ETH
Eidgenössische Technische Hochschule Zürich
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Distributed Computing

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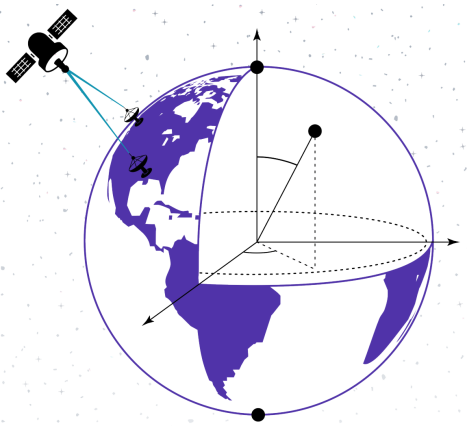
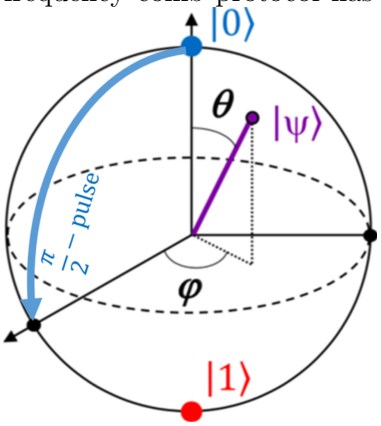
Entanglement Optimization for Quantum Mobile Networks



Global quantum networks based on mobile platforms (e.g., satellite constellations, high-altitude platforms, ground stations) are among the most promising approaches to deliver entanglement across long distances, enabling quantum teleportation, superdense coding, key exchange and distributed quantum computing [7, 8, 4]. However, realizing such networks at scale remains hindered by critical limitations: (i) free-space / satellite links suffer from time-varying attenuation, pointing error, and intermittent visibility, reducing the probability of successful photon arrival [2, 6]; (ii) quantum memories (for storage and entanglement swapping) have limited coherence times or storage durations; (iii) existing routing and scheduling protocols typically assume static or centrally-coordinated networks, and do not optimize for mesh-wide entanglement yield under dynamic topology, memory decay, and resource contention [11, 3, 4].

Long-lived quantum memories have seen substantial recent progress: for instance, a single-qubit memory based on trapped ions with coherence times exceeding 10 minutes was demonstrated [10]. A rare-earth–doped solid-state optical memory using a spin-wave atomic frequency comb protocol has achieved coherent storage of light for up to one hour [5, 13].



Nevertheless, such advances remain largely decoupled from protocol-level designs (PHY, MAC, routing) for entanglement distribution in dynamic, mobile, multi-hop networks. Survey-level analyses (e.g. on space-based quantum repeaters) emphasize that memory coherence times should match or exceed network link dynamics (tens of milliseconds to seconds) to enable usable entanglement delivery [1].

Thus, there is a need for cross-layer, resource-aware protocol design that jointly considers realistic link physics, quantum memory limitations, scheduling/medium access, and routing/swapping — and also addresses where and when to store entanglement so that useful quantum resources are available where and when needed.

Additional Resources

- Code and simulation tools and tutorials: GitLab Repo
- Quantum Mobile Networks Seminars (online): Course Material and Youtube Playlist
- List of Open Quantum Projects (e.g., Simulators): QOSF

Research Questions

In this project, we tackle the following research questions, grouped by the impacted networking layer.

- **PHY Layer**
  - RQ-PHY-1: How can adaptive physical-layer parameter tuning (e.g., photon emission rate, beam pointing accuracy, modulation/waveform selection) based on estimated free-space channel conditions maximize the success probability of qubit arrival while minimizing loss and decoherence?
  - RQ-PHY-2: Given estimated link availability windows (due to satellite visibility dynamics) and limited quantum memory coherence times, how should per-link entanglement generation be scheduled and multiplexed to maximize the injection rate of usable Bell pairs into the network under time-varying conditions?
- **MAC Layer: Link Scheduling**
  - RQ-MAC-1: Can decentralized or distributed MAC-level scheduling protocols (neighbor selection, time-slot allocation) avoid collision or quantum interference and thereby maximize the collision-free entanglement throughput in a mobile mesh network environment?
  - RQ-MAC-2: What learning-based or negotiation-based MAC policies can manage competing entanglement flows from multiple neighbor pairs under memory occupancy constraints and unpredictable link availability, so as to maximize network-wide entanglement distribution?
- **Routing Layer: Swapping and Path Selection** [12, 9]
  - RQ-R-1: How to design routing (entanglement-swapping) protocols with fidelity- and memory-aware path metrics, to maximize expected end-to-end entanglement yield (rate $\times$ fidelity) in networks with dynamic topologies and link intermittency?
  - RQ-R-2: How to exploit redundant or multipath swapping routes, possibly combined with probabilistic resource reservation, to maximize long-term entanglement availability and reliability under node/link mobility and decoherence?
- **Application-Layer: Resource Placement and Entanglement Pre-allocation**
  - RQ-APP-1: Given known system resources (satellite trajectories, memory capacities, link availability) and predicted user demand (e.g., ground stations expecting key exchange or teleportation), where and when should entangled qubit–pairs be pre-cached (i.e. stored) to maximize the probability they are available when and where needed?
  - RQ-APP-2: How to design a predictive placement algorithm that dynamically relocates or re-allocates entangled resources (via swapping or re-distribution) in anticipation of usage, while balancing memory coherence decay and storage overhead?
- **Memory Management: Qubit Caching and Coherence Tradeoff**
  - RQ-MEM-1: Given heterogeneous quantum memory types (with different coherence times, storage capacities, retrieval latencies), how to decide when and where to cache entangled qubits to maximize their usability lifetime while minimizing resource waste?

– RQ-MEM-2: How to schedule memory usage and entanglement distribution so as to balance between long-term storage (for future demand) and immediate distribution (for current network needs), considering coherence decay, memory occupancy, and network load dynamics?

Methodology

Use reinforcement learning (RL) and multi-agent learning frameworks, combined with a global network simulation environment that models free-space optical link dynamics, satellite trajectories, quantum memory characteristics (coherence times, capacity), entanglement generation and swapping, and demand patterns. The simulation can be used to evaluate and optimize policies for PHY parameter adaptation, MAC scheduling, routing/swap path selection, resource placement and caching, and memory management under realistic network dynamics.

Interested? Contact us for more information

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