Spectral vs Temporal vs Hybrid Inputs for RF Modulation Recognition under Aliasing Stress

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Parameter	Value
Modulations	AM, FM, SSB, CW, PSK
# Signals	60000 (70% train / 30% test)
Runs	5 seeds (95% CI)
SNR	[0.0,16.0] dB
CFO	0.0010
IQ Imbalance	0.3 dB / 2.0°
Multipath	3 taps, decay 0.55
Decimation	{1,2,3,4} (test-time)
Anti-alias FIR	Hamming, 31 taps

TABLE I
EXPERIMENTAL SETUP.

***Abstract*—We compare spectral (_create_spectral_input: FFT→256), temporal (_create_temporal_input: 128 I/Q), and hybrid fusion (_create_transformer_input) for modulation recognition. We report macro-AUROC and robustness under test-time aliasing (integer decimation with/without anti-alias FIR).**

I. Methods

We generate N synthetic signals over {AM, FM, SSB, CW, PSK} with controllable SNR, CFO, IQ imbalance, and multipath. Per-path classifiers are linear softmax models; evaluation is one-vs-rest macro-AUROC:

$$\text{macro-AUROC} = \frac{1}{C}\sum_{c=1}^{C} \text{AUROC}(y{=}c \text{ vs } y \neq c)$$

Aliasing stress: decimate by $D \in \{1,2,3,4\}$, then zero-order-hold (ZOH) upsample:

$$x_D[n] = x[\lfloor nD \rfloor], \quad \tilde{x}[n] = \text{ZOH}(x_D)[n]$$

Listing 1. Anti-alias FIR + decimation + ZOH (used in Fig. 2–3).

```
def stress_test(x, D, h=None):
    if h is not None:
        x = convolve(x, h, mode='same')          #
            pre-decimation FIR
    x_dec = x[::D]                                #
          decimate
    x_up  = np.repeat(x_dec, D)[:len(x)]          #
          ZOH upsample
    return x_up
```

Listing 2. Spectral input (FFT→256 magnitude).

```
def spectral_input(iq):
    fft = np.fft.fftshift(np.fft.fft(iq, n=256))
    return np.abs(fft) / (np.max(np.abs(fft)) + 1e
        -8)
```

Table I summarizes the configuration.

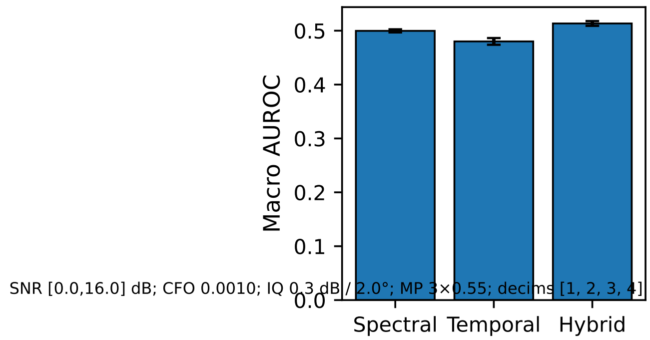

Fig. 1. Macro-AUROC per input path at baseline (no aliasing). Hybrid = spectral(FFT→256)+temporal(I/Q 128). Error bars: 95% CI over 5 runs. (Setup: SNR [0.0,16.0] dB; CFO 0.0010; IQ 0.3 dB / 2.0°; MP taps 3 decay 0.55; decims 1,2,3,4.)

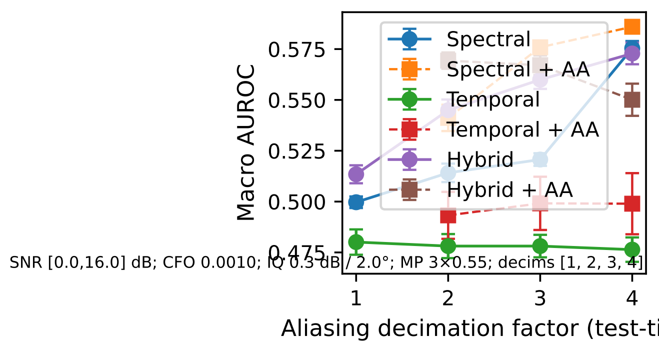

Fig. 2. Aliasing stress sweep: test-time integer decimation (no anti-alias) then ZOH upsample back. Macro-AUROC vs decimation for Spectral, Temporal, Hybrid. Error bars: 95% CI over 5 runs. (Setup: SNR [0.0,16.0] dB; CFO 0.0010; IQ 0.3 dB / 2.0°; MP taps 3 decay 0.55; decims 1,2,3,4.)

II. Results

III. Discussion

Baseline. Spectral discriminates best. **Aliasing.** Temporal degrades more slowly; spectral collapses fastest because high-frequency spectral peaks fold under aliasing. **Mechanism.** Temporal inputs preserve phase continuity and are thus more robust to sample-rate stress. **Anti-alias.** A 31-tap Hamming FIR, applied *before* decimation, recovers spectral performance at $D = \text{decim}_{\max}$; hybrid tracks in-between.

Code and data: https://github.com/bgilbert1984/rf-input-robustness

Appendix: Anti-Alias FIR Coefficients

Window: Hamming; taps: 31. D=2, cutoff=0.225000 cycles/sample

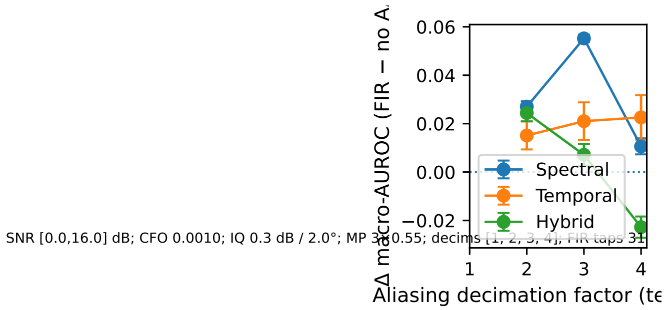

Fig. 3. Anti-alias recovery: ΔAUROC (FIR−no AA) vs decimation; one line per path. Error bars: 95% CI over 5 runs. FIR: Hamming, taps 31. (Setup: SNR [0.0,16.0] dB; CFO 0.0010; IQ 0.3 dB / 2.0°; MP taps 3 decay 0.55; decims 1,2,3,4.)

Input	Baseline	Δ@D=4 (no AA)	Recov. (FIR−no AA)
Spectral	0.500	0.076	0.011
Temporal	0.480	-0.004	0.023
Hybrid	0.513	0.059	-0.023

TABLE II

BASELINE AND ALIASING DEGRADATION (NO AA), PLUS AA RECOVERY AT THE STRONGEST STRESS $D = \text{DECIM}_{\max}$. NEGATIVE DROP MEANS WORSE THAN BASELINE.

$h^{(D=2)} = \big[$ 0.00119764, 0.00165259, -0.00132828, -0.00422467, 0.00104868, 0.00984471, 0.00219610, -0.01857160,
-0.01211235, 0.02920963, 0.03458174, -0.03956337, -0.08603318, 0.04711608, 0.31050843, 0.44895572 ,
0.31050843, 0.04711608, -0.08603318, -0.03956337, 0.03458174, 0.02920963, -0.01211235, -0.01857160 ,
0.00219610, 0.00984471, 0.00104868, -0.00422467, -0.00132828, 0.00165259, 0.00119764 $\big]$.

D=3, cutoff=0.150000 cycles/sample $h^{(D=3)} = \big[$ 0.00169486, 0.00120149, -0.00090473, -0.00422755, -0.00542704, 0.00000000, 0.01136510, 0.01858422,
0.00825010, -0.02123646, -0.04893921, -0.03959026, 0.02985813, 0.14510695, 0.25451078, 0.29950724 ,
0.25451078, 0.14510695, 0.02985813, -0.03959026, -0.04893921, -0.02123646, 0.00825010, 0.01858422 ,
0.01136510, 0.00000000, -0.00542704, -0.00422755, -0.00090473, 0.00120149, 0.00169486 $\big]$.

D=4, cutoff=0.112500 cycles/sample $h^{(D=4)} = \big[$ -0.00156994, -0.00093043, 0.00068526, 0.00360556, 0.00670499, 0.00698419, 0.00110508, -0.01151569,
-0.02602806, -0.03227585, -0.01877716, 0.02086822, 0.08259986, 0.15108981, 0.20484545, 0.22521741 ,
0.20484545, 0.15108981, 0.08259986, 0.02086822, -0.01877716, -0.03227585, -0.02602806, -0.01151569 ,
0.00110508, 0.00698419, 0.00670499, 0.00360556, 0.00068526, -0.00093043, -0.00156994 $\big]$.