QCIM-RSMA: Quantum Cognitive Interference Mapping-Aided RSMA for Dynamic Coexistence in GEO-LEO Satellite Networks

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***Abstract*—This study proposes QCIM-RSMA, combining quantum-optimized interference mapping with RSMA for GEO-LEO coexistence. A parameterized quantum optimizer adapts RSMA precoding via real-time CSI and interference feedback, guided by a spatiotemporal map $\mathcal{I}(t, f, \vec{x})$ aimed for efficient spectrum sharing with controlled GEO interference under dynamic LEO channel conditions.**

***Index Terms*—cognitive interference mapping (CIM),quantum machine learning,GEO-LEO coexistence,rate-splitting multiple access (RSMA)**

I. Introduction

The growing demand for non-terrestrial networks (NTNs) necessitates spectrum sharing between LEO (secondary) and GEO (primary) satellite systems, requiring interference-aware transmission [1]. Rate-Splitting Multiple Access (RSMA) has emerged as a robust strategy for such scenarios [2], with recent applications in GEO-LEO coexistence [3], [4]. However, existing approaches using static interference thresholds [5] fail to capture dynamic real-world conditions.

This work proposes QCIM-RSMA, integrating: 1) A cognitive interference map $\mathcal{I}(t, f, \vec{x})$ combining CSI, orbital data, and GEO feedback 2) Quantum-assisted optimization (QCIM) using parameterized circuits [6] to adapt RSMA control parameters 3) Joint precoding optimization under spatio-temporal interference constraints

To the best of the authors' knowledge, this work pioneers quantum-enhanced RSMA framework for dynamic inter-orbit coexistence, addressing both real-time interference management and adaptive resource allocation.

II. System Model

Fig. 1a (Left), illustrates the considered NTNs scenario where a LEO satellite acts as a secondary user coexisting with a primary GEO satellite. LEO employs RSMA to serve K single-antenna users using N_t transmit antennas, while ensuring that interference to the GEO segment remains below a dynamic threshold $\Gamma_{\text{thresh}}(t)$. The RSMA transmission signal expressed as: $\mathbf{x}(t) = \mathbf{p}_0(t)s_0(t) + \sum_{k=1}^{K} \mathbf{p}_k(t)s_k(t)$, where $s_0(t)$ is the common stream and $s_k(t)$ denotes the private stream intended for user k with associated precoders $\mathbf{p}_0, \dots, \mathbf{p}_K \in \mathbb{C}^{N_t \times 1}$, and subject to the respective power and GEO interference threshold constraints: $\sum_{k=0}^{K} \|\mathbf{p}_k(t)\|^2 \leq P_t$, and $\sum_{k=0}^{K} |\mathbf{g}_{\text{GEO}}^H(t)\mathbf{p}_k(t)|^2 \leq \Gamma_{\text{thresh}}(t)$, such that $\mathbf{g}_{\text{GEO}}(t)$ is the interference link to the GEO receiver, the LEO-to-user channel is modeled as:

$$\mathbf{h}_k(t) = \sqrt{G_t G_r} \cdot \left(\frac{c}{4\pi f_c d_k(t)}\right)^2 \cdot e^{j2\pi\xi_k(t)} \cdot \mathbf{g}_k(t), \quad (1)$$

where $d_k(t)$ is distance to user k, G_t and G_r are transmit and receive antenna gains, and $\mathbf{g}_k(t) \sim \mathcal{CN}(0, \mathbf{I})$ is Rayleigh fading [3]. Doppler shift is introduced as a phase rotation $e^{j2\pi\xi_k(t)}$. Channel estimation follows: $\hat{\mathbf{h}}_k(t) = \mathbf{h}_k(t) + \mathbf{e}_k(t), \quad \mathbf{e}_k(t) \sim \mathcal{CN}(0, \sigma_e^2\mathbf{I})$, to satisfy the imperfect CSI assumption. $\mathbf{g}_{\text{GEO}}(t)$ can be either estimated via spectrum sensing or predicted from satellite orbital ephemerids [1].

III. QCIM-RSMA for GEO–LEO Coexistence

Fig. 1a (Right), summarizes how RSMA precoding is optimized under cognitive interference constraints using the QCIM module which seeks to solve the following problem:

$$\max_{\mathbf{p}_0,\dots,\mathbf{p}_K,\alpha} \quad w_0 R_0(t) + \sum_{k=1}^{K} w_k R_k(t), \quad (2a)$$

$$\text{s.t.} \quad \sum_{k=0}^{K} \|\mathbf{p}_k(t)\|^2 \leq P_t, \quad (2b)$$

$$\sum_{k=0}^{K} \left|\mathbf{g}_{\text{GEO}}^H(t)\mathbf{p}_k(t)\right|^2 \leq \Gamma_{\text{thresh}}(t). \quad (2c)$$

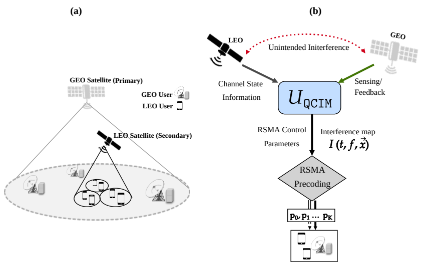
$R_{0,k}$ and R_k represent the common and private stream decoding rates, α as the power-splitting parameter. $\mathcal{I}(t, f, \vec{x})$ is then constructed using CSI and GEO feedback, and fed into U_{QCIM} to generate optimized RSMA control variables.

For real-time interference dynamics, a cognitive interference map is defined below:

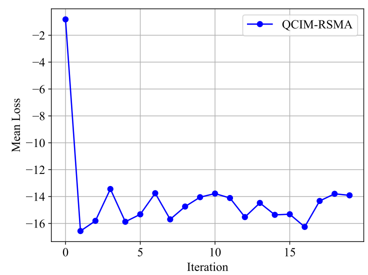
$$\mathcal{I}(t, f, \vec{x}) = \sum_{m=1}^{M} \sum_{k=1}^{K} \left|\mathbf{g}_{\text{GEO}}^{(m,k)}(t, f, \vec{x}) \cdot \mathbf{p}_k^{(m)}(t)\right|^2. \quad (3)$$

$\vec{x} \in \mathbb{R}^3$ is the spatial coordinate, $\mathbf{g}_{\text{GEO}}^{(m,k)}(t, f, \vec{x})$ is the channel gain between m LEO beam transmitting user k's stream and the GEO terminal at location $\vec{x}$, and $\mathbf{p}_k^{(m)}(t)$ is the corresponding RSMA precoding vector.

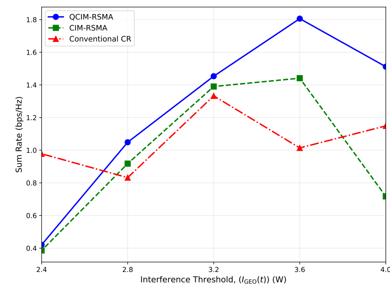
Remark: Eq. (3) captures the aggregate LEO interference at a spatial point $\vec{x}$, enabling spatio-temporal interference



(a) QCIM-RSMA architecture: (Left) GEO-LEO coexistence scenario (Right) Quantum optimization module



(b) Training loss convergence



(c) Sum rate vs. GEO interference threshold

Figure 1: (a) System model and simulation result

control. The real-time constraint in Eq. (2c) is thus a sampled evaluation of $\mathcal{I}(t, f, \vec{x})$ against a dynamic GEO threshold. Unlike conventional CR-based methods such as [7], which enforce per-beam static constraints:

$$f^{m}_{m',u',k} \cdot \rho_{m,k} \leq \Gamma_{\text{thresh}}, \quad \forall m, k, \tag{4}$$

QCIM integrates quantum optimization with spatio-temporal mapping, making it adaptable to orbital motion and environmental variability.

A. Quantum-Assisted RSMA Optimization via QCIM

The QCIM module encodes CSI and GEO interference constraints into a parameterized quantum circuit with: A normalized vector $\mathbf{c}_{\text{norm}} \in \mathbb{R}^{2KN_t}$ acts as input. A circuit with $N_q = \lceil \log_2(N_t K) \rceil + 1$ qubits, having a custom ZZ feature map $\mathbb{U}_{\text{ZZ}}(\mathbf{c}_{\text{norm}})$, an entangling layer (CZ gates), and Parameterized rotations $R_y(\theta_q^{[c]}) R_x(\theta_q^{[p]})$ is defined. During measurement, an observable $\hat{O} = Z^{\otimes N_q}$ over N_{shot} samples is simulated. The output $\text{QCIM}_{\text{out}} = [u_1, ..., u_K, \alpha]$ hence controls: $\rho_{\text{priv}} = (P_t - \rho_0)^{\alpha}$, and, $w_k = u_k \cdot \frac{P_{\text{eff},k}}{P_{\text{eff},k} + I_k}$, where $P_{\text{eff},k}$ is the effective received power, and I_k the interference. Then, precoders are updated via quantum-optimized MMSE: $\mathbf{p}_0' = (\mathbf{H}_{\text{eff},0} + \sigma^2 \mathbf{I})^{-1} \mathbf{H}_{\text{eff},0} \sum_k w_k, \mathbf{p}_k' = w_k (\hat{\mathbf{h}}_k^H \hat{\mathbf{h}}_k + \sigma^2 \mathbf{I})^{-1} \hat{\mathbf{h}}_k^H$, given $\mathbf{H}_{\text{eff},0}$ as the effective channel for $s_0(t)$. Parameters θ are trained to minimize:

$$\begin{aligned} \mathcal{L}(\boldsymbol{\theta}) = &- \sum_{k=1}^{K} w_k R_k(t) + w_0 R_0(t) \\ &+ \lambda \cdot \max\left(0, I_{\text{GEO}}(t) - \Gamma_{\text{thresh}}(t)\right)^2, \end{aligned} \tag{5}$$

using the parameter shift rule for gradient updates, considering $I_{\text{GEO}}(t)$ is the time varying interference at the GEO link.

This section presents simulation results for GEO–LEO coexistence mainly based on parameters from [4]. The QCIM-RSMA setup uses $N_{\text{episode}} = 20$, $N_{\text{data}} = 150$, and interference penalty $\lambda = 0.1$.

Figs. 1b and 1c highlight QCIM-RSMA's performance. Fig. 1b shows rapid convergence , while Fig. 1c demonstrates maximum sum rate under varying interference thresholds compared to CIM-RSMA and conventional CR. These results confirm QCIM-RSMA's efficiency for dynamic, interference-aware spectrum sharing in GEO–LEO networks.

IV. Conclusion

This paper has addressed quantum-assisted interference management for GEO-LEO coexistence using a QCIM-RSMA. It combined classical CSI with quantum optimization of RSMA parameters via cognitive interference mapping. Results validate real-time adaptation within GEO interference constraints.

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