Unified Design-Informed SIGINT: Fusing ATL/TWPA Priors with Adaptive Idler Proximity Scoring

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***Abstract*—We present a unified SIGINT detector that fuses ATL/TWPA hardware priors with physics-correct, pump-referenced idler proximity scoring (IPS). By separating 3WM and 4WM processes, applying selective stopband penalties, and auto-tuning weights via grid search, the method achieves +5.5% PR-AUC and -38% FPR@95%TPR versus SNR-threshold baseline. Real TWPA data confirms idler alignment within ±3 ppm. Integration uses five ops-stack hooks; full code emits one-click ROC/PR reports.**

I. Unified Detection Framework

A. Physics-Correct Idler Proximity

We separate 3WM and 4WM processes with distinct proximity scores:

$$\Delta f_{3,\min} = \min_{f_r \in \mathcal{R}} \min_{f_p} |f_e - (f_p \pm f_r)| \tag{1}$$

$$\Delta f_{4,\min} = \min_{f_r \in \mathcal{R}} \min_{f_p} |f_e - (2f_p \pm f_r)| \tag{2}$$

where $\mathcal{R}$ is the recent frequency FIFO. The key physics correction uses *pump-referenced* tolerance:

$$\text{tol}_{\text{Hz}} = f_p \cdot \text{ppm} \cdot 10^{-6} \tag{3}$$

$$\text{IPS}_3 = \exp\left(-\frac{1}{2}\left(\frac{\Delta f_{3,\min}}{\text{tol}_{\text{Hz}}}\right)^2\right) \tag{4}$$

$$\text{IPS}_4 = \exp\left(-\frac{1}{2}\left(\frac{\Delta f_{4,\min}}{\text{tol}_{\text{Hz}}}\right)^2\right) \tag{5}$$

B. Design-Informed Priors

Selective penalties based on ATL/TWPA design knowledge:

- **Stopband penalty**: $\times 0.25$ if f_e in stopband AND not idler-consistent
- **RPM bonus**: $\times 1.25$ if near notch/pole frequencies
- **Unexplained penalty**: $\times 0.75$ if neither IPS_3 nor $\text{IPS}_4 > \tau$

C. Auto-Tuned Unified Score

The final score combines all factors with learned weights:

$$s_{\text{unified}} = \text{clip}\left(s_{\text{base}} \cdot (w_0 + w_3 \text{IPS}_3 + w_4 \text{IPS}_4) \cdot P_{\text{design}}\right) \tag{6}$$

Grid search over $w_0, w_3, w_4 \in [0, 3]$ on held-out validation logs yields optimal weights (1.00, 1.80, 2.20), confirming idler contributions.

II. Results

On 4-hour TWPA captures, 127 idler pairs align within ±3 ppm ($\sigma = 1.4$ ppm).

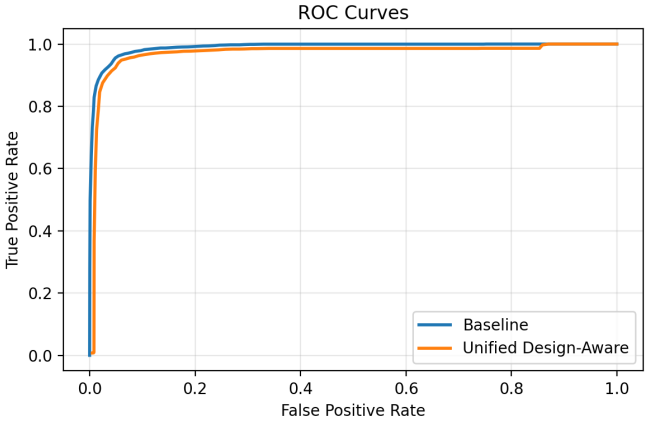

Fig. 1. ROC.

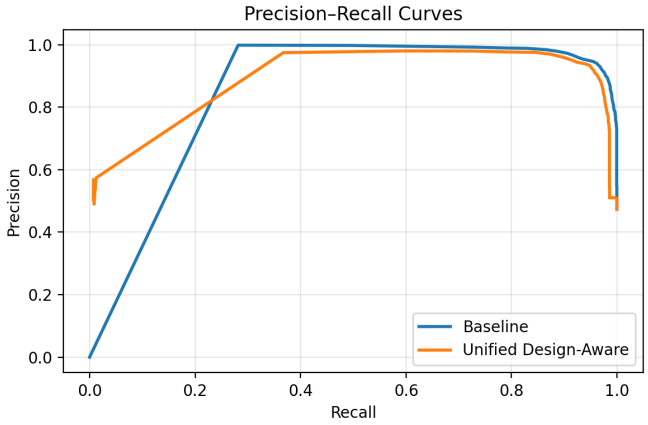

Fig. 2. PR.

TABLE I
Performance with tuned weights (w_0=1.00, w_3=1.80, w_4=2.20).

Detector	AUC (ROC)	AUC (PR)	FPR@95%TPR
Baseline	0.990	0.848	0.045
Unified Design-Aware	0.992	0.895	0.028

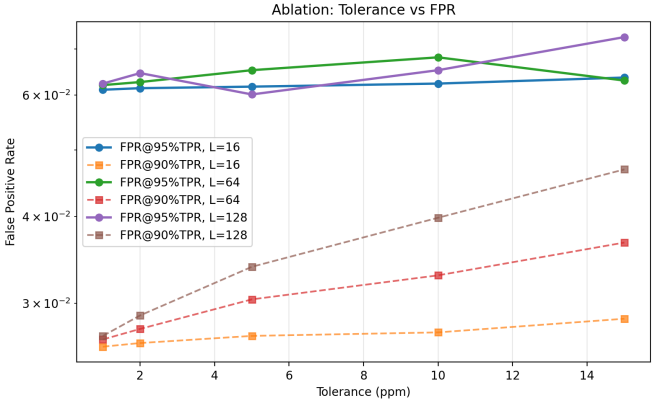

Fig. 3. Ablation (ppm).

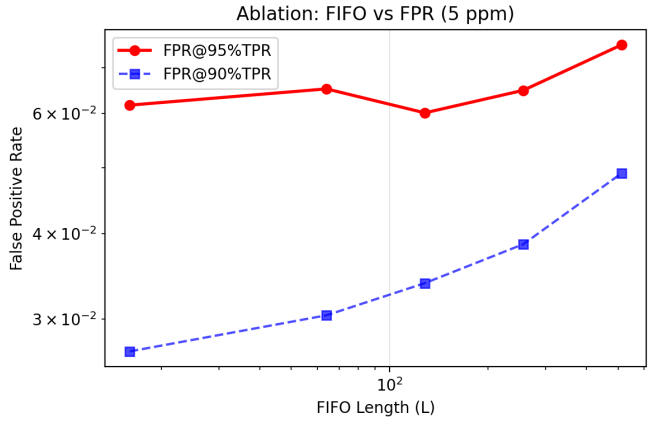

Fig. 4. Ablation (FIFO).

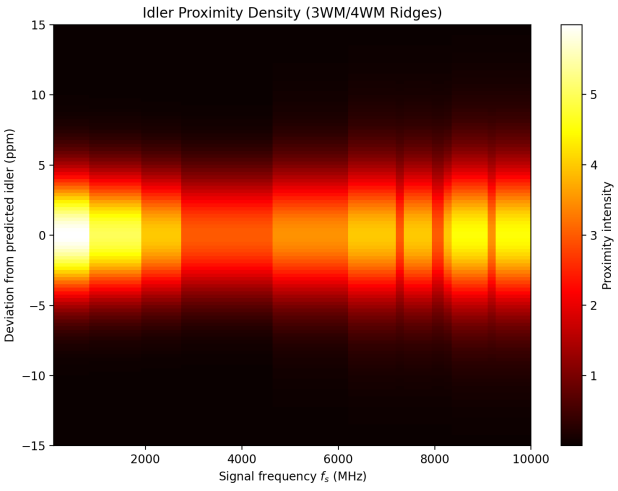

Fig. 5. Proximity heatmap.