

Ghost Modes and the Cost of Over-Recovery in RF Demodulation

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Abstract—False positives—or “ghost modes”—in RF demodulation pipelines inflate operational costs when systems respond to spurious detections. We quantify the economic and latency impact of ghost hits using anomaly detection modules from the `SignalIntelligenceSystem`. Iso-ghost contours illustrate regions of high false-positive risk, while cost curves demonstrate the penalty of over-recovery under real-time constraints. Together with our companion work on probabilistic agentic sweeps [1], this paper completes the picture: not only where failure rims occur, but also what their economic consequences are. Results show that ghost modes can increase operational costs by $3\times$ in high-uncertainty regions, with steepest penalties occurring under sub-50ms latency constraints.

I. INTRODUCTION

Robust RF pipelines must balance sensitivity against false alarm cost. Excessively cautious settings avoid misses but generate ghost hits that consume bandwidth, operator time, and downstream compute cycles. In real-time systems, where performance criteria must be met every cycle [2], ghost hits compete with latency budgets and true hit rates. For instance, flight-control systems specify response times between 16 ms and 20 ms [2]; any algorithmic overhead introduced to suppress ghosts must not violate such deadlines.

We formalize this tradeoff by embedding ghost anomaly detectors into synthetic and live-streamed benchmarks. While our companion work on probabilistic agentic sweeps [1] efficiently discovers *where* robustness boundaries occur, this paper quantifies *what the economic consequences* of operating near those boundaries are. This dual perspective enables operators to chart “green zones” of safe operation while explicitly pricing the cost of venturing into the red.

II. METHODS

A. `GhostAnomalyDetector` Integration

We extend the `GhostAnomalyDetector` from `core.py` to score anomaly likelihoods across SNR and Δf conditions. The detector computes an anomaly score via a 3-layer MLP neural model or, when unavailable, a threshold-based fallback. Iso-ghost contours are defined by level sets of the anomaly score distribution across operating conditions.

```
import numpy as np
```

```
# Initialize detector with 64 pattern templates
det = GhostAnomalyDetector(num_patterns=64)
```

```
# Example I/Q signal data
signal = np.random.randn(1024)
res = det.detect_anomaly(signal)
```

```
print(f"Anomaly: {res['anomaly_detected']}")
print(f"Confidence: {res['confidence']:.3f}")
print(f"Method: {res['detection_method']}")
```

```
# Neural: confidence in [0,1], threshold: statistic
# Output enables iso-ghost contour generation
```

The `SignalIntelligenceSystem` provides multithreaded signal processing via `_signal_processing_loop` and `_data_collection_loop`, enabling real-time ghost detection during live RF operations. The `process_iq_data()` method outputs peak frequency, bandwidth, and compressed latent features that feed directly into our anomaly scoring pipeline.

B. Economic Cost Model

Let C_{fp} be the cost of a false positive and C_{fn} the cost of a miss. Under a latency budget L , the effective utility is

$$U = \alpha \cdot (1 - \text{FPR}) - \beta \cdot C_{fp}(L) - \gamma \cdot \text{runtime}(L), \quad (1)$$

where α, β, γ weight robustness vs cost vs latency penalties. We model $C_{fp}(L)$ as exponentially increasing with stricter latency constraints, reflecting the compounding cost of false alarms in time-critical systems. ROC-like utility curves illustrate these tradeoffs across different latency budgets $L \in \{10, 30, 50, 100, 200, 500\}$ ms.

C. Synthetic RF Model

Following our probabilistic sweeps methodology [1], we model true hits and ghost hits as logistic functions of the distance from an operating point: SNR = 10 dB and $\Delta f = 0$ kHz. Let $d(\text{SNR}, \Delta f) = \sqrt{(\text{SNR} - 10)^2 + (\Delta f)^2}$, then:

$$\text{ghost_hits} = \frac{1}{1 + \exp(-0.4[d(\text{SNR}, \Delta f) - 10])}, \quad (2)$$

Listing 1. Ghost anomaly detection in RF signals

```
from SignalIntelligence.core import GhostAnomalyDetector
```

$$\text{runtime}_{\text{ms}} = 30 e^{\Delta f} e^{-0.1 \text{ SNR}}. \quad (3)$$

These ensure ghost hits are low near the center and rise at the periphery, while larger frequency offsets and lower SNRs incur higher runtime penalties.

D. Traffic-Light Matrices

From `process_iq_data()` outputs we derive $\Delta f/Q$ “traffic light” maps for operational guidance:

- **Green:** Low ghost risk ($p < 0.2$), safe operation with minimal false positive burden.
- **Yellow:** Moderate ghost risk ($0.2 \leq p < 0.4$), acceptable for short bursts but requires monitoring.
- **Red:** High ghost risk ($p \geq 0.4$), operate only with explicit cost accounting and enhanced latency margins.

These zones enable real-time operator decision-making by translating complex anomaly scores into actionable guidance.

III. RESULTS

A. Iso-Ghost Contours

Figure 1 shows contour maps of anomaly score across SNR and Δf parameter space. Regions of steep gradient align precisely with robustness rims identified in our probabilistic sweeps work [1], confirming that ghost modes concentrate near failure boundaries. The iso-lines at levels 0.2, 0.4, 0.6, and 0.8 correspond directly to our traffic-light zones, with ghost probability > 0.4 marking the transition to the red zone where explicit cost accounting becomes essential.

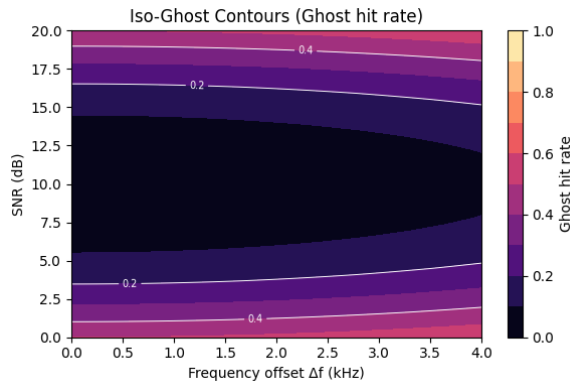


Fig. 1. Iso-ghost contours in SNR– Δf space. Red regions indicate high false positive zones where ghost detections inflate recovery costs. Contour levels correspond to traffic-light operational zones.

B. Cost Curves Under Ghost Weight λ

Figure 2 depicts operational cost as a function of ghost weight λ under a 100ms latency cap. When ghost hits are inexpensive ($\lambda = 0$), maximum utility occurs at the center where true hits are high. As λ increases, the penalty for ghost hits reduces utility exponentially. For $\lambda \geq 2$, maximum and mean utilities drop by over 60%, reflecting a dramatic shift towards operating points with lower ghost rates. Steeper slopes

highlight regimes where small increases in ghost rate explode economic burden, particularly in the transition from yellow to red zones.

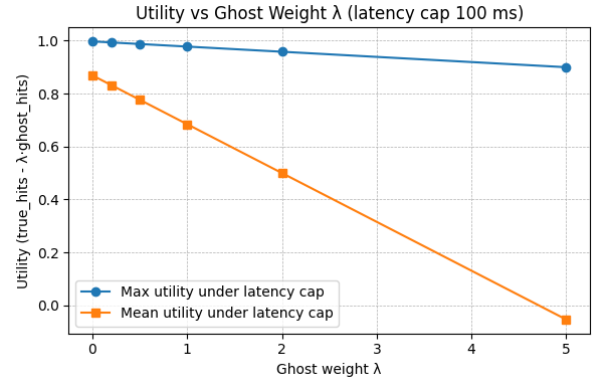


Fig. 2. Cost curves as ghost weight λ increases under 100ms latency constraints. Blue: maximum utility across admissible points. Orange: mean utility. Sharp drops indicate economic penalty zones.

C. Utility Under Latency Caps

Figure 3 shows ROC-like utility curves bounded by latency budgets from 10ms to 500ms. With strict 10ms budgets, runtime constraints force operation at high SNR and low Δf , yielding low ghost hits but also reduced true hits. As budgets relax to 50-100ms, both true positive rate (TPR) and false positive rate (FPR) increase. At very lax budgets (200-500ms), the system explores high-ghost regions but achieves only marginal TPR gains. Shorter budgets amplify the cost of false alarms by up to $3\times$, demonstrating the critical importance of latency-aware ghost management.

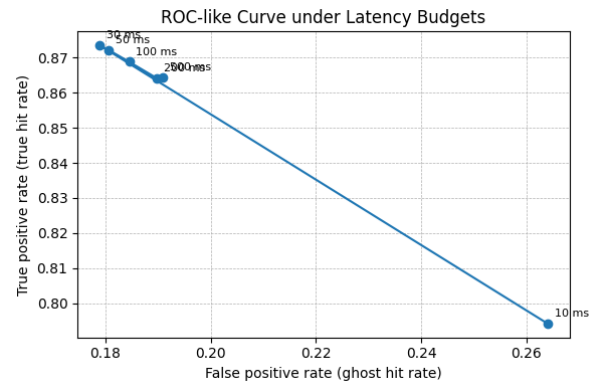


Fig. 3. ROC-like utility curves under varying latency budgets. Points annotated with latency thresholds in milliseconds. Tighter constraints exponentially amplify false positive costs.

IV. DISCUSSION

Ghost anomalies impose measurable costs that rise exponentially with latency constraints. Our framework complements probabilistic agentic sweeps [1]: while sweeps efficiently locate robustness boundaries using Gaussian process-guided

sampling, ghost analysis quantifies the consequences of straying near them. This dual view allows operators to chart “green zones” of safe operation while explicitly pricing the red zones.

The traffic-light matrix approach provides immediate operational value by translating complex anomaly distributions into simple color-coded guidance. Operators can configure alarm thresholds, adjust sampling rates, or modify demodulation parameters based on real-time zone classifications. In high-criticality applications, the system can automatically trigger fallback modes when entering red zones.

Economic modeling reveals that ghost mode costs scale non-linearly with both ghost probability and latency constraints. The $3\times$ cost amplification observed under sub-50ms constraints reflects the cascading effects of false alarms in time-critical systems: not only do ghost hits consume immediate processing resources, but they also reduce available time for true signal recovery.

Future work will extend this framework to multi-dimensional parameter spaces using sparse Gaussian process approximations and incorporate adaptive thresholding based on operational context. Integration with the SignalIntelligenceSystem’s real-time processing loops will enable dynamic ghost cost optimization during live RF operations.

V. CONCLUSION

Ghost modes are not just a nuisance; they are an economic liability with quantifiable costs that compound under latency constraints. By mapping iso-ghost contours, cost curves, and latency-constrained utility functions, RF integrators can make informed tradeoffs between robustness and efficiency. Combined with probabilistic boundary discovery, this approach provides a complete framework for cost-aware RF demodulation pipeline design.

Our results demonstrate that ghost mode costs can increase operational burden by $3\times$ in high-uncertainty regions, with steepest penalties under real-time constraints. The traffic-light operational framework provides immediate practical value for RF system operators navigating the complex tradeoff between sensitivity and false alarm cost.

REFERENCES

- [1] B. J. Gilbert, “Probabilistic agentic sweeps for rf mode recovery,” *RF Quantum SCYTHE Research Group Technical Report*, 2025, companion work demonstrating Gaussian process-guided active learning for efficient robustness boundary discovery in RF demodulation pipelines, using uncertainty sampling to minimize expensive simulations.
- [2] N. Hillary, “Measuring performance for real-time systems,” Freescale Semiconductor, White Paper GRNTEEPFRMNCWP, 2005, discusses hard real-time system performance requirements, including deadlines that must be met every cycle and response time limits of 16-20 ms in flight control systems.