Physical Modeling for Satellite-Based Quantum Networks

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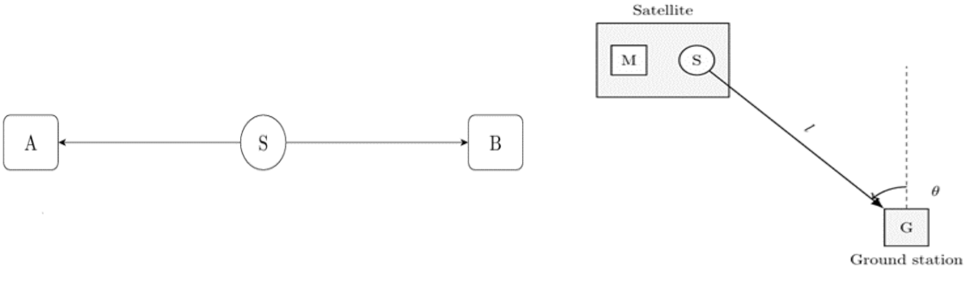
Abstract: This work presents a physical model of satellite quantum communication links supporting network-level simulations of entanglement distribution in LEO constellations, including satellite–satellite and satellite–ground channels with realistic losses, atmospheric effects, and background noise

The development of space-based quantum communication infrastructures represents a key step toward the realization of global quantum information networks. Within the framework of the NQSTI project, in collaboration with CNR and TASI, we investigate the design and performance of a satellite-based quantum network through the development of a dedicated software simulator.

The considered architecture consists of mobile satellite nodes equipped with quantum memories and photon sources, as well as fixed optical ground stations (OGSs), enabling long-distance entanglement distribution across a global network. The reference scenario assumes a Low Earth Orbit (LEO) satellite constellation arranged in a Walker-Star configuration, where satellites within each orbital plane are uniformly spaced and equipped with multiple optical terminals enabling intra-plane, inter-plane, and satellite–ground optical links.

Within this collaborative effort, our contribution focuses on the physical modeling of the quantum communication links used for entanglement distribution. The model describes the generation of entangled photon pairs via spontaneous parametric down-conversion (SPDC) and their transmission through free-space optical channels between satellites and between satellites and ground stations. Satellite–satellite links are modeled assuming vacuum propagation with geometric losses due to beam divergence and negligible background noise. Satellite–ground downlinks additionally include atmospheric attenuation and scattering, which reduce the channel transmittance and the achievable entanglement distribution rate, while sky background noise is accounted for in the fidelity model through uncorrelated detection events.

Using realistic experimental parameters drawn from recent literature, the model provides estimates of entanglement distribution rates and fidelities as functions of link distance, satellite elevation angle, and background conditions. These physical-layer models constitute a key input for the network simulator developed within the project, enabling realistic studies of entanglement distribution strategies, resource allocation, and protocol design in large-scale satellite quantum networks.



(a) Satellite-Satellite link

(b) Satellite-Ground downlink

Fig. 1: Schematic representation of the quantum communication links considered in the model. All nodes are equipped with multimode quantum memories. (a) Satellite–satellite link: a satellite S hosts an entangled photon source that distributes photons to neighboring satellites A and B. (b) Satellite–ground downlink: the satellite hosts the entangled photon source, while the ground station stores the received photons.

References

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