Simulation of Satellite and Optical Link Dynamics in a Quantum Repeater Constellation

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Satellite-based Quantum Repeater Network

Motivation

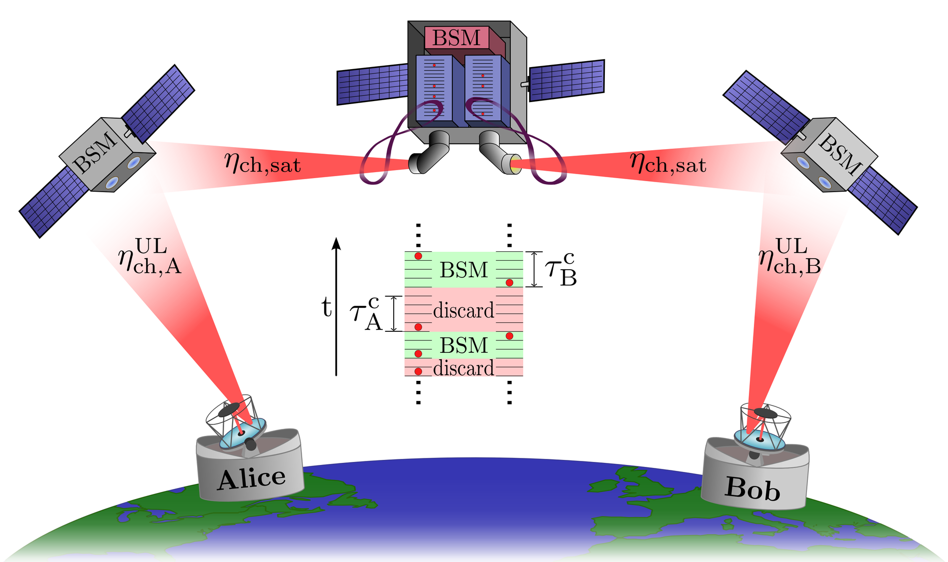
- Future developments in quantum communication and computation demand **inter-continental quantum links**
- Quantum networks on global scale require **long distance quantum repeater connections**
- **Satellite-based** quantum repeater links allow for **minimum number of nodes**

Repeater Architecture

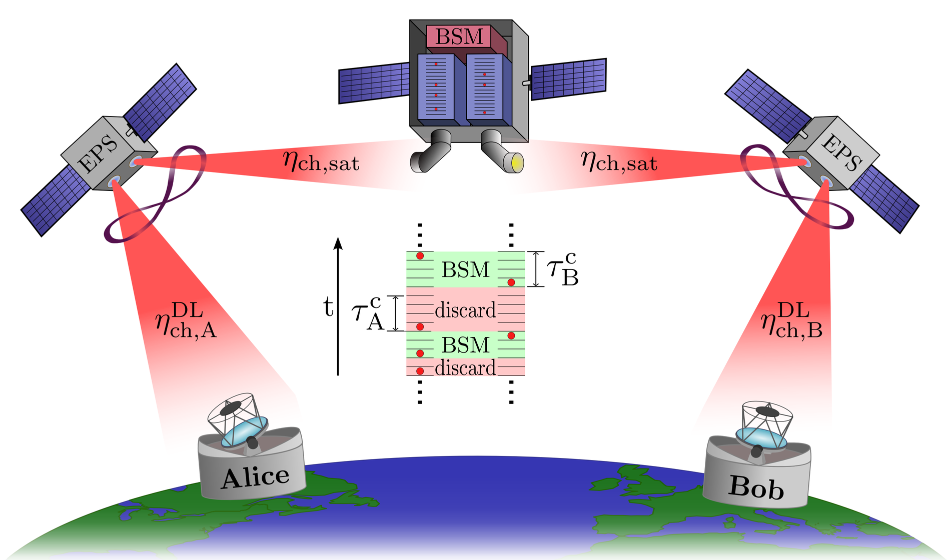
- **One node** repeater with **no entanglement distillation/purification**
- **Bell State Measurement (BSM)** between consecutive clicks in different memories within $\tau^{c}_{A,B}$

$$P_{BSM|A} = P_B(\tau^c_B)\left[1 - P_{BSM|B}\right] \qquad P_{BSM|B} = P_A(\tau^c_A)\left[1 - P_{BSM|A}\right]$$

- **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

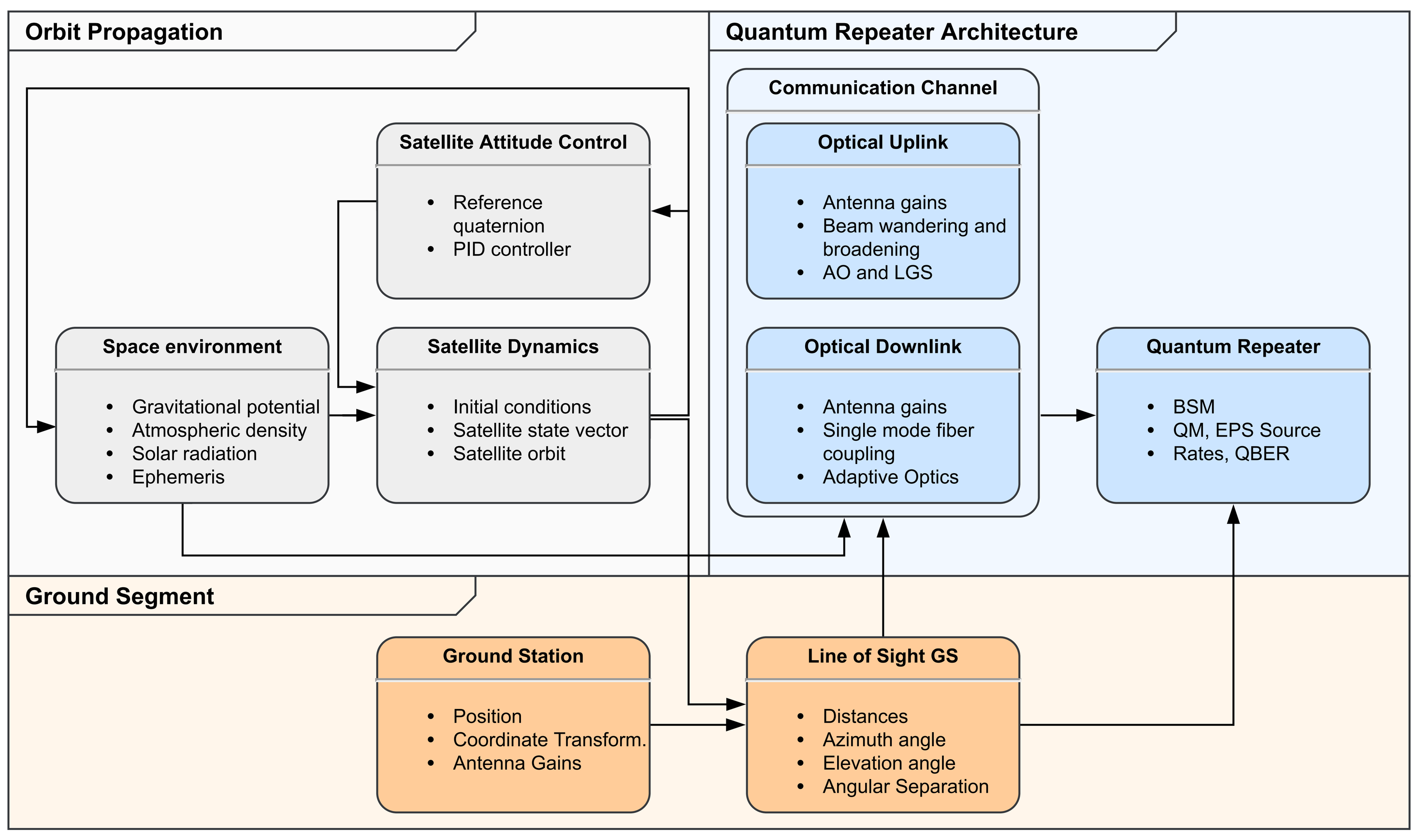


Downlink quantum repeater architecture

End-to-End Simulation Model

Simulation

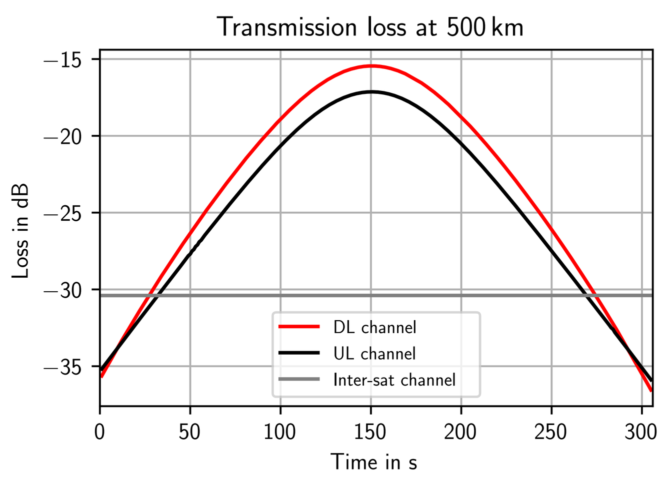
- Full **six degrees of freedom** satellite dynamics simulation
- **Arbitrary orbits** based on Kepler elements
- Including **Earth's rotation** and **satellite eclipse** condition
- **Three-dimensional** satellite-to-ground and inter-satellite links
- Analyze different operating scenarios → here: New York - Berlin

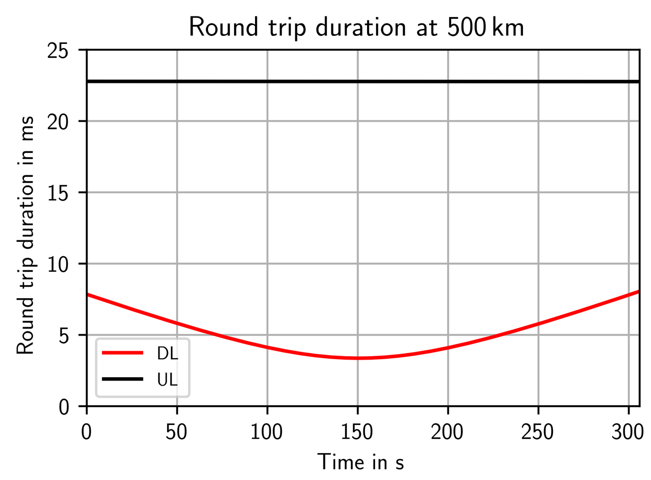


BSM Rate Analysis

Transmission Losses

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



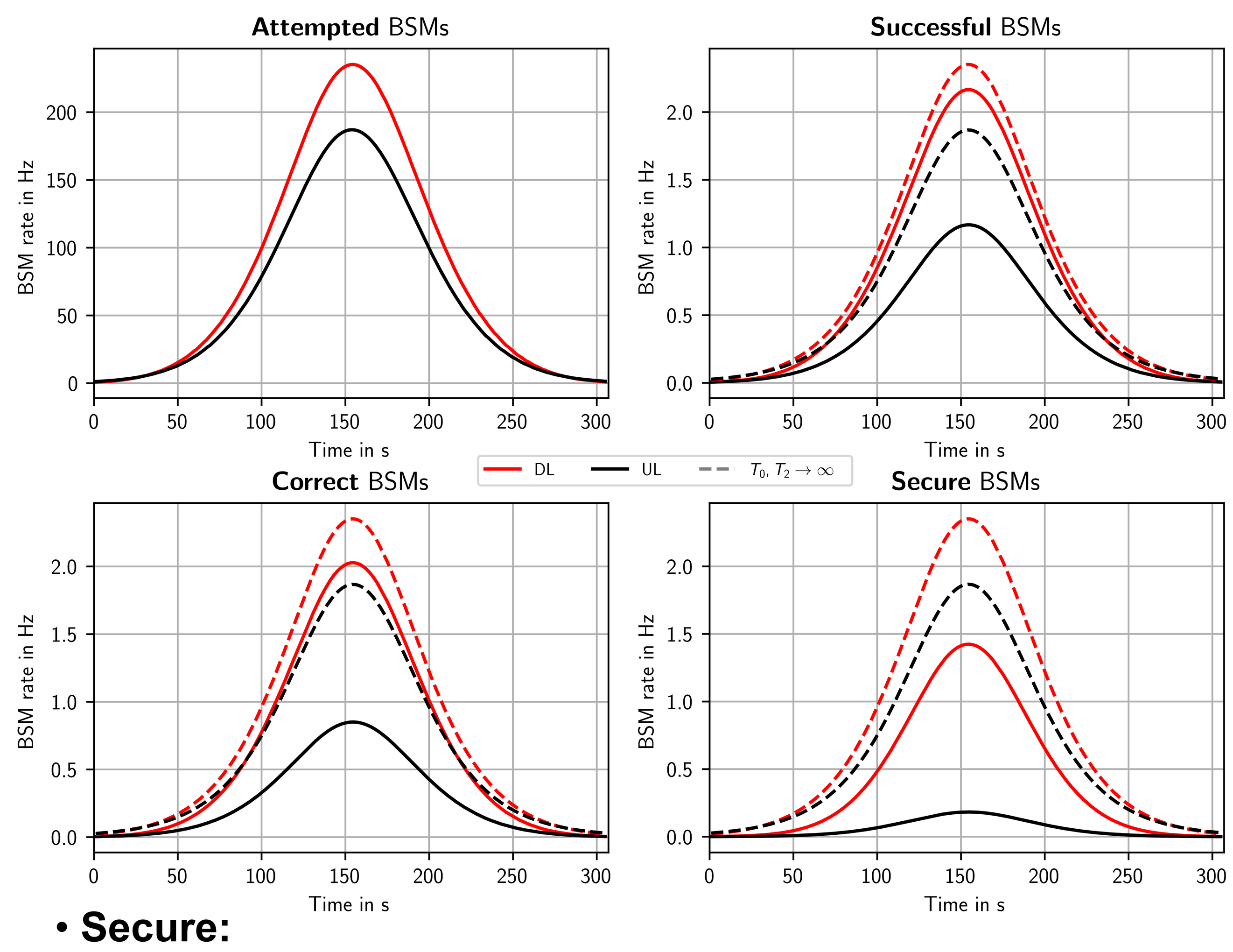


Round trip duration

- time between storage and information about entangled partner
- 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 $P_{loss}(t) = 1 - \eta_{mem} e^{-t/T_0}$
  - decay time: $T_0 = 100\,\mathrm{ms}$
  - efficiency: $\eta_{mem} = 10\,\%$
- **Correct:**
  - none (or both) photons flip → **correct result**
  - exponential flip probability $P_{flip}(t) = \frac{1}{2}\left(1 - e^{-t/T_2}\right)$
  - coherence time: $T_2 = 60\,\mathrm{ms}$
  - only phase flips (no bit flips)

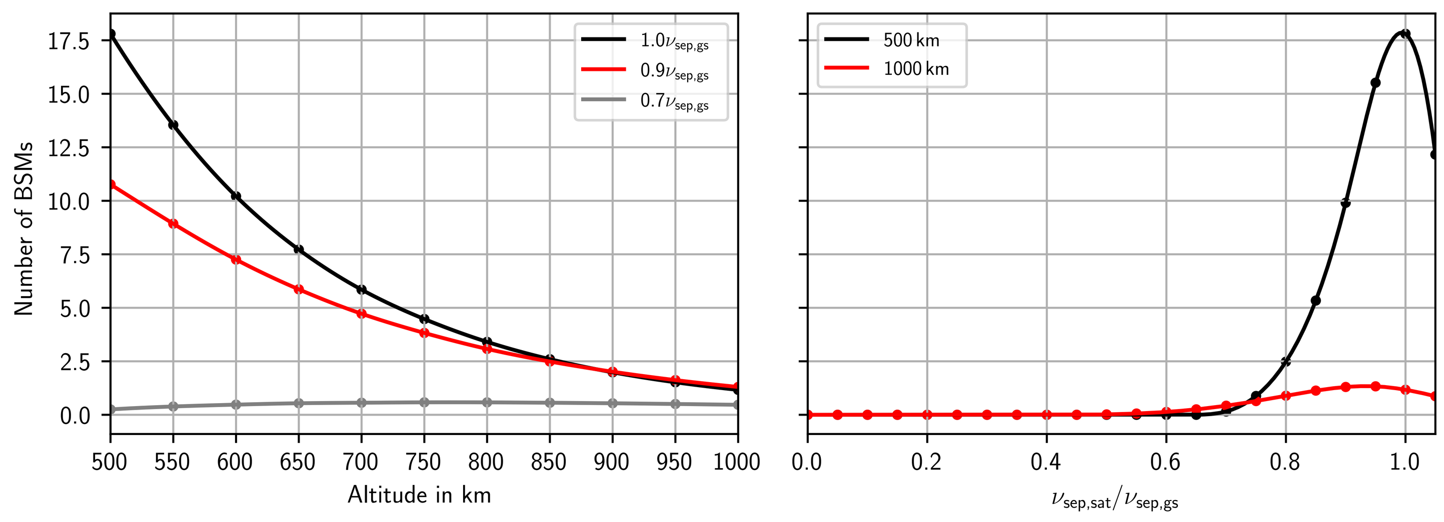


- **Secure:**
  - performance measure including **success and error rate** → subject to optimization
  - similar to **secure key rate** in quantum key distribution

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

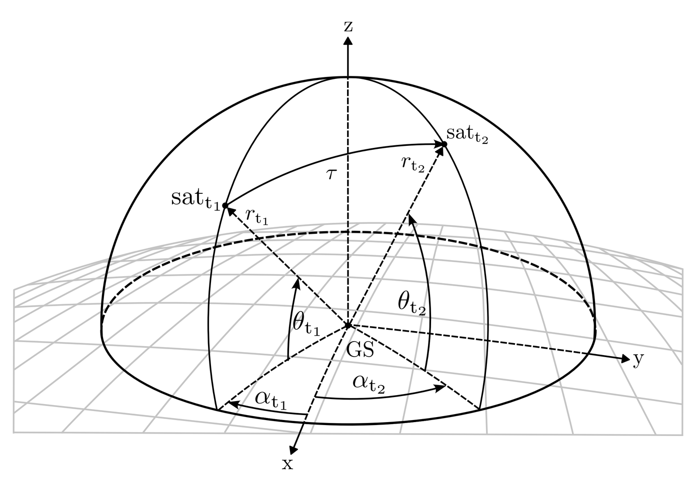
Orbit Analysis

Satellite altitude and inter-satellite distance analysis

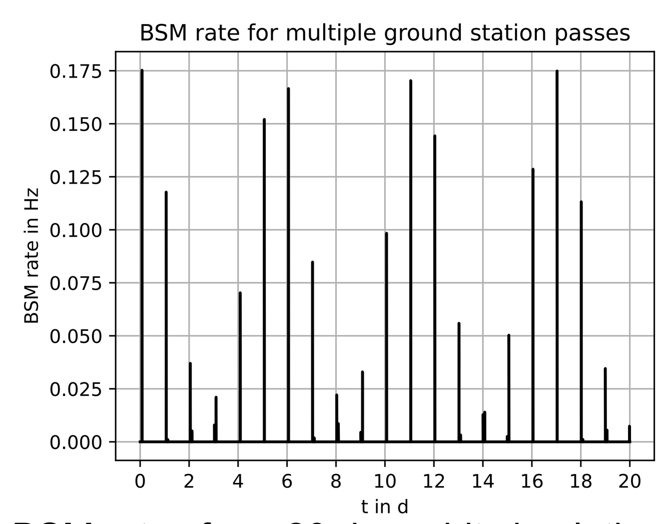


- Inter-satellite distance **adapted to ground stations**: $\nu_{sep,sat} = \nu_{sep,gs}$ → **lower satellite altitudes** lead to higer number of BSMs
- Decreasing inter-satellite distance reduces BSM rate
  - **below 60-70%** → **no line-of-sight** to ground
  - **control distance** to optimize communication link

Three-dimensional satellite ground-station pass



General ground-station pass geometry



BSM rates for a 20 day orbit simulation

- **General pass geometry:**
  - time-varying azimuth angle α and elevation angle θ
  - highest BSM rate: **zenith pass** ($\theta \to 90°$)
  - deviations from zenith pass due to Earth's rotation → lower BSM rates
- Long-term evolution: **1-2 connections per day**
  - days with two passes: **lower maximum elevation** → lower BSM rates

Conclusion

- Uplink and downlink architecture for three-satellite **one-node quantum repeater**
- **Analytic BSM rates** including exponential loss and error models
- Arbitrary **three-dimensional ground station passes and orbit parameters** → **time-resolved entanglement distribution** over each pass
- **Varying entanglement distribution rate** over multiple passes due to Earth's rotation → assessment of **long-term performance**

Outlook

- Add **additional repeater node**
- In-depth simulation of **quantum memory physics** and error models
- Operating scenarios with **multiple ground stations**

Acknowledgments

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