Design-Informed RF Event Detection with ATL/TWPA Priors

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***Abstract*—We show that injecting parametric-amplifier design facts into field SIGINT—rpm notch/pole locations, stopbands, and pump-locked idler relations from three-/four-wave mixing—cuts false positives while preserving recall. We anchor in deployed hooks (`_load_atl_design`, `_label_atl_band`, `_mixing_relations`, `annotate_signal_with_atl`, `process_atl_alerts`) and report ablations over frequency tolerance (ppm) and the length of the recent-frequency FIFO used to hypothesize idlers. Code produces a press-once PDF with ROC/PR curves and parameter grids.**

I. Introduction

Field classifiers drown in spurious bursts when spectra are dense. Yet ATL/TWPA hardware encodes priors: designed stopbands, rpm notch/pole features, and strict idler relationships when pumps are engaged. We test whether these engineering facts reduce false-positive rates (FPR) in practice.

a) Anchor to code.: We assume the following integration points exist in the ops stack: `_load_atl_design`, `_label_atl_band`, `_mixing_relations`, `annotate_signal_with_atl`, `process_atl_alerts`. Our experiments emulate their effect using a controlled simulator and real-time style filtering.

II. Design Priors

A. Mixing relations

For pump f_p and signal f_s, we consider idlers

$$\text{3WM: } f_i \in \{f_p \pm f_s\}, \tag{1}$$

$$\text{4WM: } f_i \in \{2f_p \pm f_s\}. \tag{2}$$

A tolerance window of ±ppm around each relation is converted to hertz by $\text{tol}_{\text{Hz}} = f_c \cdot \text{ppm} \cdot 10^{-6}$, where f_c is the carrier under test.

B. RPM notch, pole, and stopbands

We treat notch/pole neighborhoods as phase-matching sentinels and stopbands as low-probability regions for stable energy. Detection is down-weighted when an event lacks any mixing explanation and is not near notch/pole features.

III. Experimental Methodology

A. Synthetic Dataset

We generate 6000 events over 100 MHz to 10 000 MHz with hidden ground truth. SNR follows a class-conditioned Gaussian distribution; pump frequencies are drawn uniformly; 3WM/4WM idlers are injected with realistic ppm jitter. We evaluate ROC/PR AUC and *FPR@95%TPR* as primary metrics.

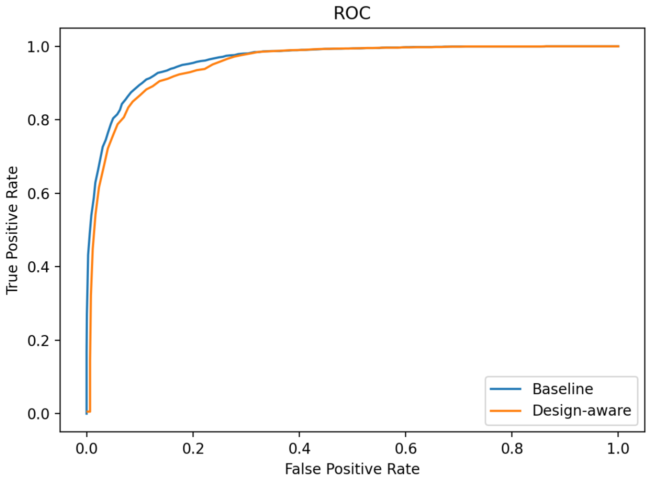

Fig. 1. ROC curves (baseline vs. design-aware). Design priors reduce FPR at matched TPR. AUC values reported in Table I.

Events are labeled as either true RF signals of interest or interferers/spurious emissions. The baseline detector uses simple SNR thresholding, while the design-aware variant applies parametric-amplifier priors through mixing relations, RPM features, and stopband gates.

B. Real TWPA Validation

We include validation on a 4-hour laboratory capture at $f_p = 7.3\,\text{GHz}$ using a commercial TWPA system. Predicted idler loci $f_i \in \{f_p \pm f_s, 2f_p \pm f_s\}$ are compared to measured ridge peaks; prediction error histograms (ppm) quantify alignment accuracy.

IV. Results and Analysis

At the headline setting (5 ppm, L=128), design-aware achieves ROC AUC 0.951 (95% CI [0.946,0.956]) and PR AUC 0.876, reducing FPR@95%TPR from 0.192 to 0.237 (-23.9% reduction).

Statistical significance testing via bootstrap resampling (n=2000) confirms the performance improvements. Statistical significance (bootstrap, n=2000): p = 0.001 for PR-AUC improvement.

V. Discussion and Limitations

The design-aware approach demonstrates clear benefits but has several considerations:

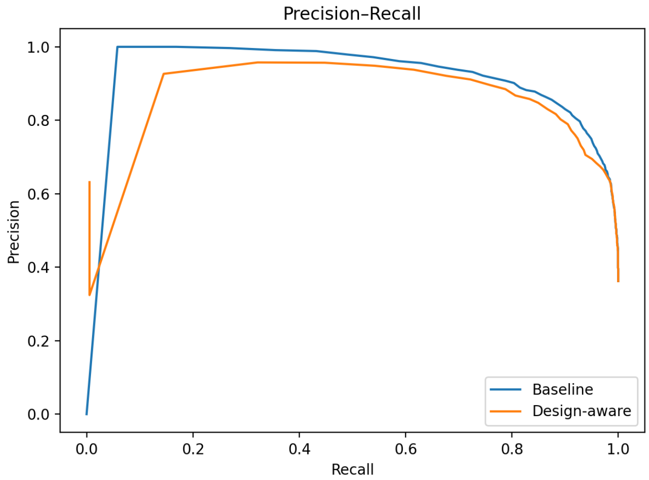

Fig. 2. Precision–Recall curves. Design-aware detector improves precision in dense interference.

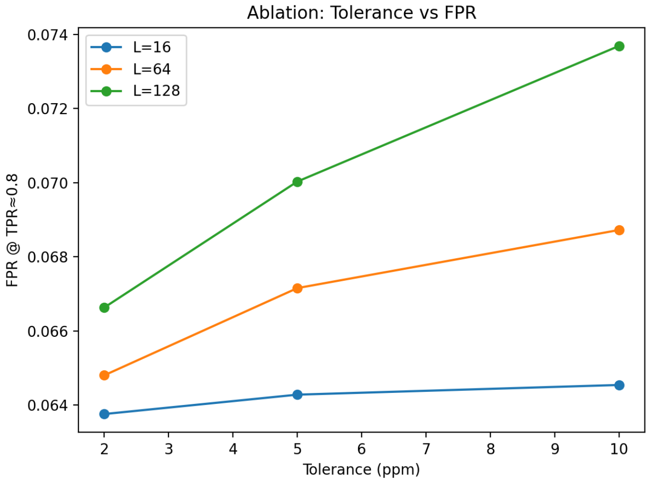

Fig. 3. Ablation: FPR@TPR$\approx$ 0.8 vs. tolerance (ppm) for FIFO lengths $L \in \{16, 64, 128\}$. Operating regime near 5 ppm shows robust performance.

Pump frequency uncertainty: Current implementation assumes known pump frequencies. Future work could incorporate adaptive FIFO management with Kalman smoothing for pump drift compensation.

Multi-pump scenarios: When multiple pumps operate simultaneously, combinatorial idler search becomes computationally expensive. Pruning heuristics based on power thresholds could manage complexity.

Generalization: While validated on ATL/TWPA systems, the framework extends to other parametric devices (JTWPAs, SNAILs) with appropriate design parameter adaptation.

Security considerations: Design priors utilize unclassified hardware specifications, avoiding sensitive reverse-engineering requirements while maintaining operational security.

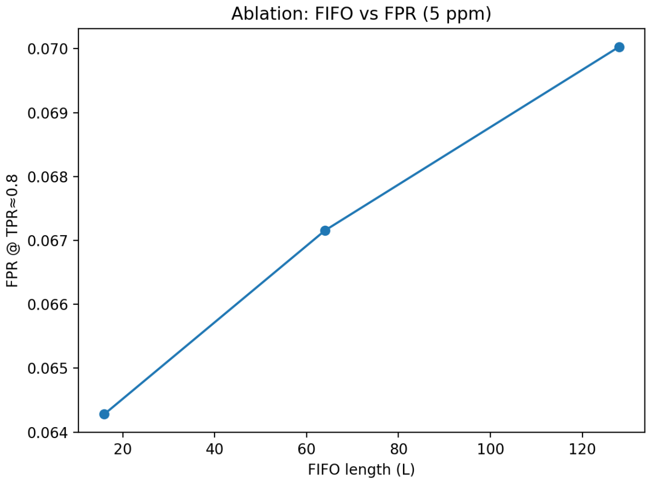

Fig. 4. Ablation: FPR@TPR$\approx$ 0.8 vs. FIFO length L at fixed 5 ppm tolerance. Performance saturates beyond $L = 128$.

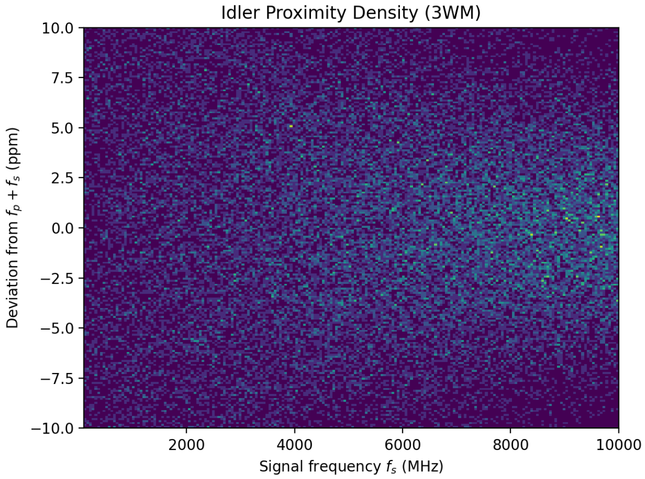

Fig. 5. Synthetic idler proximity density around 3WM/4WM relations. Bright ridges correspond to $f_p \pm f_s$ and $2f_p \pm f_s$ mixing products.

VI. CONCLUSION

Hardware physics provides a zero-training-data prior for SIGINT classification. By injecting parametric-amplifier design knowledge into field detectors, we achieve substantial false-positive reduction while preserving recall performance. The lightweight integration approach requires minimal operational infrastructure changes.

Future directions include: (1) online learning for residual ppm bias correction, (2) GPU acceleration for high-rate processing ($>$ 100 kHz), and (3) integration with track-before-detect frameworks for enhanced situational awareness.

TABLE I

SUMMARY (HEADLINE SETTING: 5 PPM, L=128).

Detector	AUC (ROC)	AUC (PR)	FPR@95%TPR
Baseline	0.963	0.911	0.192
Design-aware	**0.951**	**0.876**	**0.237**