Simulation of Satellite and Optical Link Dynamics in Advanced Quantum Communication Networks

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Satellite-based Quantum Repeater Network

Motivation

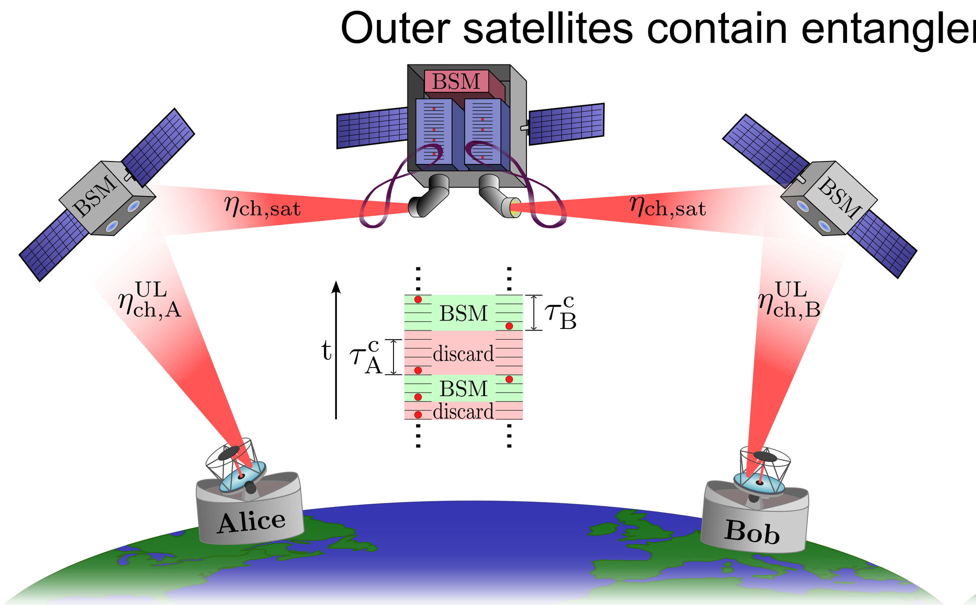
- Future developments in quantum communication and computation demand **inter-continental quantum links**
- Quantum networks on global scale require **long distance quantum repeater connections**
- **Satellite-based** quantum repeater links allow for **minimum number of nodes**

Repeater Architecture

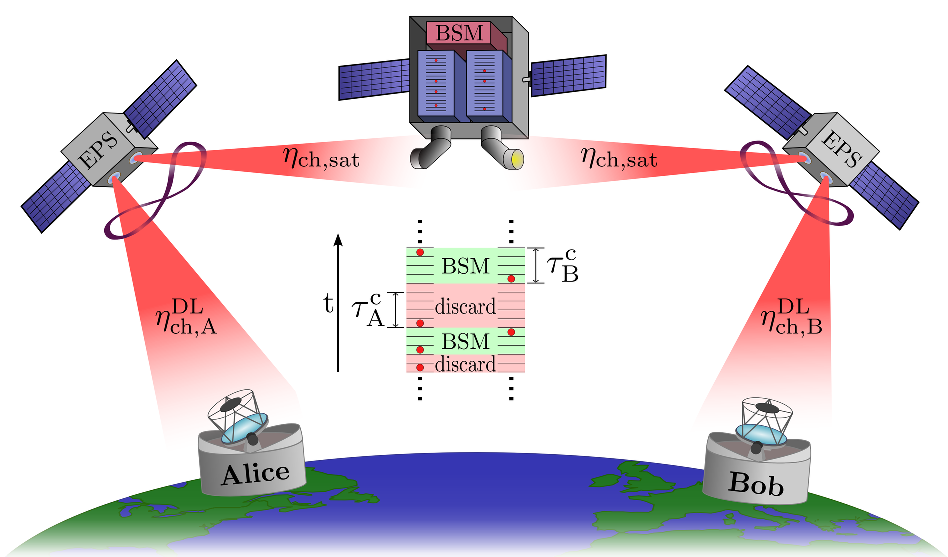
- **One node** repeater with **no entanglement distillation/purification**
- **Bell State Measurement (BSM)** between consecutive clicks in different memories within $\tau^{c}_{A,B}$

$$P_{\mathrm{BSM|A}} = P_{\mathrm{B}}(\tau^{c}_{\mathrm{B}})\left[1 - P_{\mathrm{BSM|B}}\right] \qquad P_{\mathrm{BSM|B}} = P_{\mathrm{A}}(\tau^{c}_{\mathrm{A}})\left[1 - P_{\mathrm{BSM|A}}\right]$$

- **Two configurations:**
  - Uplink (UL): Center satellite contains memories, BSM and entanglement sources; Outer satellites perform BSMs with photons from ground in uplink
  - Dowlink (DL): Center satellite contains memories, nondemolition measurement and BSM; Outer satellites contain entanglement sources



Uplink quantum repeater architecture

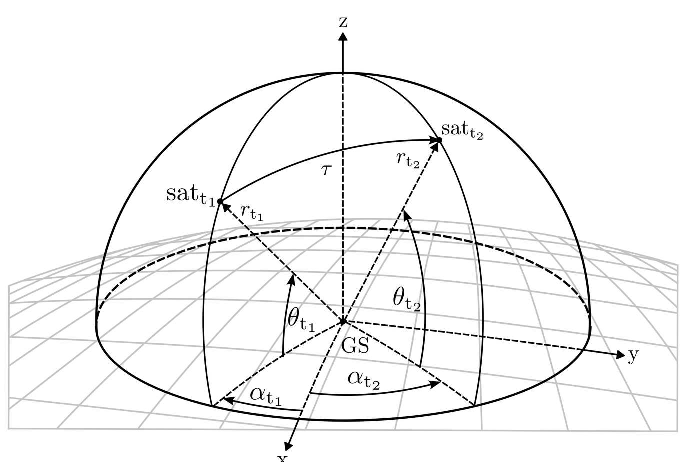


Downlink quantum repeater architecture

Simulation

- Three-dimensional satellite-to-ground and inter-satellite links
- Including **Earth's rotation** and **satellite eclipse** condition
- Time-varying azimuth and elevation
- Highest BSM rate: **zenith pass**
- 1-2 connections per day
- days with two passes: lower maximum elevation → lower BSM rates

New York to Berlin

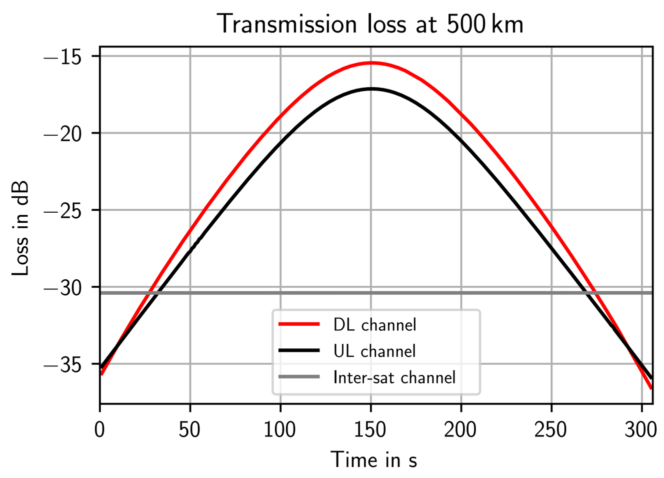


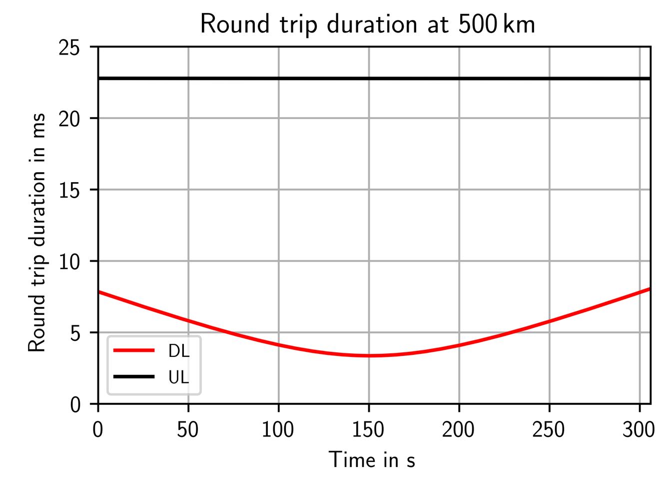
General ground-station pass geometry

BSM Rate Analysis

Transmission Losses

- Uplink:
  - **beam wandering**
  - **beam broadening**
  - atmospheric attenuation
- Downlink:
  - **fiber coupling**
  - atmospheric attenuation
- Inter-satellite link:
  - fixed distance and loss



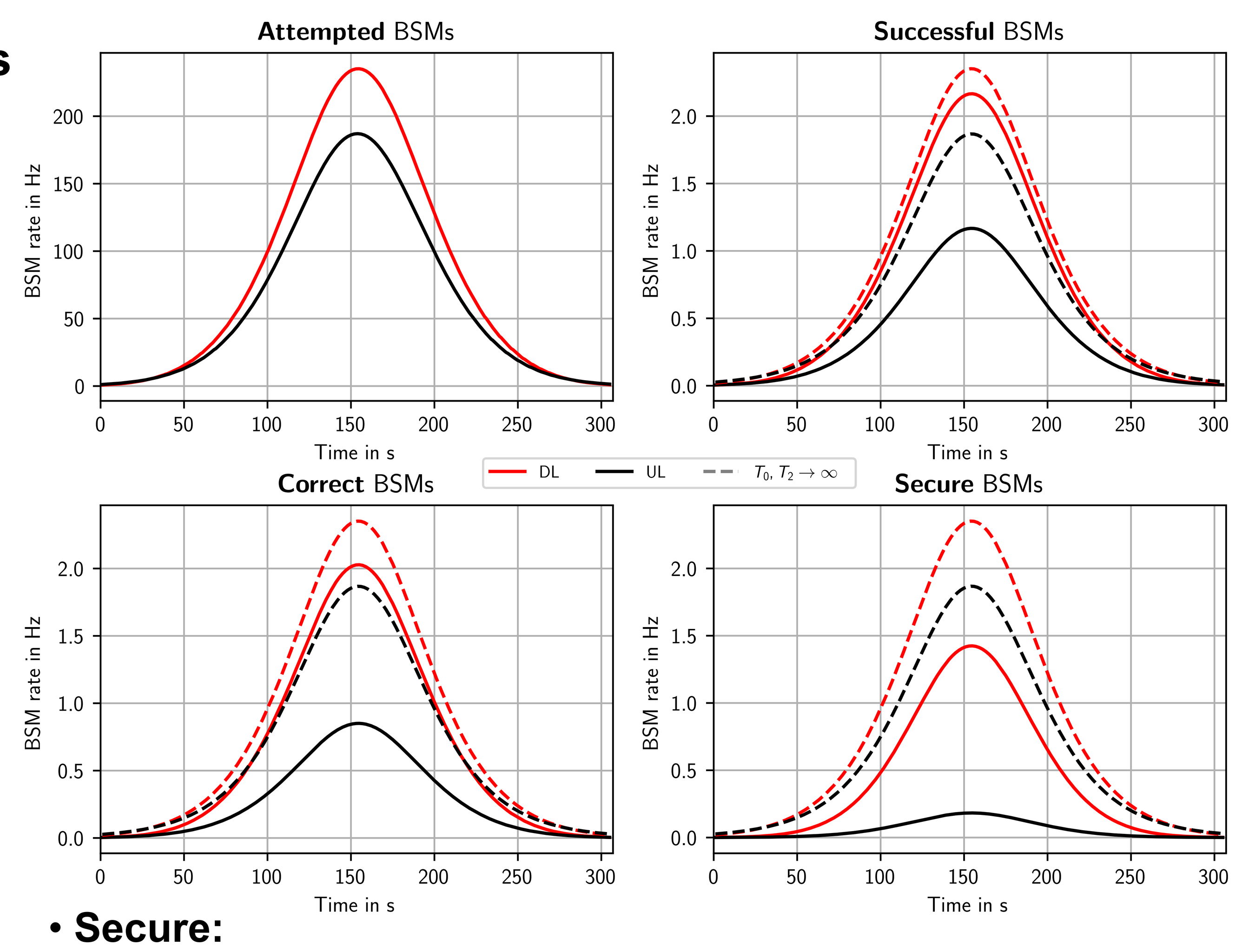


Round trip duration

- Uplink: determined by **inter-satellite distance**
- Downlink: determined by **distance to ground station**

Bell State Measurements

- **Attempted:**
  - two events within cutoff → **try to perform BSM**
- **Successful:**
  - none of the photons is lost → **valid result**
  - exponential loss model $P_{\mathrm{loss}}(t) = 1 - \eta_{\mathrm{mem}} e^{-t/T_0}$
  - decay time: $T_0 = 100\,\mathrm{ms}$
  - efficiency: $\eta_{\mathrm{mem}} = 10\,\%$
- **Correct:**
  - none (or both) photons flip → **correct result**
  - exponential flip probability $P_{\mathrm{flip}}(t) = \frac{1}{2}\left(1 - e^{-t/T_2}\right)$
  - coherence time: $T_2 = 60\,\mathrm{ms}$
  - only phase flips (no bit flips)



- **Secure:**
  - performance measure including **success and error rate**
  - similar to **secure key rate** in Quantum Key Distribution (QKD)

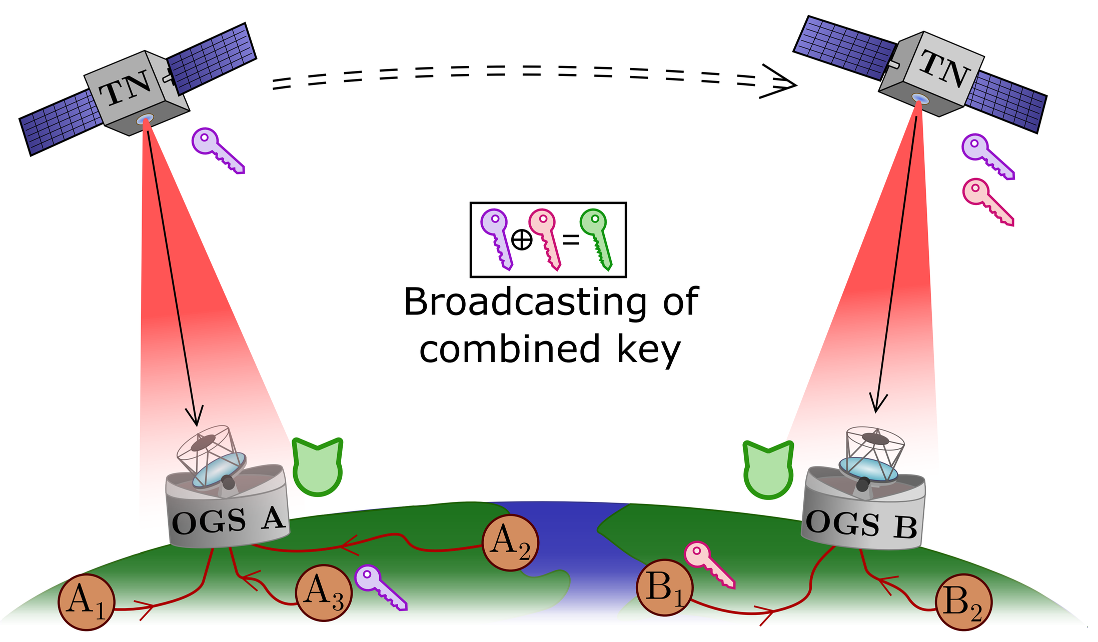
$$R_{\mathrm{sec}} = R_{\mathrm{succ}}\left[1 - H_2(\mathcal{E})\right] \qquad \mathcal{E} = \frac{R_{\mathrm{err}}}{R_{\mathrm{succ}}}$$

- Inter-satellite distance **adapted to ground stations**: $\nu_{\mathrm{sep,sat}} = \nu_{\mathrm{sep,gs}}$
- **Lower satellite altitudes** lead to **higer number of BSMs**

Trusted and Untrusted Nodes in QKD

Motivation

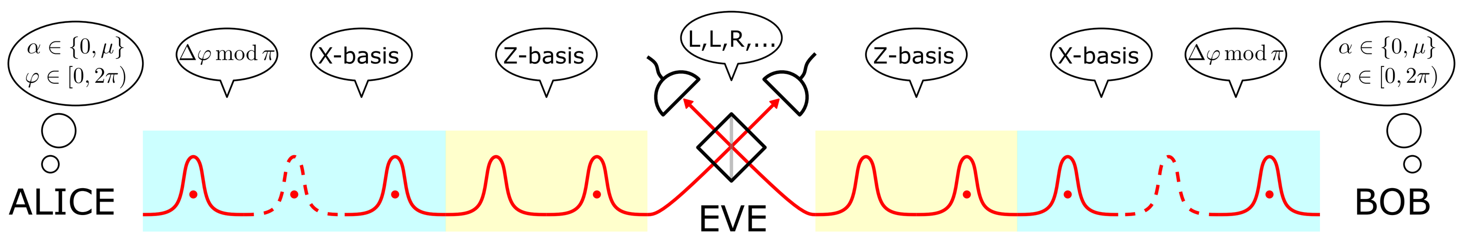
- Until repeater networks become available, **Trusted Nodes** (TN) are required to perform QKD at global scales
- TN can be mounted on satellites (safe) or on the ground (less so)
- Key relay from an **Optical Ground Station** (OGS) to the end-users can be the security bottleneck in a global-scale TN QKD network
- Recent QKD protocols such as **Twin-Field** and **Mode-Pairing QKD** yield a repeater-like secure key rate with existing technology and can be employed to remove TN from the ground segment
- Mode-Pairing is more suitable than Twin-Field in satellite QKD as it does not require global phase-locking of the signals



Scheme for global-scale QKD with trusted satellites and untrusted ground stations

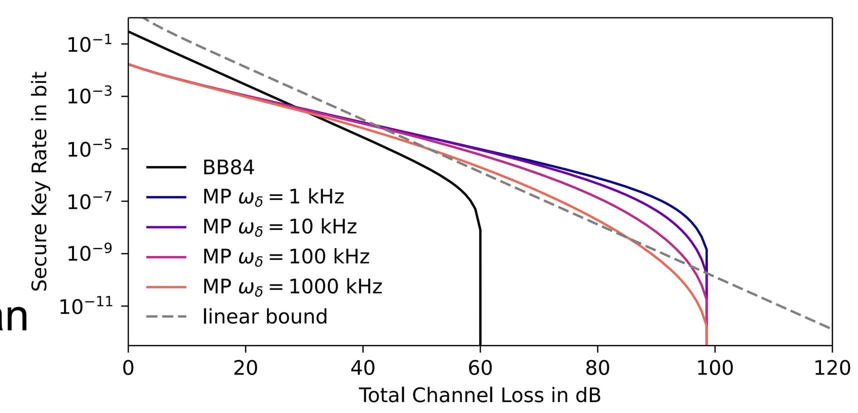
Description of Mode-Pairing QKD

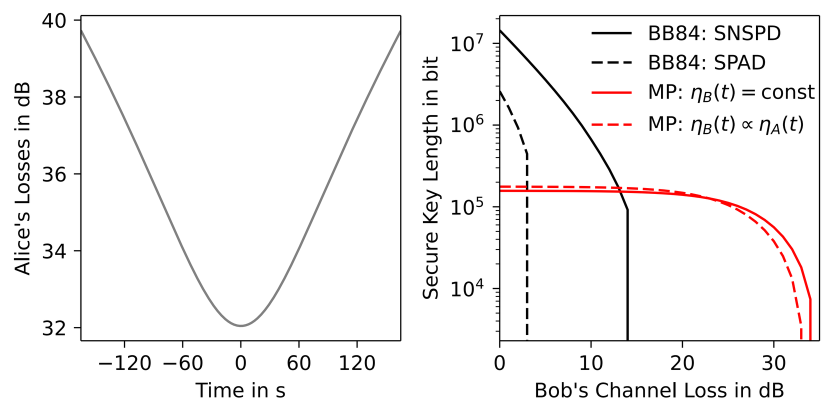
- **State preparation**: each round, Alice and Bob prepare a phase-randomised coherent state (intensity μ) or vacuum (intensity 0)
- **Measurement**: each round, the central node performs single-photon interference measurements, the click pattern (L or R) is announced
- **Mode pairing**: detections are grouped in pairs according to a preselected algorithm
- **Basis assignment**: for each pair Alice and Bob assign a basis:
  - Z-pair: (0, μ) and (μ, 0)
  - X-pair: (μ, μ)
  - 0-pair: (0, 0)
- **Basis sifting**: Alice and Bob announce the label of each pair and the invalid pairs are discarded
- **Key mapping**:
  - Z-pairs: for Alice (0, μ) → 0, (μ,0) → 1, the oppsite for Bob
  - X-pairs: pairs with equal relative phases mod π are post-selected
    - (L, L) or (R, R) → Alice and Bob assume equal phases
    - (L, R) or (R, L) → Alice and Bob assume opposite phases
- **Parameter estimation**: QBER in the X and Z basis are estimated
- **Key distillation**: if QBER are low enough, a secure key from Z bits is obtained via error correction and privacy amplification



Mode-Pairing QKD in Satellite Links

- One fibre link and one LEO satellite link
- **Challenges:**
  - **Doppler shift**: has to be corrected, residual errors can be modelled as an effective linewidth increase
  - **Time-varying transmission**: protocol parameters shall be optimsed considering a block post-processing over the whole pass





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