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Revisiting R: Statistical Envelope Analysis for Lightweight RF Modulation Classification

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Outline

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- Prior Work
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Motivation for lightweight modulation classification

- **Modulation classification** is essential in **Cognitive Radio**, **Spectrum Monitoring**, and **Electronic Warfare** for identifying signal types and ensuring reliable communication.
- Existing **deep learning** and **feature extraction** methods deliver high accuracy but are often **computationally expensive** and **memory-intensive**.
- There is a growing demand for lightweight, interpretable, and hardware-efficient classification solutions that are suitable for **resource-constrained** environments (e.g., edge devices, embedded systems).

Prior Work

Chan & Gadbois (1985) introduced the R-value metric:

- R value is defined as:

$$R = \frac{\mathrm{Var}(A(t))}{(\mathrm{Mean}(A(t)))^2}$$

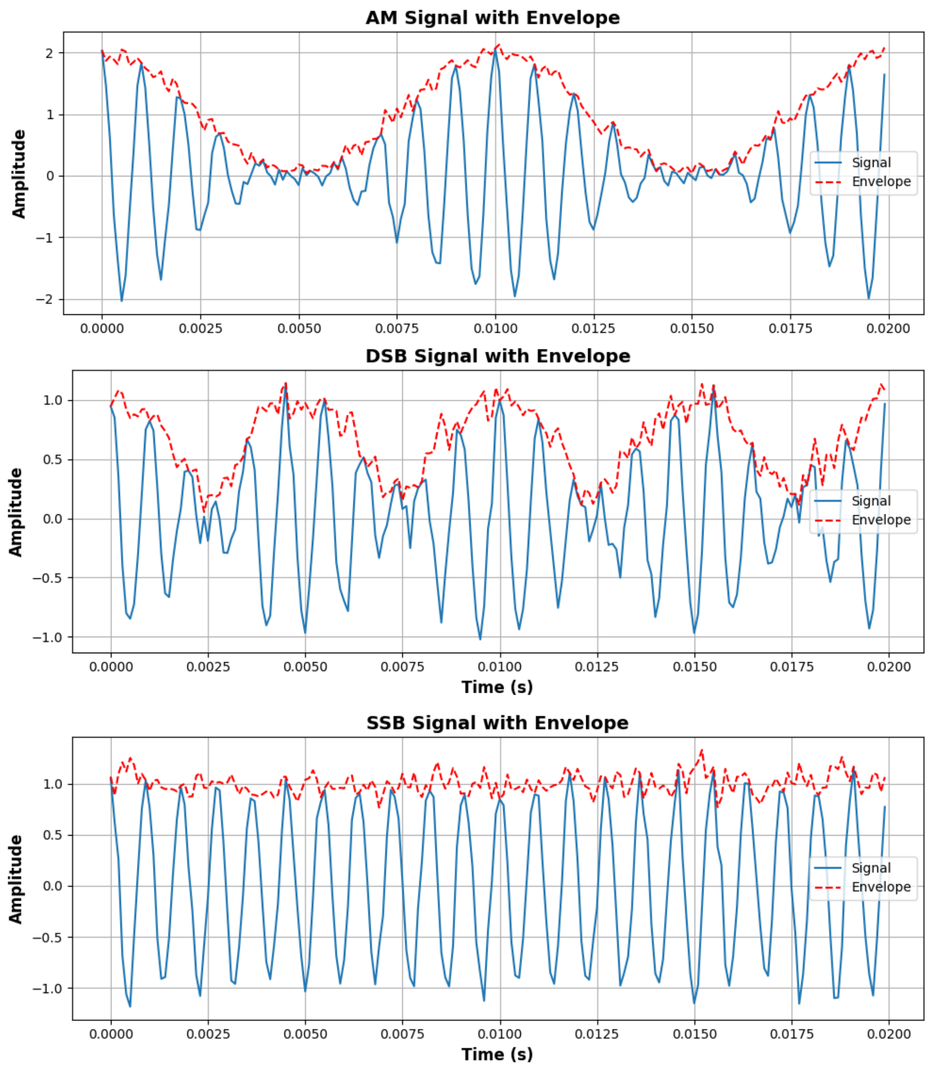
where $A(t)$ denotes the amplitude envelope of the signal.

Envelope Extraction via Hilbert Transform

- The Hilbert Transform constructs the analytic signal:
- $S_a(t) = s(t) + j \cdot \mathcal{H}(s(t))$

where $\mathcal{H}(s(t))$ is the Hilbert Transform of $s(t)$.

- The envelope is given by: $A(t) = \sqrt{s^2(t) + \mathcal{H}^2(s(t))}$



Signal envelopes for AM, DSB, and SSB (top to bottom) demonstrating R value differences using Hilbert-based envelope extraction.

Envelope Extraction via STFT

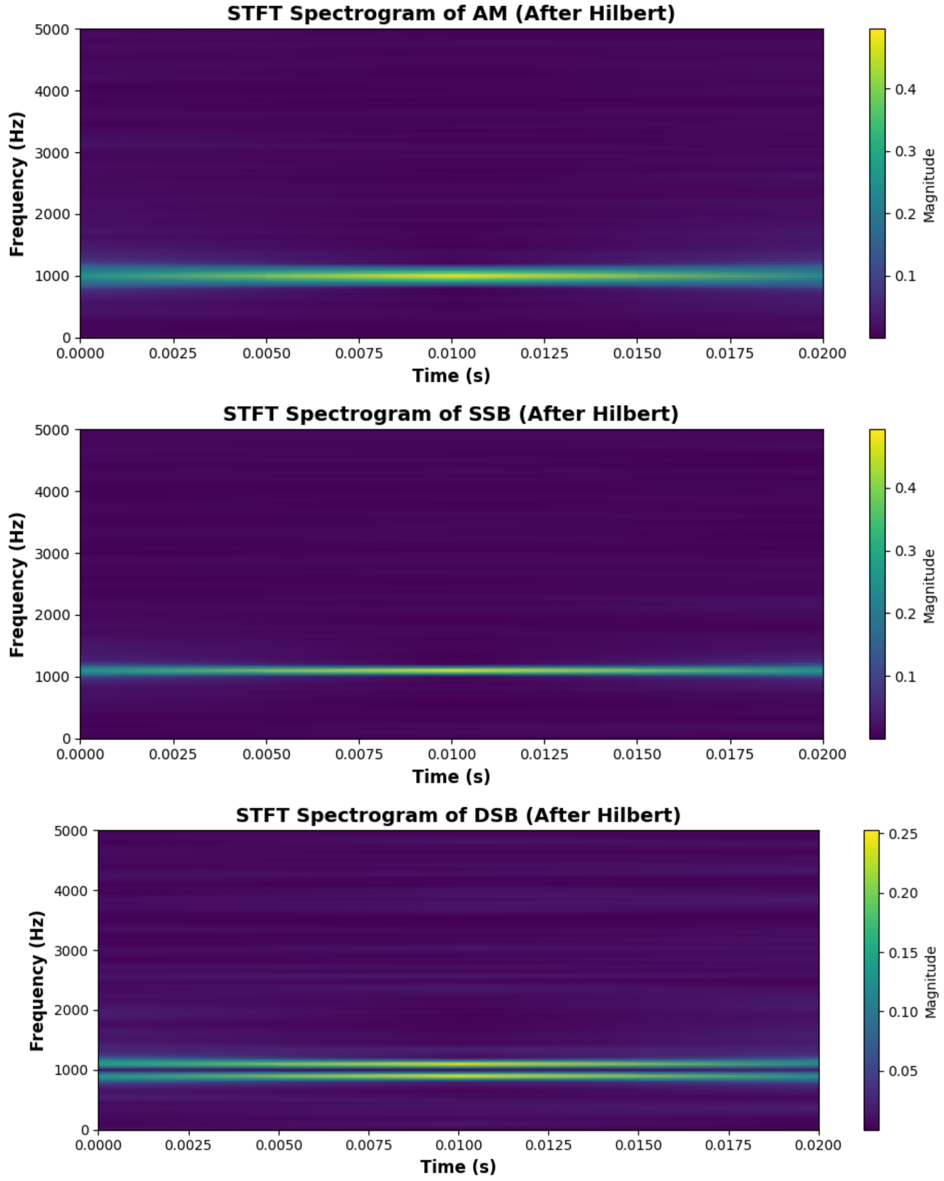
- The STFT-based envelope is computed from the magnitude of the time-localized Fourier spectrum:

$$X(f,t) = \int s(\tau)w(\tau - t)e^{-j2\pi f\tau}d\tau$$

- The envelope is approximated as:

$$A(t) = \sum_{f} |X(f,t)|$$

- This approach is better suited for wideband signals and offers robustness against noise through time-frequency resolution control.



Signal envelopes for AM, DSB, and SSB (top to bottom) demonstrating R value differences using STFT-based envelope extraction.

Our Contributions

- Revisit and statistically validate R-value as a modulation classification metric
- Extend envelope-based analysis using Hilbert Transform and STFT for feature robustness
- Validate performance on a large-scale synthetic dataset (300,000 signals: 100k each for AM, DSB, SSB)

Comparison of Training And Test Signal Parameters

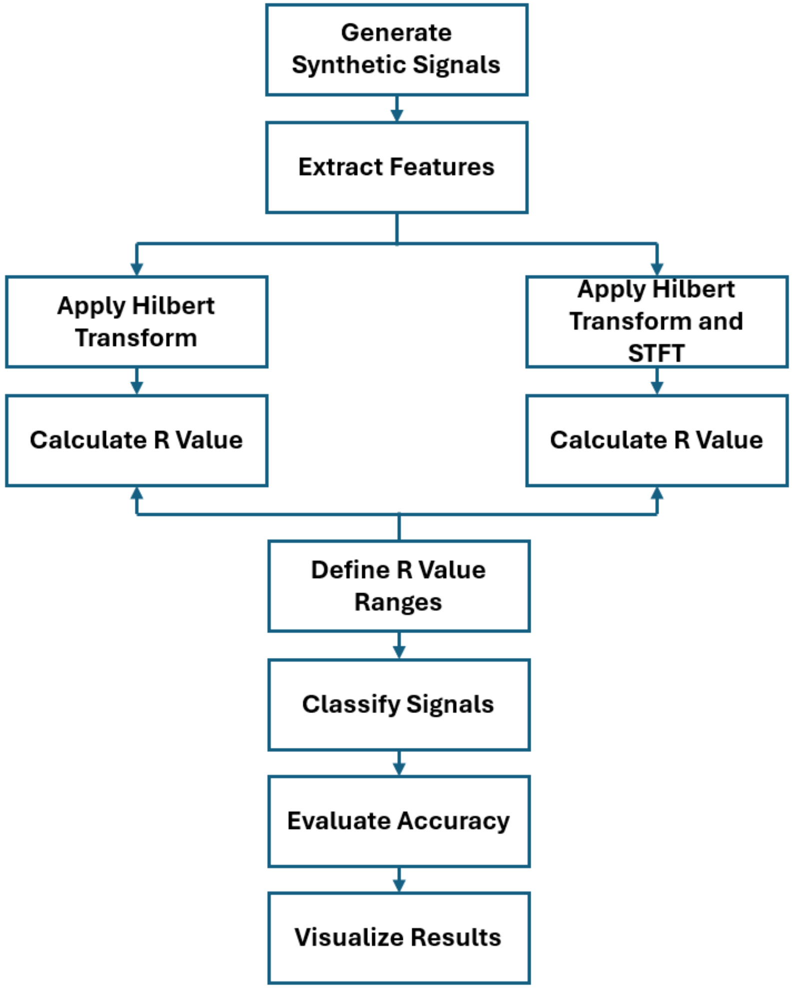
Parameter	Training/Initial Analysis	Test Signals
Modulation Types	AM, DSB, SSB	AM, DSB, SSB
Number of Instances per Class	100	100,000
Total Signals	300	300,000
Carrier Frequency	1 kHz	1 kHz
Sampling Rate	10 kHz	10 kHz
Signal Duration	Not explicitly mentioned	20 ms
Noise Type	Additive Gaussian Noise	Additive Gaussian Noise
Noise Power	0.01	0.01
Envelope Extraction Methods	Hilbert, STFT	Hilbert, STFT

Methodology

- Dataset: 100k signals each for AM, DSB, SSB
- Steps: 1. Synthesize AM, DSB, and SSB signals (100k each)
  2. Apply the Hilbert Transform to extract signal envelopes
  3. Optionally apply STFT for time-frequency feature enhancement
  4. Compute the R-value from extracted features
  5. Classify signals using empirically derived R-value thresholds

Empirical And Theoretical R Value Ranges For AM, DSB, And SSB

Modulation Type	Hilbert R Range	STFT R Range	Chan et al. R Value
AM	0.4297 – 0.4941	3.4561 – 3.9323	0.76 – 0.79
DSB	0.1970 – 0.2603	2.8268 – 3.6373	1.31 – 1.54
SSB	0.0072 – 0.0127	5.2914 – 6.4936	1.00 (constant)



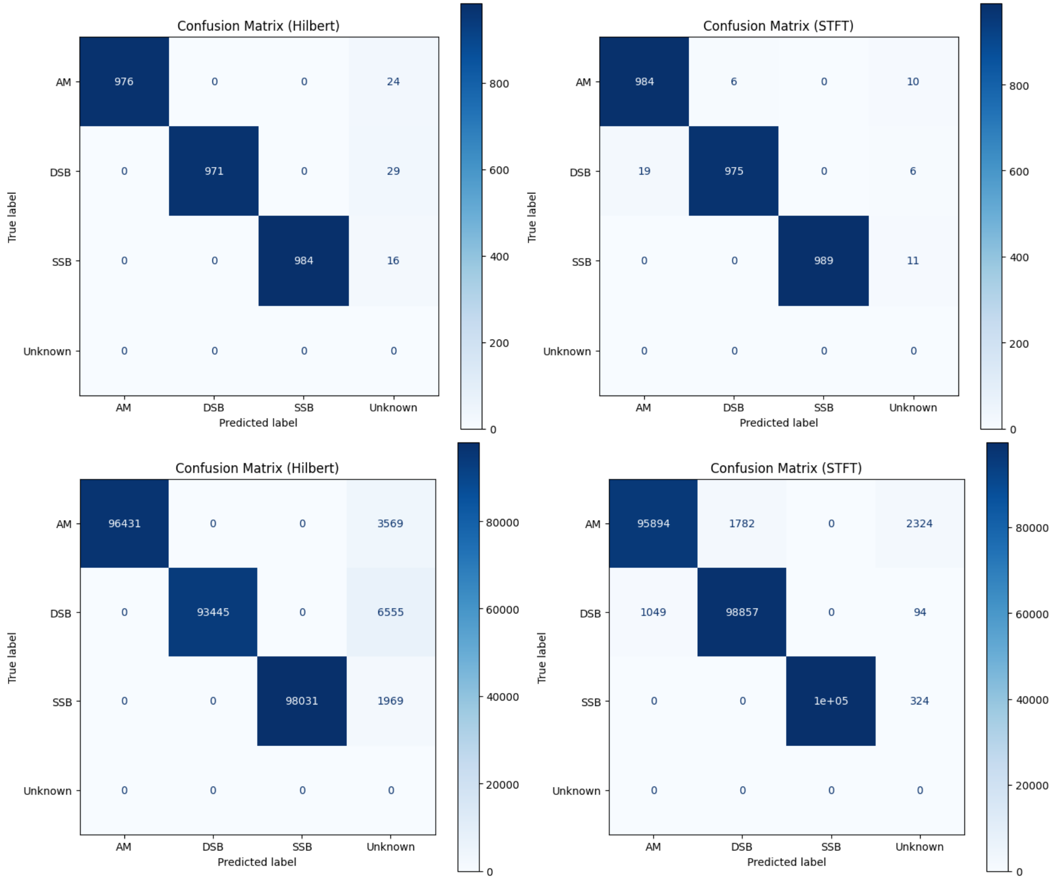
Flowchart of the proposed rule-based classification framework

Results

- STFT-based R-value classification outperforms both Hilbert-only and traditional methods, achieving up to 99.1% accuracy.

ACCURACY COMPARISON OF HILBERT TRANSFORM, STFT-BASED CLASSIFICATION, AND ORIGINAL METHOD

Modulation Type	Hilbert Accuracy (%)	STFT Accuracy (%)	Chan et al. Accuracy (%)
AM	98.60	98.80	90.5
DSB	97.30	99.10	94.0
SSB	97.90	99.00	80.0



Confusion matrices exhibit clear diagonal dominance, indicating low misclassification rates. STFT-based classification achieves slightly higher overall accuracy, especially in distinguishing DSB and SSB under noisy conditions.

Conclusion and Future Work

- **Conclusion**
  - R-value is lightweight, interpretable, and statistically robust for classification
  - STFT applied to signal envelope improves class separability
  - Achieved up to 99% accuracy, outperforming traditional theoretical approaches
- **Future Work:**
  - Combine with wavelet-based and entropy-based features for better generalization
  - Explore deployment on edge devices for real-time, low-power classification

[1] Y. T. Chan and L. G. Gadbois, “Identification of the modulation type ofa signal,” Signal Processing, vol. 16, no. 2, pp. 149–154, 1989.
[2] O. A. Dobre, A. Abdi, Y. Bar-Ness, and W. Su, “Survey of auto-matic modulation classification techniques: classical approaches and newtrends,” IET Commun., vol. 1, no. 2, pp. 137–156, 2007