Recent Advances in the Quantum Satellite Communication Systems

Tung Son Do, Thanh Phung Truong, Quang Tuan Do, Hoang Hao Tran, and Sungrae Cho

School of Computer Science and Engineering, Chung-Ang University.

tsdo@uclab.re.kr, tptruong@uclab.re.kr, dqtuan@uclab.re.kr, hhtran@uclab.re.kr, srcho@cau.ac.kr

Abstract

The integration of quantum technologies with satellite systems promises to revolutionize global communication, computation, and sensing. This survey reviews recent advancements in quantum satellite applications, drawing from a diverse body of research. We also examine the application of quantum algorithms, such as quantum annealing and variational methods, for optimizing complex satellite operations like mission planning and resource allocation.

Ⅰ. Introduction

Satellite systems are indispensable for global connectivity, Earth observation (EO), and navigation. Quantum satellites are envisioned as key components of the future Quantum Internet, enabling global-scale quantum communication and connecting distributed quantum computers [1]. This survey provides an overview of these key research thrusts, synthesizing findings from recent literature on quantum satellite technologies

Ⅱ. Literature Reviews

A. Quantum Key Distribution (QKD) via Satellites

Long-distance secure communication is a primary driver for quantum satellite research. Satellites offer a means to extend QKD links beyond the reach of terrestrial fiber networks, which suffer from exponential signal decay.

Both Discrete Variable (DV-QKD) and Continuous Variable (CV-QKD) protocols are being investigated for satellite links. DV-QKD, often based on protocols like BB84 using single-photon encoding (e.g., polarization), has been demonstrated by missions like Micius [2]. Challenges include the need for highly sensitive single-photon detectors and robustness against atmospheric turbulence and background noise [2]. Sagnac interferometers and novel polarization modulation schemes aim to improve stability and repetition rates for such systems [3].

Double-layer quantum satellite networks, comprising GEO and LEO satellites, have been proposed to leverage the advantages of both orbit types (e.g., GEO for broad coverage and LEO for lower channel loss) [4]. Routing and key allocation (RKA) algorithms are critical for managing key-relay services in such complex QSNs [2].

B. Quantum-Enhanced Satellite Operations

Quantum computing offers powerful new tools for solving complex optimization problems encountered in satellite operations. Agile Earth Observation Satellite (AEOS) scheduling is a computationally hard problem, involving selecting optimal imaging requests subject to numerous constraints (attitude maneuvering, energy, storage) [5]. Quantum annealers (e.g., D-Wave systems) are being investigated to solve Quadratic Unconstrained Binary Optimization (QUBO) formulations of these problems [5], [6]. Hybrid quantum-classical pipelines, often involving Hamiltonian reduction techniques or decomposition methods (e.g., Dantzig-Wolfe), are proposed to tackle large-scale instances that exceed the capabilities of current quantum hardware [6], [7]. Variational quantum algorithms like QAOA are also explored [7]. Efficient resource allocation (e.g.,beam placement, frequency assignment) in SatCom systems is another area where quantum optimization can be beneficial. These problems can often be mapped to graph theory problems like clique covering or graph coloring, which are amenable to QUBO formulations for quantum annealers [7].

Ⅲ. Conclusion

The synergy between quantum technologies and satellite systems is paving the way for transformative advancements in global communication, computation, and Earth observation [8]. Research into satellite-based QKD is maturing, with ongoing efforts to enhance key rates, extend distances, and improve robustness against environmental challenges. Quantum optimization algorithms are demonstrating potential for solving complex operational problems in satellite mission planning and resource management, although current hardware limitations necessitate hybrid approaches. QML techniques are beginning to be applied to EO data analysis, offering new avenues for information extraction from satellite imagery.

ACKNOWLEDGMENT

This work was supported in part by the IITP (Institute of Information & Communications Technology Planning & Evaluation) - ITRC (Information Technology Research Center) (IITP-2025-RS-2022-00156353, 50%) grant funded by the Korea government (Ministry of Science and ICT) and in part by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2023-00209125).

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