Ablation Study on Feature Engineering Strategies for Fairness-Driven LEO Direct-to-Cell

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***Abstract*—This work presents an ablation study on feature engineering strategies for fairness-aware LEO direct-to-cell (DTC) resource allocation. We systematically evaluate raw channel processing, engineered features, and compressed representations (classical 4D and quantum 2D bottlenecks). Surprisingly, raw channels achieve 45% higher fairness (FDAU = 1.076) than compressed methods (0.710–0.741), revealing a fundamental fairness-compression trade-off where aggressive dimensionality reduction destroys user correlation information critical for balanced rate allocation.**

***Index Terms*—direct-to-cell, fairness, quantum machine learning, resource allocation, RSMA**

I. Introduction

LEO satellite DTC networks enable ubiquitous smartphone connectivity without terrestrial infrastructure [1]. However, dense mega-constellations introduce severe inter-satellite interference, while rapid user mobility and heterogeneous traffic demands complicate fair resource allocation. Traditional optimization methods exhibit prohibitive computational complexity unsuitable for real-time satellite operations [2].

RSMA offers robust interference management through common-private stream splitting [3], while spatial-temporal (ST) extensions exploit Doppler diversity in mobile scenarios [2]. However, existing fairness metrics like capacity-demand gap penalize oversupply and under-supply symmetrically, obscuring meaningful efficiency-fairness tradeoffs [4].

Quantum machine learning demonstrates potential for wireless optimization through enhanced representational capacity [5]. Recent variational quantum circuits achieve strong performance in high-dimensional control tasks [6], yet lack integration with fairness-aware resource allocation for satellite networks.

This work presents an ablation study on ST-RSMA for LEO DTC networks with contributions: **(1)** A FDAU metric with asymmetric logarithmic structure, **(2)** Systematic evaluation revealing raw channels outperform compressed methods by 45%, and **(3)** Analysis identifying fairness-compression trade-offs where dimensionality reduction degrades user correlation preservation.

II. System Model and Q-STPR Framework

A. ST-RSMA with FDAU Metric

A LEO satellite at altitude $h = 600$ km with $N_t = 4$ antennas serves $K = 4$ DTC ground users (each with $M = 2$ antennas) over $T = 2$ time slots. The ST channel to user k at slot t incorporates 3GPP NTN path loss β_k and Doppler shifts:

$$\mathbf{H}_k(t) = \sqrt{\beta_k}\,\mathbf{G}_k(t) \odot \exp(j2\pi f_{D,k} t \Delta t), \tag{1}$$

where $f_{D,k} = v_k f_c / c$ with user velocity $v_k \sim \mathcal{U}[0, 120]$ km/h at carrier frequency $f_c = 20$ GHz.

RSMA transmission combines common stream $s_c(t)$ and private streams $\{s_k(t)\}$:

$$\mathbf{x}(t) = \mathbf{f}_c(t) s_c(t) + \sum_{k=1}^{K} \mathbf{f}_p^{(k)}(t) s_k(t), \tag{2}$$

subject to power constraint $\frac{1}{T}\sum_{t=1}^{T}(\|\mathbf{f}_c(t)\|^2 + \sum_k \|\mathbf{f}_p^{(k)}(t)\|^2) \leq P_{\max}$ and minimum rate $R_k \geq R_{\min} = 1.0$ bps/Hz $\forall k$. The achievable rate per user:

$$R_k = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{R_c(t)}{K} + \log_2(1 + \gamma_{p,k}(t))\right). \tag{3}$$

For heterogeneous demands $D_k \sim \mathcal{U}[2, 6]$ bps/Hz (challenging scenario), FDAU is proposed:

$$\text{FDAU} = \frac{1}{K}\sum_{k=1}^{K} \log\left(1 + \frac{R_k}{D_k}\right). \tag{4}$$

This logarithmic structure provides diminishing returns for oversupply while heavily penalizing under-supply, enabling efficient surplus allocation unlike symmetric CD-gap metrics.

B. Q-STPR Architecture

Fig. 1 illustrates Q-STPR's three-stage pipeline. **Stage 1** extracts $D = 38$ dimensional features comprising spatial characteristics (channel strength, correlations, phase relationships), temporal dynamics (magnitude variation, phase change), and Doppler statistics (shifts, velocity proxies).

Stage 2 employs a 2-qubit VQC for ultra-compact feature compression. After Hadamard initialization for superposition, feature encoding via $\mathbf{x} = \tanh(\mathbf{W}_{\text{enc}}\boldsymbol{\phi})$ followed by R_y rotations creates input-dependent quantum states. Linear Controlled-Z gates induce entanglement between qubits. A variational layer with parametrized R_y and R_z rotations yields 4 trainable quantum parameters (2 qubits $\times$ 2 rotation types). Pauli-Z measurements extract 2-dimensional quantum features, achieving 19:1 compression ratio (38D$\rightarrow$2D), expanded to 32-dimensional policy $\boldsymbol{\pi} = \tanh(\mathbf{W}_{\text{dec}}\mathbf{q} + \mathbf{b}_{\text{dec}})$.

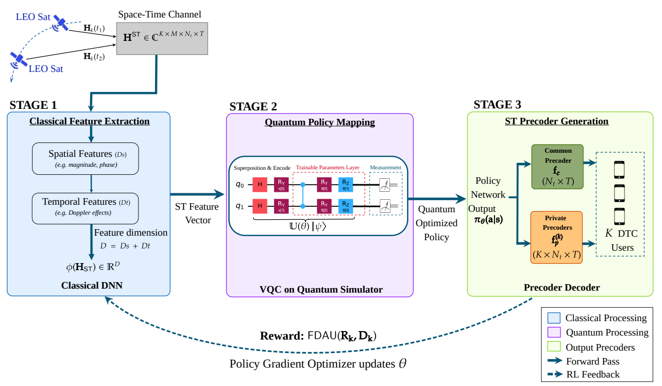

Figure 1: Q-STPR framework. **Top:** LEO satellite serving $K = 4$ DTC users. **Bottom:** Three-stage architecture: **(1)** ST feature extraction (38D), **(2)** 2-qubit VQC (4 parameters, 19:1 compression), **(3)** ST precoder generation.

Stage 3 maps the policy to space-time precoders $\{\mathbf{f}_c(t), \mathbf{f}_p^{(k)}(t)\}$ via time-specific decoders with power normalization. The model maximizes expected FDAU subject to power and minimum rate constraints through penalty-based policy gradient optimization:

$$\mathcal{L}(\boldsymbol{\theta}) = -\mathbb{E}_{\mathbf{H},\mathbf{D}}\left[\text{FDAU} - \lambda_{\text{pow}}\mathcal{P}_{\text{pow}} - \lambda_{\min}\mathcal{P}_{\min}\right], \quad (5)$$

where $\mathcal{P}_{\text{pow}} = \max(0, P_{\text{avg}} - P_{\max})$ and $\mathcal{P}_{\min} = \max(0, R_{\min} - \min_k R_k)$ are constraint violation penalties.

III. Experimental Results

LEO satellite parameters follow 3GPP NTN standards with $P_{\max} = 30$ dBm, $B_{\text{bw}} = 400$ MHz, noise power $\sigma^2 = -90$ dBm, yielding SNR of 10–20 dB. User velocities span 0–120 km/h with heterogeneous demands $D_k \sim \mathcal{U}[2, 6]$ bps/Hz. Performance evaluation uses 100 test samples.

Fig. 2 shows training convergence across four methods: C-STPR (raw channels), CF-STPR (engineered features), CFB-STPR (classical 4D bottleneck), and Q-STPR (quantum 2D bottleneck). All methods converge within 10 episodes with Q-STPR maintaining lowest variance.

Table I reveals raw channel processing (C-STPR) achieves highest FDAU (1.076), outperforming compressed methods by 45%. Feature engineering degrades fairness by -31.1% (C→CF) through information aggregation. Further compression provides no benefit: classical bottleneck (CF→CFB) shows -1.6% loss, while quantum compression (CFB→Q) yields additional -2.6% degradation. This demonstrates that fairness requires preserving user-specific correlations, which compression destroys. C-STPR also achieves highest sum rate (21.14 bps/Hz), suggesting raw channels enable both capacity and fairness.

IV. Conclusion

This ablation study reveals a fundamental fairness-compression trade-off in LEO DTC resource allocation: raw channels achieve 45% higher fairness than compressed methods by preserving user-specific correlations. Feature engineering and compression (classical or quantum) degrade fairness through information loss. Future work includes hybrid architectures and higher-qubit quantum circuits (4–8 qubits) for improved compression-fairness balance.

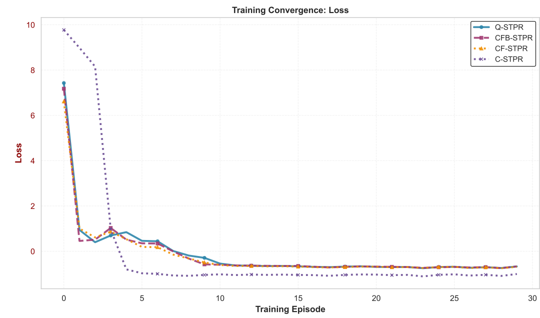

Figure 2: Training convergence: all learning methods achieve similar convergence speed, with Q-STPR maintaining lowest variance.

Table I: Ablation Study: Feature Engineering Impact

Method	Bottleneck	Ratio	FDAU	Sum Rate (bps/Hz)
C-STPR (Raw)	None	1.0	**1.076**	**21.14**
CF-STPR (Feat)	None	1.7	0.741	6.97
CFB-STPR (Class)	4D	9.5	0.729	6.79
Q-STPR (Quant)	2D	19.0	0.710	6.85
Δ(C→CF): -31.1% FDAU; Δ(CF→CFB): -1.6%; Δ(CFB→Q): -2.6%				

BN: bottleneck dimension; Ratio: compression ratio (input/bottleneck)

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