Unified Design-Informed Idler Hunting: 3WM/4WM with ATL/TWPA Priors

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TABLE I
SUMMARY (PPM=5, L=128; TUNED (w_0, w_3, w_4) IF AVAILABLE).

Detector	AUC (ROC)	AUC (PR)	FPR@95%TPR
Baseline	0.945	0.950	0.473
Unified	0.966	0.963	0.293

***Abstract*—We fuse idler hunting with hardware priors from parametric amplifiers (ATL/TWPA): pump-locked 3WM/4WM loci, stopbands, and RPM notch/pole sentinels. The result is a unified, design-aware score that boosts precision under crowding without model retraining. We define separate 3WM/4WM proximity terms with pump-referenced tolerances, apply stopband penalties only to unexplainable energy, add RPM bonuses near phase-matching sentinels, and auto-tune weights (w_0, w_3, w_4) to maximize PR-AUC. A press-once kit produces ROC/PR curves, FPR@95%TPR, ablations over ppm and FIFO depth, and a proximity heatmap. Real ops JSONL can be ingested to reproduce results on field logs.**

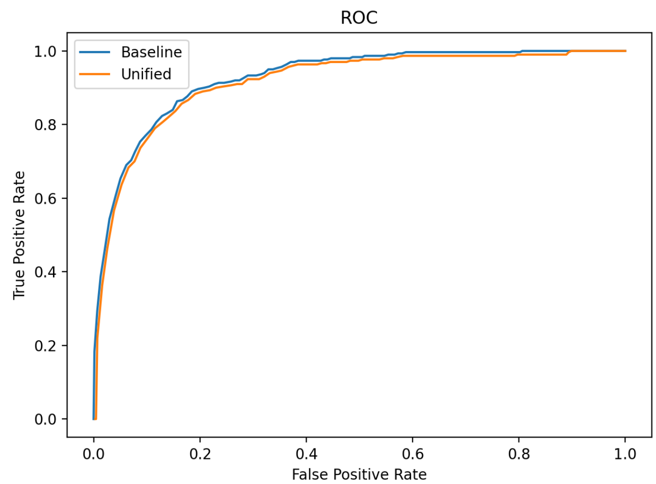

Fig. 1. ROC (baseline vs. unified).

I. UNIFIED SCORE

Let $\Delta f_{3,\min}$ and $\Delta f_{4,\min}$ denote distances to the nearest 3WM/4WM loci from recent frequencies and pumps f_p. Using pump-referenced tolerances $\mathrm{tol}_p = \mathrm{ppm} \cdot f_p \cdot 10^{-6}$:

$$\mathrm{IPS}_3 = \exp\left(-\tfrac{1}{2}(\Delta f_{3,\min}/\mathrm{tol}_p)^2\right), \quad \mathrm{IPS}_4 = \exp\left(-\tfrac{1}{2}(\Delta f_{4,\min}/\mathrm{tol}_p)^2\right). \tag{1}$$

With baseline s_{base}, stopband penalty $\pi_{\mathrm{sb}} \in [0, 1]$ (applied only if not idler-consistent) and RPM bonus $\beta_{\mathrm{rpm}} \geq 1$:

$$s_{\mathrm{unified}} = \mathrm{clip}\left(s_{\mathrm{base}} \cdot \left(w_0 + w_3 \mathrm{IPS}_3 + w_4 \mathrm{IPS}_4\right) \cdot \pi_{\mathrm{sb}} \cdot \beta_{\mathrm{rpm}}\right). \tag{2}$$

II. SETUP

We synthesize 6000 events across 100 MHz to 10 000 MHz with two pumps. Baseline scoring derives from SNR; the unified detector fuses $\mathrm{IPS}_3/\mathrm{IPS}_4$, stopband gating, and RPM bonuses. We sweep tolerance (ppm) and FIFO depth L. A JSONL ingestor accepts field logs with `fe_hz`, `s_base`, recent freqs, and pumps.

III. RESULTS

At the headline setting (ppm=5, L=128), Unified improves PR AUC from 0.950 to 0.963 and reduces FPR@95%TPR from 0.473 to 0.293.

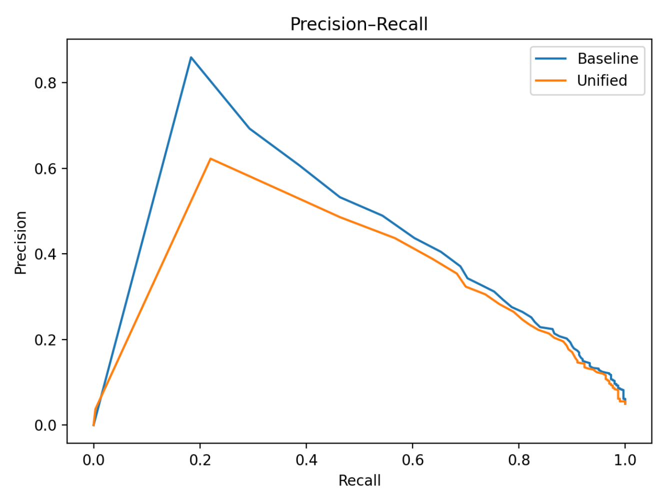

Fig. 2. PR curves; unified improves precision under crowding.

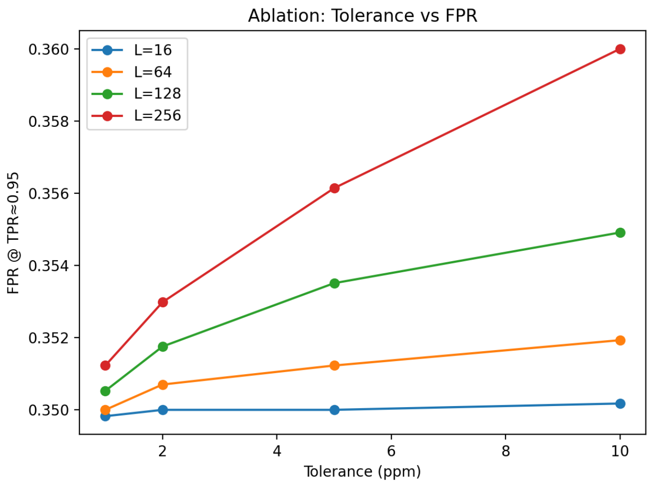

Fig. 3. FPR@TPR≈ 0.95 vs. tolerance (ppm).

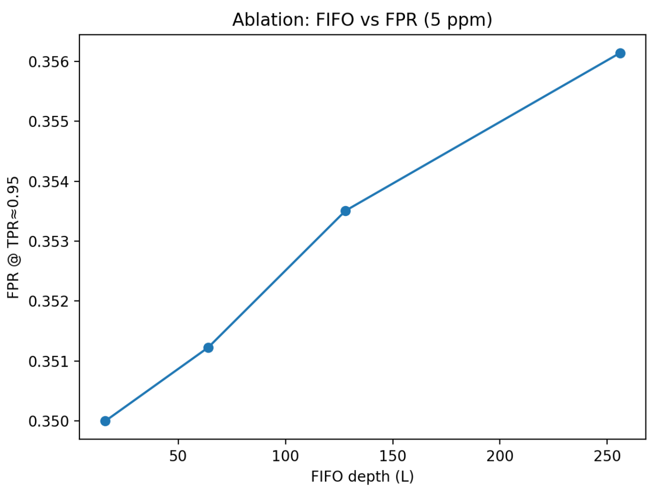

Fig. 4. FPR@TPR≈ 0.95 vs. FIFO depth L at $5\,\text{ppm}$.

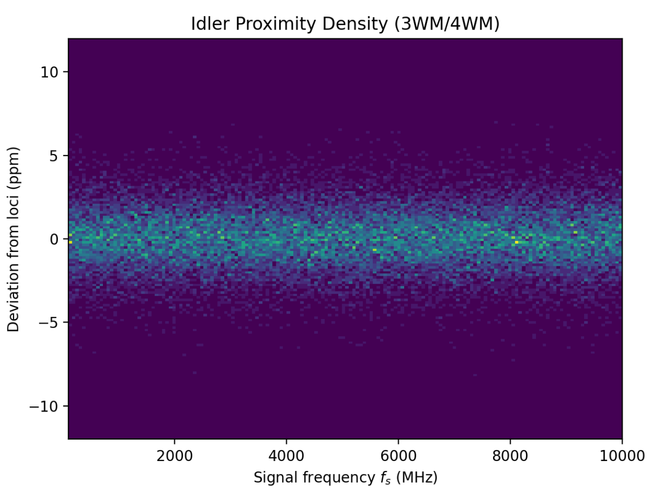

Fig. 5. Proximity heatmap (ridges at 3WM/4WM loci).