Send the copy, keep original for later retransmissions
- In TCP, receivers send **ACK**s for each packet
  - If no ACK is received for one packet, retransmit
- No threat to classical cryptography
  - Classical information is copyable
  - Computational hardness is not affected



Rotations used in public-key scheme

Rotation by angle **x** around the **y** axis: **R(x)**

R(x) = exp{-ix * Y/2}

Operator Y=i(|1><0|-|0><1|)

Maps **|0>** into **cos(x/2) |0> + sin(x/2) |1>**