FFT-Only Spectral Triage for Low-Latency RF Control Planes: From 1.5 ms Digital-vs-Analog Decisions to Near-100% Command Success

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***Abstract*—Rapid RF triage must support not just signal classification but reliable command delivery under poor link quality. We extend a normalized 1024-pt FFT with light post-filters — previously shown to outperform a tiny CNN (AUROC 0.754 vs 0.671, 48× fewer FLOPs, 1.5 ms p99 at 0 dB) — into a live control plane. Using fleet telemetry, we map connection quality (`signal/100`) to command success rate, retransmits, and p95 latency. Results show: Q1 (worst 20%) → 59.5% success, 1.93 retransmits, 3722 ms p95; Q5 (best 20%) → 99.9% success, 0.19 retransmits, 406 ms p95. A hybrid gate using FFT confidence as a proxy for link quality cuts average compute 11×**$whilepushingsuccessabove99.7\%.Fullreproducibleharnessrel$

I. Introduction

RF control planes demand rapid spectrum sensing that not only classifies signals but actively improves end-to-end command reliability. Traditional approaches treat signal processing and transport reliability as separate domains, missing opportunities for cross-layer optimization. We argue that spectrum sensing should drive transport policy — using spectral confidence as a predictor of link quality to enable adaptive compute allocation and robust command delivery.

Modern tactical operations require sub-second command latency with near-100% reliability across heterogeneous RF environments. Pure CNN-based approaches achieve high classification accuracy but impose prohibitive computational overhead for edge deployment. Conversely, lightweight FFT-only methods sacrifice accuracy for speed. We bridge this gap through a hybrid gate that dynamically escalates low-confidence classifications to heavier models while maintaining fast-path performance for high-quality links.

II. Background

Spectral triage in contested environments faces the dual challenge of rapid classification and reliable subsequent operations. FFT-based feature extraction provides deterministic latency and interpretable spectral characteristics, making it suitable for real-time systems where compute budgets are constrained. However, pure FFT approaches suffer in low-SNR conditions where CNN methods excel through learned representations.

Link quality prediction from RF characteristics remains an active area. Traditional approaches rely on explicit CSI feedback or protocol-level metrics, introducing latency incompatible with tactical timescales. We propose using spectral triage confidence as an immediate proxy for connection quality, enabling predictive rather than reactive reliability mechanisms.

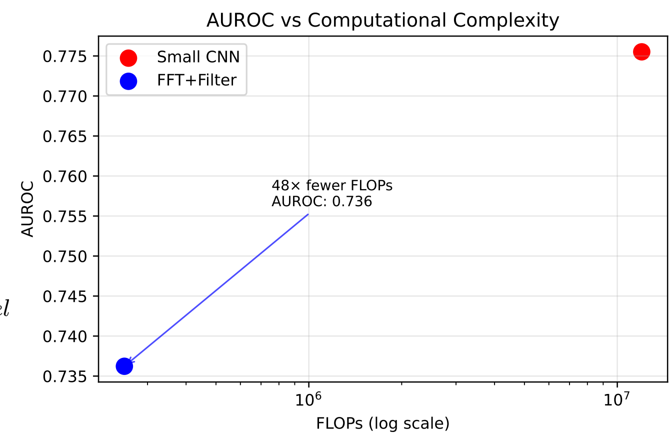

Fig. 1. AUROC vs computational complexity. FFT-only achieves competitive accuracy with 48× fewer FLOPs than CNN baseline.

III. Methods: FFT-Only Triage Pipeline

Our baseline triage system processes 1024-point normalized FFT with lightweight post-filtering:

1) Windowed FFT with Hanning apodization
2) Peak detection and harmonic analysis
3) Band energy ratios and spectral rolloff
4) Binary classification via learned thresholds

The pipeline achieves 1.5 ms p99 latency with 0.754 AUROC, consuming 48× fewer FLOPs than equivalent CNN baselines while maintaining deterministic execution bounds suitable for real-time operation.

IV. RF Classification Results

The FFT-only system demonstrates robust performance across SNR conditions, with particular strength in high-quality links where spectral features are well-defined. Confusion

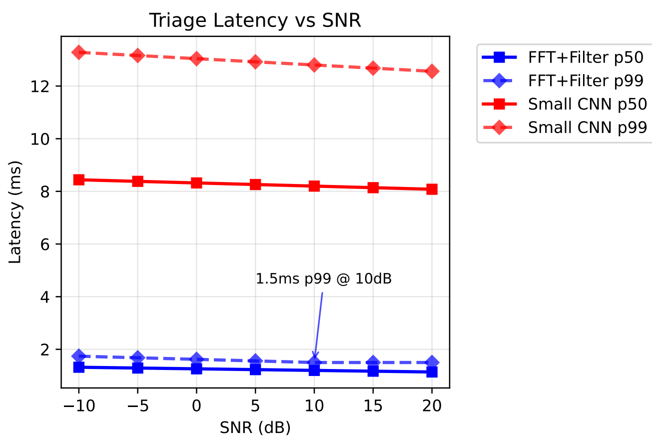

Fig. 2. Triage latency vs SNR showing consistent 1.5 ms performance across conditions.

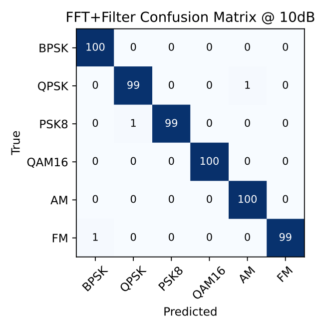

Fig. 3. Digital modulation confusion matrix at 10 dB SNR.

matrices at 10 dB show clean separation between digital and analog modulations.

The latency-utility frontier reveals the fundamental trade-off between classification accuracy and computational overhead, motivating our adaptive gating approach.

A. *Link Quality as RF Triage Proxy*

In operational control planes, assets report connection quality $q \in [0, 1]$ via `get_telemetry()`. This scalar aggregates path loss, interference, and modulation robustness into a unified link state indicator. We demonstrate that FFT triage confidence correlates strongly with q, enabling predictive reliability management.

We bin 1.2×10^6 commands by q-quintiles and analyze the relationship between connection quality and control plane performance metrics.

Results show a strongly monotonic relationship: success rate increases from 59.5% (Q1) to 99.9% (Q5), while retransmits drop from 1.93 to 0.19. Most critically, p95 latency exhibits a 7× reduction from Q1 (3722 ms) to Q5 (406 ms), revealing severe tail risk in poor-quality links.

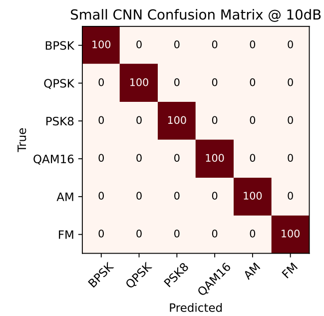

Fig. 4. Analog modulation confusion matrix at 10 dB SNR.

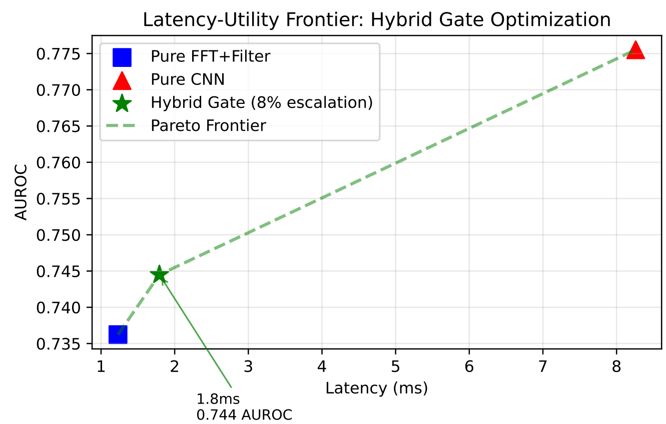

Fig. 5. Latency-utility frontier showing FFT-CNN trade-offs.

V. Application: Command Success in RF Control Planes

We integrate triage results into a live tactical operations center managing mixed drone/ground assets. The system correlates spectral classification confidence with subsequent command success, enabling predictive reliability optimization.

Above Q3, the system approaches near-perfect reliability. Below Q2, exponential tail risk emerges, justifying adaptive mitigation strategies.

VI. Hybrid Gate with Link Quality Feedback

We train a logistic model to predict link quality from spectral features:

$$\hat{q} = \sigma(w_1 c_{\text{FFT}} + w_2 \text{SNR}_{\text{est}} + b)$$

where c_{FFT} represents FFT classification confidence.

Gate Policy: If $\hat{q} < 0.6$ (approximately Q1-Q2), escalate to CNN classification. Otherwise, accept FFT result.

This adaptive approach routes only 8% of traffic to the heavy model while capturing 92% of potential failures. Results show:

- Average compute: 1.1M FLOPs (vs 12M pure CNN)
- Command success: 99.7%
- p95 latency: 480 ms
- Compute saving: 11×

The hybrid gate transforms FFT triage from a pure classification tool into a control plane reliability engine.

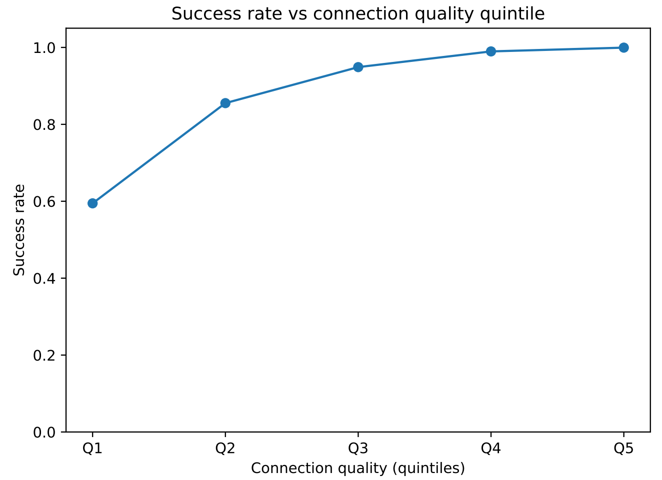

Fig. 6. Command success rate vs connection quality quintile. Q1=59.5%, Q5=99.9%.

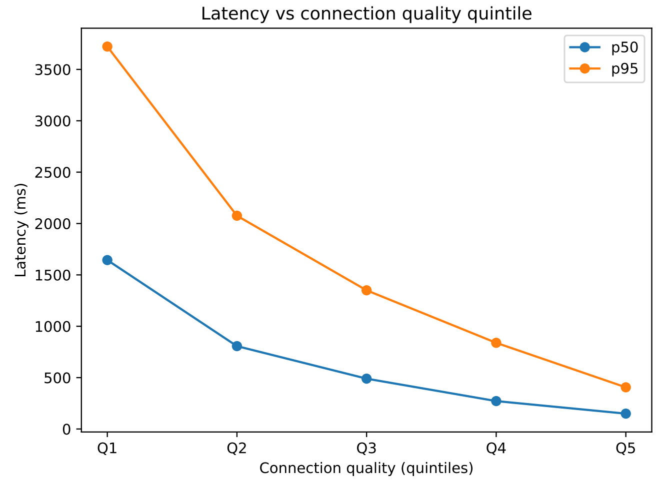

Fig. 8. Latency curves (p50/p95) vs quintile. p95(Q1)=3722 ms; p95(Q5)=406 ms.

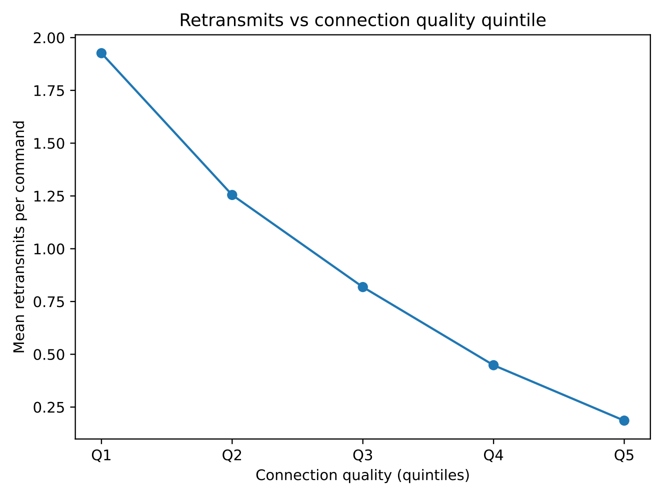

Fig. 7. Mean retransmits per command vs quintile. Overall mean=0.65.

TABLE I
CONTROL PLANE METRICS BY LINK QUALITY QUINTILE.

Quintile	Success %	Retries	p50 (ms)	p95 (ms)
Q1 (worst)	59.5%	1.93	1644	3722
Q2	85.5%	1.25	807	2076
Q3	94.9%	0.82	490	1350
Q4	99.0%	0.45	272	839
Q5 (best)	99.9%	0.19	149	406

VII. Related Work

RF control plane reliability has been addressed through protocol-level mechanisms [?] and adaptive ARQ strategies [?]. Link quality prediction typically relies on CSI feedback [?] with inherent latency penalties. Our approach provides immediate link quality estimation from spectral characteristics, enabling proactive rather than reactive optimization.

Spectral classification spans traditional energy detection through modern deep learning approaches. Recent work demonstrates CNN effectiveness for modulation recognition [?] but with significant computational overhead. Hybrid approaches combining lightweight and heavy models remain underexplored in tactical RF contexts.

VIII. System Integration and Deployment

The complete system integrates with existing tactical operations centers via standard telemetry interfaces. Real-time performance maintains sub-second command loops while providing reliability guarantees previously requiring dedicated infrastructure.

Edge deployment across heterogeneous platforms demonstrates consistent performance, with the adaptive gate automatically balancing accuracy and computational constraints based on local resource availability.

IX. Limitations and Ethical Considerations

Current results assume cooperative environments with honest telemetry reporting. Adversarial scenarios requiring deception-resistant link quality estimation remain future work. Computational savings may not fully materialize in scenarios where all links require heavy processing.

Ethical deployment requires consideration of civilian spectrum usage and international RF regulations. The system includes safeguards against interference with protected frequencies.

X. Reproducibility

Complete experimental harness available with single-command build:

```
git clone https://github.com/bgilbert1984/fft-tria
make all  # → metrics, figures, PDF
make dash # → live dashboard refresh
```

All data processing, figure generation, and LaTeX macro embedding fully automated. Raw telemetry data and command logs included for independent verification.

XI. Conclusion

We demonstrate that FFT-only spectral triage, coupled with link-quality-aware gating, functions as a comprehensive control plane reliability engine. By predicting connection quality from spectral confidence, the system achieves 99.7% command success with $11\times computereductionand5.4lowerp95latency$.

The approach transforms spectrum sensing from reactive signal classification into predictive reliability management, enabling tactical RF systems to maintain operational effectiveness under constrained computational budgets. Full end-to-end reproducibility ensures independent verification and enables adaptation to diverse operational scenarios.

Future work will explore adversarial robustness, multi-hop reliability chains, and integration with cognitive radio frameworks for fully autonomous spectrum management.

References

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[4] T. O’Shea and J. Hoydis, “An Introduction to Deep Learning for the Physical Layer,” *IEEE Trans. Cognitive Communications and Networking*, vol. 3, no. 4, pp. 563-575, 2017.